第 10 回「スペースデブリワークショップ」講演資料集

Proceedings of the 10th Space Debris Workshop

2023 年 2 月

宇宙航空研究開発機構
研究開発部門

Japan Aerospace Exploration Agency
Research and Development Directorate

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第 10 回スペースデブリワークショップ実行委員会委員長
河本　聡美
（宇宙航空研究開発機構　研究開発部門　第二研究ユニット）

Executive Chairperson of the 10th JAXA Space Debris Workshop Executive Committee
KAWAMOTO Satomi
Research Unit II, Research and Development Directorate
Japan Aerospace Exploration Agency

本資料集は、2022 年 11 月 28~30 日に JAXA 調布航空宇宙センター講堂およびオンラインのハイブリッドで開催された、第 10 回スペースデブリワークショップの講演をまとめたものである。本ワークショップは、スペースデブリに関する技術的情報交換、連携促進、裾野拡大等のため、国内最大規模の会合として隔年開催されており、今回は初めて会場およびオンラインのハイブリッドで開催した。また、日本語 Web ページに加え英語ページも開設し、初めて海外からの講演募集および参加登録受付にも踏み切った。その結果、過去最大の約 620 人が参加登録し（前回は約 320 人、前々回約 250 人）、口頭発表 58 件、パネルディスカッション 1 件を無事実施することができた。これもここまで継続できたからこそであり、第 10 回という節目の回を、無事盛況に開催できたことに感謝している。

海外では近年デブリ関係の学会、ワークショップが盛んに開催されているが、第 10 回まで継続的に開催している会合はまだほとんどない。デブリ問題の解決には、デブリ研究者・関係者だけでなく、様々なステークホルダーが集まって現状を正しく共有し、様々な観点から議論すること、そして新たなプレーヤーと共に新しい解決策を探求していくことが重要である。本講演資料集には、世界の最新動向だけでなく、日本におけるデブリ関連活動を網羅する発表が収録されており、本分野に関し最新かつ広範な情報を入手できる資料として役立てば幸いである。そして、本資料がデブリ対策の推進や、我が国の環境技術立国としての貢献、産業界の競争力向上の一助となることを祈りつつ、早くデブリ対策が当たり前のものとなり、デブリに特化したワークショップや資料集が不要となる日を期待している。

口頭セッション

Oral Session

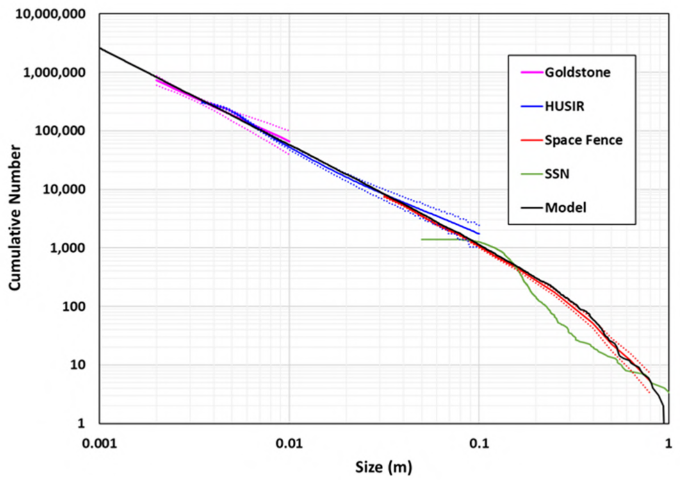
A01 Invited Lecture

Highlights of Recent NASA Orbital Debris Program Office (ODPO) Activities

〇J.-C. Liou (NASA Orbital Debris Program Office)

The NASA Orbital Debris Program Office (ODPO) has a long history of conducting orbital debris measurements using radars, optical telescopes, in-situ measurements, and laboratory experiments, to collect data to monitor the ever-changing orbital debris environment and to characterize the debris populations. The ODPO also uses the measurement data to support the development of different models to assess (1) near-term risk from orbital debris for mission support, (2) long-term risk to the environment for orbital debris mitigation and remediation best practices and policy support, and (3) human casualty risk from the reentries of upper stages and spacecraft.

This presentation will first highlight the ODPO's recent measurement activities from the Haystack Ultrawideband Satellite Imaging Radar (HUSIR), the Goldstone radar, the Eugene Stansbery Meter Class Autonomous Telescope (ES-MCAT), the inspection of hardware surfaces returned from space, the DebriSat experiment, and the development of the Multi-layer Acoustics & Conductive-grid Sensor (MACS). The second part of the presentation will summarize the ODPO's on-going effort to utilize measurement data to build the next generation Orbital Debris Engineering Model version 4.0 (ORDEM 4.0), including the implementation of a fragment shape distribution to improve the fidelity of orbital debris impact risk assessments for the safe operations of future space missions. Finally, the presentation will focus on the ODPO's activities after the Russian anti-satellite (ASAT) test on Cosmos 1408 in November 2021, including the timely collection of measurement data on Cosmos 1408 fragments from different sources, the upgrade of ORDEM to version 3.2 with Cosmos 1408 fragments, and the release of ORDEM 3.2 in March 2022.



The cumulative size distribution of Cosmos 1408 fragments based on different measurement data. The black curve is the ODPO's model prediction.

National Aeronautics and Space Administration

Highlights of Recent NASA Orbital Debris Program Office (ODPO) Activities

J.-C. Liou, PhD
Chief Scientist for Orbital Debris
National Aeronautics and Space Administration

The 10th JAXA Space Debris Workshop
JAXA Chofu Aerospace Center, 28-30 November 2022

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ODPO's Roles and Responsibilities (1/3)

- **Monitor the ever-changing OD environment**
  - The ODPO has led the characterization of OD too small to be tracked by the DOD but large enough to threaten human spaceflight and robotic missions for more than 30 years
    - **Collect/analyze radar measurement data on OD in low Earth orbit (LEO)**
    - **Build/operate telescopes, collect/analyze optical measurement data on OD from LEO to geosynchronous Earth orbit (GEO)**
    - **Collect/analyze space-based *in-situ* measurement data on sub-millimeter debris, develop *in-situ* sensor technologies in preparation for future mission opportunities to address the millimeter-sized OD data gap**
    - **Design/conduct laboratory experiments and collect/analyze test data for debris characterization and assess risk from OD**
  - Critical data gap: millimeter-sized OD at 600-1000 km altitude; such small debris drives the mission-ending risk to LEO spacecraft

Credits, left-to-right: Reprinted with permission Courtesy of MIT Lincoln Laboratory, Lexington, Massachusetts; NASA (PIA13277); https://deepspace.jpl.nasa.gov/galleries/goldstone/#gallery; NASA ODPO; NASA (S125E007413); Arnold Engineering Development Complex/Air Force; NASA HVIT

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ODPO's Roles and Responsibilities (2/3)

- **Develop and update OD modeling and mission support tools**
  - The ODPO has led the development of OD environment, risk assessment, and mission compliance models and tools for more than 30 years
    - **ODPO models and tools are used by hundreds of operators (NASA, USG, commercial), academia, and research groups around the world**
- **Provide OD mitigation mission support**
  - OSMA and the ODPO oversee NASA mission compliance with OD mitigation requirements per NS 8719.14, which is NASA's implementation of the USG ODMSP
    - **Control the generation of mission-related debris**
    - **Limit accidental explosions (during- and post-mission)**
    - **Limit accidental collisions**
    - **Conduct post-mission disposal, limit reentry risk**

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ODPO's Roles and Responsibilities (3/3)

- **Provide USG interagency, international, commercial, and outreach support**
  - The ODPO has led the development/implementation of OD mitigation best practices in the U.S. and has promoted the adoption of the USG ODMSP by the international community since 1995
    - **USG ODMSP (2001, 2019): The ODPO led the interagency working group on the efforts**
    - **IADC OD Mitigation Guidelines (2002, 2020): The ODPO leads the U.S. delegation to the IADC**
    - **UN COPUOS OD Mitigation Guidelines (2007) and UN COPUOS LTS Guidelines (2019): The ODPO supports the U.S. delegation to UN COPUOS**
    - **ISO Orbital Debris Mitigation Standard (2010, 2019): The ODPO supports the development of and updates to the standard**
    - **Commercial support (via Space Act Agreements)**
    - **ODQN: more than 1700 subscribers from the global space community**
    - ***Etc.***

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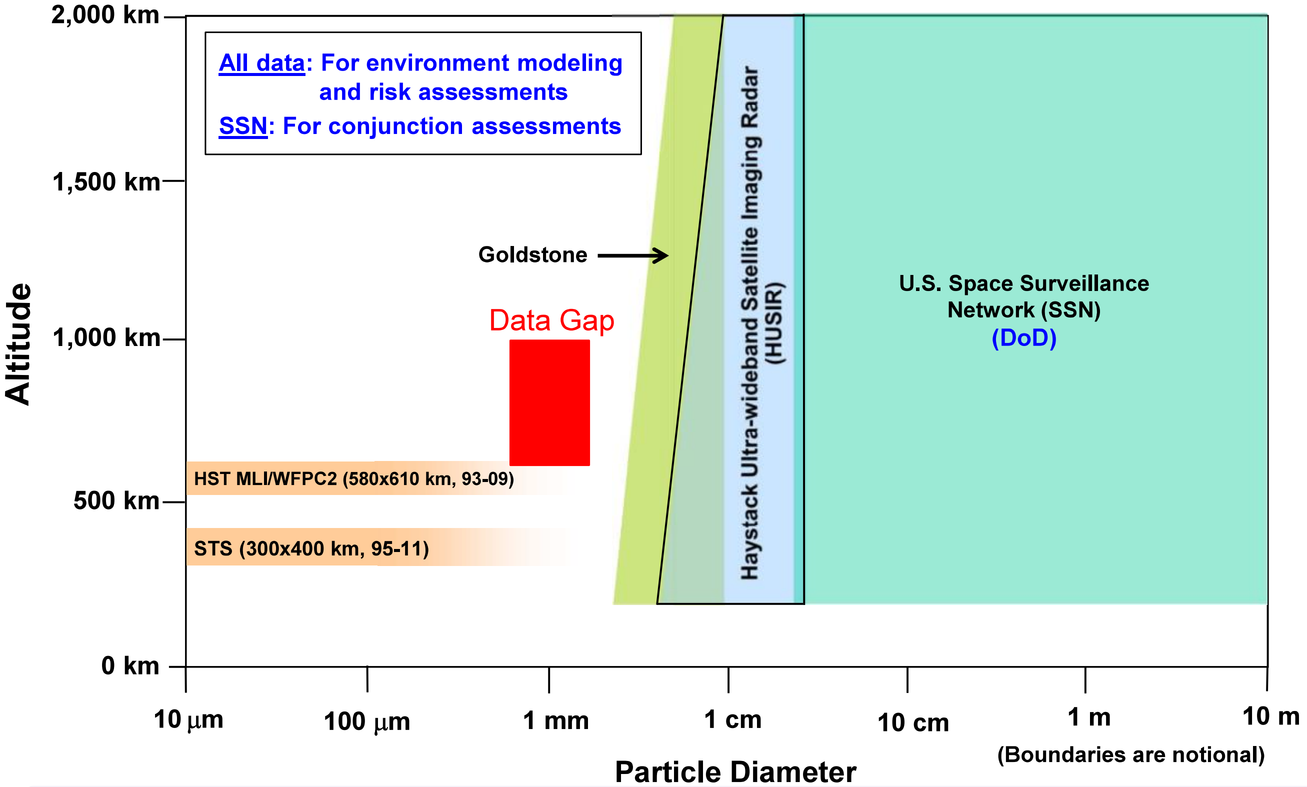
Current NASA OD Measurements in LEO



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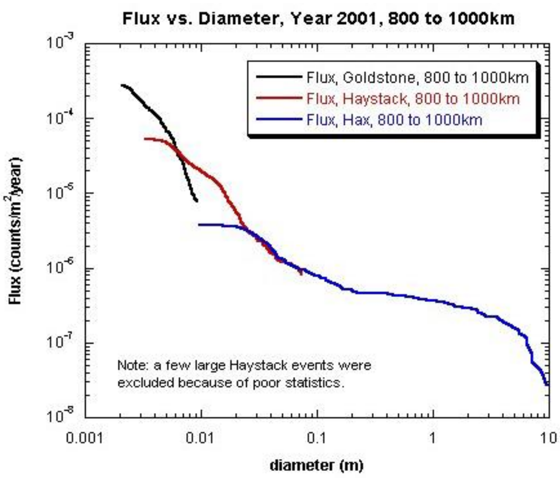
ODPO's Radar Measurements

- Data processing
- Object detection/correlation
- Debris size estimation
- Orbit determination
- Environment definition



Credit: Courtesy NASA JPL-Caltech, (left) https://deepspace.jpl.nasa.gov/galleries/goldstone/#gallery; (right) retrieved from https://www.gdscc.nasa.gov/wp-content/uploads/2018/12/BWG-Sign-2018-mm-2-27-18.jpg

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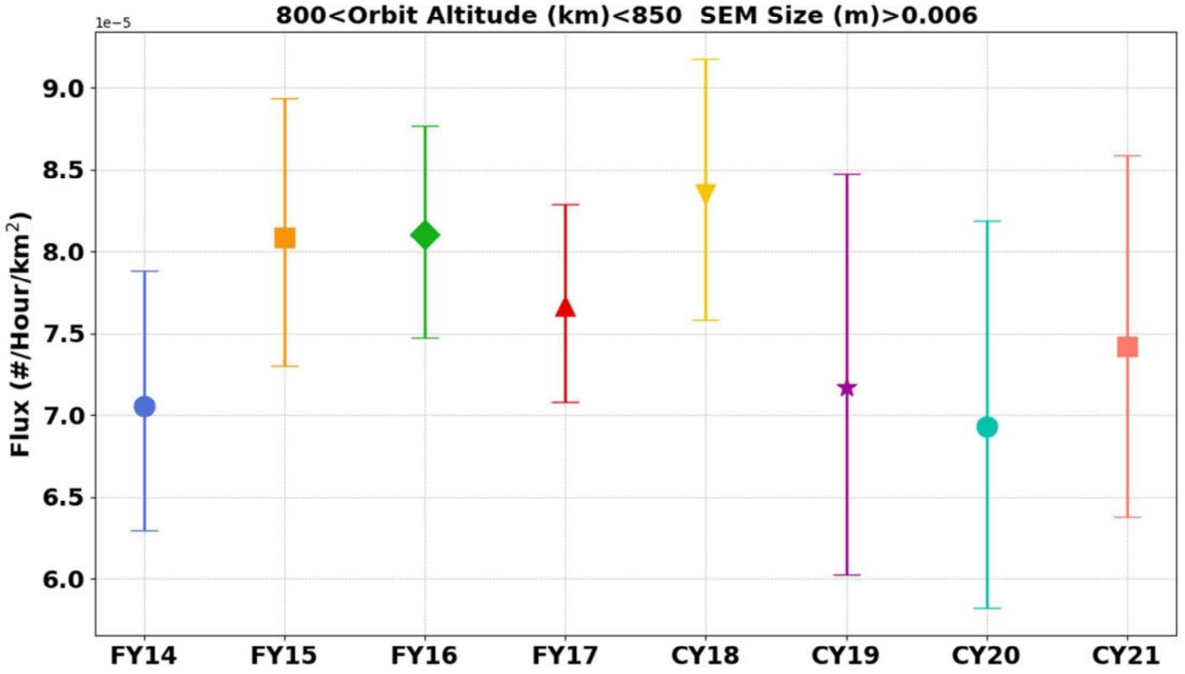
HUSIR Measurements, 2014-2021



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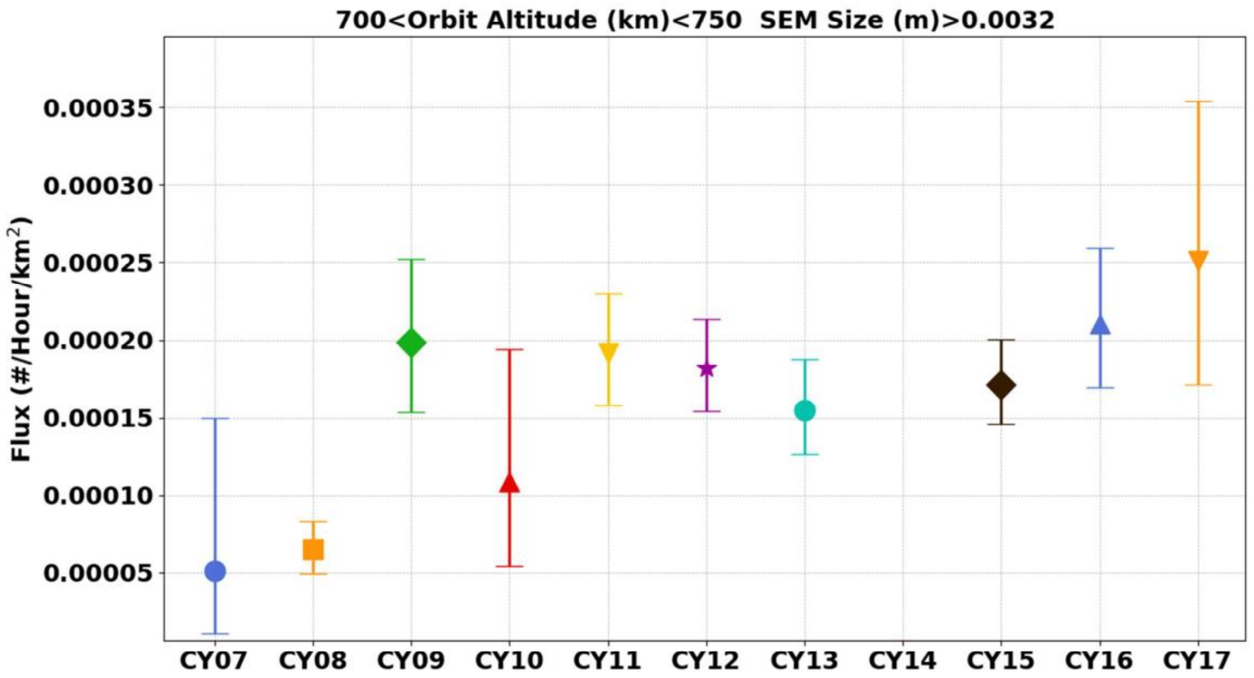
Goldstone Measurements, 2007-2017



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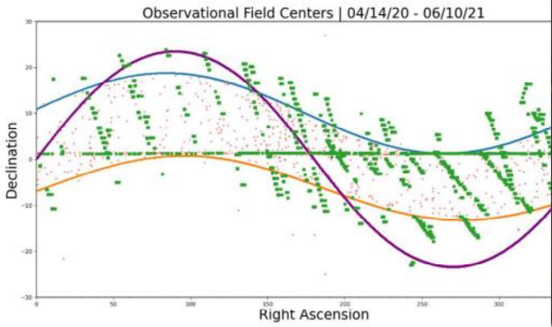
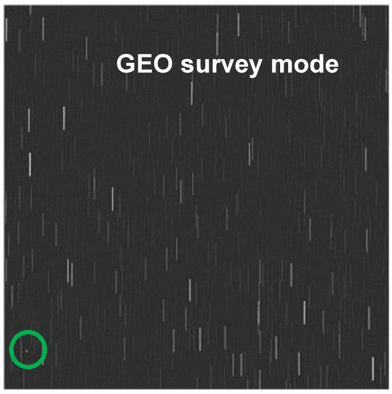
ODPO's Optical Measurements

- **Object detection and correlation**
  - Eugene Stansbery Meter Class Autonomous Telescope (ES-MCAT)
- **Orbit determination**
- **Environment definition**
- **Optical Measurement Center (OMC)**
- **Surface material identification**

Credit: Ben Hanna




OMC



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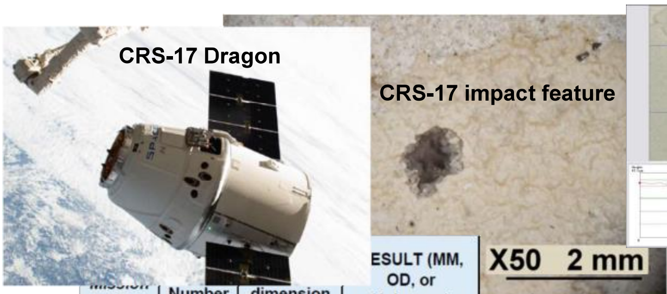
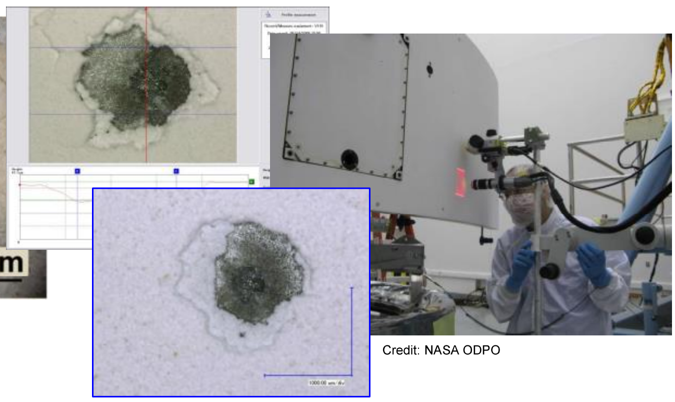
ODPO's *In-Situ* Measurements

- **The ODPO, in collaboration with the NASA Hypervelocity Impact Technology (HVIT) group at JSC, inspects hardware surfaces returned from space to characterize the small debris population**
  - Hubble Space Telescope Wide-Field Planetary Camera-2 radiator
  - ISS Pressurized Mating Adapter 2 blanket
  - SpaceX Dragon capsule from Commercial Resupply Service (CRS) mission




Credit: NASA ODPO

ID	Number	dimension (mm)	ESULT (MM, OD, or Unknown)
CRS-13	211	4.79	OD
CRS-15	226	4.15	MM
CRS-18	273	3.635	OD

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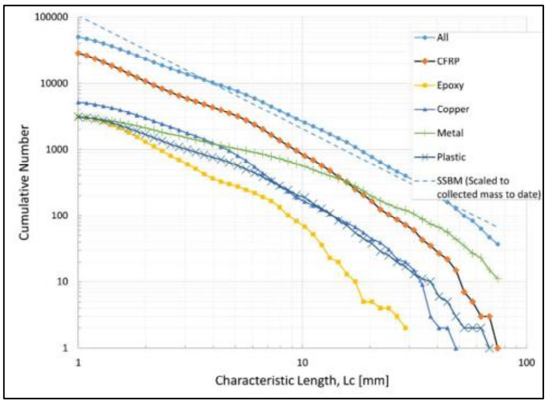
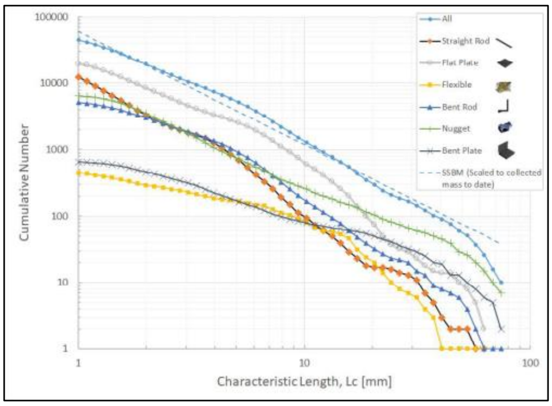
ODPO's Laboratory Measurements

- **The DebriSat project aims to characterize fragments, large and small, generated from a laboratory-based impact test on a markup modern spacecraft**





Credit: Arnold Engineering Development Complex/Air Force

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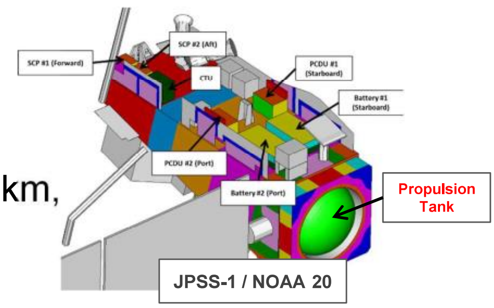
Risk from Small Debris (1/2)

- **Millimeter-sized orbital debris represents the highest penetration risk to most operational spacecraft in LEO**
  - As concluded by a NASA Engineering and Safety Center panel study (NASA/TM 2015-218780)
- **Currently, more than 400 spacecraft operate at 600–900 km altitudes**
  - Including 18 NASA missions (A-Train@705km, NOAA@825km, IXPE@600km, *etc.*)



- **There is a lack of measurement data on millimeter-sized orbital debris above 600 km altitude**
  - Direct measurement data on such small debris is needed to support the development and implementation of cost-effective, protective measures for the safe operations of future missions

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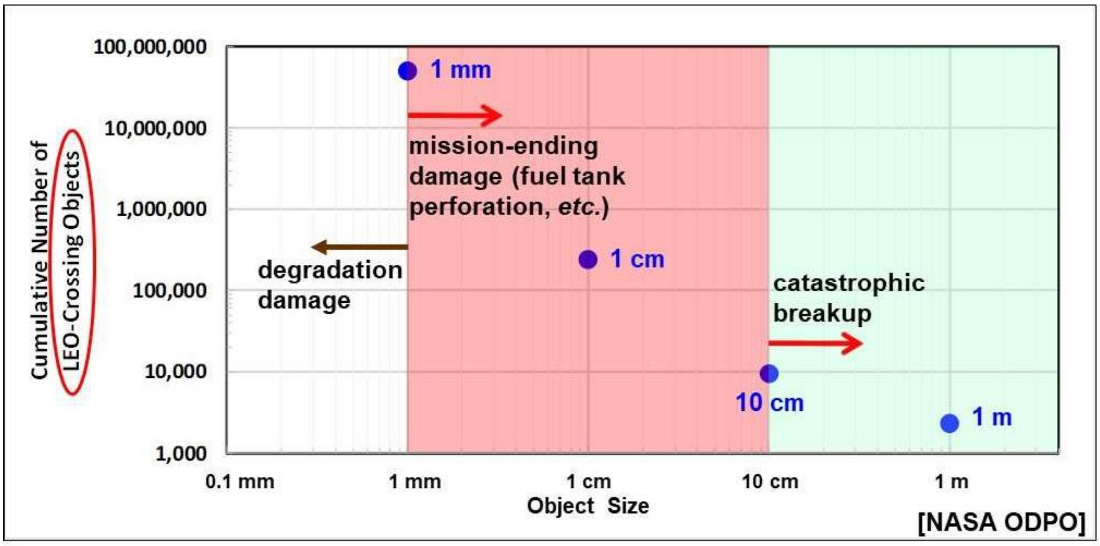
Risk from Small Debris (2/2)

- **There is far more small debris than large debris**
  - Mission-ending risk is driven by millimeter-sized debris in LEO, but there is a lack of direct measurement data on such small debris
  - Conjunction assessments and collision avoidance against the large (≥10 cm) tracked objects only address <1% of the mission-ending impact risk



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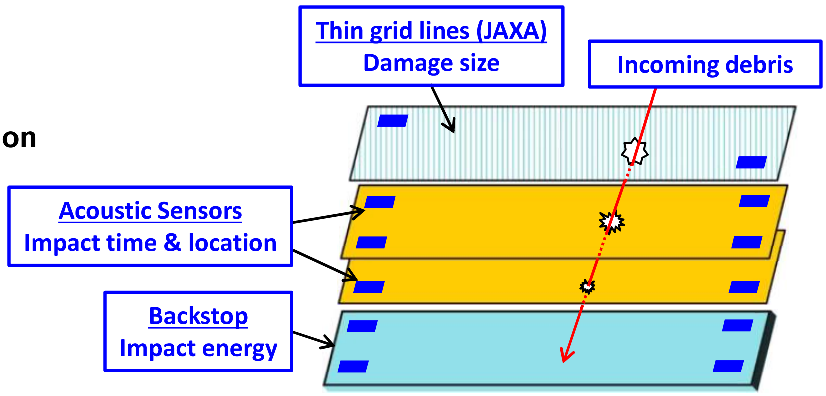
ODPO's In-Situ Measurements

- **The ODPO has led the development of innovative *in-situ* measurement technologies since 2002**
  - In collaboration with NRL, USNA, VT, U. Kent, and JAXA
- **Multi-layer Acoustics & Conductive-grid Sensor (MACS)**
  - Designed to detect/measure debris in the millimeter-size regime
  - Combines several impact detection technologies to maximize information that can be extracted from the detected impact events
    - **Impact time**
    - **Impact location**
    - **Particle size**
    - **Impact speed/direction**
    - **Impact energy/ particle density**



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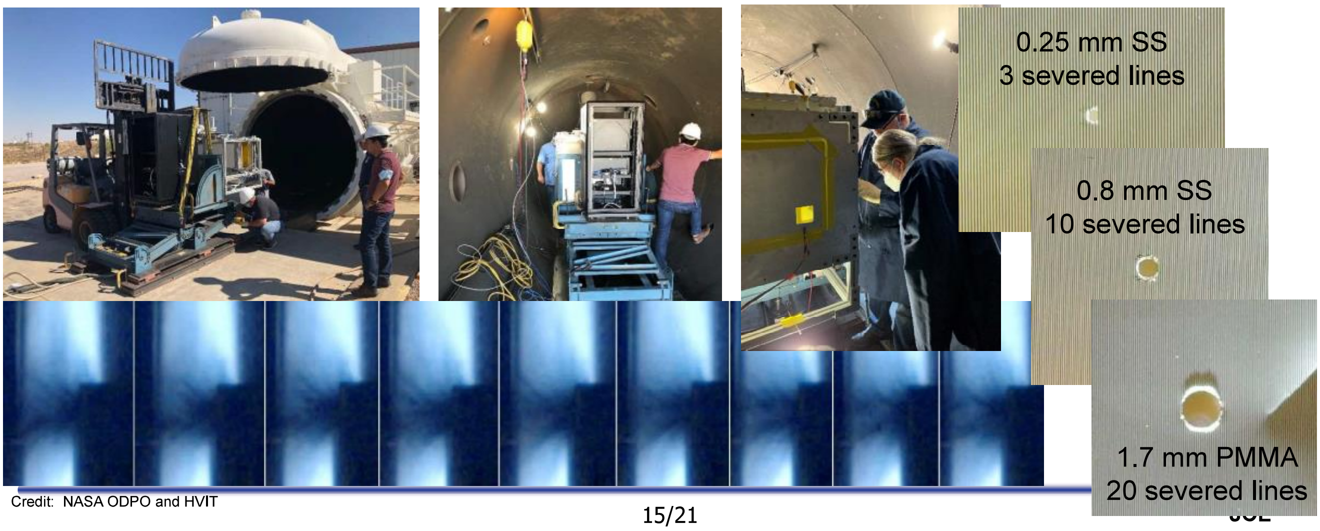
MACS Developments

- **The MACS prototype unit has been designed, built, and tested in 2021-2022**
  - Ten-week hypervelocity impact test series at White Sands
  - Component-level environmental testing (vibration, thermal-vacuum, shock)
  - A week-long mission architecture study at Goddard's Mission Design Lab



Credit: NASA ODPO and HVIT

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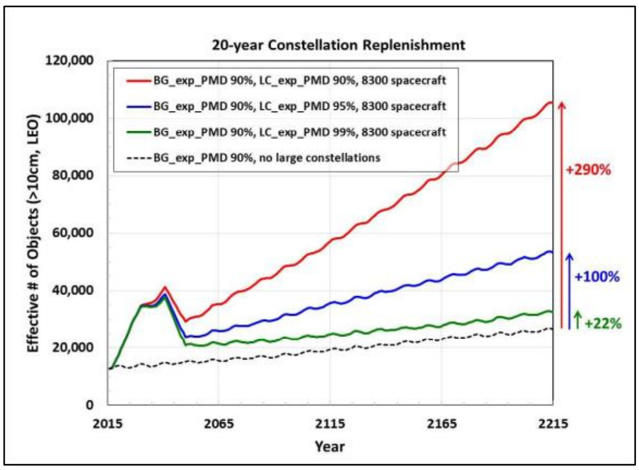
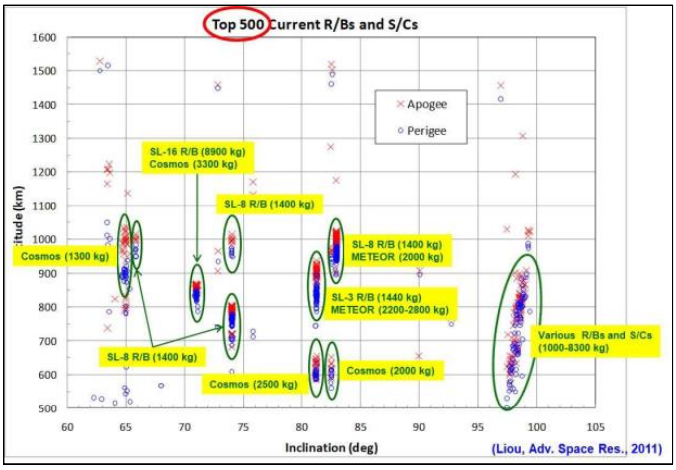
ODPO's Modeling Activities (1/2)

- **Modeling**
  - Long-term environment modeling
    - **Assess impacts from new missions and operations (CubeSats, large constellations, *etc.*) to the environment**
    - **Assess the effectiveness of various mitigation and remediation measures to support policy development**





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ODPO’s Modeling Activities (2/2)

- **Modeling**
  - Engineering modeling (Orbital Debris Engineering Model, ORDEM)
    - **Predict OD impact risk for mission support**
    - **ORDEM is used by hundreds of operators (NASA, USG, industry), academia, and research groups around the world**
    - **ORDEM 3.2 was released as a cloud-based application in March 2022**
  - Short-term risk assessment tool
    - **Calculate impact risk from new breakup events to critical NASA assets**
  - Debris Assessment Software (DAS)
    - **Assess mission compliance with orbital debris mitigation requirements**
    - **The No. 1 requested software in NASA Software Catalog**
  - Object Reentry Survival Analysis Tool (ORSAT)
    - **Model human casualty risk from satellite reentries**

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Cosmos 1408 Measurements and Modeling

- **The Russian ASAT test on Cosmos 1408 (1750 kg, 490 x 465 km altitude) occurred on 15 November 2021**
- **The ODPO led efforts to assess risks from Cosmos 1408 fragments to the ISS and supported mitigation measure development to protect the crew**
- **The ODPO also made special arrangements to collect timely radar measurement data on small Cosmos 1408 fragments immediately after the R-ASAT test occurred**
  - MIT/LL’s Haystack Ultrawideband Satellite Imaging Radar (HUSIR)
  - JPL’s Goldstone radar
  - DOD’s Space Fence
- **The ODPO used the measurement data to validate its risk assessments and to update ORDEM with a new Cosmos 1408 fragment component**

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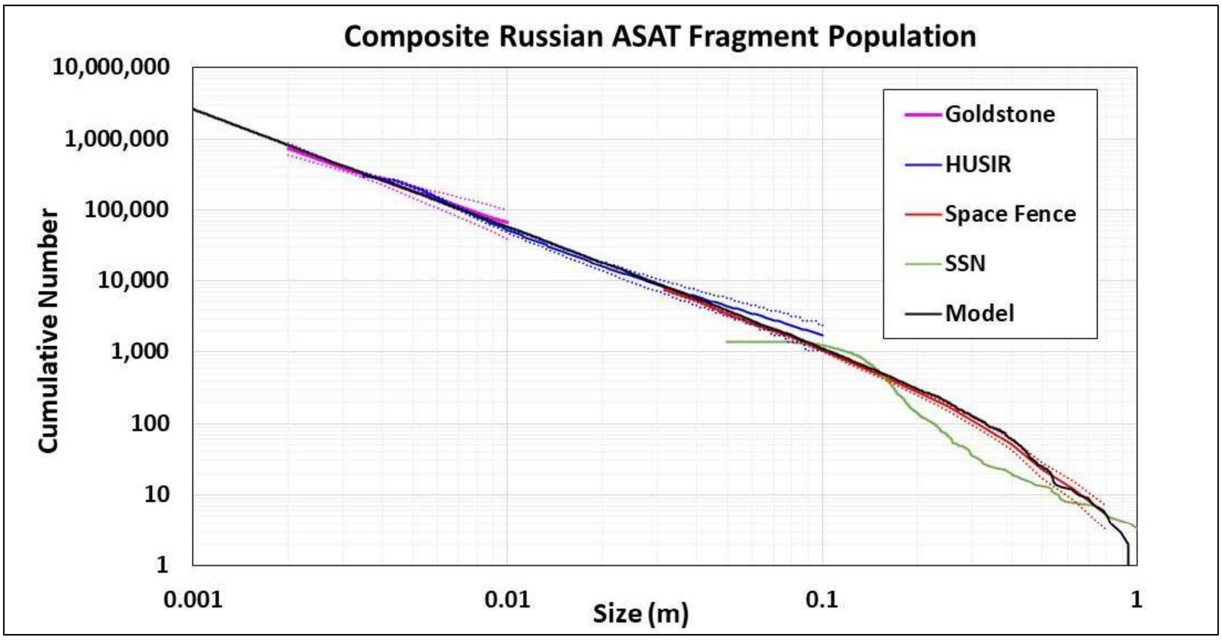
Cosmos 1408 Fragments – Data and Model

- **The ODPO's prediction matches the radar measurement data well**
- **The updated ORDEM 3.2 with a new Cosmos 1408 fragment component was released in March 2022**



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ODPO's Near- and Long-Term Priorities

- **Measurements**
  - Collect radar and optical measurement data with improved sensing capabilities to update the environment definition
- **Modeling**
  - Update ORDEM to 4.0 with new measurement data and a fragment shape distribution
  - Upgrade ORSAT with new capabilities and lab-based experimental data on composite materials
- **Millimeter-sized debris data gap**
  - Advance MACS development to an engineering unit
  - Pursue a MACS mission opportunity
- **Environment management**
  - Support USG and the international community to improve orbital debris mitigation and manage the orbital debris problem for the long-term sustainability of the near-Earth space environment

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The 2nd International Orbital Debris Conference (IOC II)

- **Preparation is underway for the 2nd International Orbital Debris Conference (IOC II)**
  - This quadrennial conference will take place in Sugar Land, Texas (greater Houston area), 04-07 December 2023
  - The four-day conference will cover all aspects of micrometeoroid and orbital debris research, mission support, and other activities
    - **Measurements, modeling, hypervelocity impacts, operations and mission support, and environment management**

All are invited to attend the 2023 IOC!

https://www.hou.usra.edu/meetings/orbitaldebris2023/

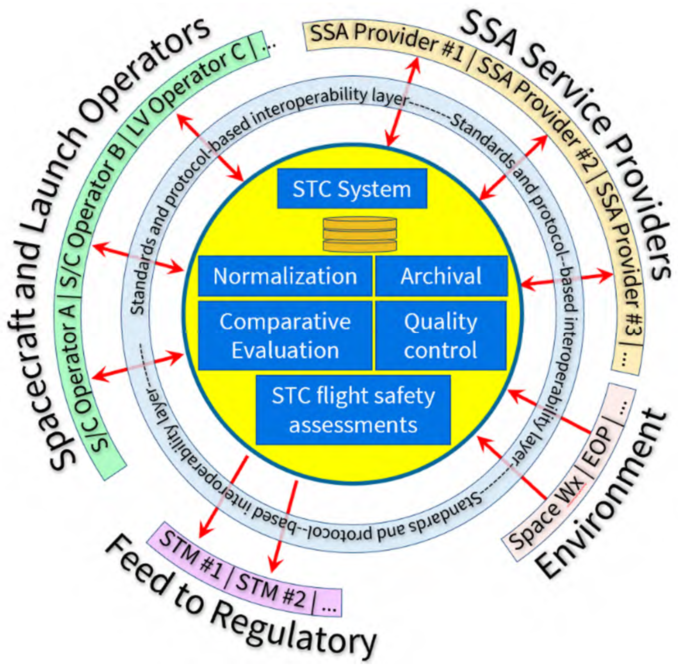
JCL

A02 Invited Lecture

Essential Elements of STCM Enterprise

〇Dan Oltrogge (COMSPOC Corporation)

This presentation will explore the essential components that make up a successful Space Traffic Coordination and Management (STCM) enterprise. The basic terminology for space safety and security is defined, including Space Domain Awareness. Then, we will examine State Actor regulatory regimes and differences between country instantiations, monitoring of adherence to regulations, government and commercial sources for Space Situational Awareness (SSA) information, data fusion and analysis. We will discuss both short-term and long-term situational assessment tools (on-orbit conjunction assessment, launch collision avoidance, threat assessment, space events, and space environment) and their application. And finally, the presentation will examine how State Actors and commercial industry are working to implement the 21 Long-Term Sustainability guidelines adopted by the United Nations.



Essential elements of STCM enterprise

Dan Oltrogge, COMSPOC Corporation

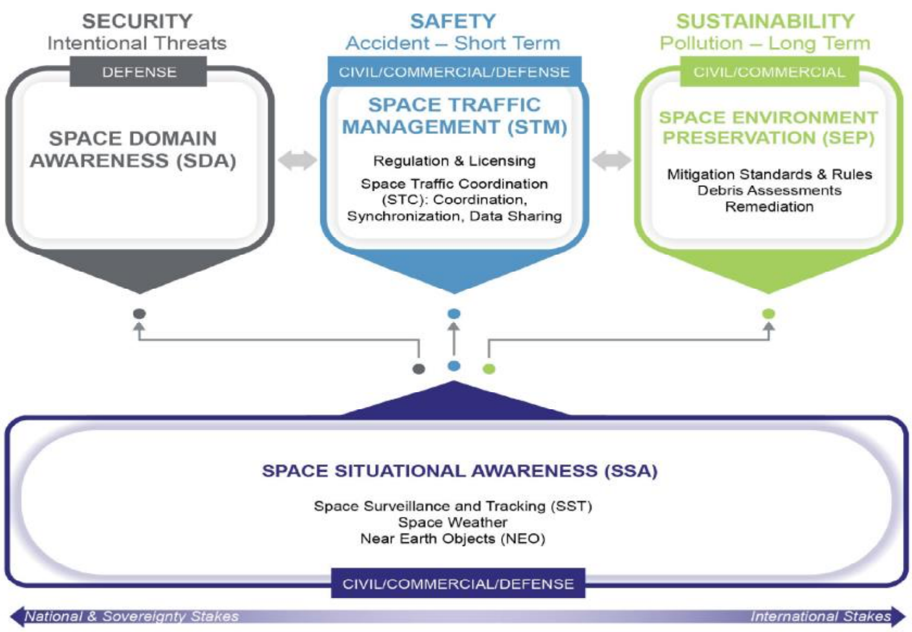
JAXA Space Debris Workshop

27 Nov 2022

AGENDA:

- Terminology and scope: What is STCM?
- STCM regulations, standards, guidelines, norms
- STCM basic services and derived components
- Non-cooperative maneuver processing
- Sensor and format-agnostic data fusion
- Commercial STCM capabilities and offerings

Space Traffic Coordination and Management (STCM) terminology



COMSPOC

Mark A. Skinner et al., "Space Traffic Management Terminology," 2022 Journal of Space Safety Engineering.

IAF TC26 STM Terminology WG adopted definitions

- **Space Domain Awareness (SDA)** is the effective identification, characterization, and understanding of any factor, passive or active, associated with the space domain (the area surrounding the Earth at altitudes equal to, or greater than, 100 km) that could affect space operations and thereby impact the security, safety, economy, or environment of a nation.
- **Space Traffic Management (STM)** is the assurance value chain that contributes to a safe and sustainable space operations environment, composed of **Space Traffic Coordination (STC)** and Regulation & Licensing, and dependent upon a foundation of continuous Space Situational Awareness (SSA).
- **Space Environment Preservation (SEP)** is the activity of preserving and sustaining the space operations environment, accomplished by space debris mitigation (adherence to post-mission lifetime and disposal guidelines and rules, prevention of release of mission-related debris, and collision avoidance) and remediation (derelict object removal, relocation, and collision prevention).

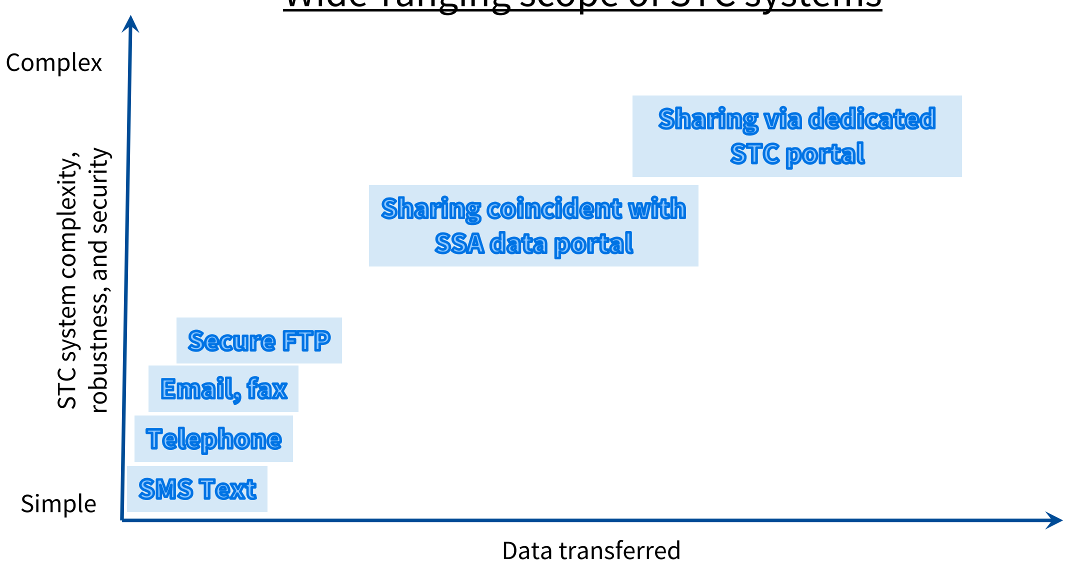
- **Space Situational Awareness (SSA)** is "the understanding, knowledge, characterization, and maintained awareness of the space environment: artificial space objects, including spacecraft, rocket bodies, mission-related objects and fragments; natural objects such as asteroids (including Near Earth Objects or NEOs), comets and meteoroids, effects from space weather, including solar activity and radiation [3]; and potential risks to persons and property in space, on the ground and in air space, due to accidental or intentional re-entries, on-orbit explosions and release events, on-orbit collisions, radio frequency interference, and occurrences that could disrupt missions and services.

COMSPOC

Oltrogge, D.L., et al, "Recommendations of the IAF Space Traffic Management Terminology Working Group, 11th IAASS Conference – Managing Risk in Space, Virtual, International Association for the Advancement of Space Safety, 19-21 October 2021

3

Wide-ranging scope of STC systems



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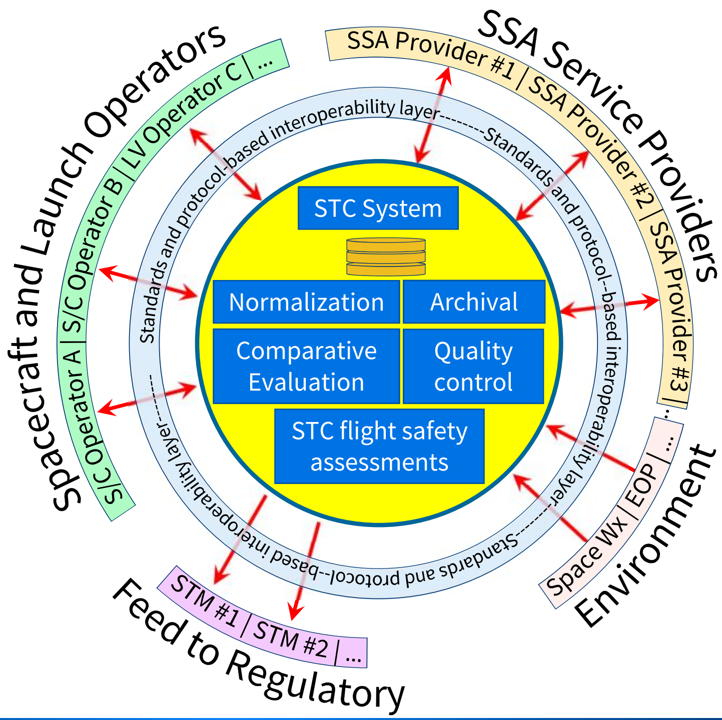
STCM framework



COMSPOC

Oltrogge, D.L., "Maintaining safe and efficient use of space in the New Space era," International Space Radio Monitoring Meeting, Paris France, 13 Sep 2022.

5

Comparison of STCM-related regulations, treaties, standards, best practices, and guidelines

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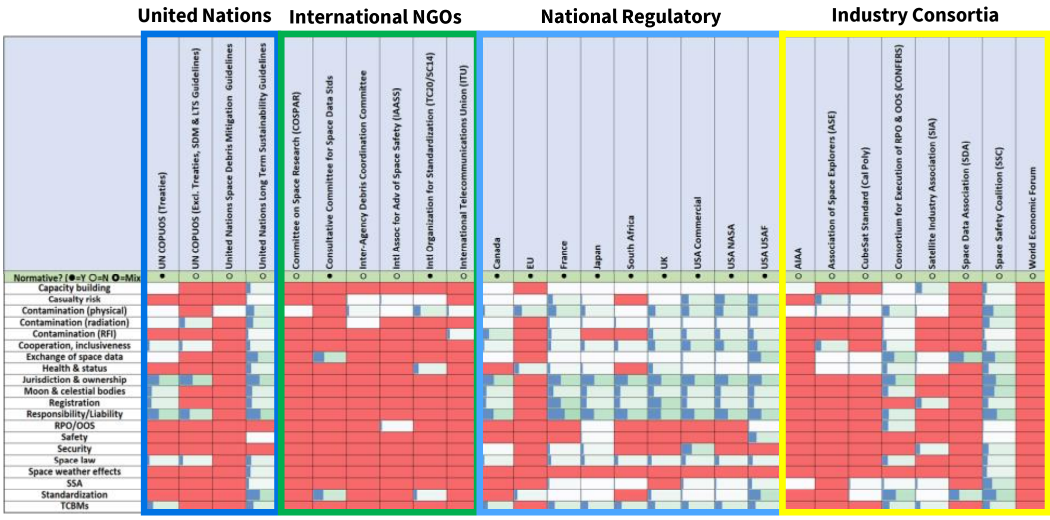
Contributions of global space governance to STCM and sustainability



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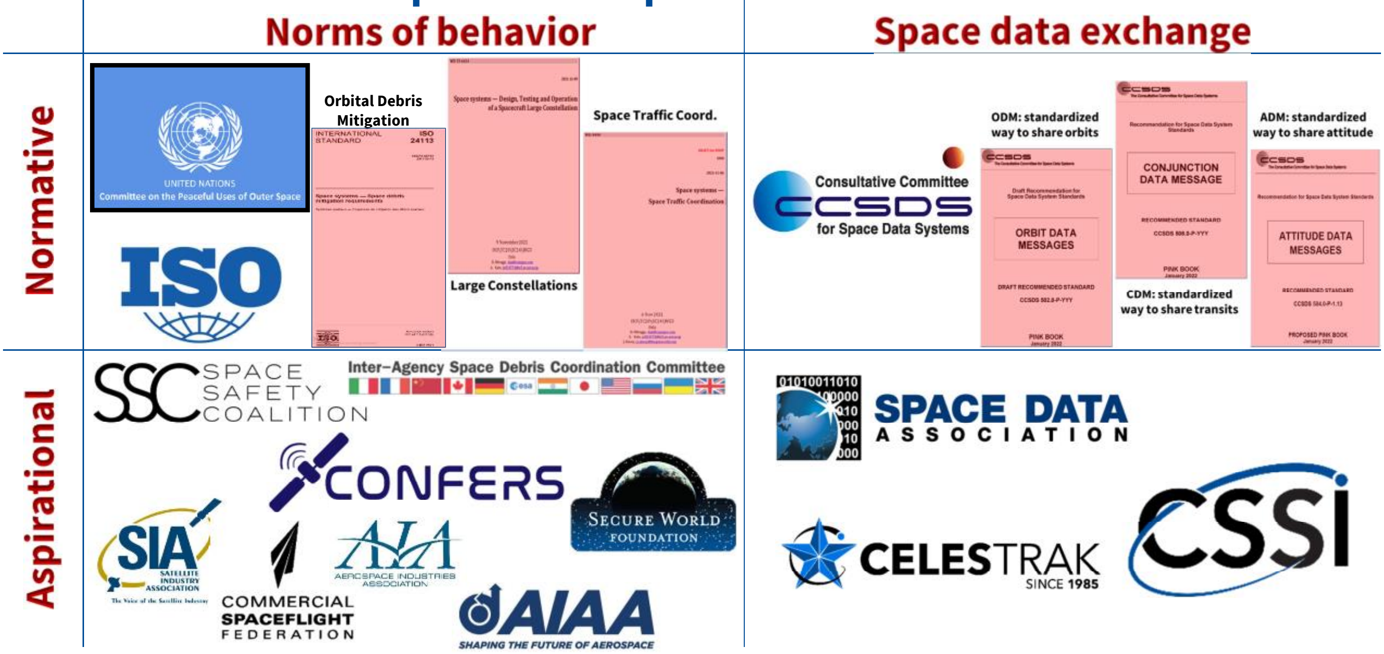
Oltrogge, D.L. and Christensen, I.A.," Space governance in the new space era" Journal of Space Safety Engineering, https://doi.org/10.1016/j.jsse.2020.06.003, July 2020.

Standards and best practices of particular relevance to STCM



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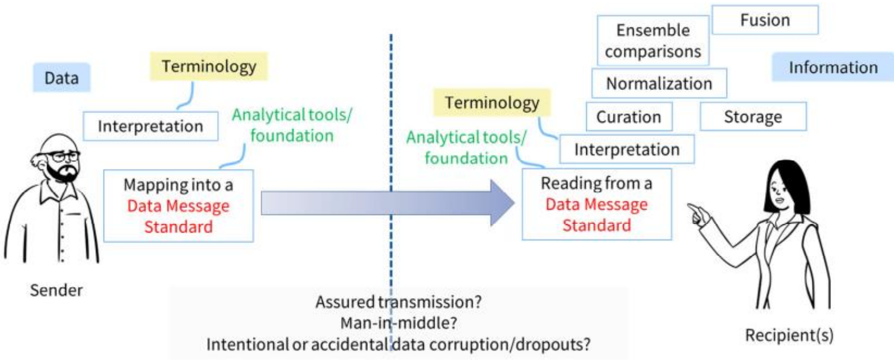
STCM standards for data exchange & integrity (security + quality)

- Ensuring data exchange integrity between and within space systems includes:
  - Data creation, data format, interpretation, exportation, transmittal, ingestion, re-interpretation, normalization, curation, comparison, analysis/fusion, and storage.

	Existing CCSDS messages and related standards										
	Attitude Data Message	Conjunction Data Message	Digital Motion Imagery	Events Message*	Orbit Data Message	Pointing Request Message	Radio Freq & Mod. Systems	Re-entry Data Message	Space Data Link Security Stds	Time Code Formats	Tracking Data Message
Attitude	•				•	•				•	
Conjunctions	•	•			•					•	
Maneuvers					•					•	
Orbit & errors					•					•	
"Phonebook"					•						
Reentry								•			
RF, RFI, Geoloc							•				
RPO/OOS			•		•		•		•		•
Space catalog					•	•				•	•
Space events	•	•		•	•			•		•	•
S/C chars, SoH					•					•	
Sensor trk, obs						•				•	•
STC system									•		



Essential elements of the STCM enterprise

Some basic STCM safety services for space environment sustainability

- Data portal for operators to share data for safety/sustainability
  - Ephemerides
  - Maneuver plans
  - Phonebook
  - Spacecraft characteristics (e.g., mass, dimensions)
  - Spacecraft astrometric obs
- Conjunction Assessment based on accurate* ephemerides
  - CDMs w/TCA, Miss, Pc, Orbit Determination (OD) characteristics
  - Quality assessment of ODs & predictions (transparency)
  - Using appropriate/effective Pc assessment method
- Proximity/neighborhood watch
- Launch COLA for launches from government launch ranges
- Technical support services staffed 24 x 7 x 365
- Breakup/fragmentation detection, tracking
- Pc variability =f(covariance scale factors, size, attitude)
- Maneuver recommendations (mitigation trade space)

- Accurate CDMs will depend upon:
  - Dynamically-calibrated atmosphere model(s)
  - Multi-source data fusion
  - Non-cooperative maneuver detect/char/process/refine
  - ODs incorporating maneuver plans, spacecraft operator observations, space weather
  - Realistic covariances
  - Space weather and storm warnings/compensation
  - Standardized Earth Orientation Parameter data

STCM error sources

- Positional knowledge approximate inaccuracies by source†:

Inaccuracy	Orbit regime(s)	Source
Up to **1500 km**	All	Unmodeled maneuvers (ir[illegible] Latencies of up to 1 week to recover OD solution
100 – 200 km	GEO	Cross-tagging & track mis-association
Up to **50 km**	All	Obs undersampling
Variable	All	Sensor priority/mission
1 – 100 km; 1-5 km typically	All	Lack of operator sensor calibration (biases)
Average of **12 km/day**	Low LEO (250 km)	Inaccurate space weather predictions
< **2 km**	All	Orbit theory limitations (TLEs)*

Helped by non-cooperative maneuver processing

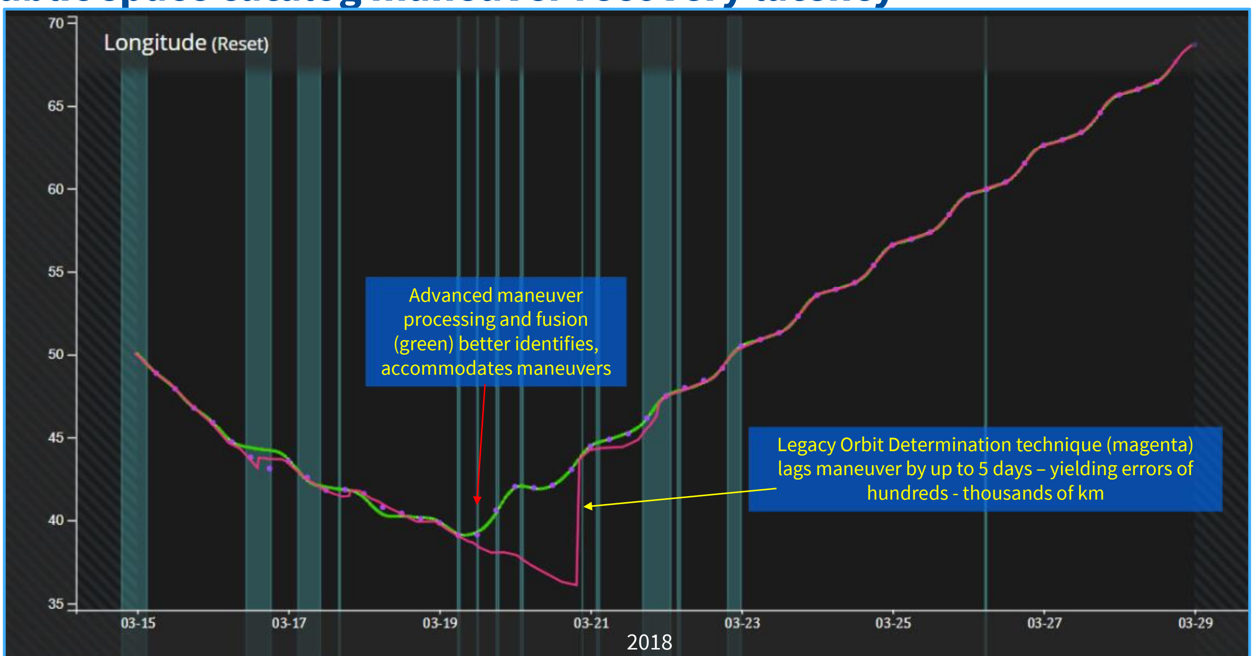
Helped by data fusion

- Errors lead to false alarms, missed threats, incorrect actions
- These can be mitigated and/or accommodated using better algorithms

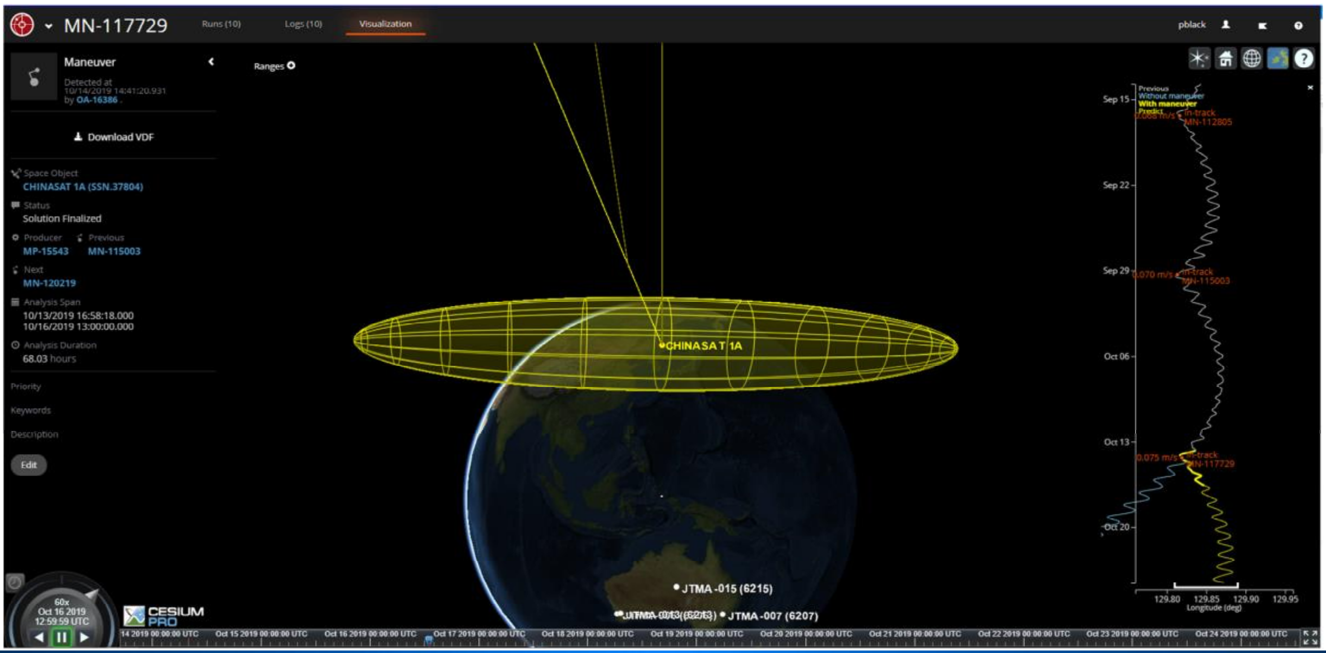
† Oltrogge, D., et al, "Order-of-Magnitude Actionability Characterization for SSA," Improving Space Operations Workshop, 31 April 2013.
* Oltrogge & Ramrath, "Parametric Characterization of SGP4 Theory and TLE Positional Accuracy," AMOS 2014.

Maneuver detection and processing

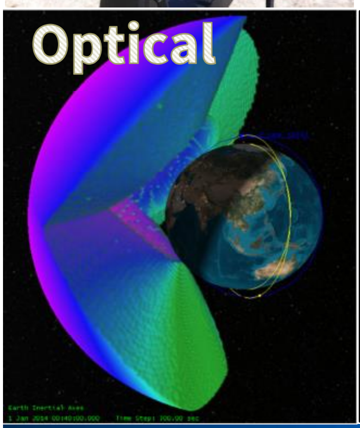
Public space catalog maneuver recovery latency

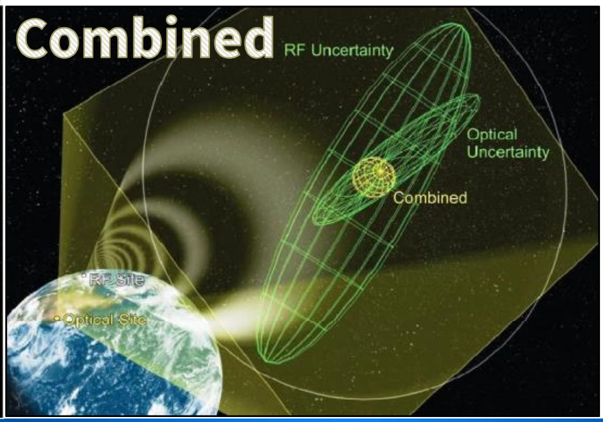


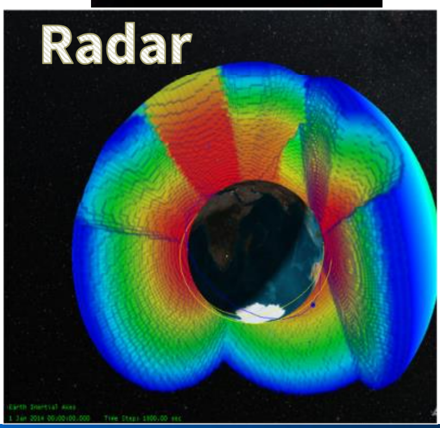
Operator displays and maneuver inference tools



Accuracy through data fusion







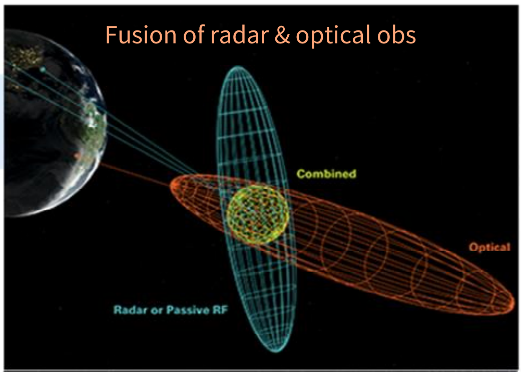
Motivation for sensor data fusion?

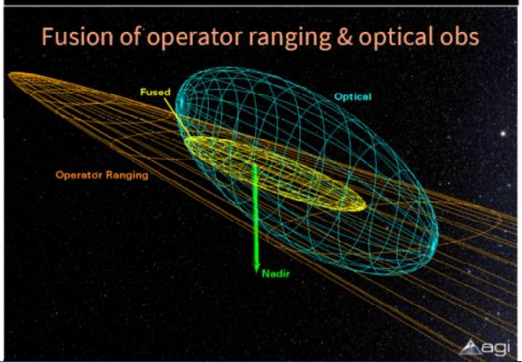
- Optical cheaper, excels at GEO
- Radar yields exquisite orbits in LEO
- Passive RF yields exquisite orbits in LEO - GEO
- Operator transponder ranging can be fused as well

The whole is greater than the sum of the parts

Sensor type:	Doesn't require operator cooperation	GEO coverage	LEO coverage	Not lighting-dependent	All weather	Range	Range rate	Angles
Spacecraft transponder ranging and range rate	○	●	○	●	●	●	●	◒
1-way Doppler	●	●	●	●	●	○	●	○
Radio Telescopes	●	●	●	●	●	○	○	●
Passive RF (TDOA/FDOA)	●	●	●	●	●	●†	●	○
Onboard GNSS	○	●	●	●	●	●†	●†	●†

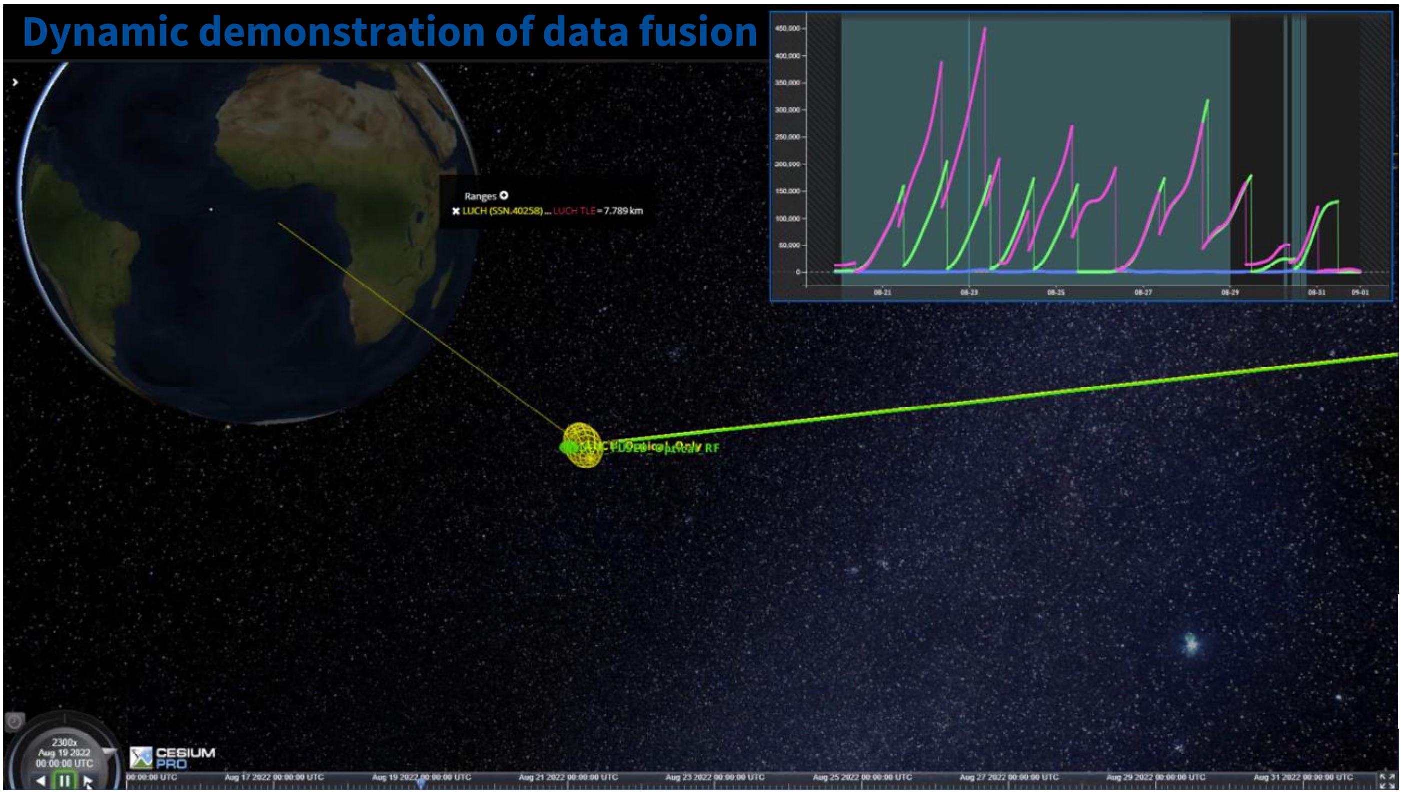
† Derived quantity ●=full, ◒=partial and ○=little or no capability



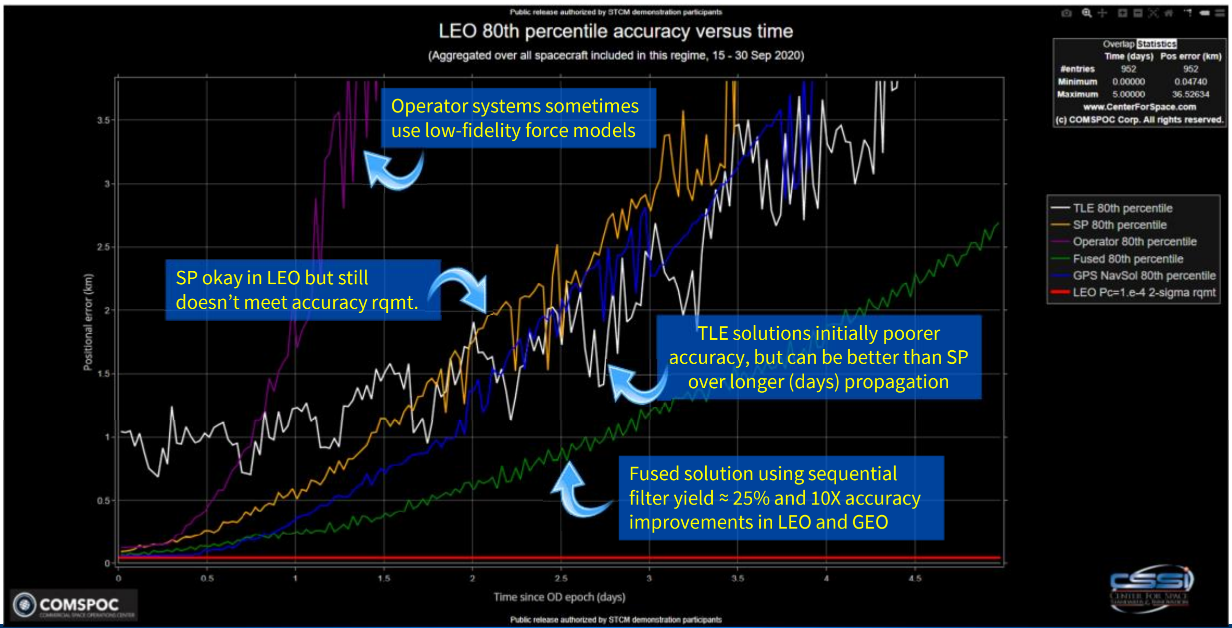


COMSPOC 17

Dynamic demonstration of data fusion



Comparison of public catalog and fused solution prediction accuracy



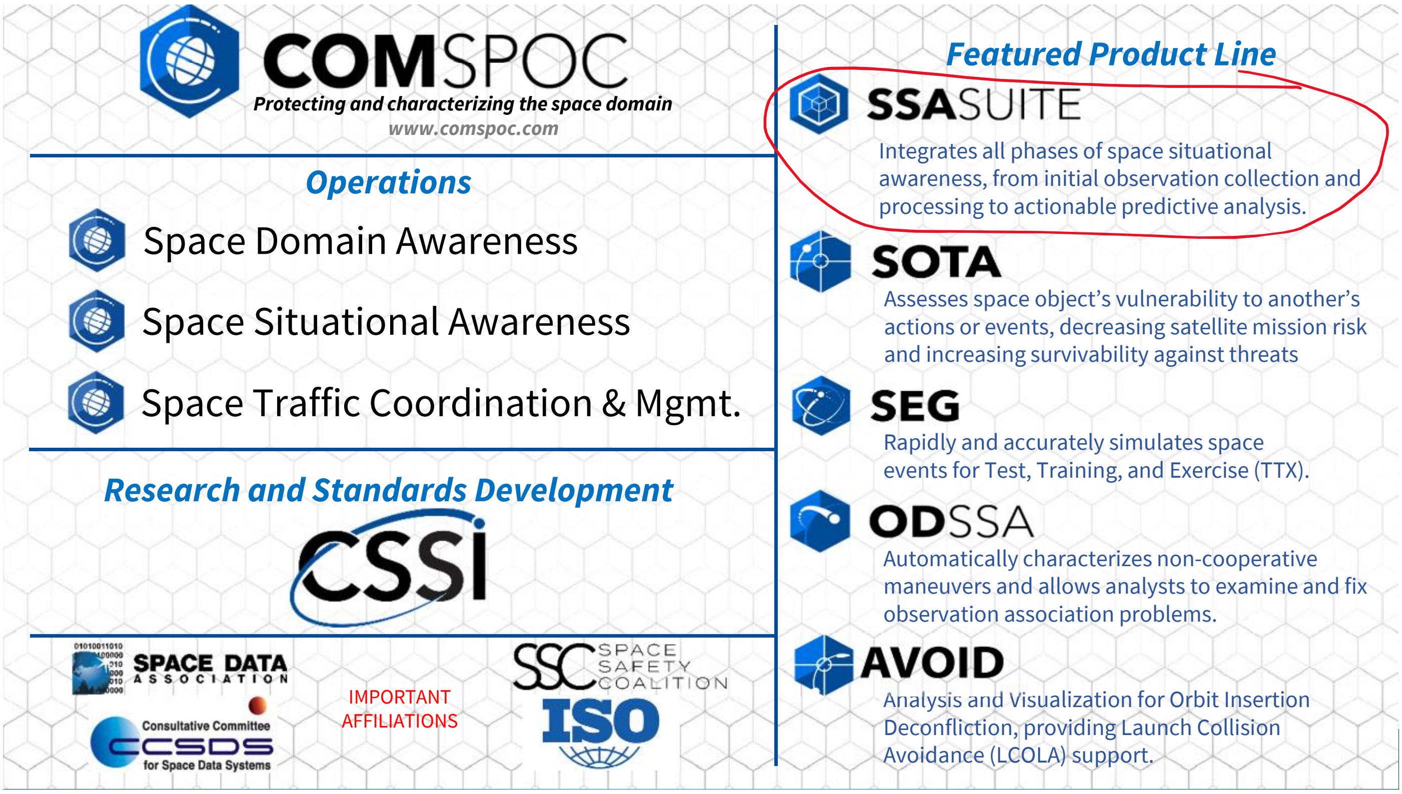
COMSPOC 19

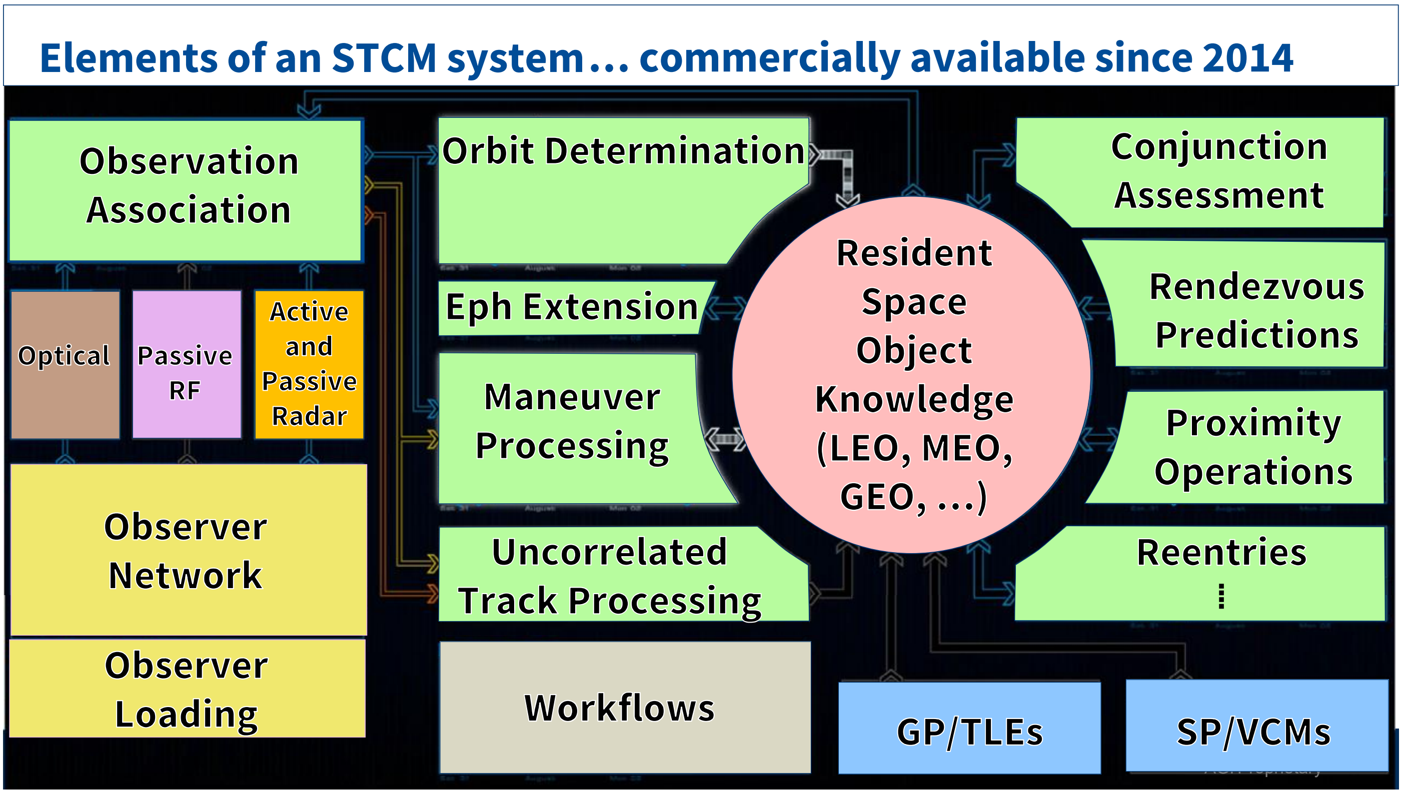
Commercial SSA services

COMSPOC

Provides unmatched space situational awareness services using cloud-hosted ***processing*** software and a global network of ***commercial sensors***

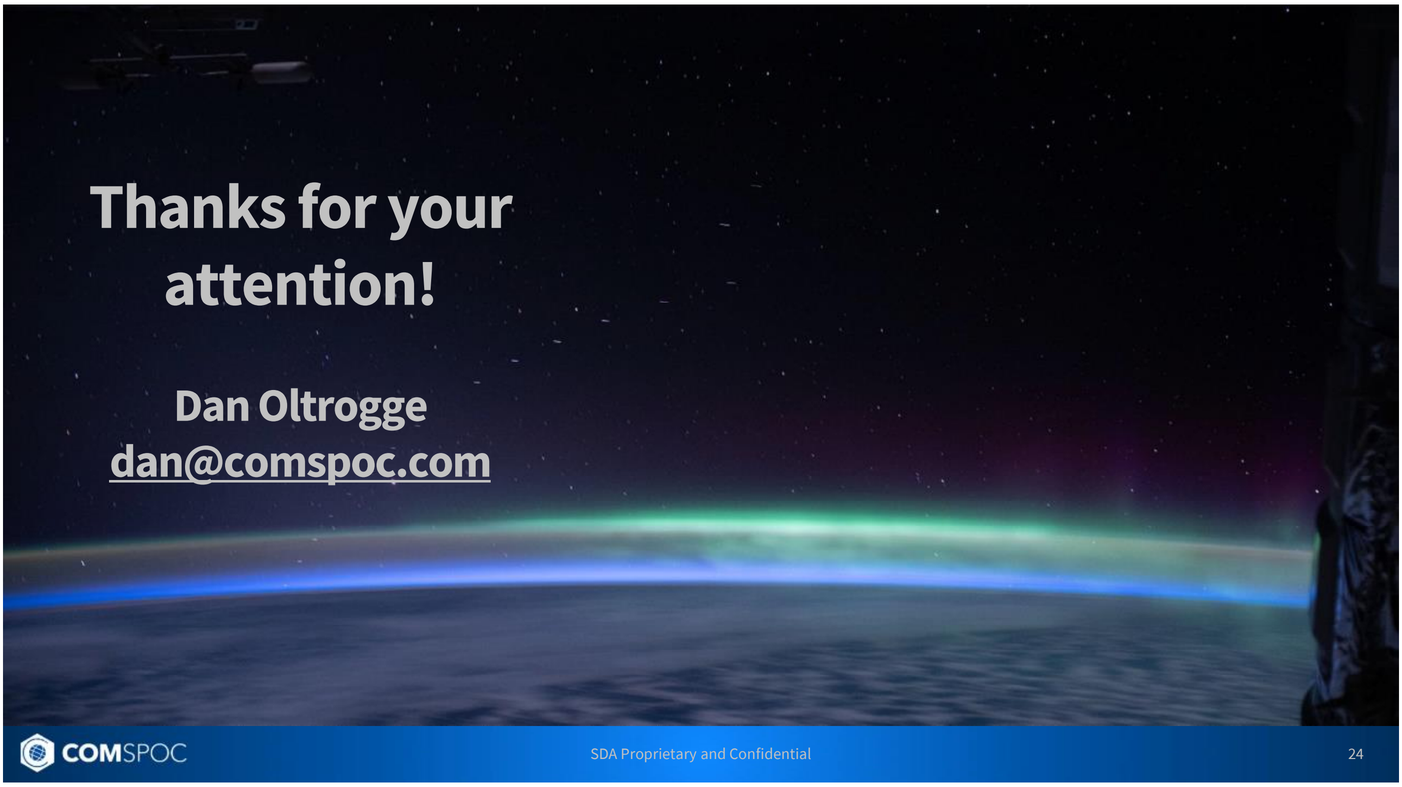
COMSPOC 20


COMSPOC
Protecting and characterizing the space domain
www.comspoc.com
Operations
Space Domain Awareness
Space Situational Awareness
Space Traffic Coordination & Mgmt.
Research and Standards Development
CSSI
SPACE DATA ASSOCIATION
Consultative Committee CCSDS for Space Data Systems
IMPORTANT AFFILIATIONS
SSC SPACE SAFETY COALITION
ISO
Featured Product Line
SSASUITE
Integrates all phases of space situational awareness, from initial observation collection and processing to actionable predictive analysis.
SOTA
Assesses space object's vulnerability to another's actions or events, decreasing satellite mission risk and increasing survivability against threats
SEG
Rapidly and accurately simulates space events for Test, Training, and Exercise (TTX).
ODSSA
Automatically characterizes non-cooperative maneuvers and allows analysts to examine and fix observation association problems.
AVOID
Analysis and Visualization for Orbit Insertion Deconfliction, providing Launch Collision Avoidance (LCOLA) support.


Elements of an STCM system… commercially available since 2014
Observation Association
Optical
Passive RF
Active and Passive Radar
Observer Network
Observer Loading
Orbit Determination
Eph Extension
Maneuver Processing
Uncorrelated Track Processing
Workflows
Resident Space Object Knowledge (LEO, MEO, GEO, …)
Conjunction Assessment
Rendezvous Predictions
Proximity Operations
Reentries
⋮
GP/TLEs
SP/VCMs

Summary

- Space increasingly dangerous from orbital debris and security standpoints
  - Challenging new era for SSA, SDA, STCM, and SEP.
  - Globally, must adhere to existing debris mitigation and space operations best practices & international standards.
  - Spacecraft operators, SDA users, and regulators need better STCM information.
- Requires STCM essential capabilities, elements, and information to be provided.
- Many of these essential SSA and STCM capabilities are commercially available in enterprise (turnkey) solution format.
  - COMSPOC partners with several Japanese firms to meet Japanese customer needs.



A03

Preventive Measure to Mitigate Debris by Using ElectroDynamic Tether System for Space Debris Prevention, Considering Sustainable Space Development

スペースデブリ発生防止用導電性テザーシステムを用いた、持続可能な宇宙開発を踏まえた予防的デブリ除去の取組み

○UTO Yasuhito, OKAJIMA Lena, ISHII Munehiro, KAMACHI Koh (ALE Co., Ltd.),
KAWAMOTO Satomi, OHKAWA Yasushi (JAXA), SATO Tsuyoshi (Kanagawa Institute of Technology)
○宇藤恭士、岡島礼奈、石井宏宗、蒲池康（株式会社 ALE）、
河本聡美、大川恭志（JAXA 研究開発部門）、佐藤強（神奈川工科大学）

While the space industry is drastically expanding, there are not yet enough measures to maintain the environment on orbit which are critical to the industry. If we do not adequately address the disposals of space debris after missions, which may harm the future project, these debris could prevent the industry from developing properly. ALE and Japan Aerospace Exploration Agency (JAXA), as a part of the JAXA Space Innovation through Partnership and Co-creation (J-SPARC) project, are developing a PMD device using an Electrodynamic tether (EDT) to demonstrate the deorbit of satellites. In this project, we are planning to launch a satellite equipped with a PMD device. There are two approaches to mitigate space debris; ADR (dealing with space debris once after the mission of spacecrafts has ended, Active Debris Removal) and PMD (preventing spacecrafts from becoming space debris beforehand, Post Mission Disposal). Our developed EDT is categorized in PMD and able to significantly reduce the time required for the satellite to reenter the atmosphere. It can be utilized as a countermeasure for the prevention of space debris. This paper provides the impact of the developed PMD device for de-orbit and issues and current solutions about the coming mission.

宇宙産業が拡大する一方で、産業の基盤である軌道環境を維持・管理する活動は未だ途上である。ミッション後の宇宙機「スペースデブリ」の処理・破棄の履行が不徹底なまために将来の開発に悪影響が生じた場合、産業全体のボトルネックとなることが懸念される。ALE と JAXA では導電性テザー(EDT:Electrodynamic Tether)を用いた PMD デバイスによる軌道離脱の技術実証を目的とした事業協同実証(J-SPARC)を行っており、足元での当該技術の実証を計画している。当 EDT は、宇宙デブリに対処するアプローチである ADR（別機による事後的な処理）と PMD（自機へのデバイス搭載等による予防的な処理）のうち後者に属するものであり、軌道降下時間を大幅に短縮することが可能なため今後のスペースデブリ対策の一つとして効果的である。本講演では実証に向け開発を進める PMD デバイスの軌道降下への影響及びミッション実現に向けた課題とこの解決策についてこれまでの検討内容について紹介する。

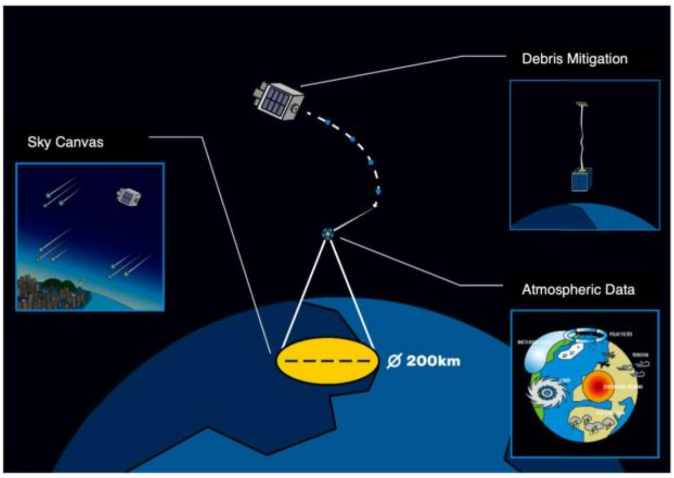
Preventive Measure to Mitigate Debris by using ElectroDynamic Tether System for Space Debris Prevention, considering Sustainable Space Development

Yasuhito Uto, Lena Okajima, Munehiro Ishii, Koh Kamachi (ALE Co., Ltd.)
Satomi Kawamoto, Yasushi Ohkawa (JAXA)
Tsuyoshi Sato(Kanagawa Institute of Technology)

Company profile

Company name	**ALE Co., Ltd**
Our Vision	**Anchor space into our culture to empower humankind to new endeavors** ALE aims to contribute to the sustainable development of humankind by expanding the area of human activity outside of Earth, to discover, collect, and apply the data mined from space.
Head office	**Tokyo, Japan**
Founder & CEO	**Dr. Lena Okajima**
Employees	**About 40**

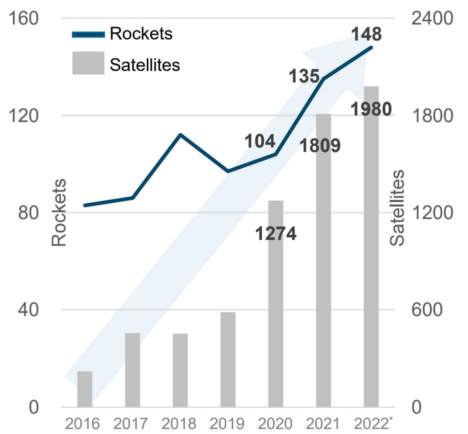
Nature of business
- -Sky Canvas
- -Debris Mitigation
- -Atmospheric Data



Global trends about space debris

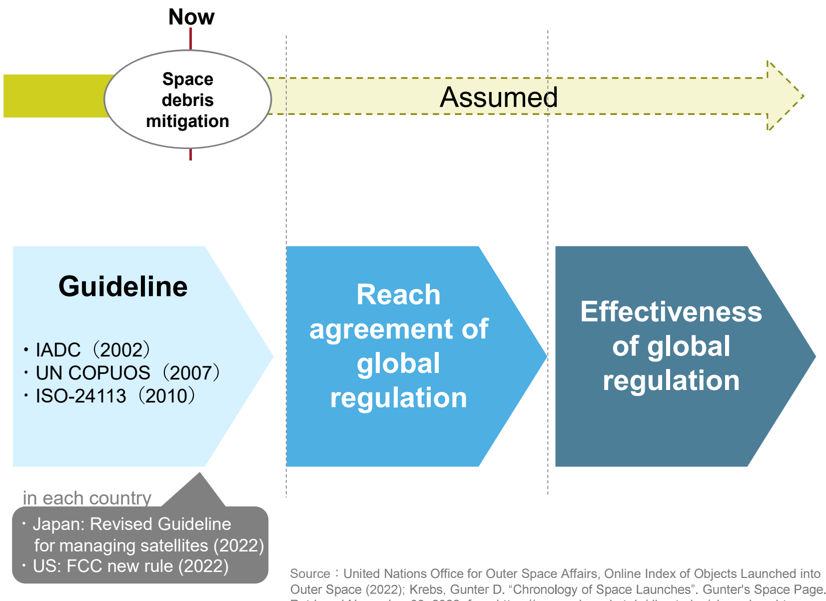
Given the deterioration in orbit, regulation on space debris is about to be embodied.

# of Rockets/Satellites Launched



- Deterioration of orbital environment
- Discussion about strict regulation

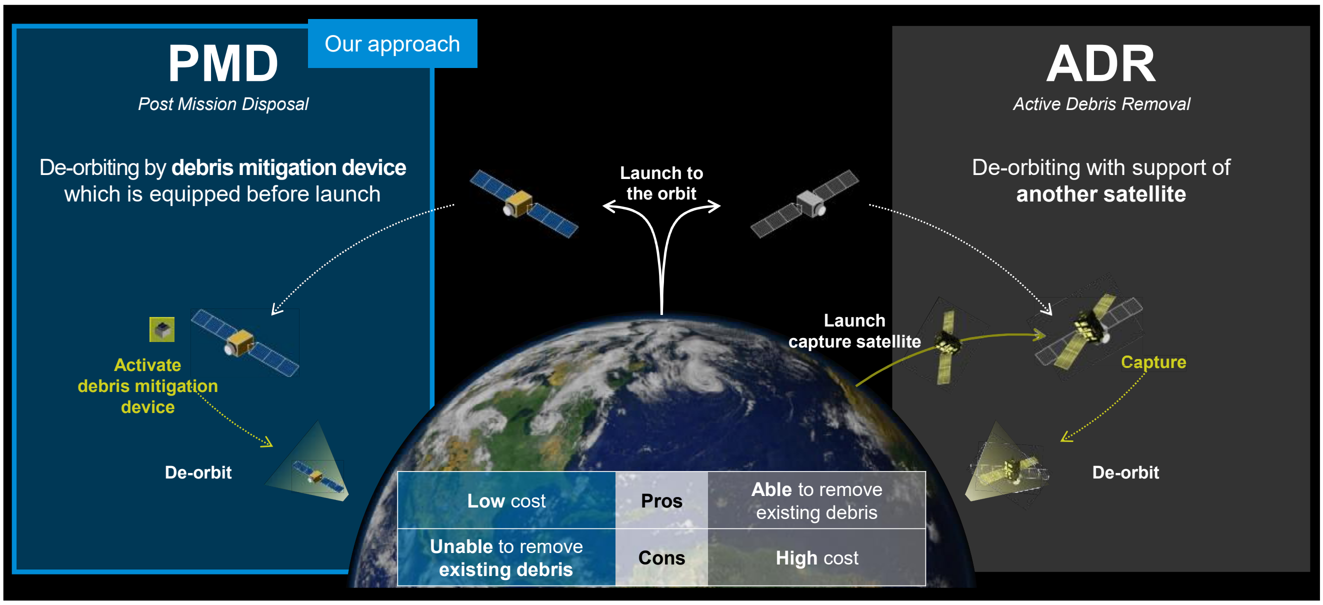
* As of November, 2022



Source：United Nations Office for Outer Space Affairs, Online Index of Objects Launched into Outer Space (2022); Krebs, Gunter D. "Chronology of Space Launches". Gunter's Space Page. Retrieved November 06, 2022, from https://space.skyrocket.de/directories/chronology.htm

Approaches to mitigate space debris

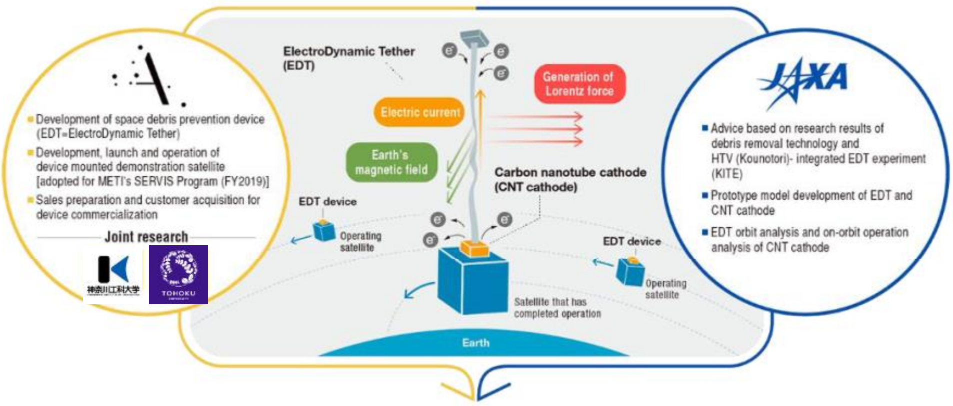
Human-kind needs both of PMD and ADR since they have each Pros-Cons.



Collaboration with JAXA

Maximizing the probability of success on first on-orbit demonstration through collaboration with JAXA, which has knowledge and technique of EDT.

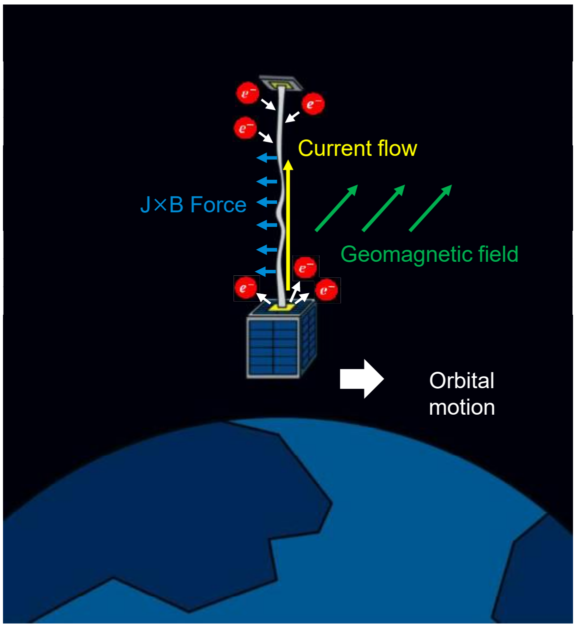
The project members are collaborating with us, and we will utilize their knowledge and experience to further enhance the technology.



Extend conductive tether from EDT device mounted on microsatellite and de-orbit.
Mitigate the generation of space debris thereby contributing to sustainable space development.

EDT De-orbit Mechanism (1/2)

EDT accelerates spacecrafts' deorbiting by two drags.



The bare tether utilize interactions with space environment to accelerate the de-orbit of spacecraft through **atmospheric drag** and **electromagnetic force**.

Mechanism of electromagnetic drag

1. During the conductive tether orbiting, it across the geomagnetic field and electromotive force on the bare tether is generated.
2. The biased tether attract electrons from ambient plasma. Then, current flows in the tether.
3. Due to the interaction between the current and the geomagnetic field, Lorentz (electromagnetic) force is induced to opposite direction of orbital motion.

* Electron emitter increases the current and Lorentz force can be enhanced.
* Compared with another PMD device, such as Dragsail, EDT works well in the high altitude because of Lorentz (electromagnetic) force.

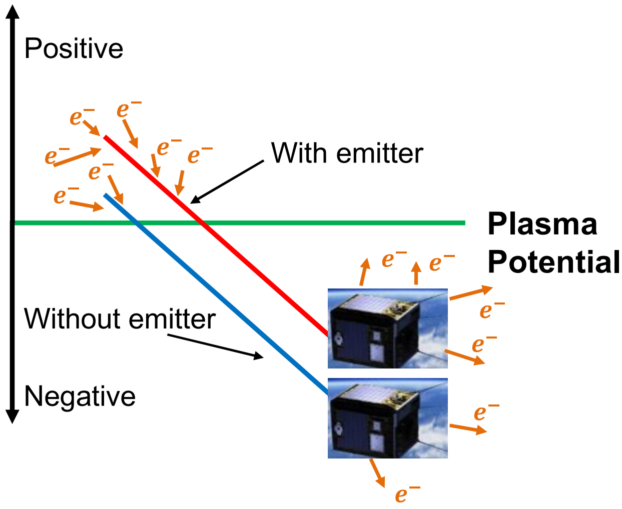
EDT De-orbit Mechanism (2/2)

Electron emitter

- Apparatus for emitting electrons into space.
- Installed on the end of the tether where the potential is negative.

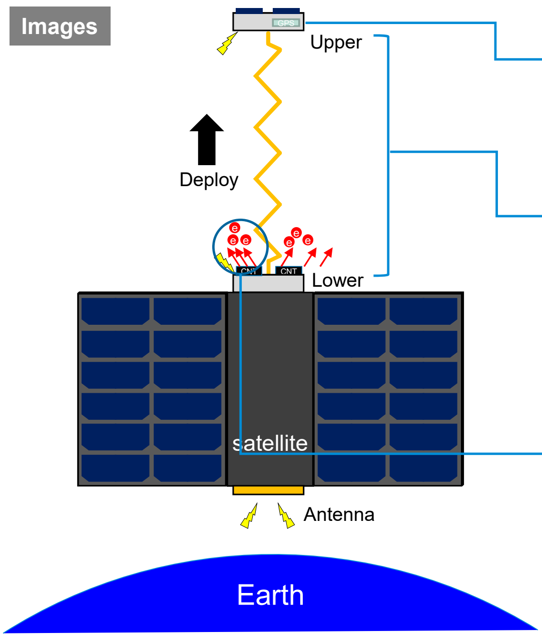
More electrons can be collected from the tether surface, thereby increasing the current flowing.

- ✓ Can shorten the time required for deorbiting.
- ✓ Reduce the risk of debris collision during PMD device operation.
- ✓ Collision avoidance maneuver may be possible.



Advantages of EDT

Even if main spacecrafts break down, EDT can independently work securely as a back-up.



1. Lightness of Tether

Deploying light tether suggests **a bigger projected area** rather than other existing structures, utilizing **stronger atmospheric drag.**

2. Gravity Gradient

Gravity gradient from an altitude difference works at both ends of tether and **keeps tether fully extended between the center of the earth and the zenith**. As a result, tether will utilize stable aerodynamic drag on the running direction. The system passively works and **does not need an attitude control.**

3. Current Flows

With the fully extended position, electric current flows in the tether from induced electromotive force and cosmic plasma, which system **works as a break force** to the spacecrafts. Installing Field Emission Cathodes (**FECs**) **on both sides of EDT**, we can **enforce the force** and does not need to care positions of a parent and a child mass.

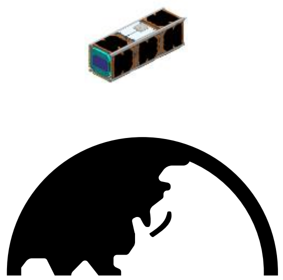
EDT-sat Project

Purpose

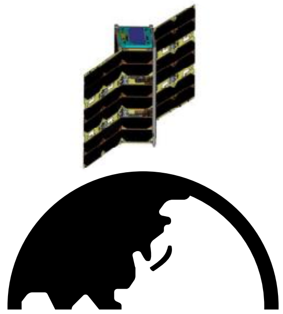
Demonstration of de-orbiting with using EDT and CNT.

Minimum Success

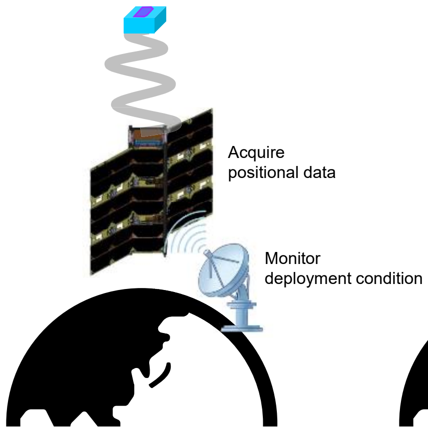
Deploy tape tether and confirm the de-orbiting.



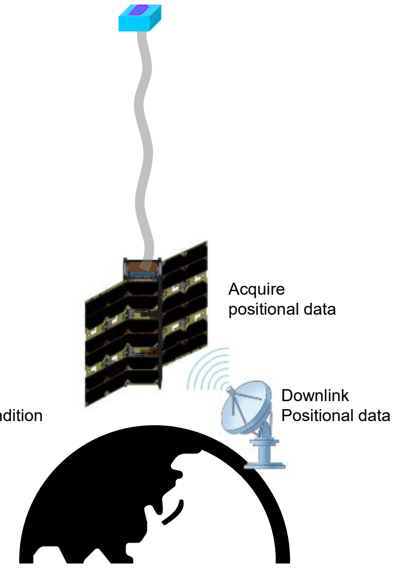
0: Earth orbit



1: Attitude control

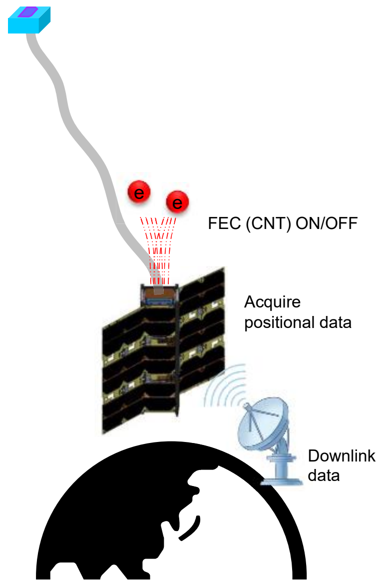


2: Start to deploy tether



3: Complete tether deployment

EDT-sat Project



Full Success

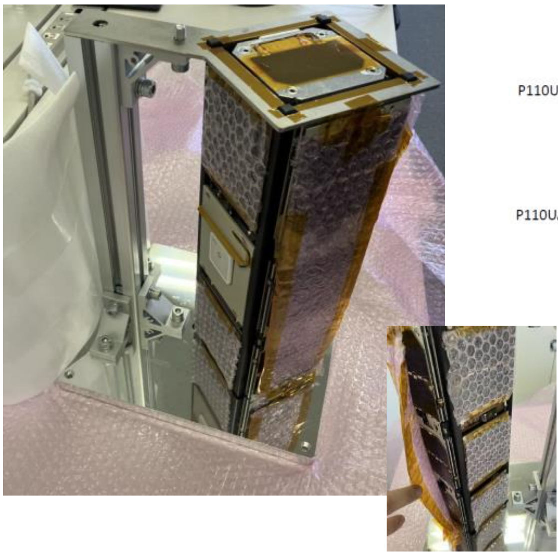
Confirm the change of de-orbiting performance by ON/OFF of CNT electron emitter.

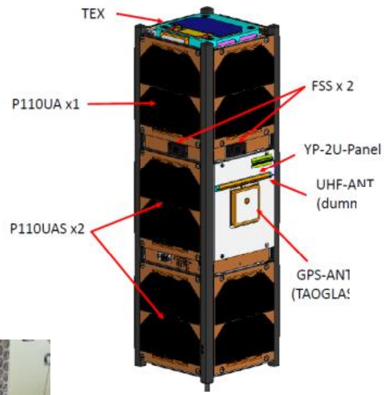
Extra Success

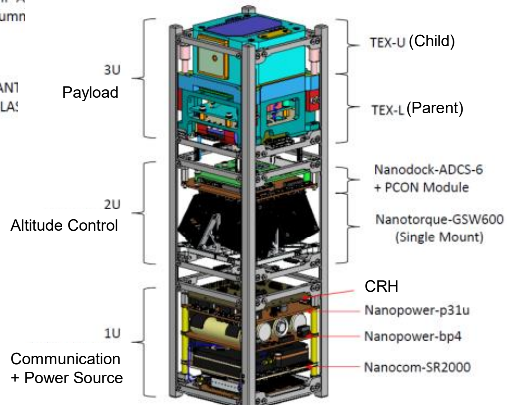
Measure the tether position and confirm the effect of Lorentz force.

Development of EDTsat

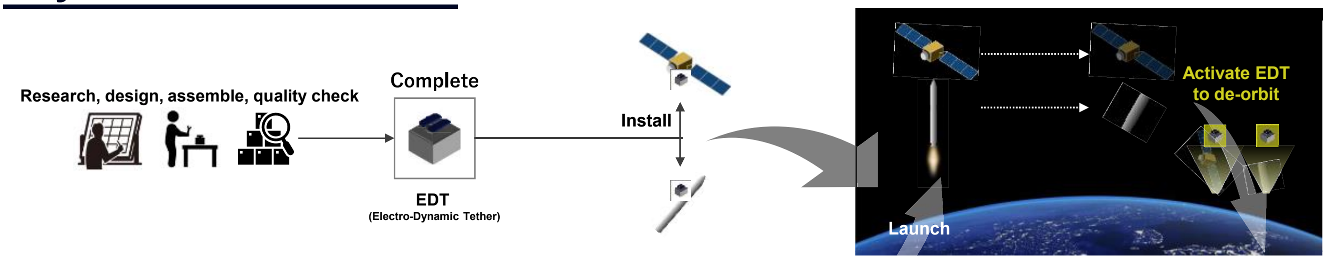
We have almost completed FM of EDTsat, waiting for an adequate launch opportunity.







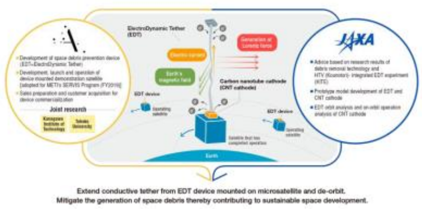
Key Features of EDT



R&D + Manufacturing	BEFORE launching	After launching
High reliability	**High efficiency**	**Low burden**

High reliability

- ✓ **Collaboration with Japan Aerospace Exploration Agency, JAXA** in the joint demonstration



High efficiency

- ✓ **Quite small and light device** for de-orbiting to spacecrafts
- ✓ **Minimum interfaces** needed
- ✓ **No other satellite** required for de-orbiting

Low burden

- ✓ **No additional operations** needed from ground
- ✓ **Secured redundant design** installed
- ✓ **Telecommunication** may be available, if needed
- ✓ **Works securely as a back-up** even if the main spacecrafts break down

Key Notes

Broad and practical acknowledgement of space debris are needed.

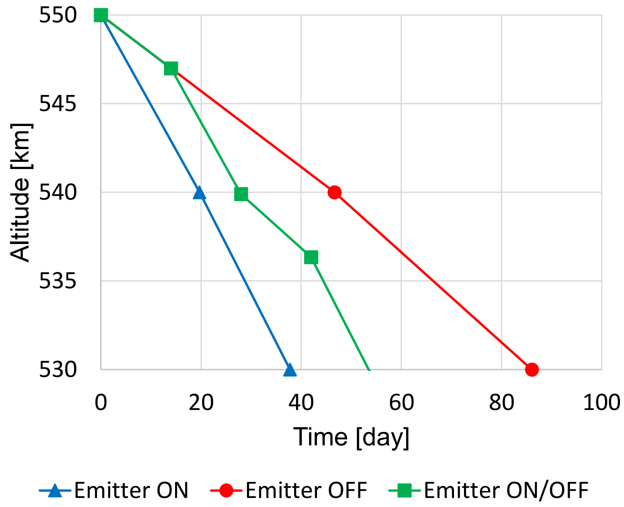
The problem of space debris…

- Imposes **a comprehensive topic** not only on space industry but also on humankind
- Shows **a long-term issue** that we need to continuously empower practical activities
- Needs **practical approaches for "not increasing"** (which is NOT "decreasing")

Acknowledgment

- This work is supported by JAXA Space Innovation through Partnership and Co-creation (J-SPARC).
- Demonstration of EDT-sat is partly funded by Space Environment Reliability Verification Integrated System (SERVIS) project.

Appendix: Case Study



※ OML available ratio: about 50%
※ The solar activity was assumed to minimal.
※ FEC(CNT) ON/OFF：
The case of assuming electron emitter was turned on/off every two weeks.

In this case, clearly, orbital descent ratio is differed between with and without an electron emitter.

The effect of EDT can be confirmed by orbital descent ratio.

- The performance obtained varies depending on the tether dimensions, orbital parameters, and other factors.
- By making such evaluations, the specifications of the tether and electron emitter can be determined for such electrodynamic tether requirements as orbital conditions, weight, and deorbit time.

ALE Co., Ltd.

A04

Activities in Japan to Reduce Slag Generated from Solid Rocket Motors

固体ロケットモータから発生するスラグ低減に向けた国内の取り組みについて

○KINOSHITA Masahiro, UI Kyoichi (JAXA Space Transportation Technology Directorate),
SATO Kenichi, NITTA Kumi (JAXA Safety and Mission Assurance Department),
IKEDA Hirohide, MORISHITA Naoki (JAXA Research and Development Directorate),
TOKUDOME Shinichiro, HORI Keiichi (JAXA ISAS),
MATSUURA Yoshiki (IHI Aerospace Co., Ltd.,)
○木下昌洋、宇井恭一（JAXA 宇宙輸送技術部門）、佐藤健一、仁田工美（JAXA 安信部）、
池田博英、森下直樹（JAXA 研開部門）、徳留真一郎、堀恵一（JAXA 宇宙研）、
松浦芳樹（IHI エアロスペース）

According to the ESA's MASTER model, a large proportion of debris with a diameter of 0.1 to 1 mm is slag generated from solid rocket motors and poses the risk of collision with LEO satellites. Furthermore, ISO-24113 was revised in 2019, and the range of slag emission limits for solid rocket motors larger than 1 mm was expanded from GEO to LEO and the GEO protected region. Against this background, slag emissions for solid rocket motors must be eliminated or reduced, especially in the orbital stage. Latest solid rocket motor in Japan has much less slag compared with past studies in NASA. This is shown by the amount of slag collected in the static firing test of Epsilon's upper-stage motors. However, limited research has been conducted on the physical properties of the discharged slag, and whether domestic solid rocket motors comply with the ISO standard of 1 mm remains unclear. Consequently, JAXA is planning activities to better understand the properties of the slag and reduce its discharge.

本発表では、日本の固体ロケットモータの固体推進薬の開発経緯と、軌道投入段に使用する固体ロケットモータからのスラグ低減に向けた活動方針を示す。ESA のデブリ環境モデル（MASTER）によれば、LEO における直径 0.1mm～1mm のデブリの中で大きな割合を占めるのは固体ロケットモータからから発生するスラグであるとされており、LEO 衛星への衝突危険性が指摘されている。また、2019 年に ISO-24113（Space system -Space debris mitigation requirements）が改訂され、固体ロケットモータの 1mm 以上のスラグ排出制限範囲が従来の GEO から LEO and GEO protected region に拡大された。このような背景から、軌道投入段に用いる固体ロケットモータについては、排出スラグの排除・低減が求められている。一方で、日本の固体ロケットモータは、JAXA/ISAS Mu rocket 開発の頃から継続的に残留推力の低減・性能向上を目的とした固体推進薬の改質に取り組んできている。この活動はアルミ粒子の燃焼性向上を目指す活動と同義であり、結果としてスラグ発生抑制に寄与する内容である。これらは、実機サイズの地上燃焼試験におけるスラグ回収量等から示されている。このため、国内固体ロケットモータから排出されるスラグは他例と比較してもごく少量である。しかし、排出されるスラグの物性に関する研究は少なく、国内固体ロケットモータが ISO 規格である 1mm に対して適合しているか、不明である。このため、JAXA を中心に、スラグの性状把握、排出低減に向けた活動を計画している。

Activities in Japan to Reduce Slag Generated from Solid Rocket Motors

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IKEDA Hirohide, MORISHITA Naoki, TOKUDOME Shinichiro, HORI Keiichi
Japan Aerospace Exploration Agency

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IHI Aerospace Co., Ltd.

10th Space Debris Workshop
Chofu, 28 November 2022

Contents

- Introduction
- Slag of Solid Rocket Motor
- Reduction Plan in Japan
- Conclusion

Contents

- **Introduction**
- Slag of Solid Rocket Motor
- Reduction Plan in Japan
- Conclusion

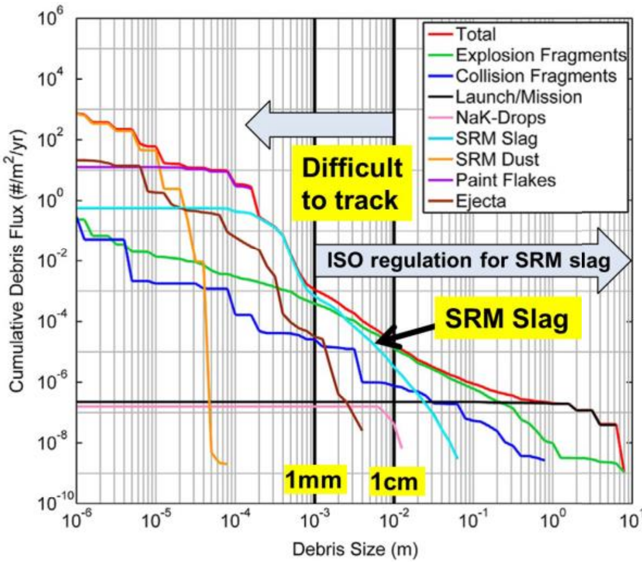
Effects of Different Space Debris Size on Spacecraft

- **Space debris are need to be mitigated.**
- **2 options for eliminate spacecraft damage: avoidance or protection.**

Size	--
～ 0.1 mm	･Very high collision frequency but low risk ･Peeling off the harness covering when it hits
0.1 to 1 mm	･High collision frequency ･Cause serious damage depending on the location ･Several methods of protection are proposed
1 mm to 1 cm	･Middle collision frequency ･Potential to cause serious damage
1 cm to 10 cm	･Low collision frequency but high risk ･Tracking and avoidance (2 cm ～)
10 cm ～	･Tracking and avoidance

SRM-Slag as Space Debris

- **In ESA/MASTER model, a large proportion of the space debris in the 1mm to 1cm is slag from solid rocket motor (SRM).**
- **The flux of SRM slags in this range are 100 times or more larger than the cm grade debris which have high risk, but those debris on LEO will falls to the ground in a few days or weeks.**



MASTER-2009 debris source population fluxes for the ISS orbit in 2014

Krisko, P.P., Flegel, S., Matney, M.J., Jarkey, D.R. & Braun, V.(2015). ORDEM 3.0 and MASTER-2009 modeled debris population comparison. Acta Astronautica 113(2015), p.204-211.

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Latest Space Debris Mitigation Requirements

- **ISO-24113 (Space system -Space debris mitigation requirements) was revised in 2019 as follows;**

Solid rocket motors shall be designed and operated so as not to release space debris larger than **1 mm** in their largest dimension into **LEO and GEO protected regions**.

Note
The main aim of this requirement is to limit the generation of slag debris ejected into Earth orbit during the final phase of combustion. Slag debris is potentially hazardous to current and future space operations due to its **size, number and orbital lifetime**. **This is particularly the case when slag debris is ejected into a high orbital region where it can pose an impact risk for a long period of time.**

- **How to reduce slag size, number and orbital lifetime ?**
- **How to mitigate risk of slag in orbit ?**

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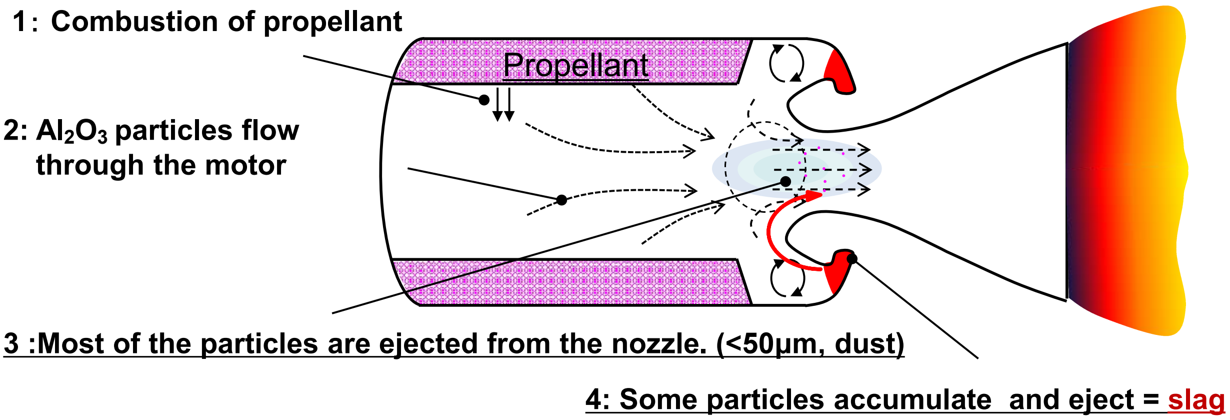
What's Slag ?

- **Slag is mainly Al_2O_3 generated from solid propellant.**
- **Past studies (NASA/TP-2007-213738) shows follows;**
  - **Mechanisms of slag generation and accumulation**
  - **Ratio of slag to propellant (0.04 – 0.65 %)**
  - **Size of slag (0.1mm – 5 cm)**

Propellant Composition	
Oxidizer	:NH_4ClO_4 (AP)
Fuel	:Al
Binder	:HTPB



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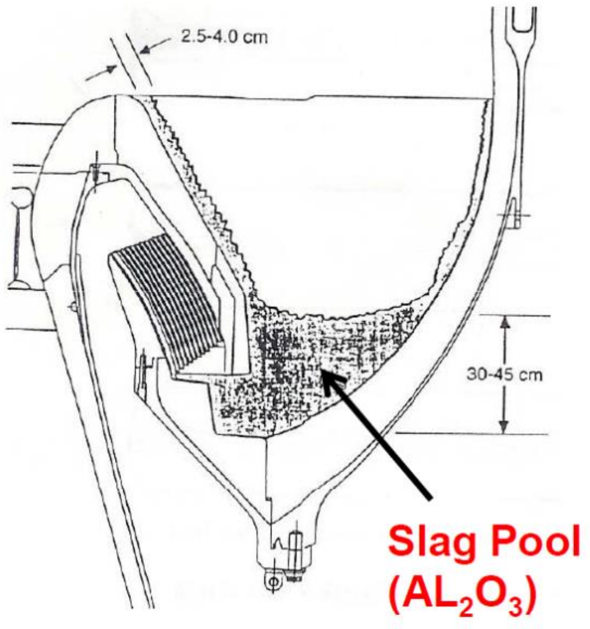
What's Slag ?



NASA/TP-2007-213738

Solid Rocket Motor Slag

NASA/TP scenario

Al_2O_3 accumulation during combustion

⇩

The chamber pressure has declined

⇩

SRM-Slag spread throughout the chamber from **Slag Pool**

⇩

Begun to diffuse out the nozzle

⇩

Can be very **large (cm) size**

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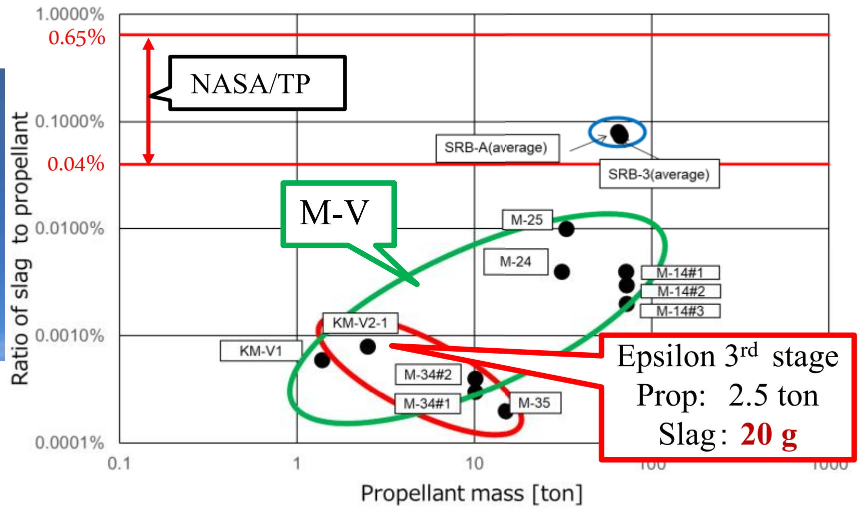
Slag of SRM in Japan

- **Japan has been working on improving propellant combustibility**
- **The ratio of slag to propellant in Epsilon 3rd stage is less than 0.001%**

M-V
(1997-2006)

Epsilon
(2013-)



Slag of each solid motor in Japan (in horizontal static firing test)

⇒Newest Orbital Stage SRM (Epsilon 3rd stage) has less or no Slag Pool ?

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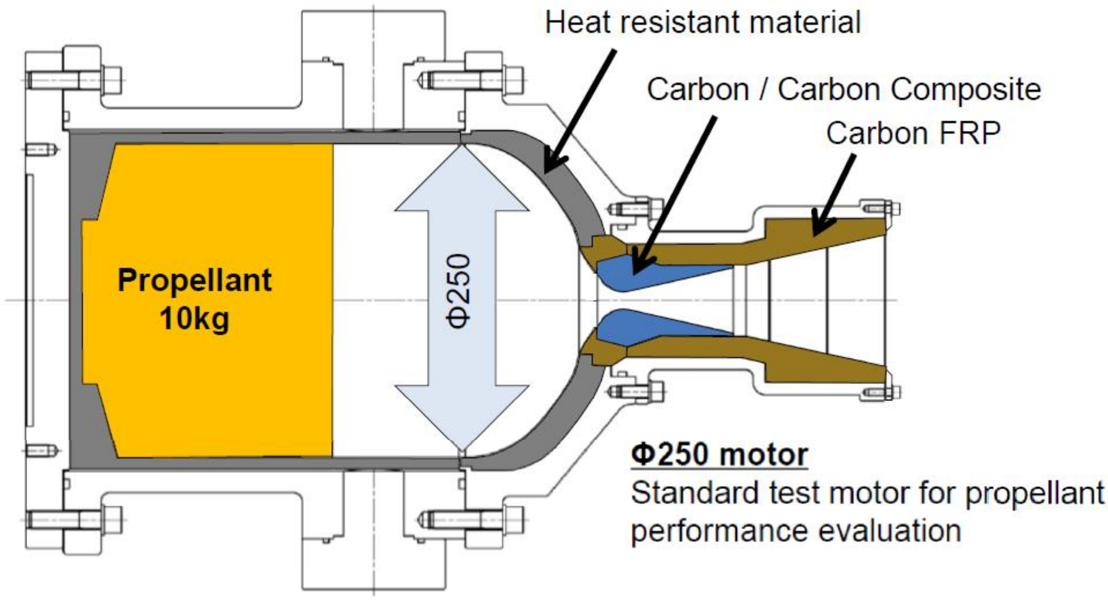
Reduction Plan in Japan

- **JAXA examines this issue from three perspectives.**
  - **Ultimately reduce the amount of slag by improving the aluminum combustion efficiency.**
    Today's topic
  - **Evaluate of physical properties of slag to accurately predict the orbital behavior**
  - **Quantitative evaluate of the risk of slag in orbit to conduct the impact assessment.**
    In progress

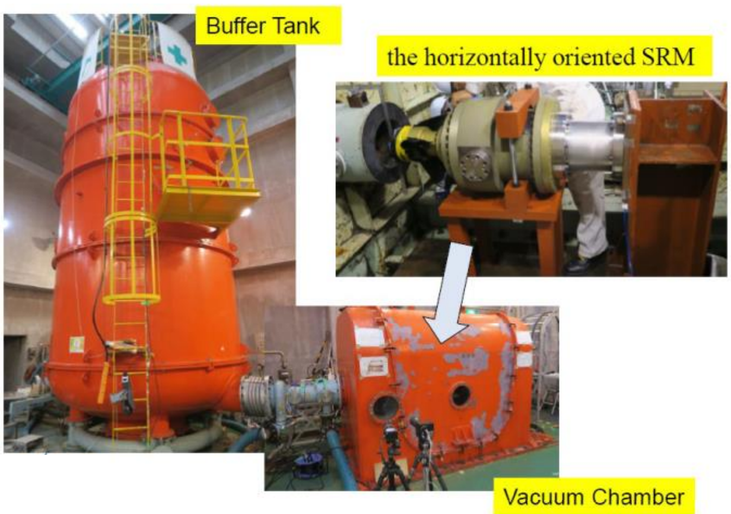
Reduce the Amount of Slag

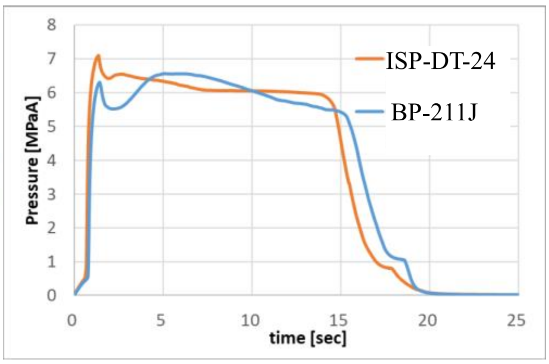
- **Static firing test was conducted in 2020**
- **Comparing 2 propellants :**
  - **BP-211J** :Newest propellant for orbital / upper stage
  - **ISP-DT-24** :Aluminum combustion efficiency improved

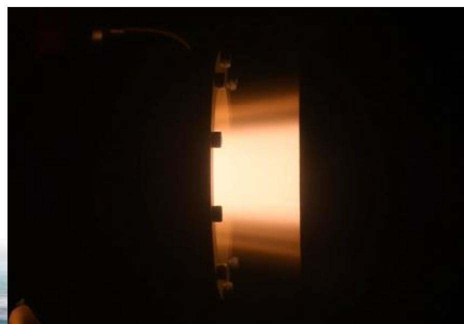


Reduce the Amount of Slag

- **Test facility : Akiruno Experiment Lab in JAXA**
- **Static fire in low-pressure environment (around 5 kPa)**







Reduce the Amount of Slag

- **Results : amount of slag in the motor ; A >> B**

Reduce the Amount of Slag

- **All the slag particles were picked up and sorted by size.**
- **Impressively reduction of number and weight with ISP-DT-24**

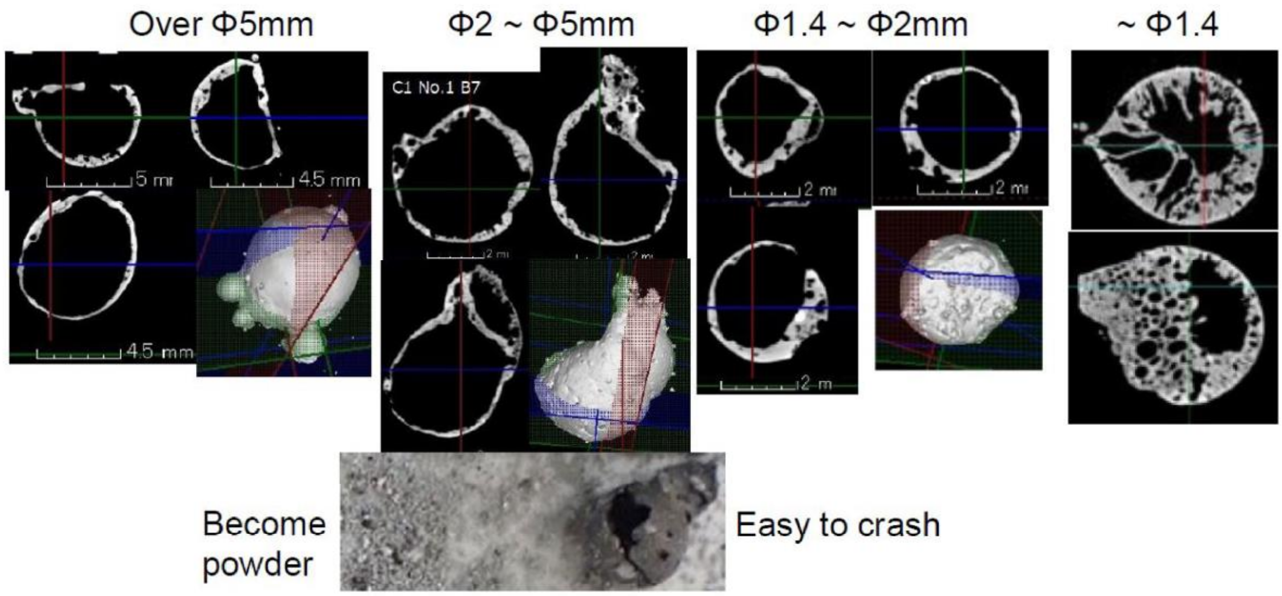
No.	Propellant	Number of SRM-Slag								
		~ Φ5.0	Φ2.0~ Φ5.0	Φ1.4~ Φ 2.0	Φ1.0~ Φ1.4	Φ0.71~ Φ1.0	Φ0.5~ Φ0.71	Φ0.425~ Φ0.5	Φ0.425~	Total
1	BP-211J	11	111	743	188	156	306	226	0	1741
2	ISP-DT-24	0	0	11	8	4	0	0	0	23
3	ISP-DT-24	0	0	10	10	6	0	0	0	26
4	ISP-DT-24	0	1	1	2	7	0	0	0	11

No.	Propellant	Weight of SRM-Slag (g)									(ppm)
		~ Φ5.0	Φ2.0~ Φ5.0	Φ1.4~ Φ 2.0	Φ1.0~ Φ1.4	Φ0.71~ Φ1.0	Φ0.5~ Φ0.71	Φ0.425~ Φ0.5	Φ0.425~	Total	Slag to Prop. Ratio
1	BP-211J	1.581	2.254	2.677	0.354	0.097	0.086	0.022	0.161	7.232	7.2
2	ISP-DT-24	0.000	0.000	0.110	0.017	0.004	0.000	0.000	0.000	0.131	0.1
3	ISP-DT-24	0.000	0.000	0.078	0.019	0.004	0.000	0.000	0.000	0.101	
4	ISP-DT-24	0.000	0.012	0.004	0.002	0.004	0.005	0.000	0.000	0.027	

Less than **1/50**

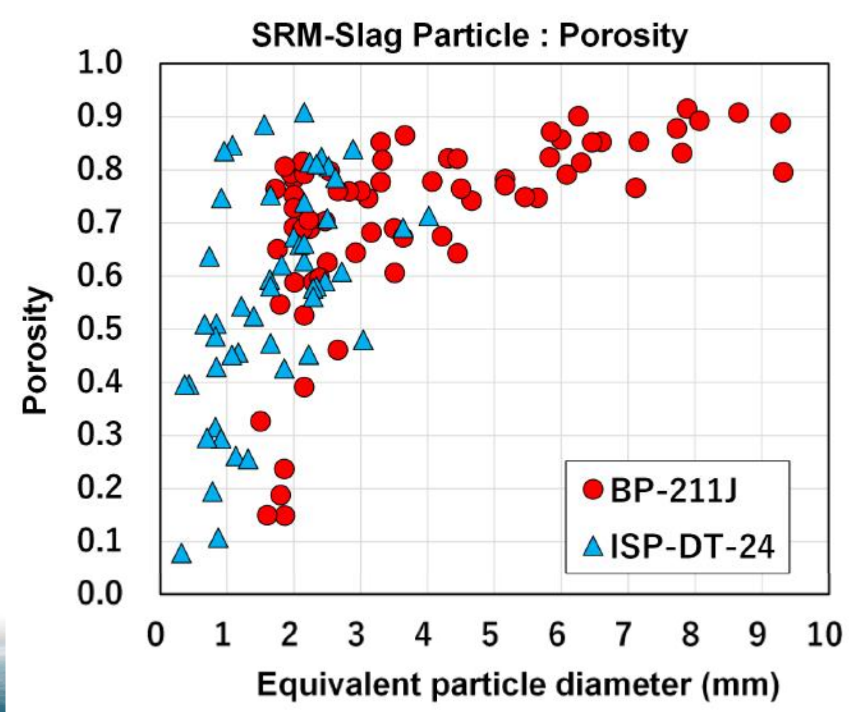
Evaluate of physical properties of slag

- 40 particles picked after firing test are investigated with X-CT
- In large ones, the inside is hollow, very fragile
- Many small voids in the outer shell.



Evaluate of physical properties of slag

- The larger the size, the higher the porosity, so the outer shell should be thinner.



Contents

Conclusion

- Slag emissions from SRM should be mitigated, especially in the orbital stage.
- Japanese newest orbital stage SRM has less or no slag-pool, much less slag amount than past studies of NASA/TP.
- JAXA examines this issue from three perspectives.
  ① Ultimately reduce the amount of slag by improving the aluminum combustion efficiency.
  ② Evaluate of physical properties of slag to accurately predict the orbital behavior
  ③ Quantitative evaluate of the risk of slag in orbit to conduct the impact assessment.
- JAXA is tackling this research to realize new SRM that contributes to the orbital environmental conservation and sustainability of Space Development.

Thank you for your attention

Questions & Comments ⇒ kinoshita.masahiro@jaxa.jp

A05

Active Debris Removal by Electric Propulsion: Charging Mitigation on Target Debris in Debris Capture Sequence

電気推進搭載衛星による能動的デブリ除去技術の開発：デブリ捕獲シーケンスにおけるターゲットデブリの帯電緩和

〇MURANAKA Takanobu (Chukyo Univ.),
CHO Shinatora, OKUMURA Teppei, OHKAWA Yasushi (JAXA Research and Development Directorate)
〇村中崇信（中京大学），張科寅，奥村哲平，大川恭志（JAXA 研開部門）

Active debris removal (ADR) of large-scale debris is expected to suppress number of space debris in next 100 years. An ADR method is proposed by JAXA using electric propulsion to deorbit large-scale debris existing in congestion orbit. To prevent charging-arcing failure for deorbiting satellite at the debris capturing moment, we numerically studied charging mitigation by thermal ions produced in Hall thruster plasma plume on the target debris in polar orbit which is exposed by high-energy auroral electrons. In a debris capture sequence that the satellite approaches to the target from the direction of orbital motion of the target, it was obtained that the target debris could have a potential of ¬–100 V to that of the satellite due to lower incoming orbital ions compared to the satellite. Also, we obtained that thermal ions which were produced in the thruster plasma plume diffused toward the target debris and could mitigate the negative charging on the debris, although equivalent potential to the satellite could not be achieved in this case.

混雑軌道における大型デブリの能動的除去（ADR）は，今後 100 年にわたりスペースデブリの増加を抑制する有力な手法であると考えられている．JAXA では，混雑軌道に存在する大型デブリの除去技術のひとつとして，電気推進搭載衛星によるデブリの軌道遷移を提案し，実用化に向けた研究を進めている．軌道上のデブリとデブリ除去衛星は，宇宙環境プラズマによって各々が帯電すると考えられるが，両者に電位差がある場合，デブリ除去衛星がデブリを捕獲する際に放電事故が発生する可能性がある．とくに，これらが極域にあるとき keV オーダの高エネルギーをもつオーロラ電子に暴露され，帯電の絶対値も増加する．そこで，本研究では極軌道における宇宙機帯電の最悪ケースを想定し，プラズマシミュレーションでデブリ除去衛星の電気推進から放出される熱的イオンの挙動解析を実施し，ターゲットデブリに流入するイオン電流と，環境プラズマ電流とを比較し，デブリの帯電緩和を評価した．

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A05

Active Debris Removal by Electric Propulsion: Charging Mitigation on Target Debris in Debris Capture Sequence

○Takanobu Muranaka[1)]
Shinatora Cho[2)], Teppei Okumura[2)], Yasushi Ohkawa[2)]
[1)]*Chukyo University, Japan*, [2)]*JAXA*

10^{th} Space Debris Workshop, @JAXA Chofu Aerospace Center, November 28-30, 2022

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Contents

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- Background and motivation
- Spacecraft charging and charging mitigation
- Space environment parameters
- Charging mitigation using thermal ions produced in EP operation
  - Numerical Code
  - Parameters
  - Results(Conclusion)

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Importance of ADR

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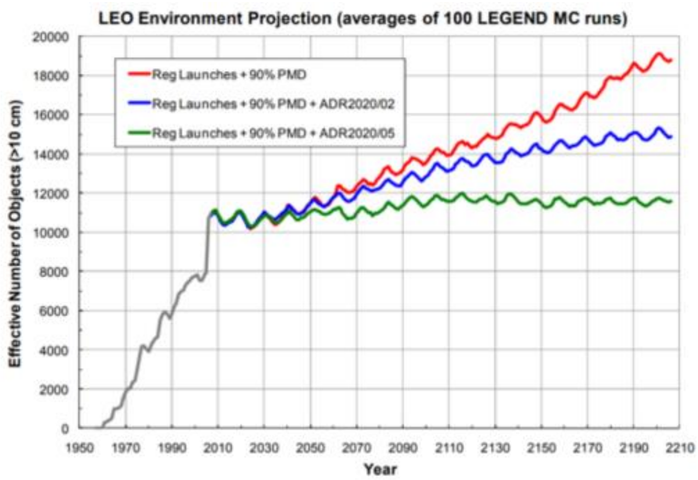

Expected number of debris (>10cm) for PMD + ADR[1]

[1] Liou, J.C., Advances in Space Research 47, 1865–1876, 2011

- Increasing number of space debris has become serious risks to orbital services
- Suppressing large-scale debris (> 10 cm) which causes fatal disruption is of importance
- 90% of PMD cannot suppress the increase of those debris
- Multiplying ADR (5 large-scale debris/year) can suppress those debris for next 200 years
- ADR for large-scale debris on congestion orbit (600-800km) can be efficient for that

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Expected Target Debris in JAXA

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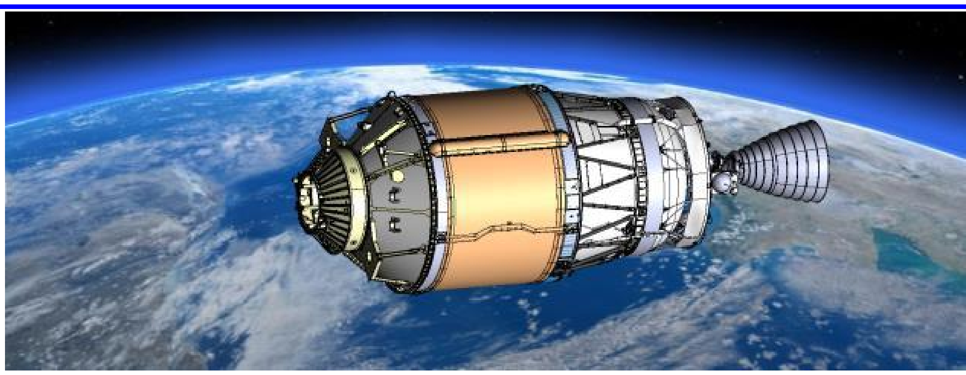
Upper stage of launch vehicle
(Expected H-II launch vehicle)

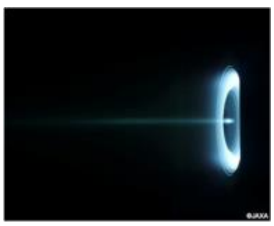
Length：~10m
Mass：~3,000 kg (3 tons)

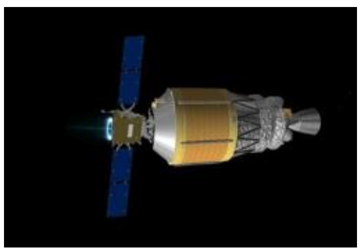
800km-1000km
originally sun-synchronous orbit
(polar orbit)



Deorbiting 3,000 kg-class large-scale debris
→Needs large total impulse
→use electric propulsion (Hall thruster)

1kW-class Hall thruster (JAXA)





[2] Yamamoto, 8th European Conference on Space Debris (virtual), 2021
[3] Cho, presented at GEC2022

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Charging-Arcing Risks at Debris Capture Sequence

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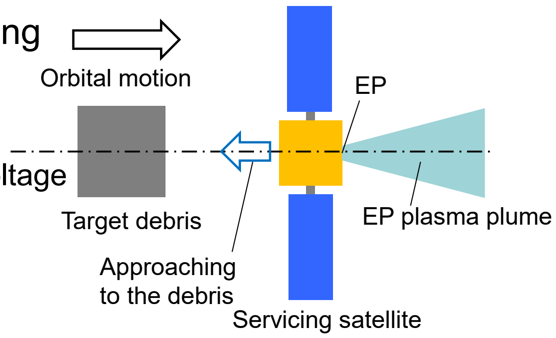
- Debris capture sequence for servicing satellite with EP
- Arcing risks due to spacecraft charging at the docking are concerned
- Arcing risks:
  - Arcing occurs between the objects which have different voltage
  - Threshold voltage: ~100 V on LEO
  - Risks: burning damage,　EM pulse
- Preventing arcing at the docking:
  - Analyze spacecraft charging on the expected orbit
  - Need some measures if the potential difference exceeds to the threshold voltage
  - One solution is charging mitigation using EP exhausted plasmas



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Purpose of This Study

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Purpose:

- Study on charging mitigation on target debris using EP to prevent arcing failure at the docking

This presentation:

- Preliminary investigation on charging mitigation by EP-produced ion flux on a target debris

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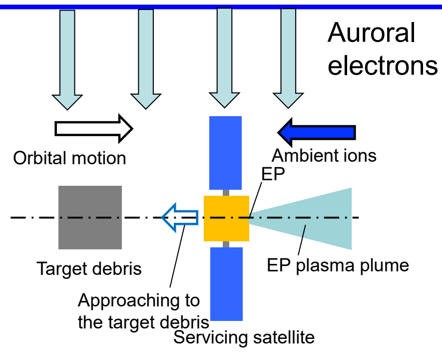
Charging & Charging Mitigation in DCS

1) Spacecraft charging on LEO
   Net current equal zero at a potential
   $$I_e(\phi_s) + I_i(\phi_s) = 0$$
2) Risk of S/C charging on LEO
   High energy auroral electrons on polar orbit
   $$I_e = I_{e(bg)} + I_{e(aurora)}$$
   when $I_{e(bg)} = I_{i(bg)} < I_{e(aurora)}$, $\phi_s \sim -1{,}000V$
3) Potential difference between S/C and debris is caused by Lower $I_{i(bg)}$ on the objects due to ion wake downstream of the S/C to compensate for $I_{e(aurora)}$.
4) CEX ions are produced in EP operation and they could mitigate negative potential ϕ_s on debris by collecting the CEX ions



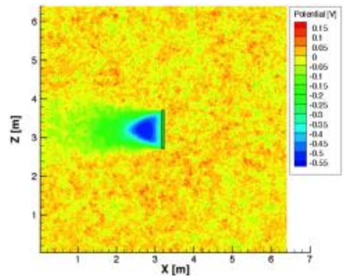


Fig. 3. Potential structure around the membrane at the membrane potential of 0 V. The black rectangle in the domain indicates the cross section of the membrane model.

How to Determine Charging Mitigation

We performed numerical simulation to obtain CEX ion current on debris under expected charging status on PEO

In our simulation:

- Charging analysis and thruster plume analysis are separately performed
- Both satellite and debris are considered as 1 m cube (not so large)

Procedures to determine charging mitigation:

1. Determine parameters for space environment to cause sufficient charging and calculate surface charging on both satellite and debris
2. Calculate distribution of CEX ions and the ion flux on the debris in EP operation
3. Compare magnitude of the auroral and the CEX ion currents on the debris, and determine if charging mitigation is possible or not

Space Environment Parameters

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N_p: 1.56×10⁸/m³			N_p: 3.12×10⁸/m³			N_p: 3.12×10⁹/m³			N_p: 3.12×10¹⁰/m³		
J_a A/m²	T_a eV	V_{diff} V	J_a A/m²	T_a eV	V_{diff} V	J_a A/m²	T_a eV	V_{diff} V	J_a A/m²	T_a eV	V_{diff} V
1.0E-5	1000	772	1.0E-5	1000	637	1.0E-5	1000	-9	1.0E-6	1000	0
1.0E-5	2000	1303	1.0E-5	2000	1152	1.0E-5	2000	-9	1.0E-6	2000	0
1.0E-5	4500	2210	1.0E-5	4500	2180	1.0E-5	4500	-9	1.0E-6	4500	0
1.0E-5	10000	3338	1.0E-5	10000	3723	1.0E-5	10000	-9	1.0E-6	10000	0
1.0E-4	1000	775	1.0E-5	30000	6466	1.0E-5	20000	-9	1.0E-5	1000	0
			1.0E-4	1000	867	1.0E-4	1000	633	1.0E-5	2000	0
			1.0E-4	2000	1408	1.0E-4	2000	1050	1.0E-5	4500	0
			1.0E-4	4500	2328	1.0E-4	4500	1385			

- Obtained by charging analysis using MUSCAT (a charging analysis code)
- Ambient ion density of over 10^{10}/m^3 mitigate charging due to auroral electrons
- We determine space environment parameters for "possible" charging due to auroral electrons: Ja=10^{-4} A/m^2,Ta=1000eV, ambient ions: Np=3.12 x 10^9 m^{-3}

Okumura, IAC 2022.

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Determine Potential Difference

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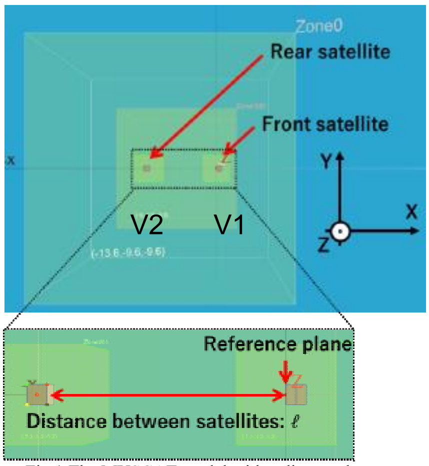

Fig.1 The MUSCAT model with a distance between satellites of 6 m

V1(upstream) ~ –600 V
V2(downstream) ~ –700 V
V0=V2 – V1 = –100 V

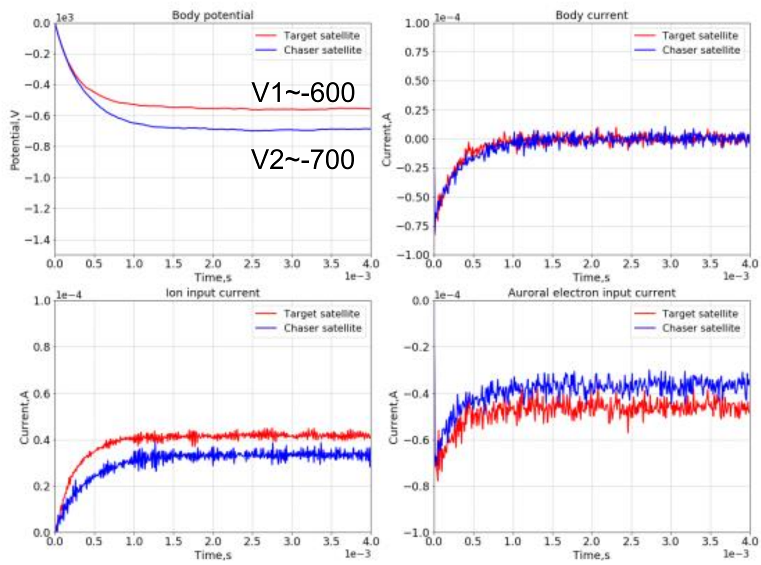

Fig.2 The profile of potential, body current, ion input current, and auroral electron current for ℓ = 6 m

Okumura and Cho, SCTC 2022

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Numerical Code for the Analysis

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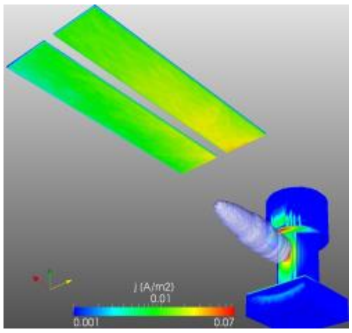
Numerical code: 3D hybrid-PIC + Particle Tracking plume analysis code [4]

PIC method

- Treat beam & CEX ions, neutral particles as particles
- Production of CEX ions
- Treat Electrons as fluid (1-temp. Boltzmann distribution)
- Solve Electric potential



PT method

- Trajectories of particles (beam and CEX ions, neutrals)
- Ion flux and physical properties due to ion bombardment (torque, sputtering rate)

[4] T. Muranaka and Y. Inanaga, Trans. JSASS, Aero. Tech. Japan, Vol. 16. No. 5, pp. 366-373, 2018.

Numerical Domain

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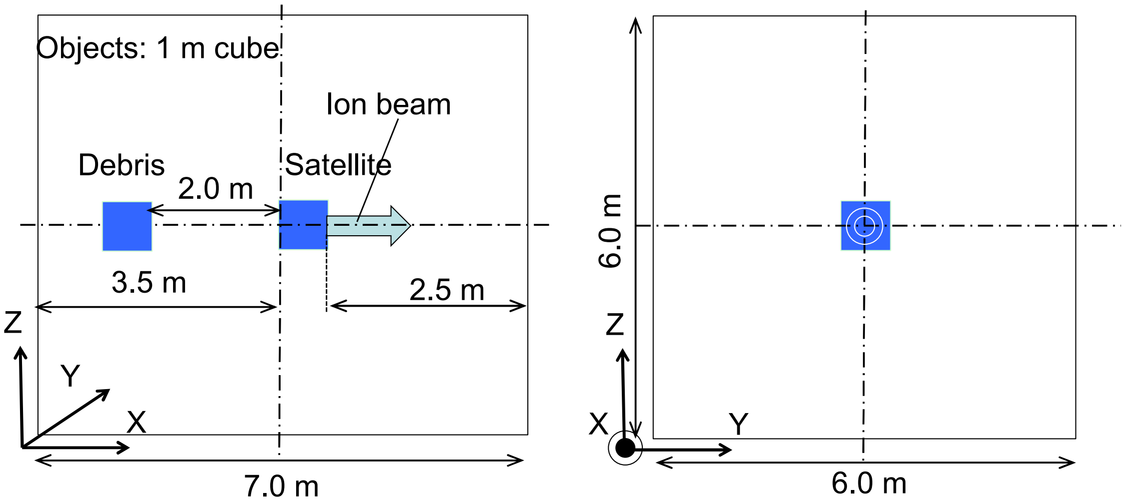
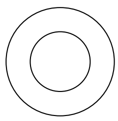


Objects(satellite and debris): 1 m cube
Distance between satellite and debris is 2.0 m



Thruster Exit Diameter
Outer : 100 mm
inner : 69 mm

Numerical Parameters

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Calculation Parameters

Domain [m]	7.0 × 6.0 x 6.0
Satellite scale [m]	1.0 × 1.0 x 1.0
Spatial width [m]	0.05
Time width [$\times 10^{-4}$ s] neutrals/beam/CEX	0.31/0.021/1.16
Computation time [s] Debris surface pot. 0V/–100V	0.505/1.25
Debris surface pot.[V]	0 / –100
Electron temp. [eV]	1.5

Thruster Parameters

Exit diam. (outer/inner) [mm]	100/69
Mass flow rate [mg/s]	5.54
Beam current [A]	2.0
Output power [W]	500
Mean of beam energy [eV]	245
Ratio of 2+ ion current [%]	14
Neutral gas temp. [eV]	0.1

Boundary conditions
Potential：
- outer： Neuman
- object surface：fixed (0V, -100V)

Particles：
- outer：disappear
- object surface： disappea

Referring SPT-100*, we changed beam current from 3.27 A to 2.00 A.
In this case, electric power can be estimated as,
$P_2 = (I_{b2}/I_{b1})^2 P_1 = (2.00/3.27)^2 \cdot 1350 = 505$ [W]

*1.4 kW-class Hall thruster, thrust 85 mN

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Results： Ion Number Density Distribution

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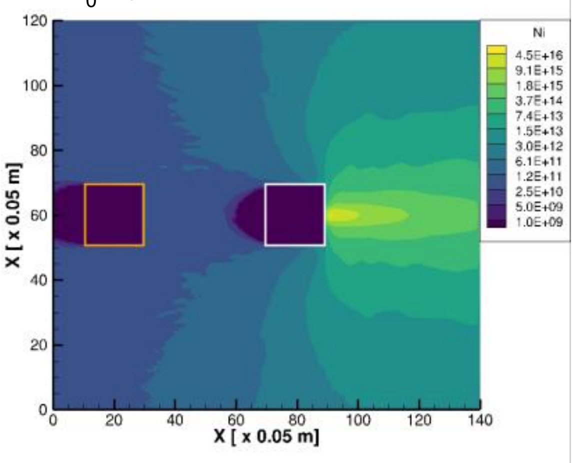
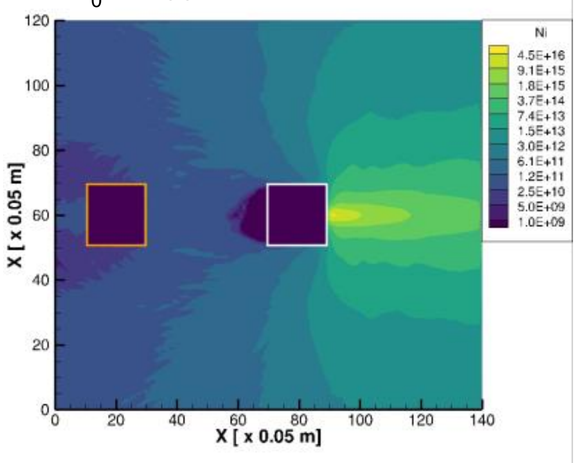
V_0= 0 V



V_0= –100 V



- Ion wake (rare ion density region) is formed in downstream of the objects
- Scale of the ion wake is almost same as objects scale
- Ion density in the downstream of the debris is higher at V_0=–100V compared to that at 0V.

V_0： relative voltage of the debris to the satellite

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Results： Ion Flux on the Objects

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Observation point: upstream

V_0= 0 V

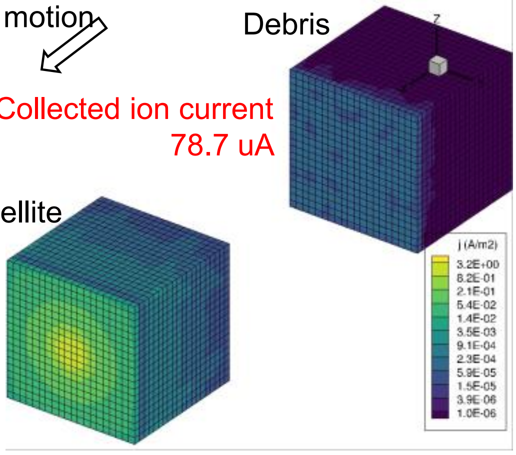
V_0= –100 V

Orbital motion

Debris

Collected ion current
78.7 uA

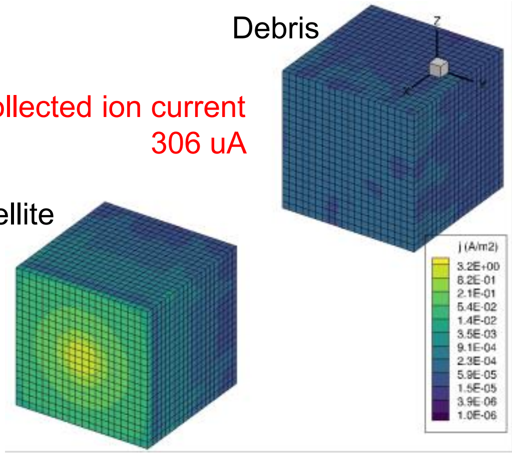
EP satellite



Debris

Collected ion current
306 uA

EP satellite



- Ions hardly flow onto the bebris except on the front surface at V_0=0 V
- Ions can flow onto the bebris on the front and side surfaces at V_0=–100 V.

Conclusions: Charging Mitigation

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- Collected ion current (CEX ion) on the debris
  - 78.7 uA (satellite-debris potential diffs：0) < 100 uA (auroral current)
  - 306 uA (satellite-debris potential diffs -100V) > 100 uA (auroral current)
- Charging mitigation
  - satellite-debris potential diffs 0: complete charging mitigation
  - satellite-debris potential diffs -100V：partial charging mitigation
- Expected debris potential (in this case only)
  - Saturated to negative several tens of volt in EP operation
- Difference of the collected ion current
  - Caused by difference of collective surface on the debris for CEX ions:
  - front surface only or front, sides and back surfaces

A06

Monocular Image Measurement of Space Debris Attitude and Motion

宇宙デブリの姿勢・運動の単眼画像計測

〇NISHIDA Shin-Ichiro, NAKAMURA Shunsuke (Tottori University)
〇西田信一郎、中村駿介（鳥取大学）

We have been studying so-called “template matching” using 2D patterns in monocular images. However, since the upper stage of the rocket, which is assumed to be the target debris for the time being, is the shape of the central axis, a one-to-one correspondence cannot be established by using the contour image of the outer shape as a template, resulting in frequent misrecognition problems. Furthermore, matching with a large image size requires a large amount of arithmetic and memory data, and the onboard computer of a radiation-resistant spacecraft has less than 1/100th of the storage capacity of a ground-based computer, so reducing the amount of template data is a major issue.
In a previous study (Kikuchi, Nishida, 2016), the effectiveness of dimensionality reduction using the eigenspace method was demonstrated as a method to reduce the amount of template data while using information other than contours. However, there remained the problem of preparing templates for various sunlight irradiation directions. In this study, we report the results of a method to reduce the amount of template data by applying the eigenspace method to the templates for various sunlight irradiation directions and setting appropriate threshold values.

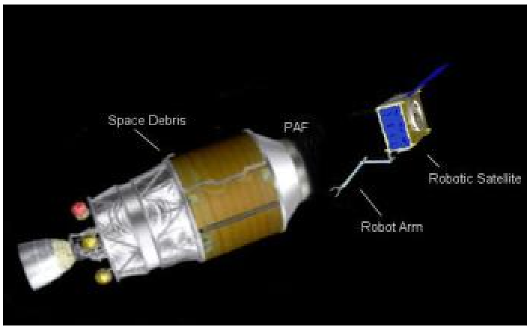
我々はこれまで、宇宙デブリの姿勢・運動計測に単眼画像中の 2 次元パターンを利用した、いわゆる「テンプレートマッチング」の研究を行ってきた。しかし、当面の対象デブリと想定されるロケットの上段は中心軸の形状であるため、外形の輪郭画像をテンプレートとした 1 対 1 の対応付けができず、誤認識問題が多発する。また、画像サイズが大きい照合は、大量の演算データ、記憶データを必要とし、耐放射線宇宙機の搭載コンピュータは、地上コンピュータの 100 分の 1 以下の記憶容量しかなく、テンプレートデータ量の削減は大きな課題であった。
先行研究（菊池、西田、2016）では、輪郭以外の情報を利用しながらテンプレートデータ量を削減する方法として、固有空間法を用いた次元削減の有効性が示された。しかし、様々な太陽光の照射方向に対応したテンプレートを用意する必要があるという問題が残されていた。そこで、本研究では、様々な太陽光の照射方向に対するテンプレートに対して固有空間法を適用し、適切な閾値を設定することで、テンプレートデータ量を削減する方法を検討した結果を報告する。

The 10th Space Debris Workshop

Monocular Image Measurement of Space Debris Attitude and Motion

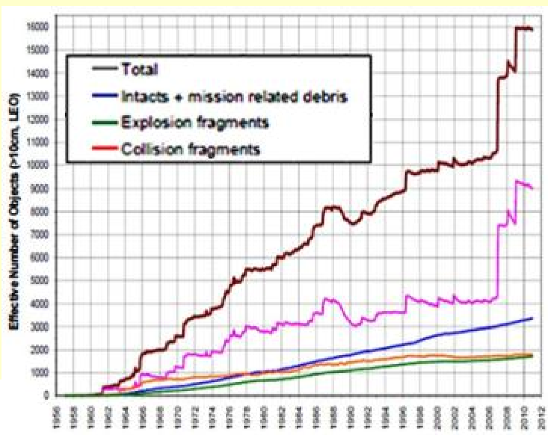
Shin-Ichiro Nishida and Shunsuke Nakamura

Tottori University, Japan

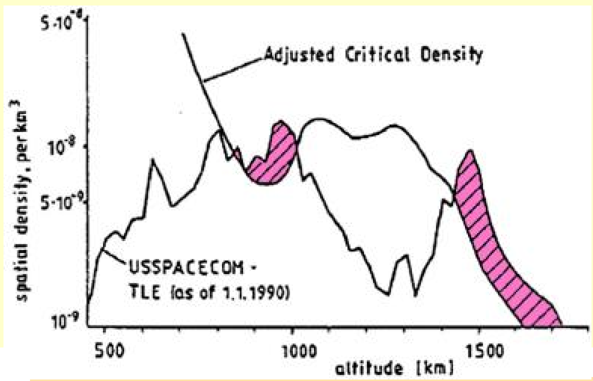


Introduction

- Since the number of space debris in Earth orbit is steadily increasing, it will eventually pose a serious problem to near-Earth space activities.
- The active removal of space debris by robotic space craft is the most effective measures to mitigate space debris.
- Active Debris Removal (ADR) as soon as possible is needed to prevent mutual collision of space debris.



Effective number of objects forecasted by NASA (LEGEND): NASA The Orbital Debris Quarterly News



Kessler, Collisional cascading: The limits of population growth in low Earth orbit, Advances in Space Research 11(12):63-66, 1991

Assumed removal targets

Assumed H-series rocket upper stage to be removed

- Ownership of space debris originating from other countries is secured by other countries
- For the time being, the target is to remove space debris from Japan

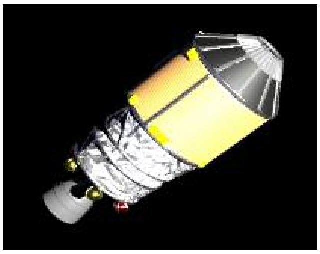
The reasons for targeting them are that are;

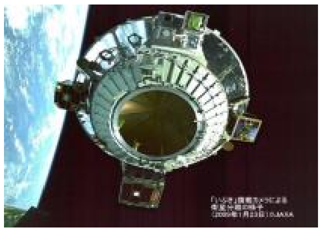
① numerous in useful orbits

② large space debris

③ similar in shape and the same strategies can be applied

④ known dimensions and mass properties





A view on the Ibuki released ©JAXA

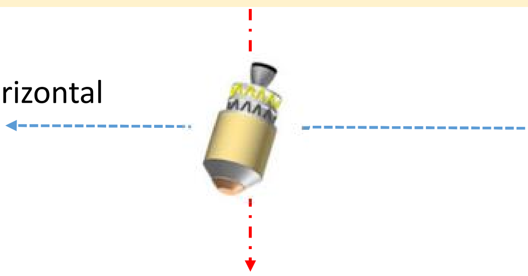
Assumed removal targets

- Non-cooperative body without attitude control

  (No markers for rendezvous or docking, etc.)
- Converges to a vertical attitude with its center axis due to high gravity-gradient torque due to its elongated shape
- Low rotational rate, with only a slight residual pawing motion

  (Note that ground-based observations of high-speed rotation are not included.)

Local horizontal



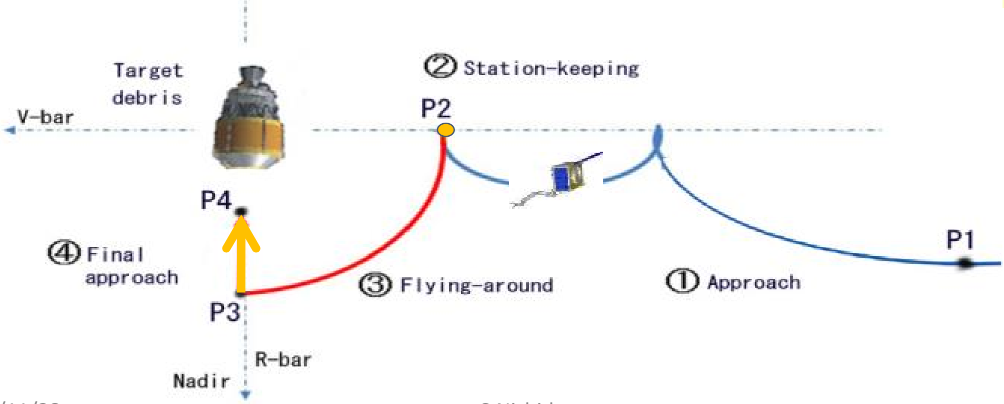
Nadir

Rotation rate 0.1～3[deg/s]

Mission scenario

Sensing

①On approach phase, a GPS-receiver & stereo vision are used
②Observation of attitude & rotational motion of target in relative station keeping at P2
③Continuously measures distance and relative attitude during the flying-around
④On final approach, relative position and attitude are measured

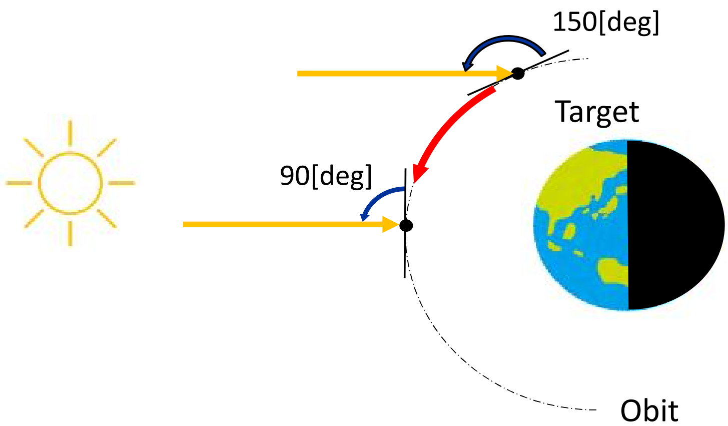


Assumed removal targets

Attitude, motion and lighting environment

- The object will circle the earth in about 90 minutes at the assumed orbit around 700 km.

- Lighting conditions vary with local-sun-time
  (Sunlight and Earth albedo light)



Measurement system consideration

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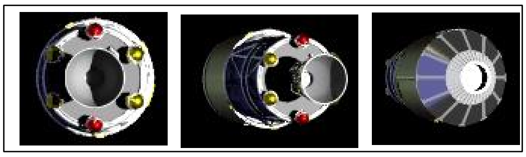
Comparative Study of Measurement Sensors

Method	Pros.	Cons.
Monocular camera	･Light weight ･Low cost	･Low accuracy in distance meas.
Stereo cameras	･Light weight ･Low cost	･Large calculation volume for 3D
Laser sensor	･High accuracy	･High cost ･Large calculation volume for 3D

Learning images



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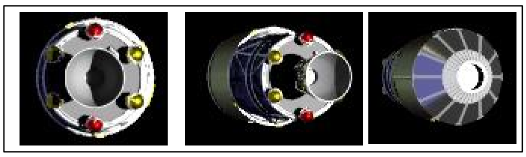
Attitude measurement from monocular images

- From the contour, it is not possible to distinguish between the back and front inclination
- Shading from sunlight is excessively sensitive to posture
- Shaded areas are also illuminated by albedo light from the earth
- During eclipse, LED lighting is applied, so the effect of shading is small

･As a method that can be applied both during both daytime and eclipse, consider using only low-dimensional information in eigenspace for the 2D patterns in the target image

･Switch matching patterns by local-sun-time

target images



Proposed method

Research Objectives

- Reduction of template image data volume on a limited computer
- Reduction of calculation volume when estimating posture and motion by template matching
- Confirmation of attitude estimation method for different sun light directions

Proposed method

- Pose and motion estimation using eigenspace method and Kalman filter
- Reduction of data volume and calculation volume of database for each sun irradiation direction
- Motion model considering gravity-gradient torque

Proposed Attitude Estimation Algorithm

① The learning process for the eigen space method

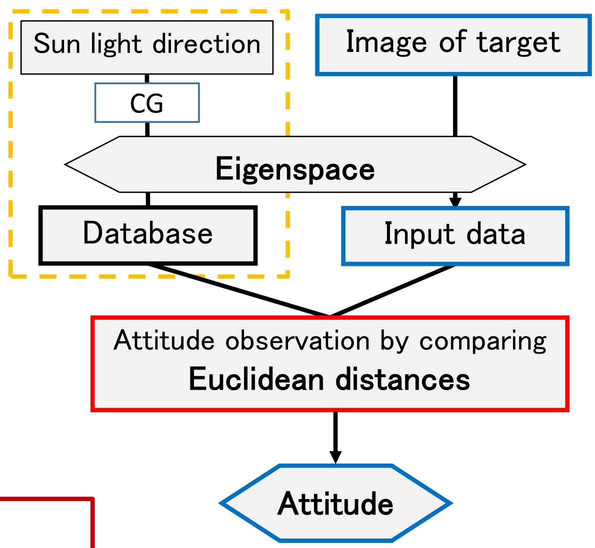
Prepare learning images before operation

② Recognition process of eigen space method

Debris is photographed in orbit and attitude estimation in eigenspace

③ Kalman filter processing

From the time series of attitude measurements state estimation by Kalman filter



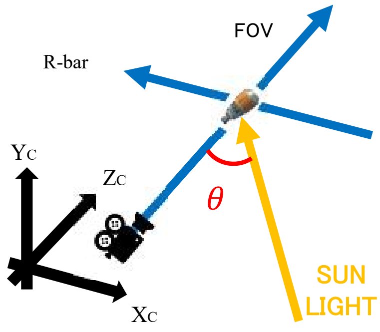
Attitude Estimation Algorithm

Attitude estimation by eigenspace method

Learning Process for Eigen Space Method

- 3D-CG to create a projected image on orbit

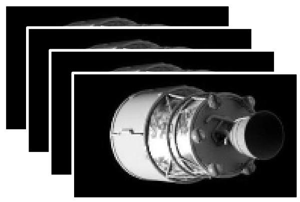
(Change debris shape, motion, and lighting conditions freely → Represent how debris is expected to look in orbit)



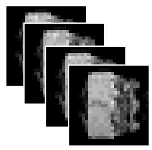
Pre-processing of the created learning images

- Crop processing and contrast adjustment
- Reduce the image size to 25 x 25[pixel]

Original image



After cutout and After Shading Extraction Process

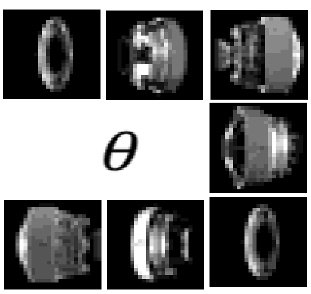


After reduction

Attitude estimation by eigenspace method

Learning Process of Eigen Space Method

- Creation of eigenspace according to the direction of sunlight
- Project the learning images onto the eigenspace (eigenspace), where each image is represented as a point by using the following equation

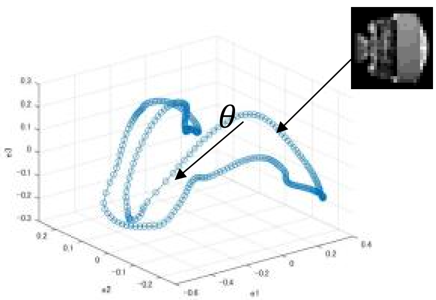


Projection onto eigen space

$$g = E^T(x - c)$$

x: Learning image

c: Average image

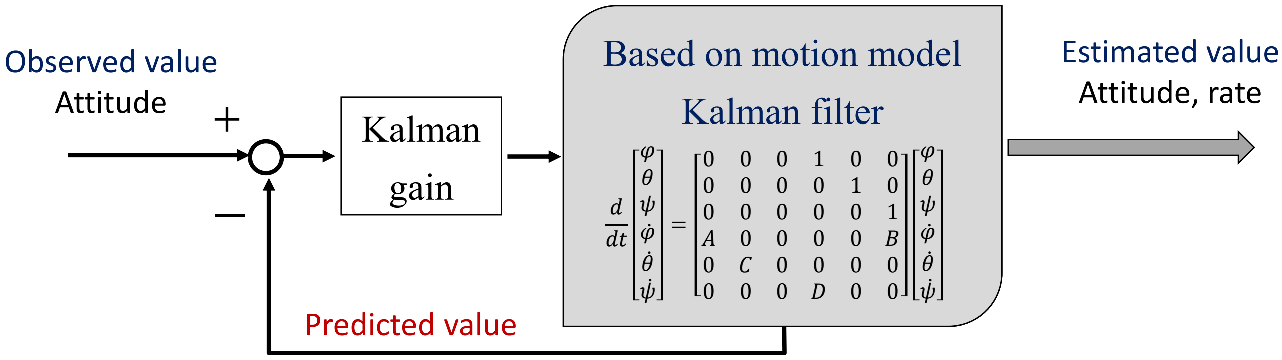


- Perform this process for each direction of sunlight irradiation to build a database.

State Estimation by Kalman Filter

Kalman filter application

- Inputs the posture estimate by the eigenspace method as observed values
- Predicts the posture from the target motion model and adds it to the observed values by the eigenspace method to rigorously estimate the state (posture and angular velocity).
- Outlier elimination process is incorporated to eliminate specific errors.



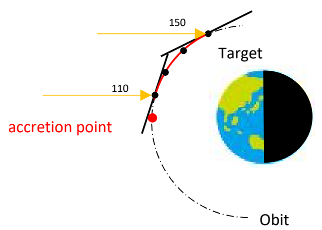
$$\frac{d}{dt}\begin{bmatrix}\varphi\\ \theta\\ \psi\\ \dot{\varphi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix}=\begin{bmatrix}0&0&0&1&0&0\\0&0&0&0&1&0\\0&0&0&0&0&1\\A&0&0&0&0&B\\0&C&0&0&0&0\\0&0&0&D&0&0\end{bmatrix}\begin{bmatrix}\varphi\\ \theta\\ \psi\\ \dot{\varphi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix}$$

Simulation

Case study

- Assume sun-synchronous orbit
- Target motion is assumed to be pendulum motion due to gravity-gradient torque
- Amplitudes in outward and inward directions are set to 5[deg] and 10[deg], respectively.
- Observation time is set to 10 minutes, and the target is measured moving in orbit (orbital angular velocity 0.06[deg/s])

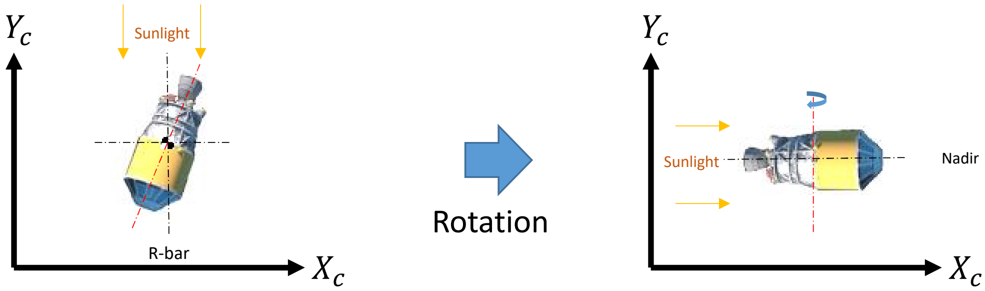
Templates for each direction of the sunlight are available from 150 to 110 degrees (in 10-degree increments). Switch according to observation time.



Simulation

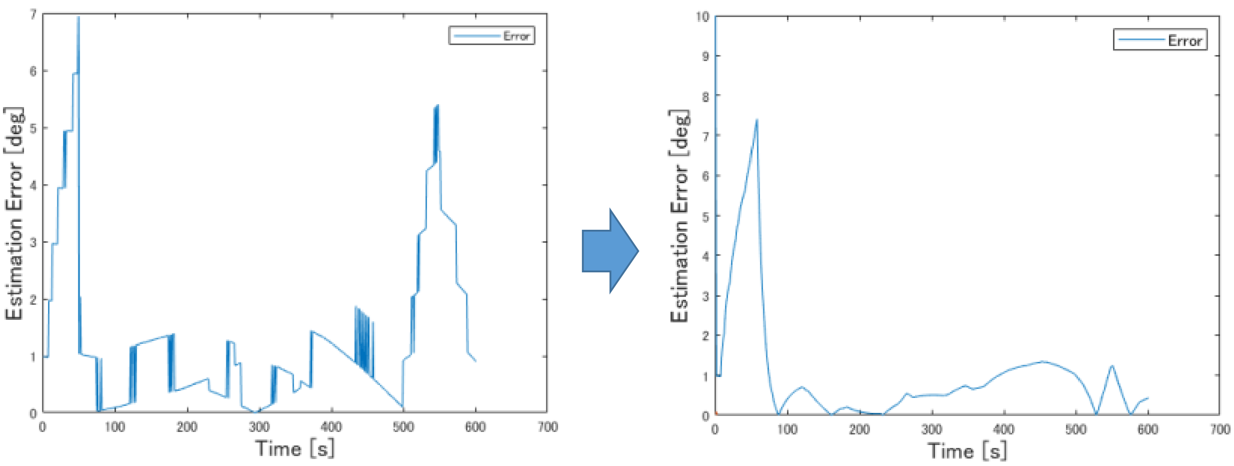
Two-axis attitude estimation

- Pose estimation using the eigenspace method is performed only in the in-plane direction of the orbit.
- Pose estimation in the camera frame plane is obtained by rotating the camera so that the long axis direction is parallel to the X_c axis.
- Only the angle to the camera frame plane is estimated by the eigenspace method.
- The amount of computation can be reduced by limiting the eigenspace method's pose estimation to one axis.



Simulation

Evaluates the attitude estimation error in the in-plane direction of the target's



Pose estimation error by eigenspace method
Maximum error is **5.5 [deg]**
between 500～600[s]

Pose Estimation Error by Kalman filter
Maximum error is **1.25 [deg]**
between 500～600[s]

Simulation Results

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Data volume reduction effect

- Evaluation of Pose Estimation Error, Number of Dimensions, and Amount of Data
- When template images are stored as they are, the data volume is 25[MB].
- Data volume can be reduced to 1/100 when storing images with 10 dimensions.
- Accuracy increases with the number of dimensions, but decreases more than 10 dimensions.
- By applying the Kalman filter, it is possible to estimate the attitude with an attitude estimation error of about 1[deg].

	Number of dimensions		
	6	10	14
Maximum error of posture estimate [unit:deg](500～600[s])	3.88	1.25	2.98

	Number of dimensions		
	6	10	14
Data volume[kB]	95	160	225
Calculation volume(x 10^3)	3.75	6.25	8.75

Conclusion

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What we did

•Created orbital images simulating various sunlight directions

•Estimated attitude motion using eigenspace method and Kalman filter

Simulation results

•Good attitude estimation with a maximum error of 1.25[deg] was obtained using template images with 10-degree increments in the sun's irradiation direction.

•By setting the number of dimensions to 10, the average error of the attitude estimation by the eigenspace method was reduced to 1.27[deg].

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Thank you for your attention.

Prototype of robot arm for target capturing

A07

人工衛星の光学 CAD モデルと衛星材料 BRDF を用いたライトカーブの推定

Photometric Light Curve Estimation Using GEO Satellite CAD Models and Material BRDFs

○遠藤 貴雄，尾野 仁深，辻 秀伸（三菱電機株式会社）
○ENDO Takao, ONO Hitomi, TSUJI Hidenobu (Mitsubishi Electric Corporation)

近年は，地球の軌道上にある人工衛星等の飛翔体に燃料を補給したり，または役目を終えたロケットボディ，スペースデブリ等の軌道上残物体（Resident Space Objects)を軌道上から取り除く等の，軌道上サービスが計画されている．サービス相手の状態をあらかじめ知ることができれば，サービスの提供が容易になると考えられるが，相手が RSO の場合，その状態を把握することは困難である．そこで，隕石のスピンレートや，形状を求めるように，光度の時間変化，光度曲線（ライトカーブ）を利用して，人工衛星や RSO の姿勢や運動状態，形状を調べる方法が提案，研究されている．
しかしながら，観測される光度は，照明光源である太陽と観測者との位置関係のほか，物体の形状や，表面の散乱特性にも依存するため，非常に複雑で，正確に理解するのは困難である．そこで，これら軌道上の照明条件を再現するシミュレータを構築し，光度曲線を推定することを試みた．

In the past, analyses of light curve data have been applied to determine the axis of rotation, spin rate and shape of asteroids. In recent decades, these analyses have begun to be applied in the domain of Earth-orbiting satellites. Due to the complex shape of a satellite, these analyses require more complex assumptions and greater knowledge about the object being studied. This paper presents a ray-tracing system to model the reflectance of satellites, represented as a bidirectional reflectance distribution function (BRDF), by applying a satellite's surface material reflectance characteristics to its computer-aided design (CAD) model.
In this paper, we will discuss the performance of the ray-tracing system and the resulting photometric light curve of satellites in geostationary orbit obtained from the ground-based telescope.

A07

人工衛星の光学CADモデルと衛星材料BRDFを用いたライトカーブの推定

第10回スペースデブリワークショップ

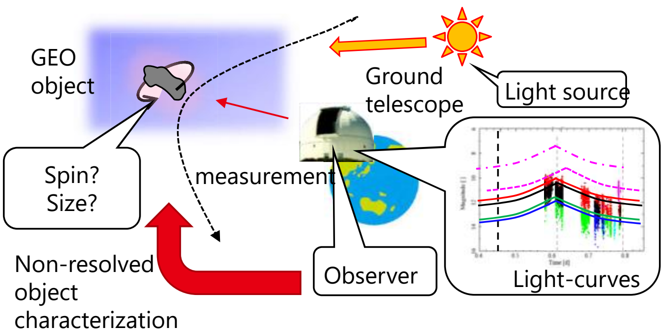
2022/11/28

三菱電機株式会社

Motivation

- Space situational awareness (SSA) data provides information on satellite activity.
- In the future, SSA data will be an important part of operational services such as on-orbit services, space logistics, and active debris removal.

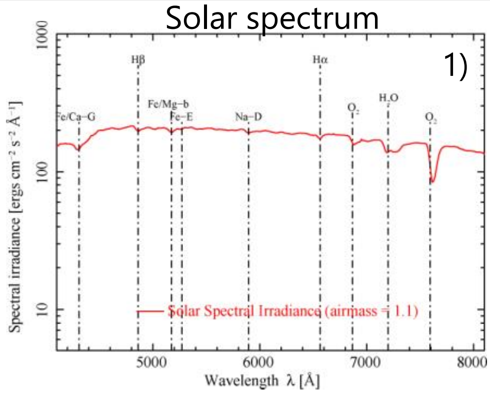
- The Geostationary Earth Orbit (GEO) objects cannot be spatially resolved even by current large aperture ground-based optical telescopes.
- Therefore, unresolved optical measurements such as light-curve photometry or spectroscopy can be a good tool for understanding individual characteristics of each GEO object.



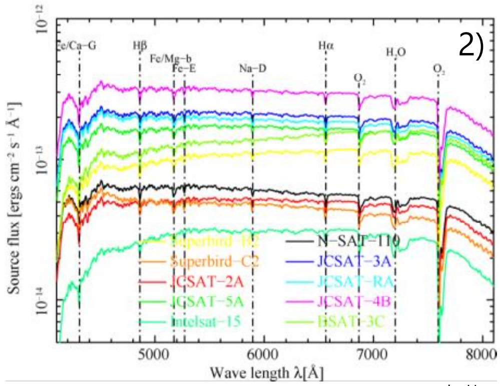
Recent study

- We have observed the spectra of GEO satellites with GLOWS at GAO in 2016.
- All the spectra of GEO satellites were similar to the solar spectrum.

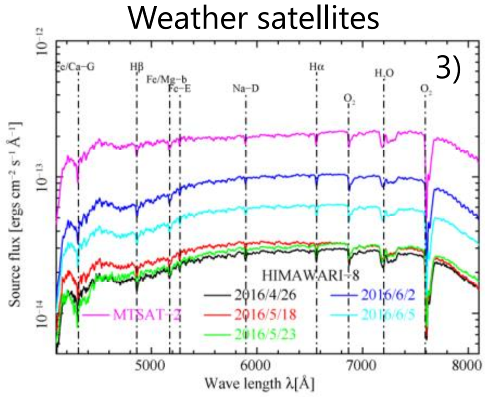
Solar spectrum



Communications/Broadcasting satellites



Weather satellites

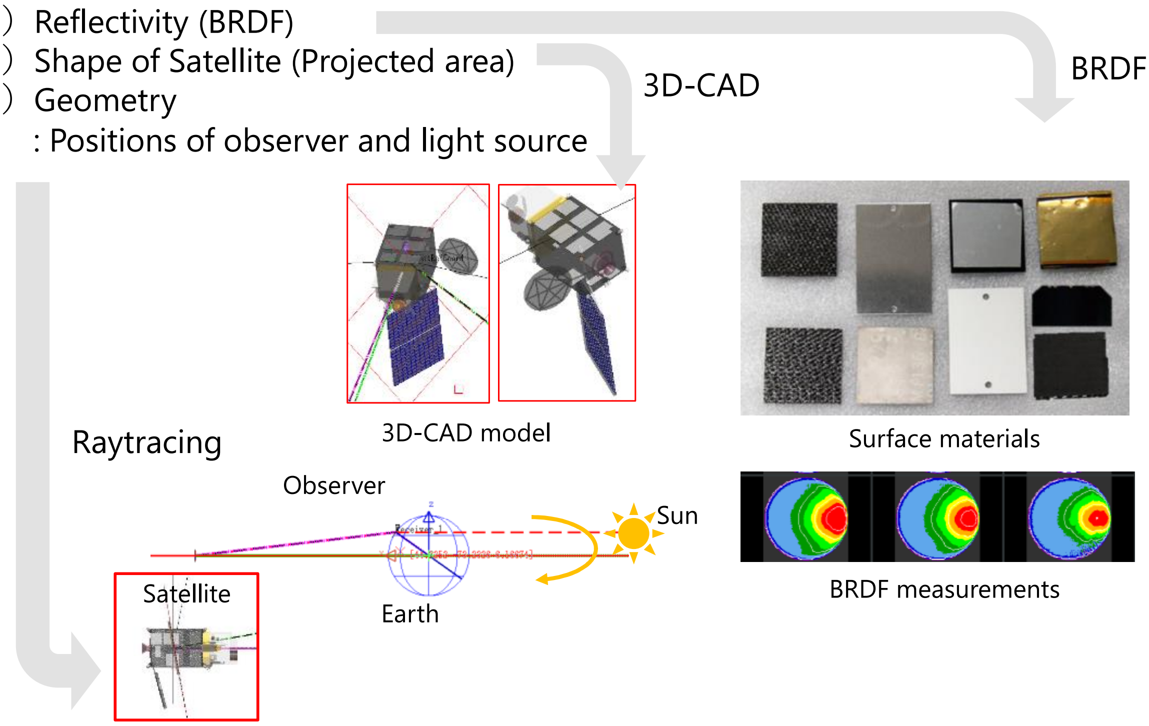


1)-3) 遠藤、他
ぐんま天文台分光撮像装置による静止衛星の分光観測と特徴抽出
宇宙科学技術連合講演会講演集 pp. 4027(2017)

Analysis

Light-curve prediction from raytracing calculation

1） Reflectivity (BRDF)
2） Shape of Satellite (Projected area)
3） Geometry
: Positions of observer and light source

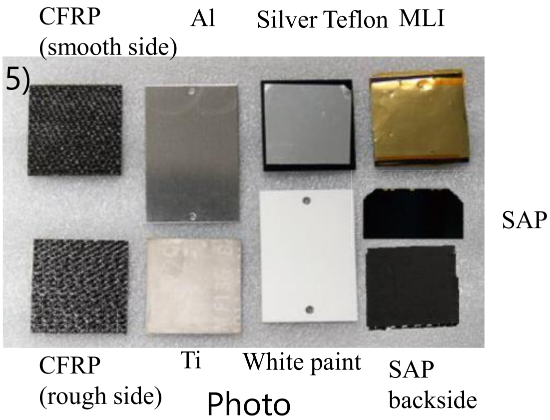


Satellite surface materials

- The artificial satellites shine brightly by mainly reflection of sunlight.
- Characteristic features are probably due to the multilayer coatings of SAP surface.

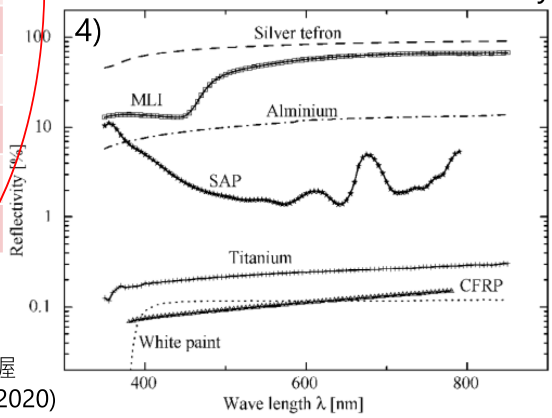
I.D.	Sample	Surface Properties
1…	CFRP	Black, smooth
2…	Al	Sliver, smooth
3…	Silver Teflon	Silver, smooth
4…	MLI	Gold, smooth
5…	CFRP	Black, rough
6…	Ti	Silver, matte
7…	White paint	White, matte
8…	SAP	Black, smooth
9…	SAP(backside)	Black, rough

→ BRDF measurement



Photo

Reflectivity



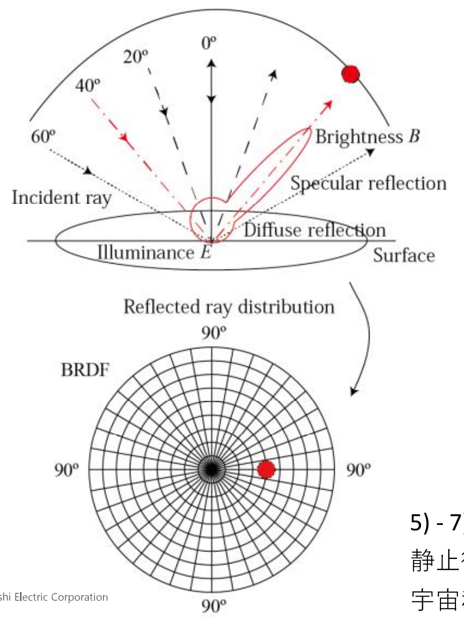
4) 遠藤、他
静止衛星の地上分光観測による特性把握
日本赤外線学会誌 Vol.30,No.1,P61-68 (2020)

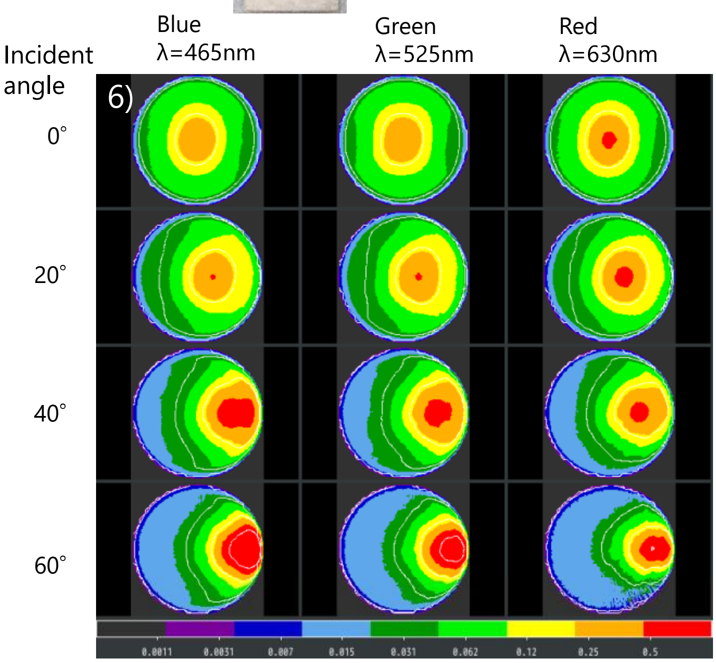
BRDF measurement

Sample material: Ti

Bidirectional Scattering Distribution Function (BRDF) measurements

- Color: R/G/B
- Incident angle: 0/20/40/60 deg
- Resolution: 1deg





BRDF distributions

5) - 7) 遠藤、他
静止衛星の光学散乱モデルによる地上観測光度曲線の推定
宇宙科学技術連合講演会講演集 pp. 4293(2022)

Raytracing results of sample materials

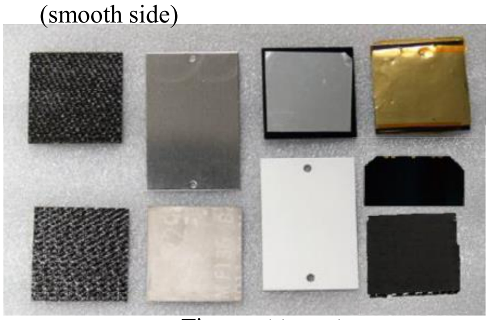
MITSUBISHI ELECTRIC Changes for the Better

LightTools: Commercial illumination design tool

Raytracing results of sample materials
- color
- matte / glare

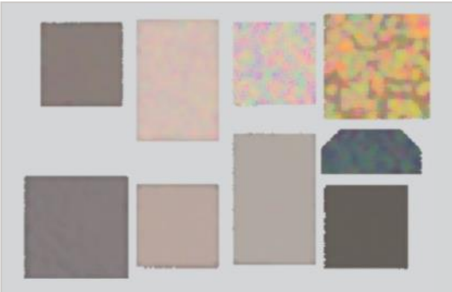
→ Not to achieve a perfect match...

5)

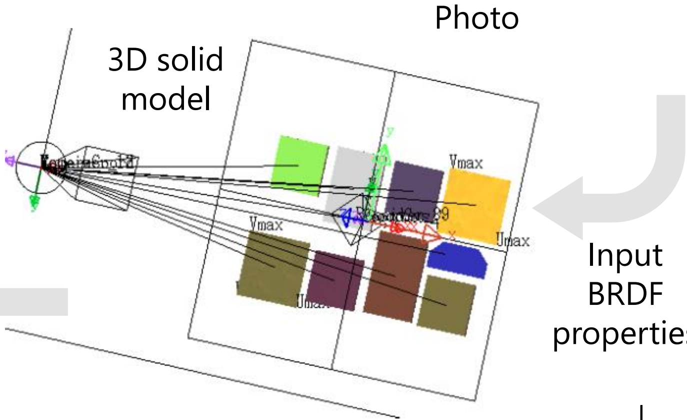


Photo

7)



Raytracing results using measured BRDFs

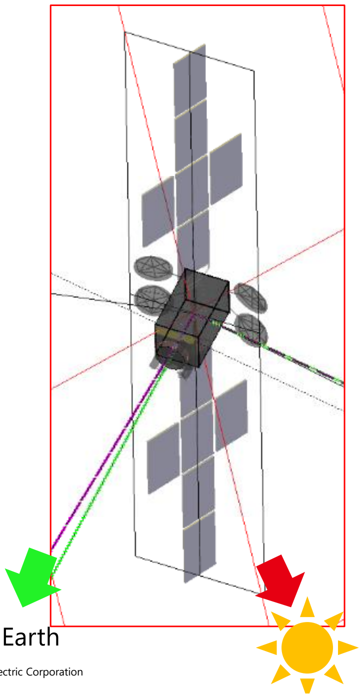


3-D model of GEO Satellite

MITSUBISHI ELECTRIC Changes for the Better

- In normal operation, the satellite bus always orients to the earth (nadir).
- The solar panels are always seen face-on as they track the Sun.
- Geometry was referenced to public data.

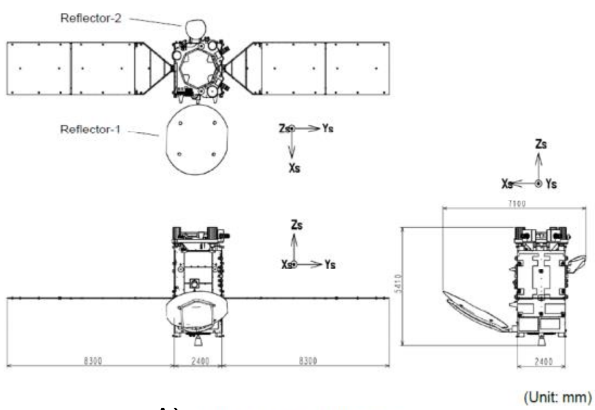
GEO satellite



Public data (QZS-3)

6. Geometry

The spacecraft dimensions are described in Figure 4.

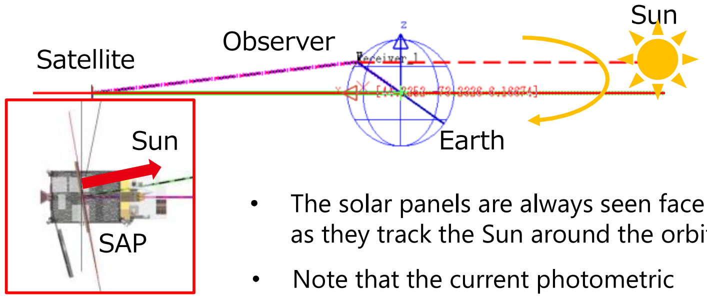


A) Figure 4 Satellite dimensions

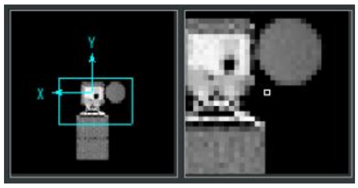
https://qzss.go.jp/en/technical/qzssinfo/khp0mf0000000wuf-att/spi-qzs3_e.pdf

Light-curve calculation

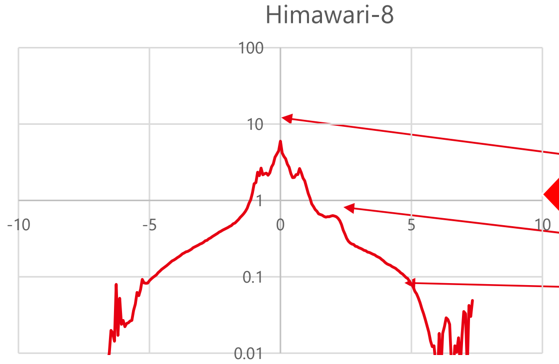
- Raytracing → (2-D Brightness) → Light-curve



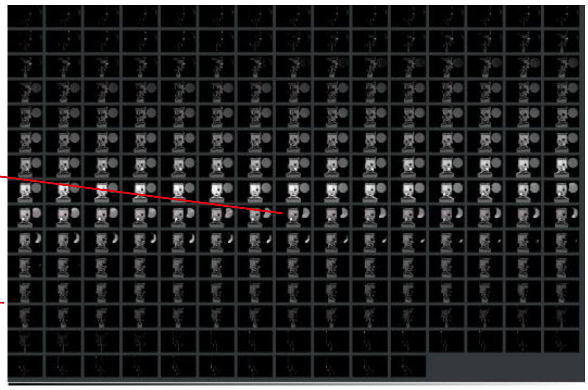
- The solar panels are always seen face-on as they track the Sun around the orbit.
- Note that the current photometric model ignores the Earthshine.



2-D Brightness



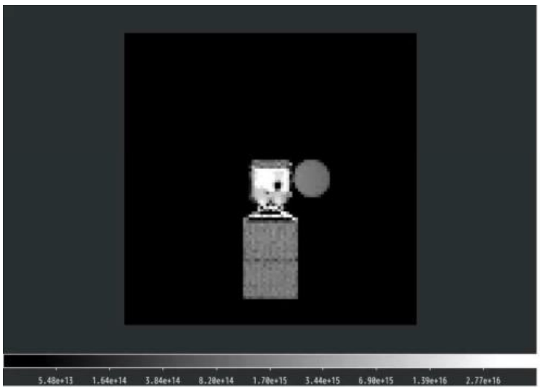
T_{start} Light-curve T_{end}



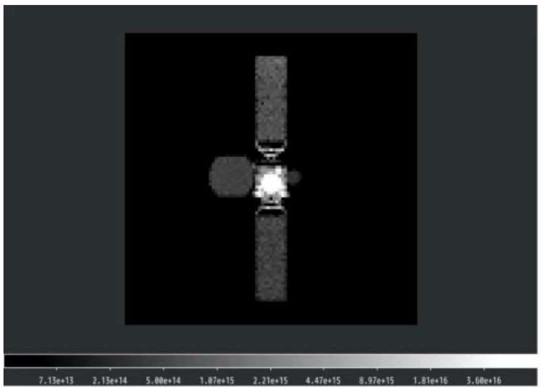
$T = T_{start} \sim T_{end}$

Sample movies

Himawari-8



QZS-3



QZS-3 light-curves

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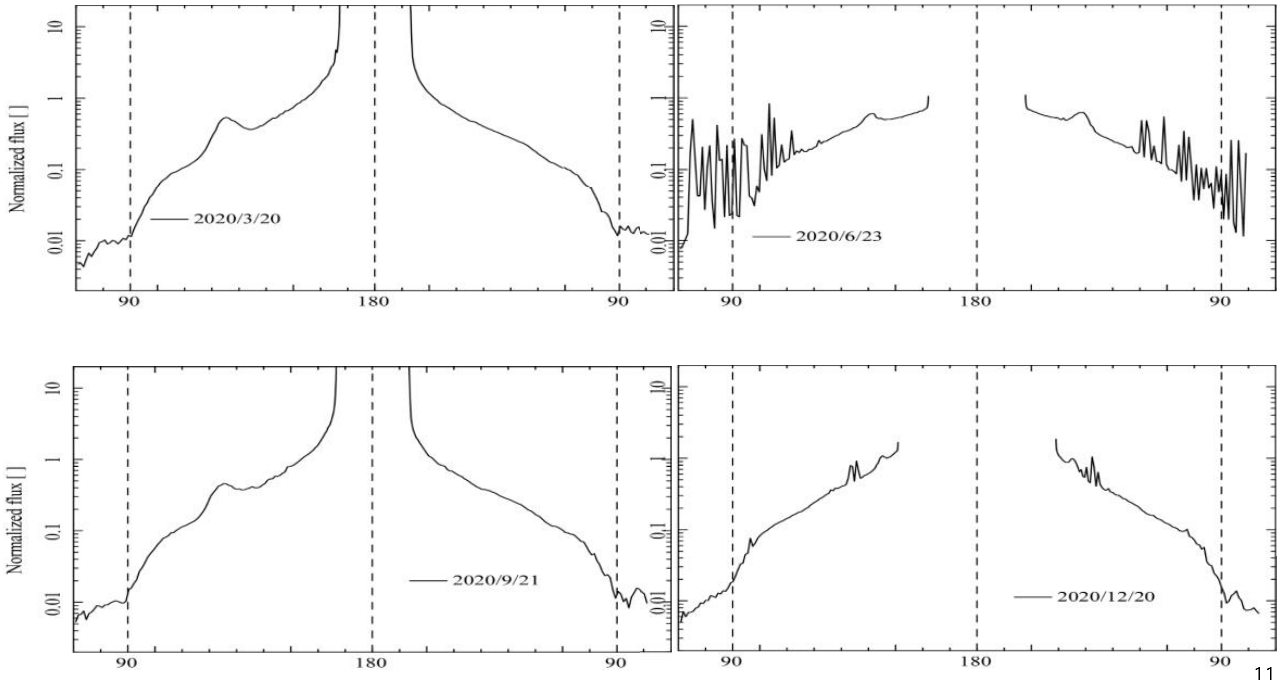
Changes for the Better

- The predictive light curves explain the major features in observed light curves.



Phase angle: the angle between the Sun and satellite as seen from the observer.

QZS-3 light-curves

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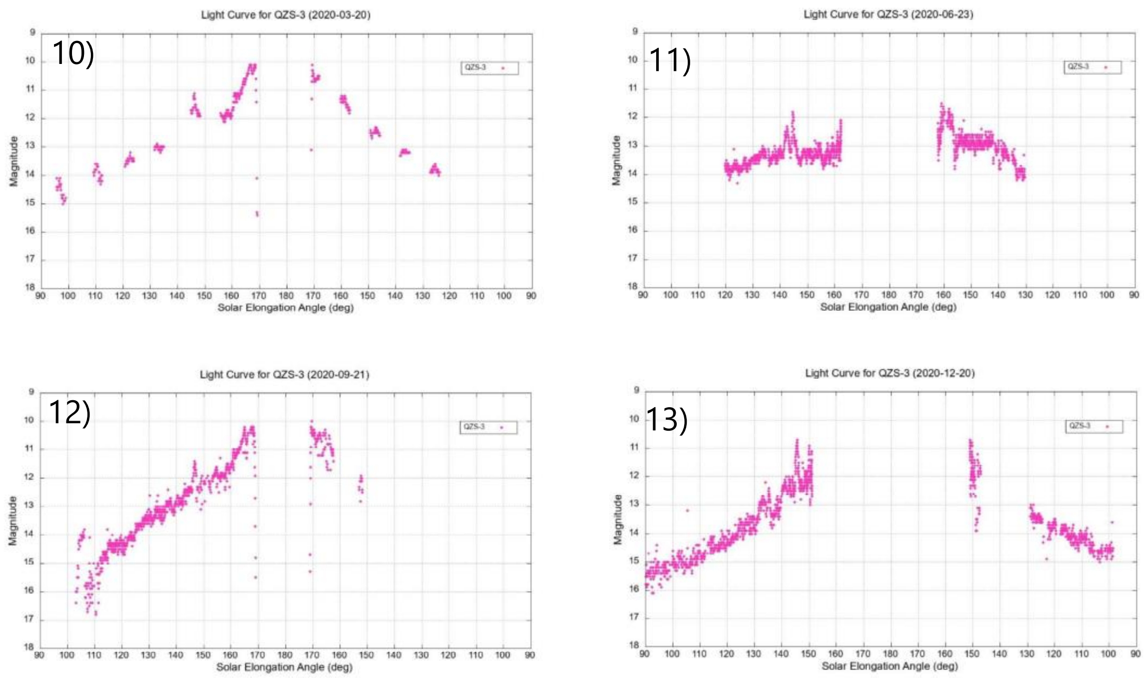
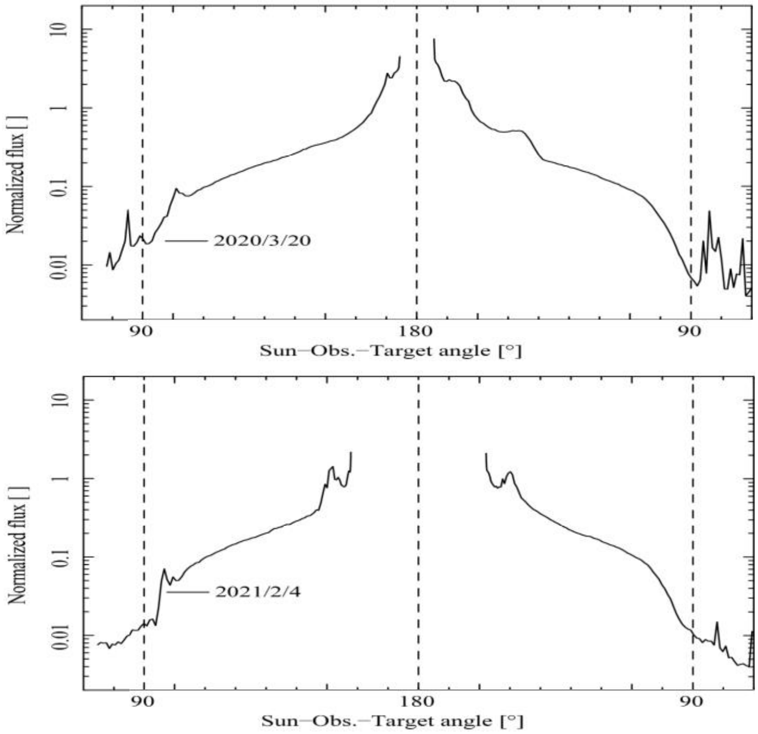
Changes for the Better

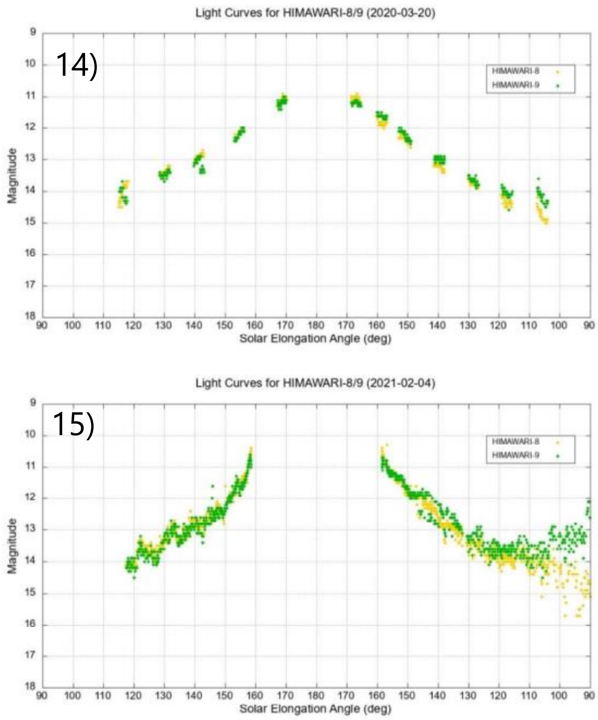


10) -13) T. Fujiwara et.al.
Photometry and Spectroscopy of GEO satellite
The 9th Space Debris Workshop (2021)

Himawari-8/9 light-curves



Himawari-8/9 light-curves



14) -15) T. Fujiwara et.al.
Photometry and Spectroscopy of GEO satellite
The 9th Space Debris Workshop (2021)

Summary

- We have been developing new methods of characterizing space objects using unresolved optical imagery. A 3D-CAD based ray-tracing system allows us to analyze the light curves of satellites in GEO.
- Preliminary results was obtained using models of the Himawari-8 and QZS-3 satellites. The predictive light curves explain the major features in observed light curves. However, perfect agreement between the observations and the theoretical models has not been achieved.
- This study is also useful for simulating operational services as seen from the perspective of an on-orbit observer.

References

1)-3) 遠藤、他

ぐんま天文台分光撮像装置による静止衛星の分光観測と特徴抽出

宇宙科学技術連合講演会講演集 pp. 4027(2017)

4) 遠藤、他

静止衛星の地上分光観測による特性把握

日本赤外線学会誌 Vol.30,No.1,P61-68 (2020)

5) - 7) 遠藤、他

静止衛星の光学散乱モデルによる地上観測光度曲線の推定

宇宙科学技術連合講演会講演集 pp. 4293(2022)

10) -15) T. Fujiwara et.al.

Photometry and Spectroscopy of GEO satellite

The 9th Space Debris Workshop (2021)

A) https://qzss.go.jp/en/technical/qzssinfo/khp0mf0000000wuf-att/spi-qzs3_e.pdf

MITSUBISHI ELECTRIC

Changes for the Better

A08

スタートラッカを用いた宇宙状況監視による衛星衝突回避運用の改善

Improving Collision Avoidance Operations of Satellites by Space Situation Monitoring Using Star Tracker

〇岩城 陽大（JAXA 経営推進部推進課）、秋山 恭平（JAXA 第一部門衛星測位システム技術ユニット）、
柳沢 俊史（JAXA 研究開発部門第二ユニット）、日南川英明（JAXA 追跡ネットワーク技術センター）
〇IWAKI Akihiro (JAXA Management Division, Strategic Planning and Management Department),
AKIYAMA Kyohei (Space Technology Directorate I, Satellite Navigation Unit),
YANAGISAWA Toshifumi (Research and Development Directorate, Research Unit II),
HINAGAWA Hideaki (Space Tracking and Communications Center)

地上の経済社会が宇宙システムへの依存を増す一方で、宇宙デブリ、メガコンステレーション等により宇宙空間は混雑し、宇宙状況監視（SSA）の必要性が高まっている。本発表では、スタートラッカを用いた革新的手法によって、従来よりも高精度な物体接近情報を生成し、人工衛星運用者の軌道上での衝突回避運用の負担を軽減するための技術開発について紹介する。

While the society and economy on the ground is becoming increasingly dependent on space systems, space debris, mega-constellations, etc. are crowding space and increasing the need for space situational awareness (SSA). This presentation will introduce the development of an innovative method using the Star Tracker to generate more accurate object proximity information than ever before and to reduce the burden of on-orbit collision avoidance operations for satellite operators.

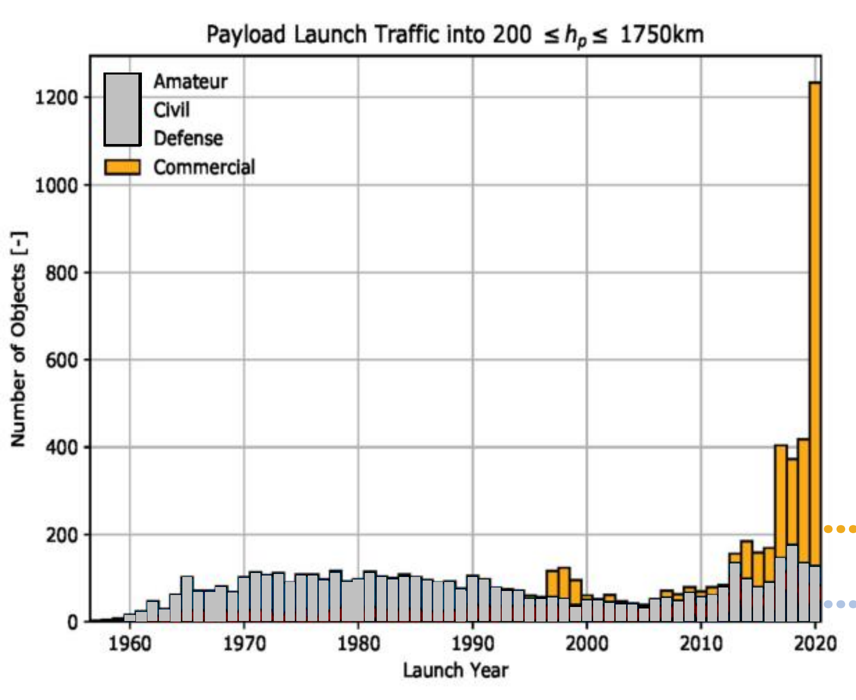
Improving Collision Avoidance Operations of Satellites by Space Situation Monitoring Using Star Tracker

28th November 2022

IWAKI Akihiro, AKIYAMA Kyohei,
YANAGISAWA Toshifumi, HINAGAWA Hideaki (JAXA)

STAR SIGNAL SOLUTIONS

Can we say that outer space activities will be sustainable?



The number of commercial satellites has increased dramatically.

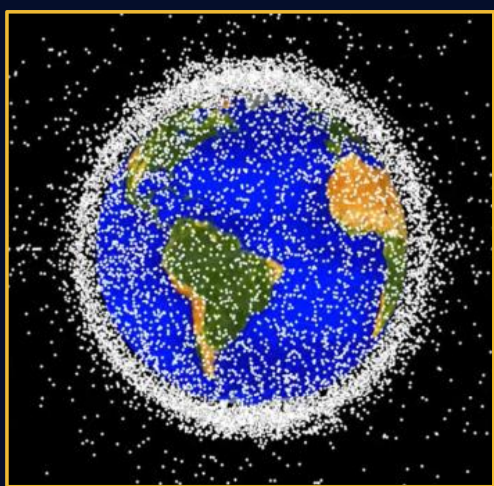
…Commercial Satellites

…Other Satellites

(ESA's Space Environment Report 2021)

Outer Space is getting crowded

1990

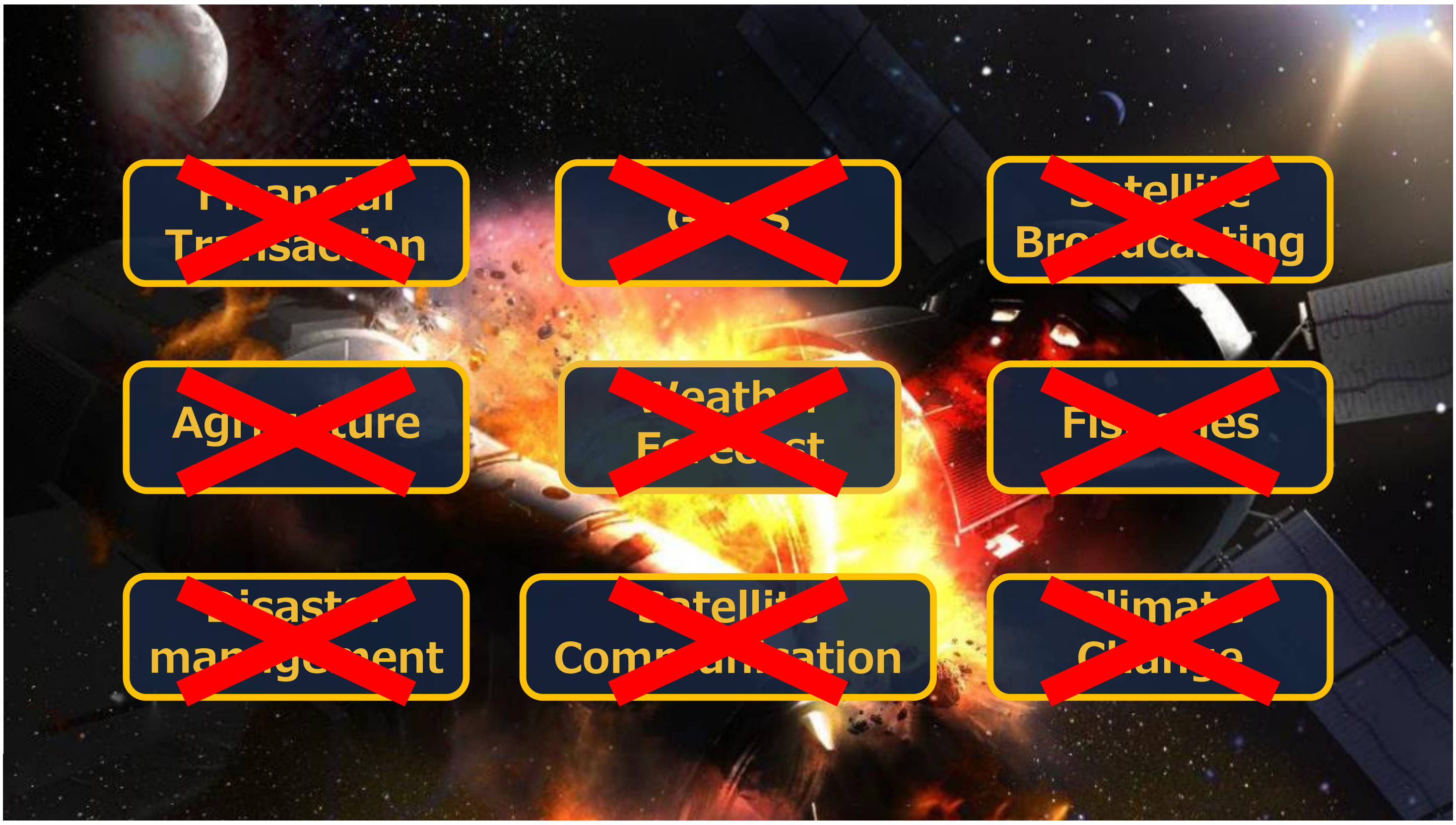


2019

Credit: NASA

Outer Space is getting crowded

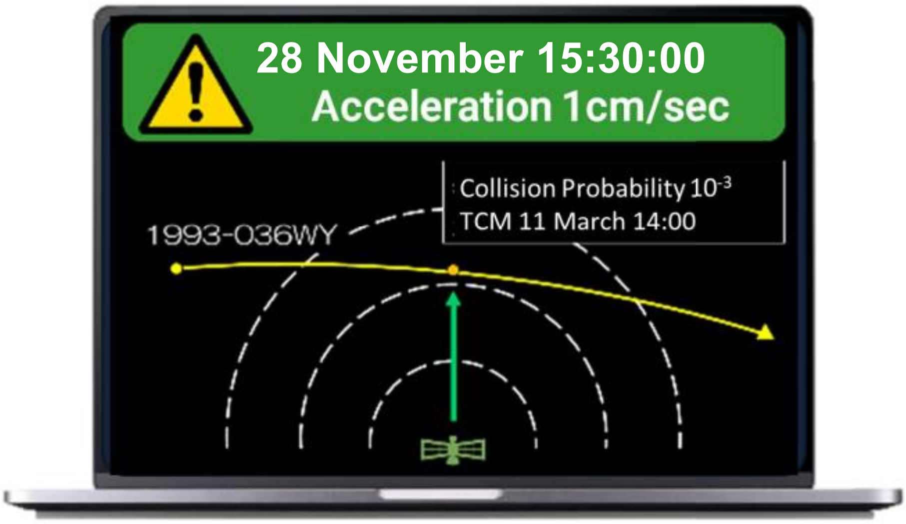
Credit: European Space Agency

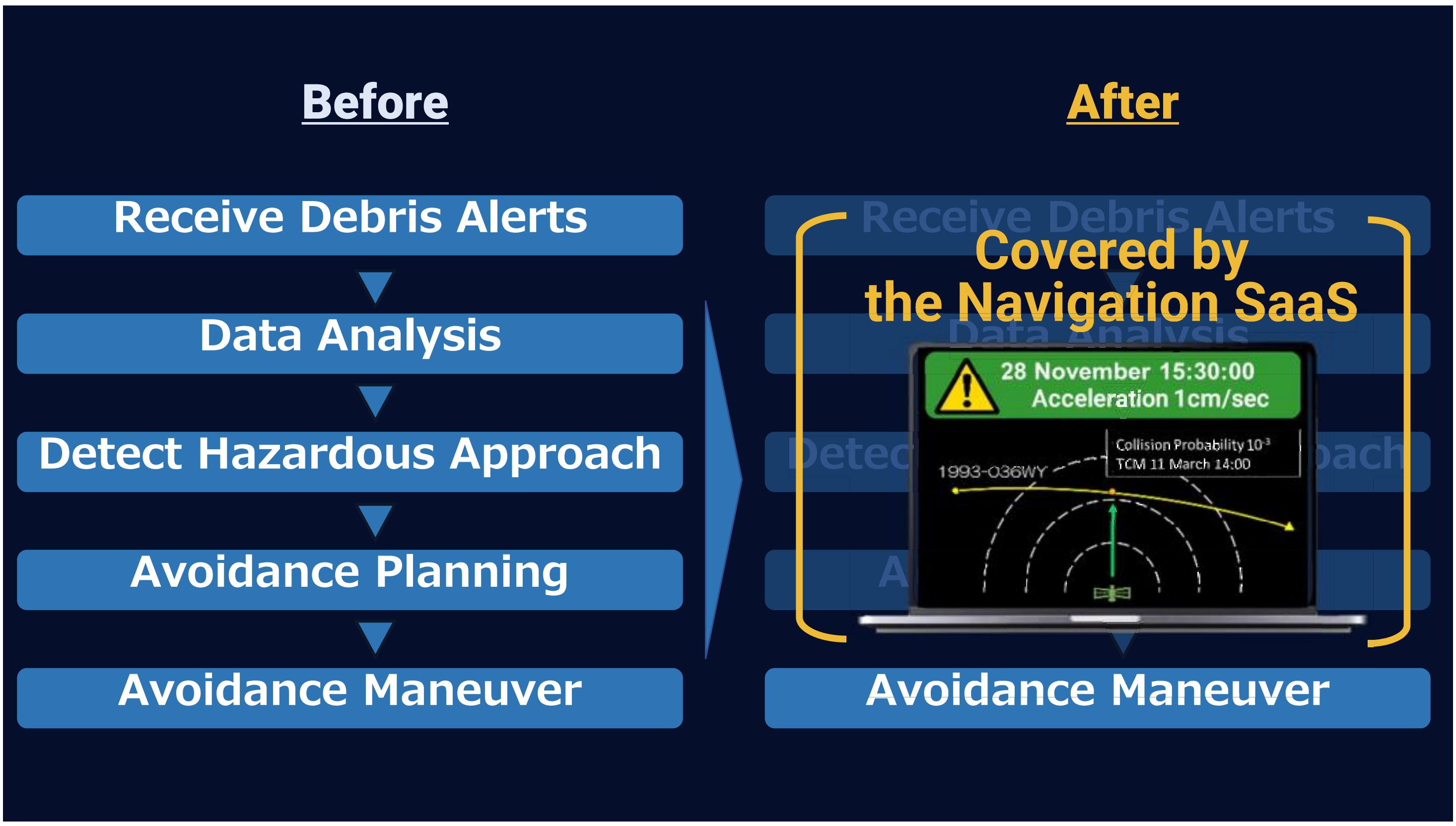


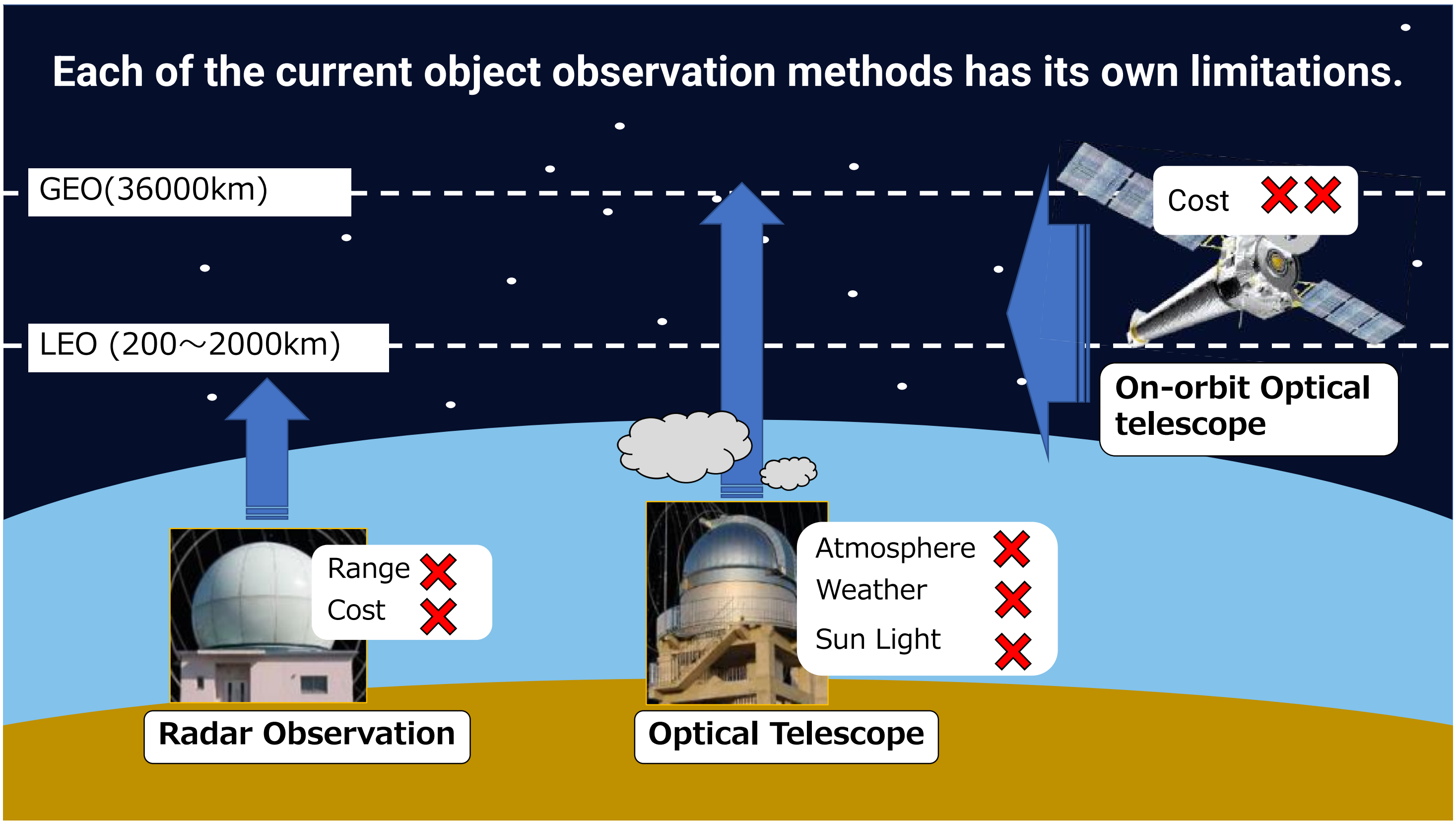
Collision avoidance is a huge burden for satellite operators.

Receive CDMs	300 in a day
▼ Data Analysis	300 in a day
▼ Detect Hazardous Approach	1 in 2 days
▼ Avoidance Planning	1 in 1 month
▼ Avoidance Maneuver	1 in 3 months

“Lean" and “Easy“ Navigation SaaS for the safety of satellites operations.

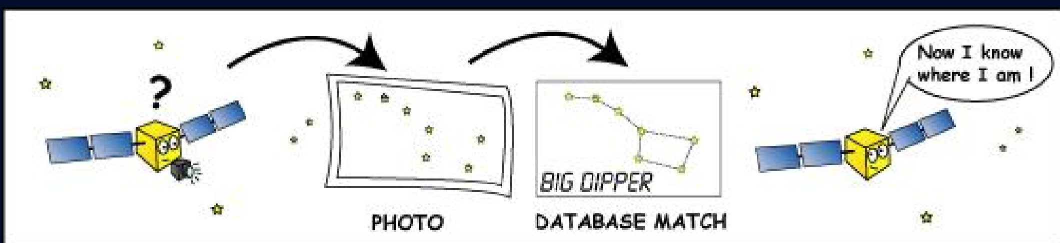





Each of the current object observation methods has its own limitations.
GEO(36000km)
LEO (200～2000km)
Cost
On-orbit Optical telescope
Range
Cost
Atmosphere
Weather
Sun Light
Radar Observation
Optical Telescope

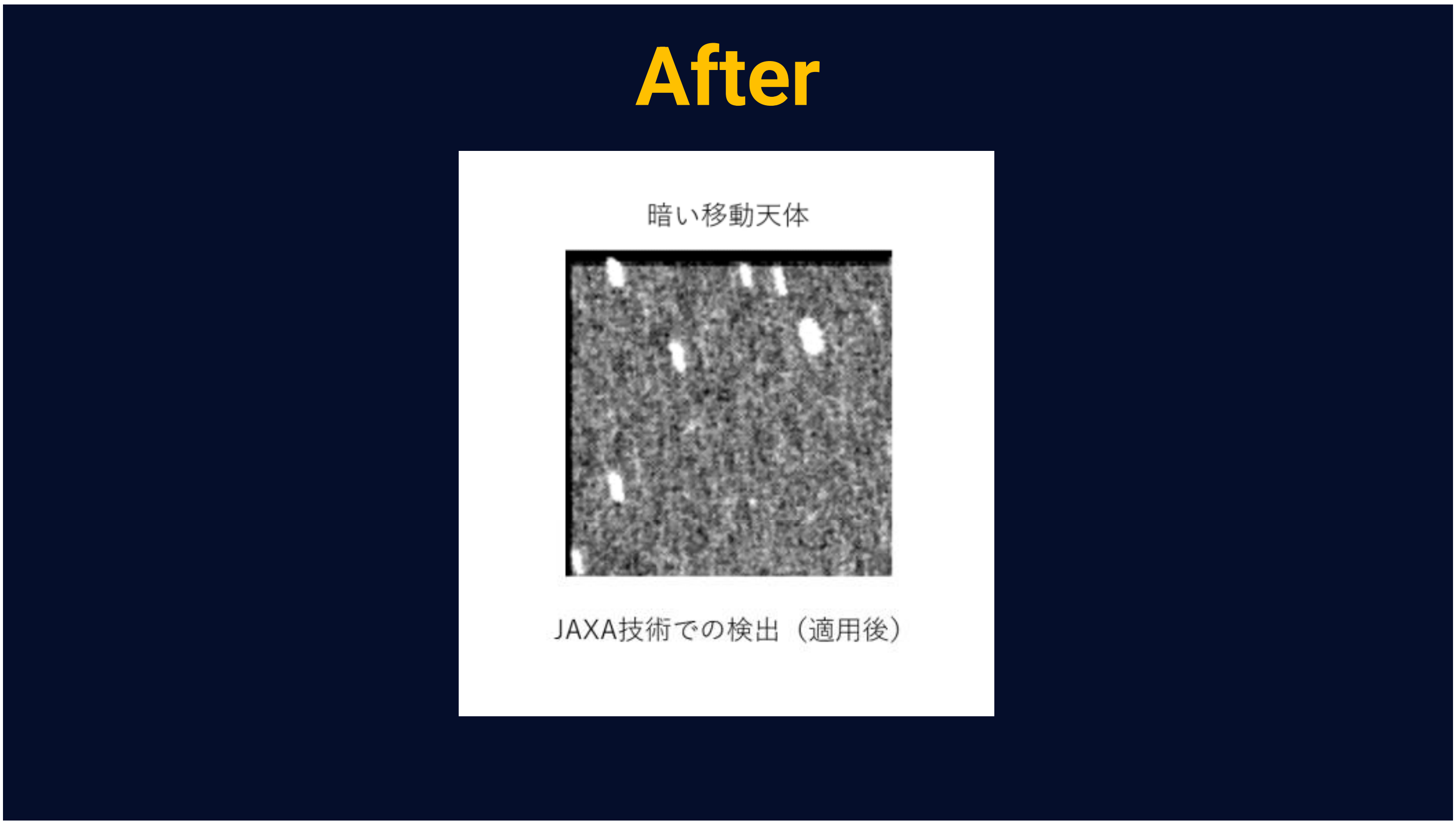

Our Solution
Using Star Trackers for Object Observation
Provided by: National Space Policy Secretariat, Cabinet Office

©NASA

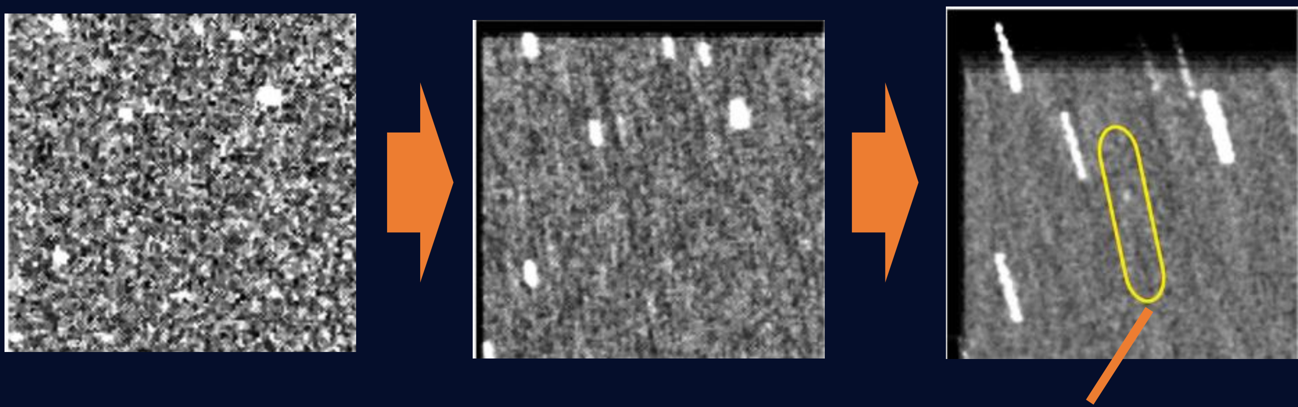


©NASA


Before
暗い移動天体
JAXA技術での検出（適用前）

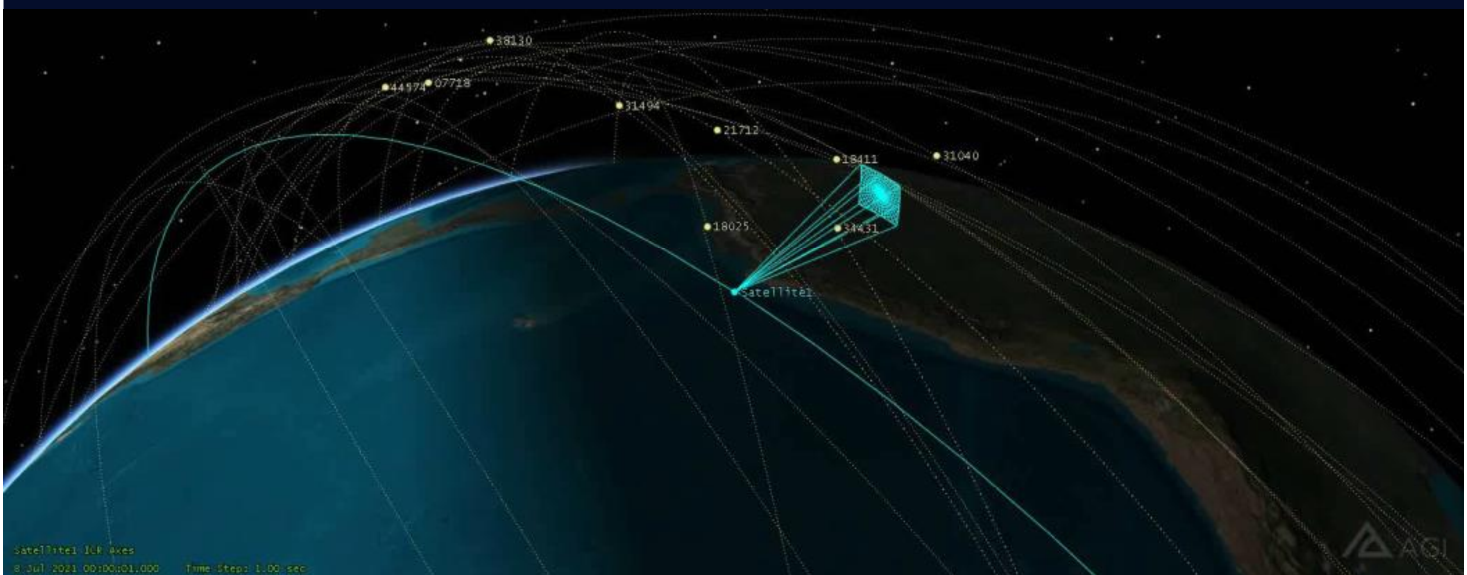

After
暗い移動天体
JAXA技術での検出（適用後）

Original image **Processed image**

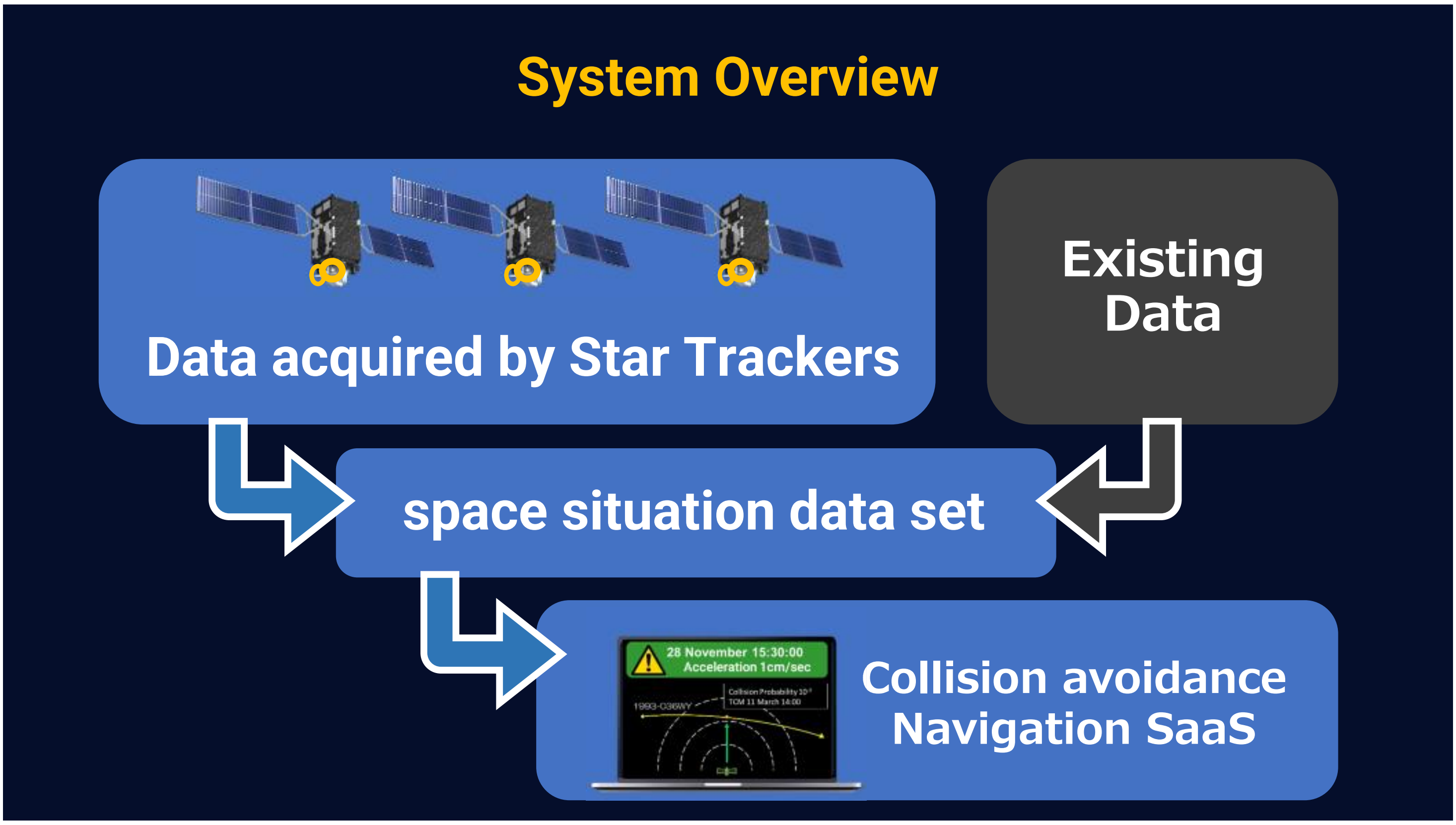


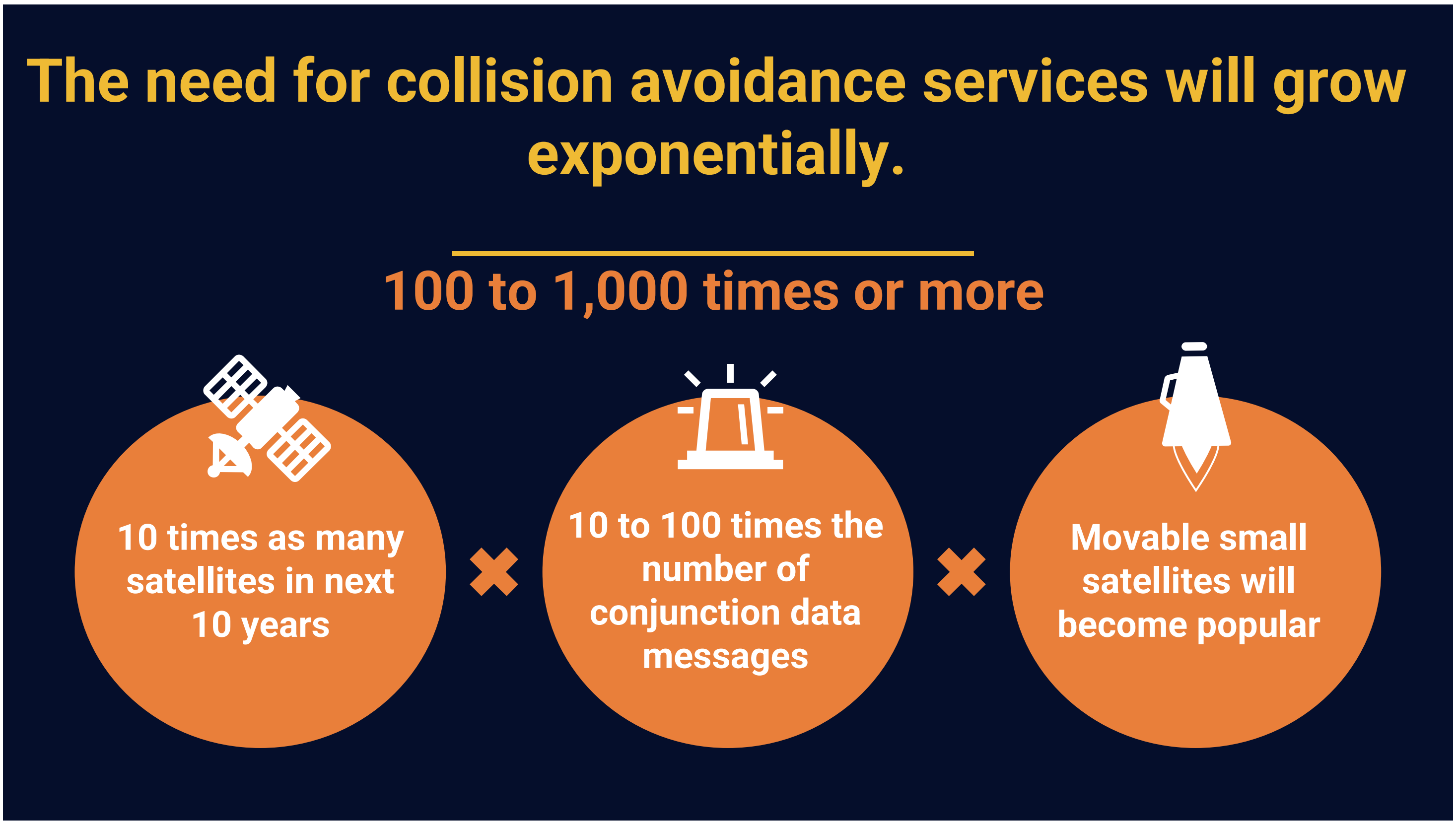
The indistinguishable space objects can be identified by our unique technology.

Applying this method on STT,
Over 90% objects trajectory recognition capability in ± 100km

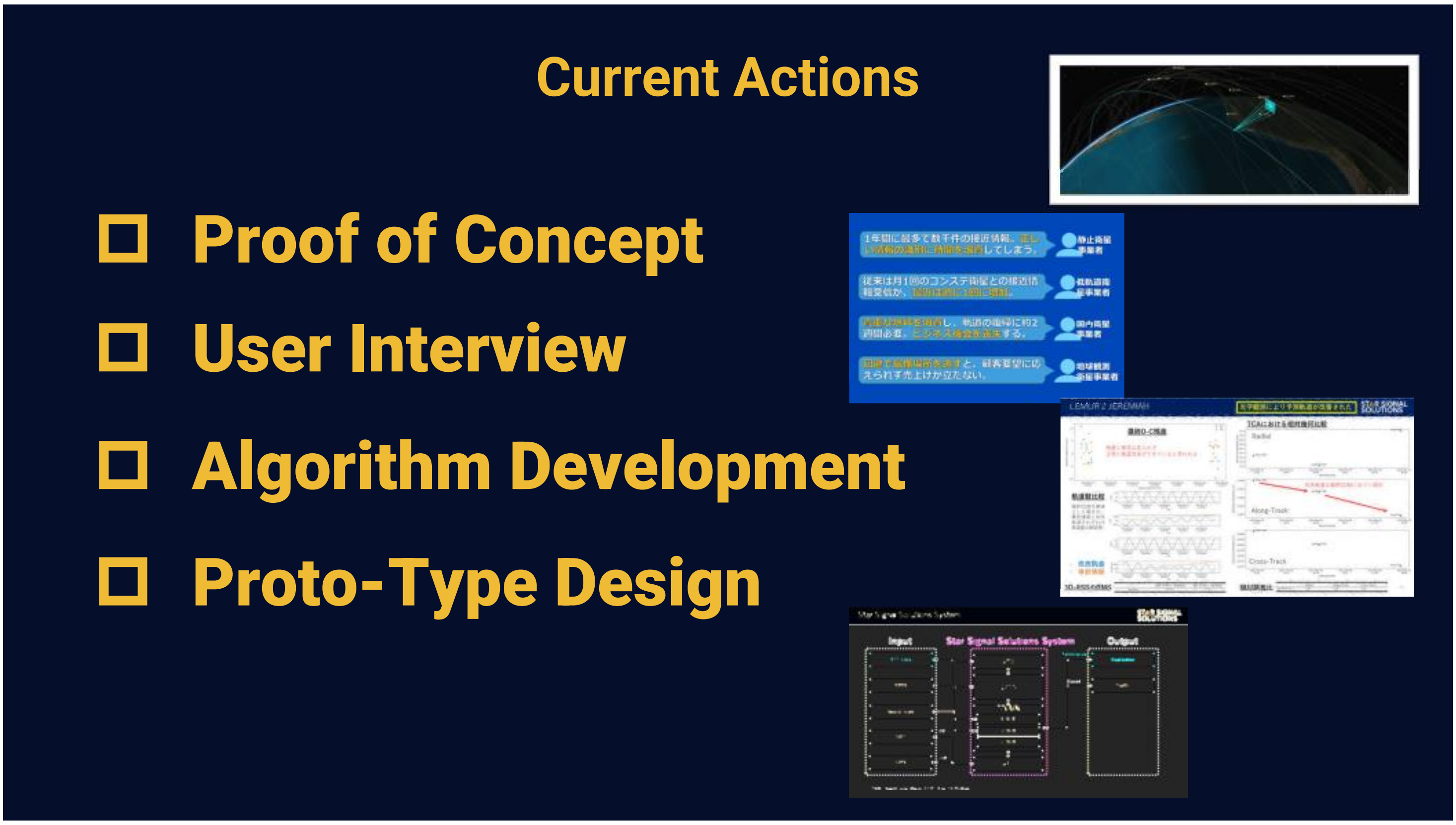


※Simulation result by 4 Star Trackers at 800km SSO


System Overview
Data acquired by Star Trackers
Existing Data
space situation data set
28 November 15:30:00
Acceleration 1cm/sec
Collision avoidance
Navigation SaaS


The need for collision avoidance services will grow exponentially.
100 to 1,000 times or more
10 times as many satellites in next 10 years
10 to 100 times the number of conjunction data messages
Movable small satellites will become popular


Preventing space traffic accidents to navigate to a sustainable and prosperous future colored by diverse space activities.


Current Actions
☐ Proof of Concept
☐ User Interview
☐ Algorithm Development
☐ Proto-Type Design

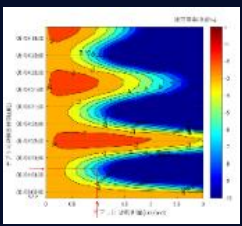
Our Team

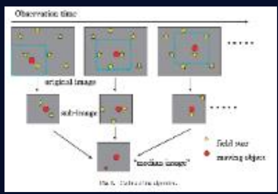

Akihiro Iwaki

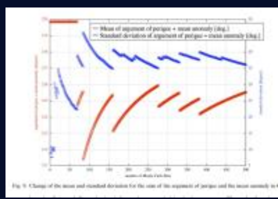

Kyohei Akiyama


Toshifumi Yanagisawa


Hideaki Hinagawa







2021 'STI for SDGs' AWARD

S-Booster 2021

Debris observation, Collision avoidance, Orbit determination, Int'l guidelines, STI for SDGs Award, S-Booster 2021 Special Judges' Prize.

Call for Partners

- ✓ **Star Tracker Data Provider**
- ✓ **Satellite Operator**
- ✓ **Business Partner**


Thank you for your attention
iwaki.akihiro@jaxa.jp
STAR SIGNAL
SOLUTIONS

A09

低軌道分析評価ツールについて
LEO Analytic Assessment Tools

〇藤本浩平, Darren McKnight, Erin Dale, Rachit Bhatia, Matthew Stevenson, Mohin Patel (LeoLabs), Chris Kunstadter (AXA XL)
〇FUJIMOTO Kohei, Darren McKnight, Erin Dale, Rachit Bhatia, Matthew Stevenson, Mohin Patel (LeoLabs), Chris Kunstadter (AXA XL)

LeoLabs は、世界中に建設された 8 基のレーダーからのデータに基づき、低軌道で運用中の衛星の 65%以上を支援する準リアルタイム衝突回避サービスを提供している。本サービスは軌道航行安全の重要な能力であるだけではなく、サービス提供に必要な低軌道の継続的な監視によって独自のデータが集積され、結果、様々な分析評価ソリューションを実現可能とする。本講演では、LeoLabs が開発した 3 つの分析評価ツールを要約する。宇宙保険用衝突ハザード評価ツールは、論理的な衛星・コンステレーションのリスク配列に基づき、衝突ハザード評価アルゴリズムを直感的なインタフェースで提示する。接近マッピングツールは、LeoLabs 創設以来モニターされてきた何百万にも及ぶ高リスク接近イベントを縮約する。低軌道の「物騒な地区」、つまり、デブリ生成能力の観点から見た統計的にもっとも懸念される物体や物体群を判定することが可能である。最後に、破砕イベント特徴付けツールは、破砕によって発生したデブリの分布に基づき、その原因の迅速な評価手法を提供する。

LeoLabs has deployed a suite of eight radars worldwide fueling near real-time collision avoidance services supporting over 65% of all operational satellites in low Earth orbit (LEO). While this is a vital space safety capability, the persistent surveillance of LEO required to provide this service creates a unique corpus of data that enables a variety of other analytic assessment solutions. Three analytic assessment tools are reviewed: Space Insurance Collision Hazard Tool, Conjunction Mapping Tool, and Breakup Characterization Tool. The Space Insurance Collision Hazard Tool provides an intuitive interface with embedded collision hazard algorithms through a logical satellite/constellation risk sequence. This tool is commercially available. The Conjunction Mapping Tool reduces data on millions of high-risk conjunctions in LEO monitored by LeoLabs since its inception. This tool is not commercially available but rather provides the ability to determine the “bad neighborhoods” in LEO and the statistically-most-concerning objects and classes of objects from a debris-generation potential perspective. The Breakup Characterization Tool provides a rapid assessment of the cause of a satellite fragmentation based upon the distribution of the debris created.

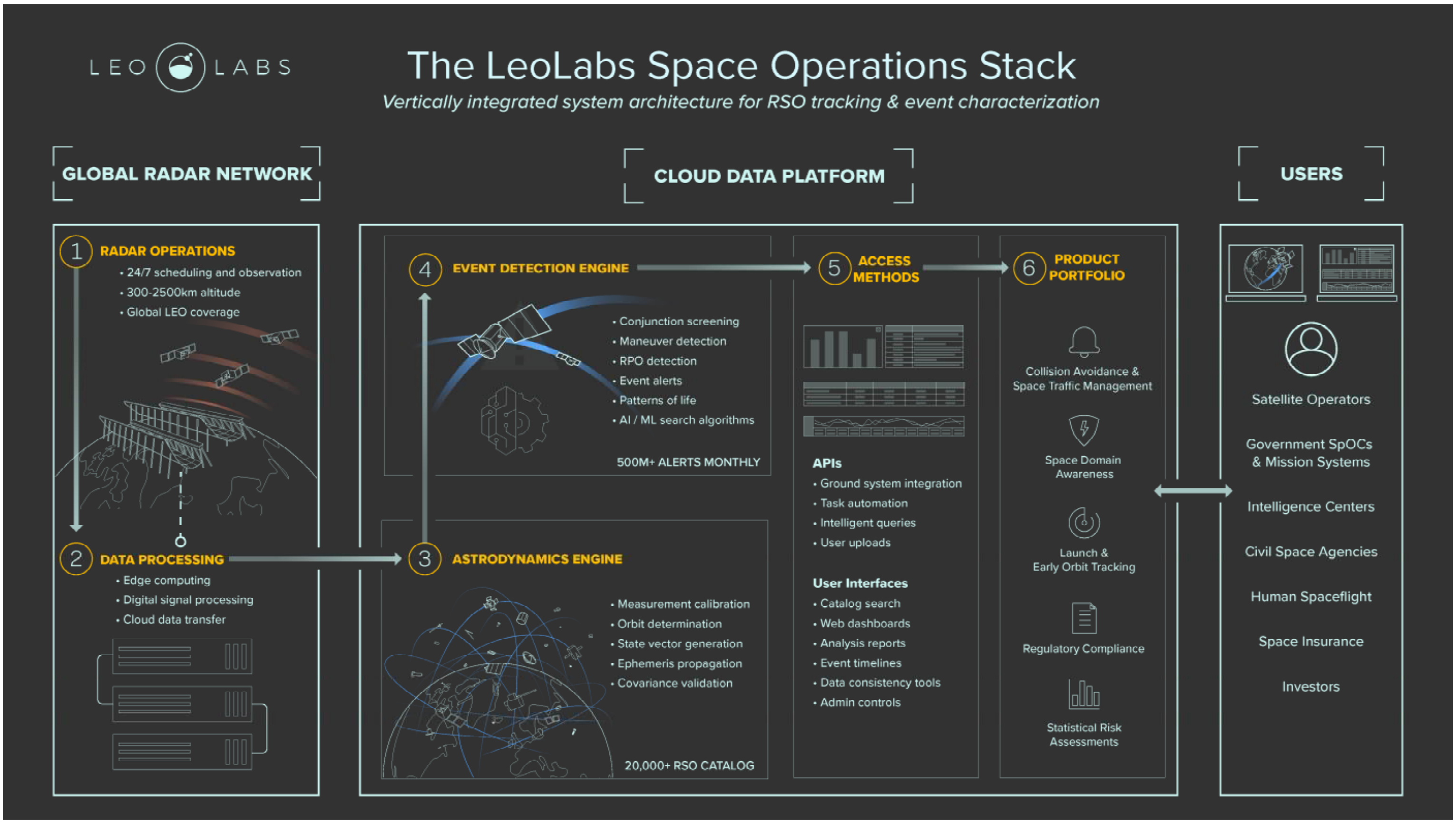
低軌道分析評価ツールについて
LEO Analytic Assessment Tools

Kohei Fujimoto, Darren McKnight, Erin Dale, Rachit Bhatia, Matthew Stevenson, Mohin Patel (LeoLabs)
Chris Kunstadter (AXA XL)

Inform, Serve & Secure LEO

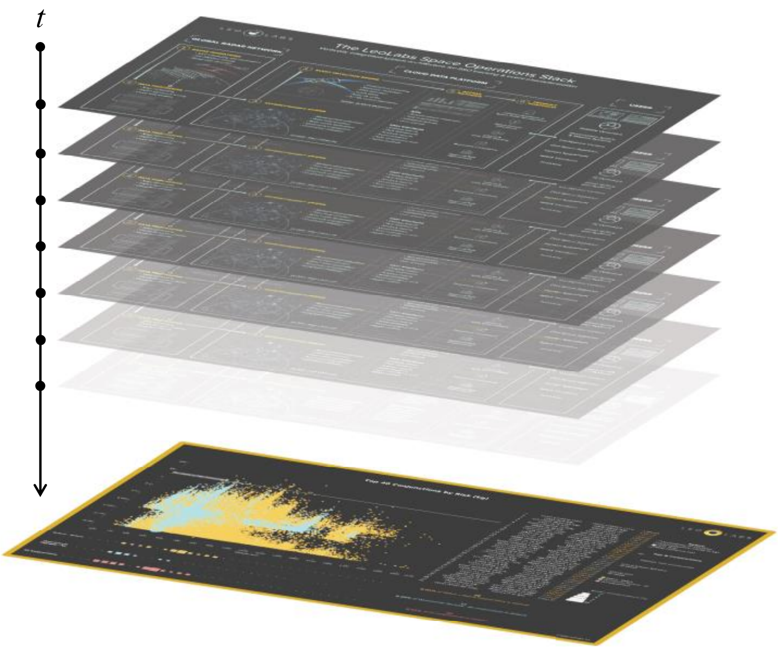
Overview

- The LeoLabs Space Operations Stack
- LEO analytic assessment tools
- Conjunction mapping tool
- Space insurance collision hazard tool
- Conclusions



LEO analytic assessment tools

LEO LABS



The persistent surveillance of LEO required to provide LeoLabs' operational services creates a unique corpus of data that enables a variety of analytic assessment solutions

Number of data points (all time)	
Measurements	750,000,000 +
State vectors	20,000,000 +
CDMs	10,000,000,000 +

▼

Analyze with respect to :

Orbital parameters | **RCS** | **Probability of collision**
Object mass | **Spatial density** | **Future events** | ...

LEO analytic assessment tools

LEO LABS

Provides the ability to determine statistically-most-concerning objects and classes of objects from a debris-generation potential perspective

Provides an intuitive interface with embedded collision hazard algorithms through a logical satellite/constellation risk sequence

(Public release in Q1 2023)

Provides a rapid assessment of the cause of a satellite fragmentation based upon the distribution of the debris created

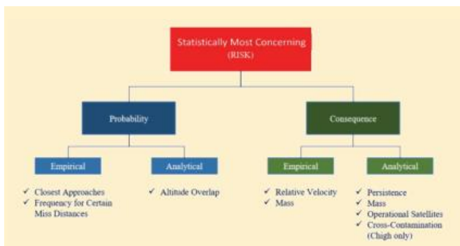
(TBA in 2023)

Conjunction mapping tool

LEO LABS

Mapping high risk conjunctions in LEO over long periods creates the foundation for many insights on space safety:

- Examine balance of Space Debris Management (SDM) and Space Traffic Management (STM)
- Characterize debris-generating potential as function of altitude
- Identify objects posing the greatest debris-generating potential
- Specify statistically-most-concerning objects in LEO
- Determine most likely future types of collision events



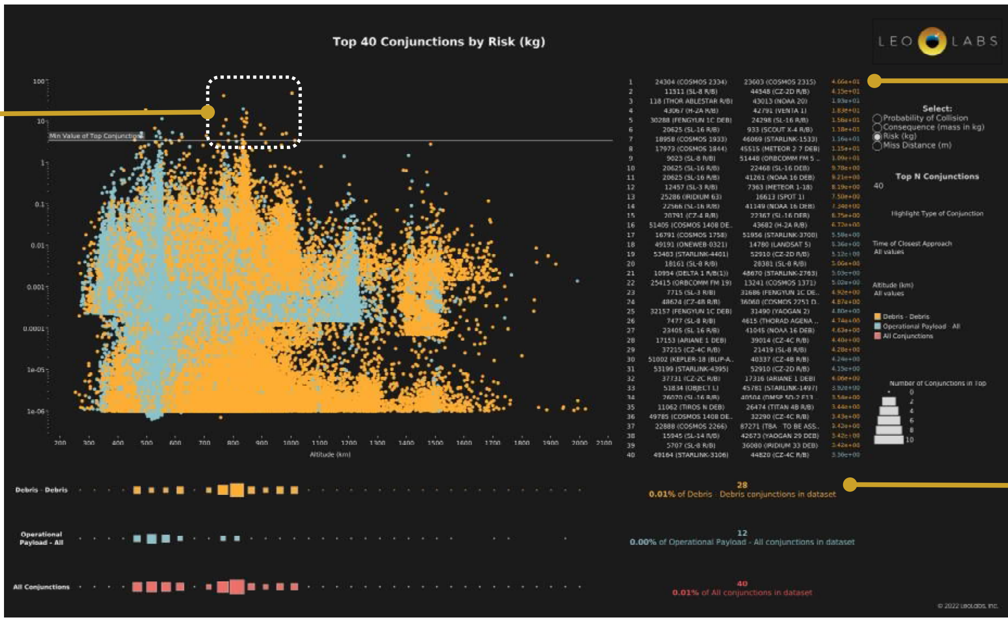
Here, risk is defined as follows:

Risk [kg] = (Probability of collision P_c) × (Consequence)

This presentation analyzes all LeoLabs generated CDMs between Jan 1, 2022 and Sept 15, 2022 where Pc > 1e-6.

Conjunction mapping tool

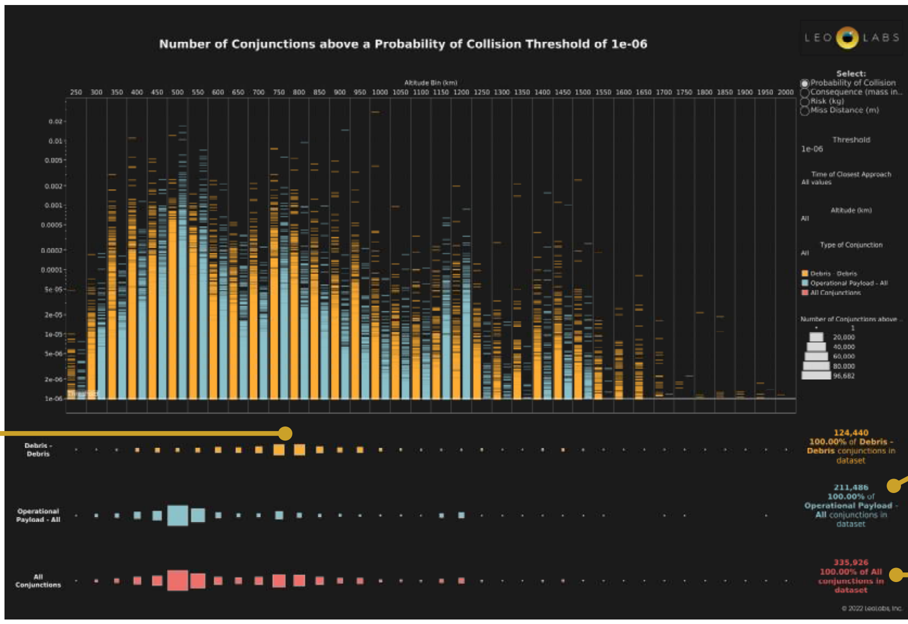
High risk conjunctions concentrated between 700 km and 1000 km altitude



Highest Pc conjunction to date in 2022 also has the highest risk

70% of the top 40 high risk conjunctions involve two non-operational objects

Conjunction mapping tool



- Approx. 30% of conjunctions involve fragments from DA ASAT tests (FENGYUN 1C and COSMOS 1408)
- Next two largest debris clouds (COSMOS 2251 and NOAA 16) contribute another 13%

Debris-on-debris conjunctions peak at 700 – 850 km altitudes (realm of SDM)

Approx. 60% of high Pc conjunctions involve operational payloads (realm of STM)

On average, approximately 1 high Pc conjunction has occurred every minute

Conjunction mapping tool

LEO LABS

In this chart, objects are aggregated by name (family) and plotted against risk and # of conjunctions

COSMOS 1408 debris continue to pose high risk despite reduction in fragments over time

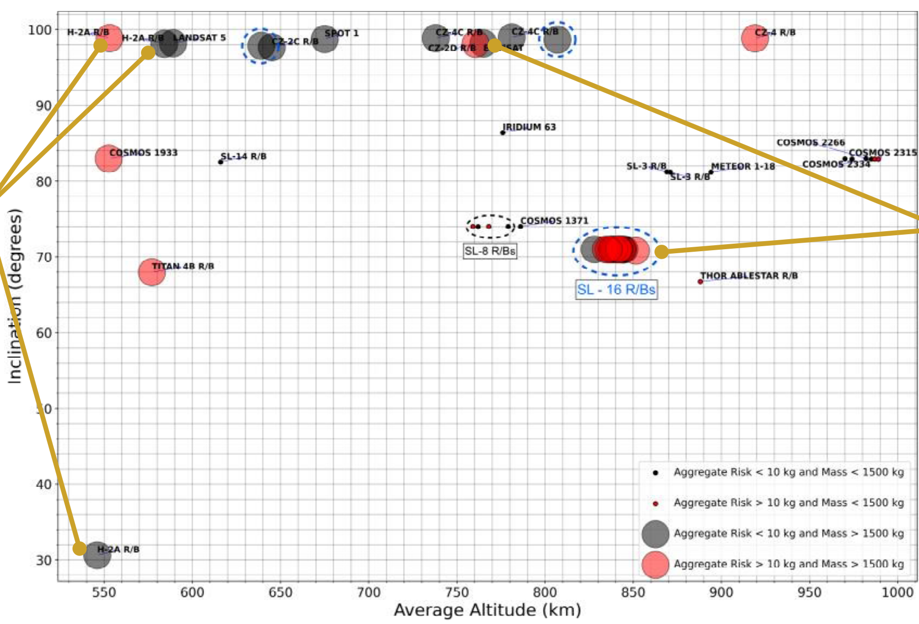
Several R/B families rank high (SL-16, SL-8, CZ-2D, H-2A, CZ-4C) due to their large mass

Conjunction mapping tool

LEO LABS

Top 50 objects with highest aggregated risk. Objects with mass less than 525 kg or average altitude below 525 km are excluded.

3 H-2A R/B listed in top 50



ENVISAT and 19 SL-16 R/B objects are repeat entries from 2020 study

Changes from study in 2020 include:

- Percentage of Chinese and US objects each increased by 8+ points
- Percentage of objects below 750 km altitude increased by 15+ points

Space insurance collision hazard tool

Collision avoidance burden and event (i.e., future debris-generating collision events) data are derived from the **LeoLabs' catalog and history of low Earth orbit (LEO) conjunctions**

+

Mission-terminating risk data (i.e., 1 to 10 cm object population) derived from the **ESA MASTER model** as of January 2022

+

User inputs :

Number of satellites, satellite physical dimensions, satellite altitude, mission lifetime, etc.

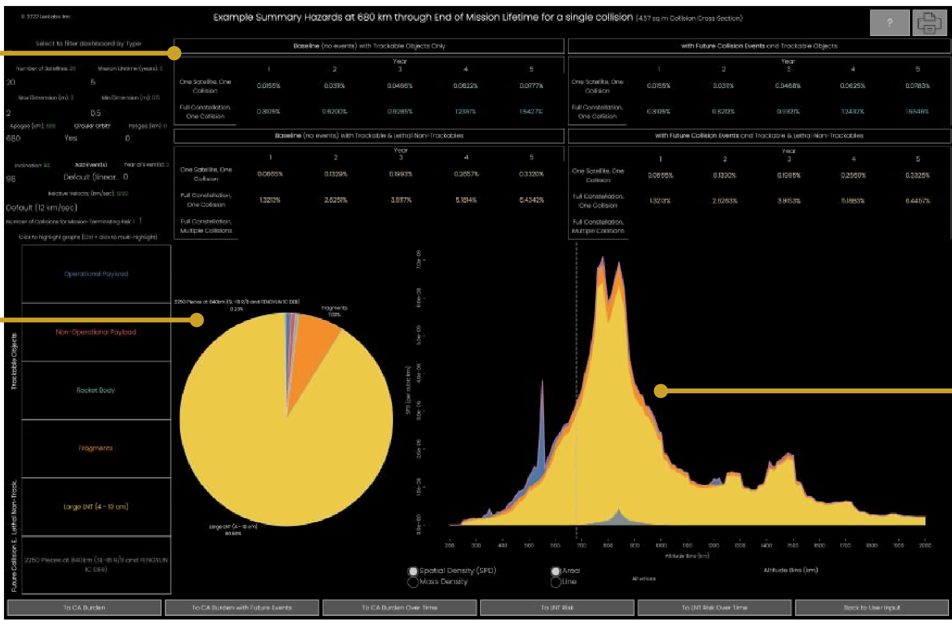
The objective of this tool is to provide a calculator for **characterizing the orbital debris collision risk** relative to the risk exposure an insurance broker has accepted or might accept.

- For trackable (cataloged, > 10 cm) objects, collision avoidance burden
- For lethal non-trackable objects (1 – 10 cm), mission terminating risk

Space insurance collision hazard tool

Collision avoidance burden and mission terminating risk tracked over time

Makeup of collision avoidance burden (trackable) and mission terminating risk (LNT) for each object type

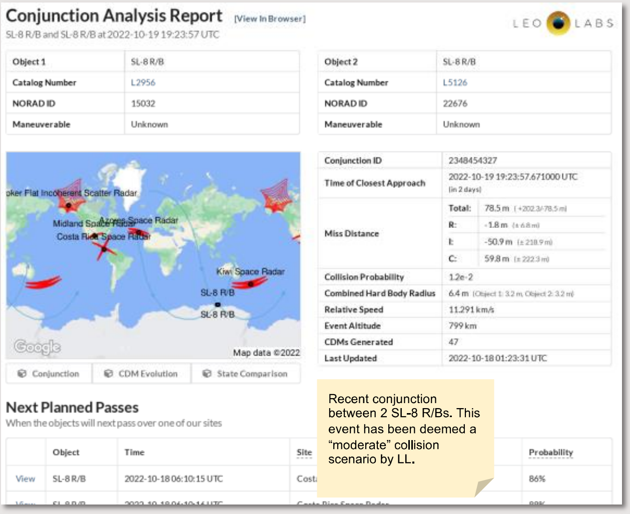


Spatial and mass density of objects can be displayed, including:

- Currently cataloged
- Lethal non-trackable (LNT)
- Expected fragments from the most likely collision events (what-if analysis)

Space insurance collision hazard tool

Real-time products



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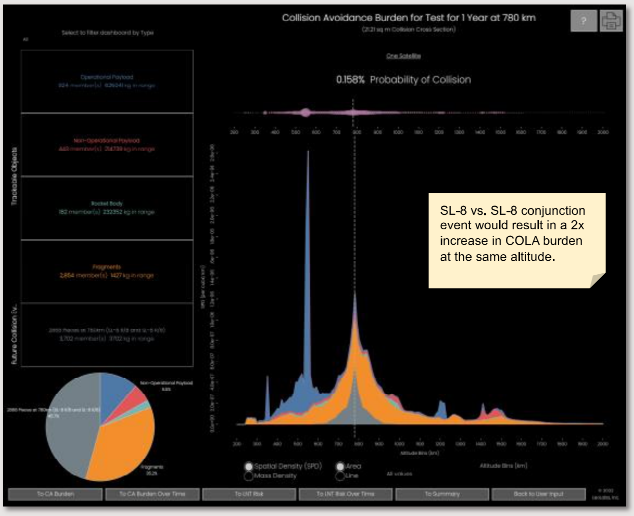
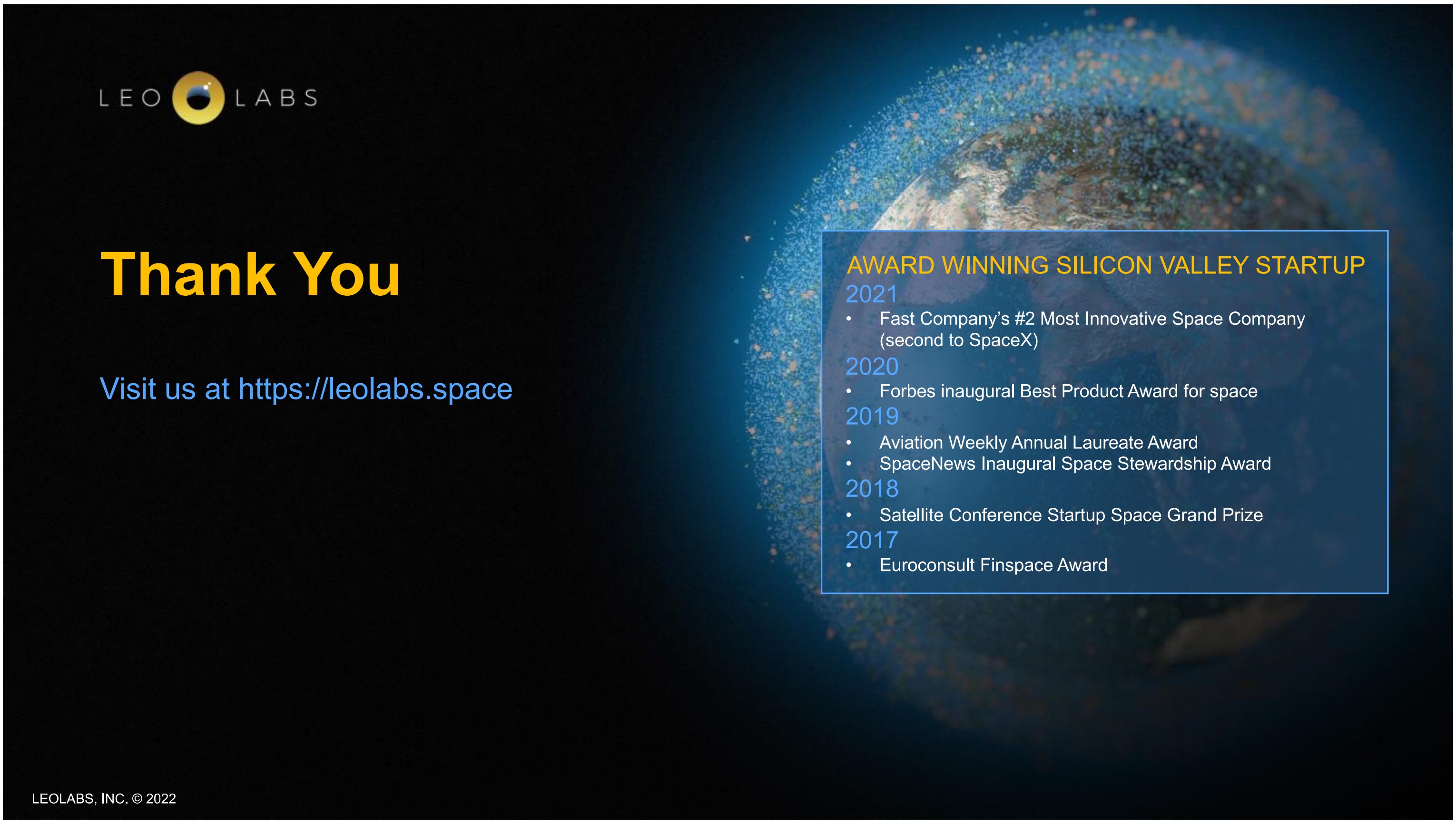
Analysis products



Conclusions

- The persistent surveillance of LEO required to provide LeoLabs' operational services creates a unique corpus of data that enables a variety of analytic assessment solutions
- The mapping of the probability of collision and debris-generating risk as a function of altitude provides a compelling message about space safety in LEO, where risk is defined as (probability) × (consequence)
- By overlaying past conjunction data with models for future collision events and lethal non-trackable debris, one can characterize both collision avoidance burden and mission terminating risk for new launches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2021
• Fast Company's #2 Most Innovative Space Company (second to SpaceX)
2020
• Forbes inaugural Best Product Award for space
2019
• Aviation Weekly Annual Laureate Award
• SpaceNews Inaugural Space Stewardship Award
2018
• Satellite Conference Startup Space Grand Prize
2017
• Euroconsult Finspace Award
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A10

初期軌道誤差及び大気密度誤差がもたらす 軌道予測誤差の解析解とその応用

Analytical Solution and Application for Orbit Prediction Error Due to Initial Orbit and Atmospheric Density Errors

○日南川英明（JAXA 追跡ネットワーク技術センター）
○HINAGAWA Hideaki (JAXA Space Tracking and Communications Center)

大気抵抗がもたらす高度低下によって軌道長半径が小さくなり軌道周期が短くなる．軌道周期は軌道周回速度と密接な関係にあり，大気抵抗に誤差（本発表では大気密度誤差に由来するとみなす）がある場合，進行方向速度に誤差をもたらすため，軌道伝播した際の軌道位置にも誤差が発生する．昨今の混雑化する宇宙環境において，予測軌道誤差を正しく見積もることは接近解析における衝突確率算出時に必要不可欠である．特に進行方向誤差は初期軌道誤差及び大気密度誤差の影響を受けやすく，それぞれの誤差に対する感度を把握することで接近解析における予測軌道誤差の変化をある程度予測することができる．本発表では，この進行方向誤差に関して，初期軌道誤差及び大気密度誤差に起因する軌道誤差を従来のように数値的に得るのではなく，ある前提条件のもと解析的に計算する方法を提案する．さらに，JAXA が研究開発中の大気密度モデルがその目標性能を達成することで期待される軌道予測誤差の改善度や，接近情報から大気密度予測誤差を推定した結果などの応用例を示す．

Atmospheric drag force decreases spacecraft’s altitude, and its orbital period decreases as well. Uncertainty of the drag force causes uncertainty of propagated orbital position because the orbital period directly effects on its orbital velocity. It is essential to properly estimate uncertainty of the orbital position for conjunction assessment in this congested and contest space. Especially, in-track position is easily influenced by change of the drag force. This presentation proposes an analytical solution for orbital prediction error in along-track due to errors of initial orbit and atmospheric density under some assumptions although prior research already reported numerical solutions. In addition, the author presents analysis of expected orbital prediction error of atmospheric density model developed by JAXA. Furthermore, estimated error of atmospheric density is presented using conjunction data messages.

Analytical Solution and Application for Orbit Prediction Error Due to Initial Orbit and Atmospheric Density Errors

Hideaki HINAGAWA
Space Tracking and Communications Center
JAXA

Background

OD: Orbit Determination
OP: Orbit Prediction
TCA: Time of Closest Approach

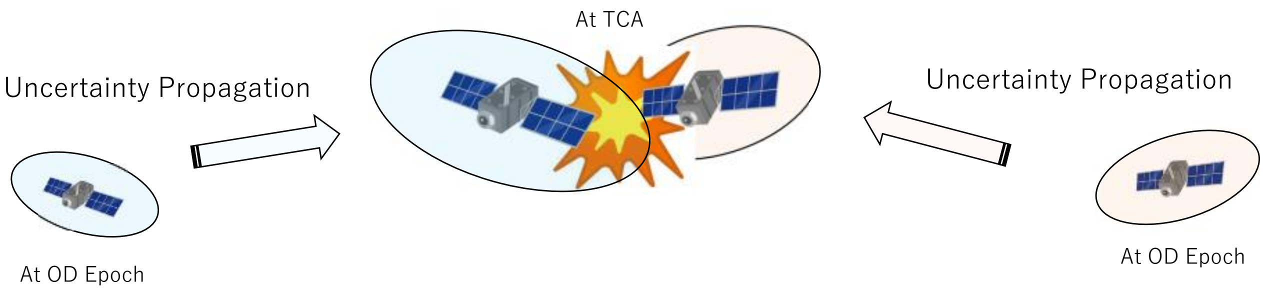
In conjunction assessment, you might hear conversations like:

"A high interest event was detected, but a covariance is still large….   "

"Hold on, atmospheric drag could cause a large error in OP. We should consider both."

"OK, but how much does the OD and drag uncertainties affect on OD and OP, respectively?"

<u>"Can we model them?"</u>



Solutions?

- **Numerical Approach:**
  - Propagate a covariance to an arbitrary epoch by a linear/nonlinear method
  - Advantages: a full orbital dynamics model and a nonlinear propagation are available
  - Disadvantages: a large computation cost

$$\boldsymbol{P}_{k+1} = \boldsymbol{\Phi}(t_{k+1}, t_k)\boldsymbol{P}_{k+1}\boldsymbol{\Phi}^T(t_{k+1}, t_k)$$

Traditional noise-only covariance propagation

- **Semi Analytical Approach (Prior research at JAXA) :**
  - 1st order approximation of OP due to the drag considering partially a full orbital dynamics model
  - Advantages: Easy to compute
  - Disadvantages: A full model is still required, and it does not consider an initial state error

- **This presentation reports a complete analytical approach:**
  - 1st order approximation of OP due to the drag and initial orbit's uncertainties.
  - Advantages: **Very** easy to compute
  - Disadvantages: an eccentricity of orbit of interest must be small enough.

Proposed Models

Assumptions:

① **This presentation reports an uncertainty modeling in along-track only**
- Position uncertainty in along-track has an important role in CA because the component is larger than other components and can be easily affected by disturbances such as drag.

② **Orbit of interest must be close to a circular one**
- This relaxes derivations of equations

③ **Considered orbit perturbation is an atmospheric drag only**
- Atmospheric drag is a major source of uncertainty

④ **An OP period of interest is up to 5 days, and atmospheric variations are relatively stable**
- JAXA starts to monitor a conjunction 5 days before TCA.
- Static use of a density makes derivations relaxed

Proposed Models

Mean Anomaly Propagation Models:

<u>SEDR: Specific Energy Dissipation Rate</u>
$S(t) = -\ddot{\boldsymbol{r}} \cdot \dot{\boldsymbol{r}}$

	Traditional Drag Model	SEDR Model
Acceleration	$\ddot{r} = -\frac{\rho\delta v^2}{2}$	$\ddot{r} = -\frac{S}{\dot{r}}$
Time derivative of semi-major axis	$\dot{a} = -\frac{a^2\rho\delta v^3}{\mu}$	$\dot{a} = -2\frac{Sa^2}{\mu}$
Mean Anomaly	$M_t = n_{t_0}\left(t + \frac{3\rho\delta n_{t_0}^{\frac{1}{3}}\mu^{\frac{1}{3}}}{4}t^2\right) + M_0 = \frac{3\rho\delta n_{t_0}^{\frac{4}{3}}\mu^{\frac{1}{3}}}{4}t^2 + n_{t_0}t + M_0$	$M_t = n_{t_0}\left[t + \frac{3}{2}(n_{t_0}\mu)^{-\frac{2}{3}}St^2\right] + M_0$

ρ: atmospheric density δ: ballistic coefficient v: velocity S: specific energy dissipation rate
$\ddot{r}$: acceleration a: semi major axis $\dot{a}$: time derivative of semi major axis μ: gravitational parameter
M_t, M_0: mean anomaly n_{t_0}: mean motion

Proposed Models

Mean Anomaly's Uncertainty Propagation Models:

<u>Traditional Drag Case:</u>

$$\Delta M_t = \sqrt{\left(\frac{\partial M_t}{\partial a_0}\right)^2 \Delta a_0^2 + \left(\frac{\partial M_t}{\partial \rho}\right)^2 \Delta\rho^2 + \left(\frac{\partial M_t}{\partial M_0}\right)^2 \Delta M_0^2}$$

<u>SEDR Case:</u>

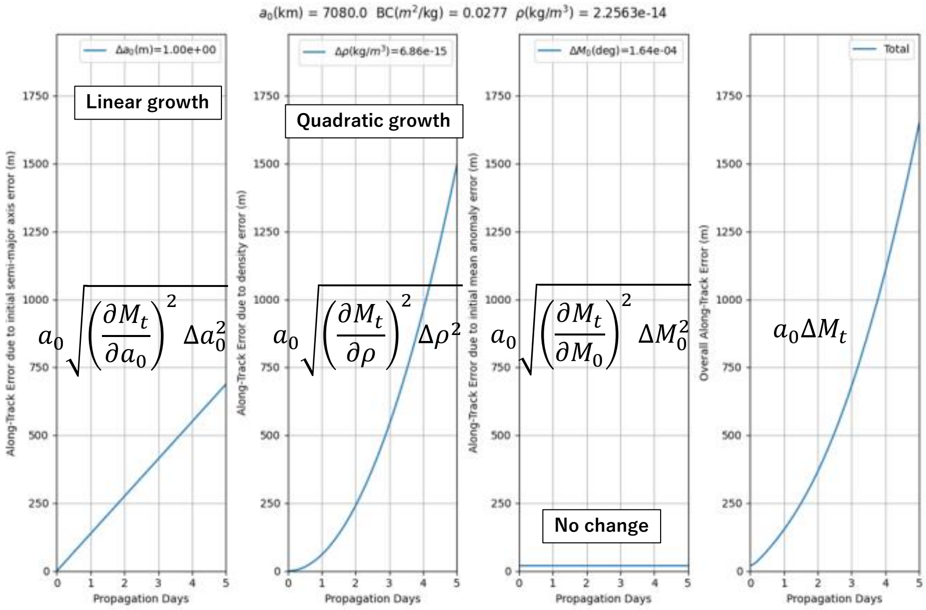
$$\Delta M_t = \sqrt{\left(\frac{\partial M_t}{\partial a_0}\right)^2 \Delta a_0^2 + \left(\frac{\partial M_t}{\partial S}\right)^2 \Delta S^2 + \left(\frac{\partial M_t}{\partial M_0}\right)^2 \Delta M_0^2}$$

Traditional Drag Case		SEDR Case	
Semi major axis	$\frac{\partial M_t}{\partial a_0} = -\frac{3n_{t_0}}{2a_0}t - \frac{3\rho\delta n_{t_0}^{\frac{4}{3}}\mu^{\frac{1}{3}}}{2a_0}t^2$	Semi major axis	$\frac{\partial M_t}{\partial a_0} = -\frac{3n_{t_0}}{2a_0}t - \frac{n_{t_0}}{a_0}St^2\mu^{-\frac{2}{3}}\left(n_{t_0}^{-\frac{2}{3}} - \frac{3}{2}n_{t_0}^{\frac{8}{3}}\right)$
Mean anomaly	$\frac{\partial M_t}{\partial M_0} = 1$	Mean anomaly	$\frac{\partial M_t}{\partial M_0} = 1$
Atmospheric density	$\frac{\partial M_t}{\partial \rho} = \frac{3\delta n_{t_0}^{\frac{4}{3}}\mu^{\frac{1}{3}}}{4}t^2$	SEDR	$\frac{\partial M_t}{\partial S} = \frac{3}{2}n_{t_0}(n_{t_0}\mu)^{-\frac{2}{3}}t^2$

Demonstrations

High Solar Activity

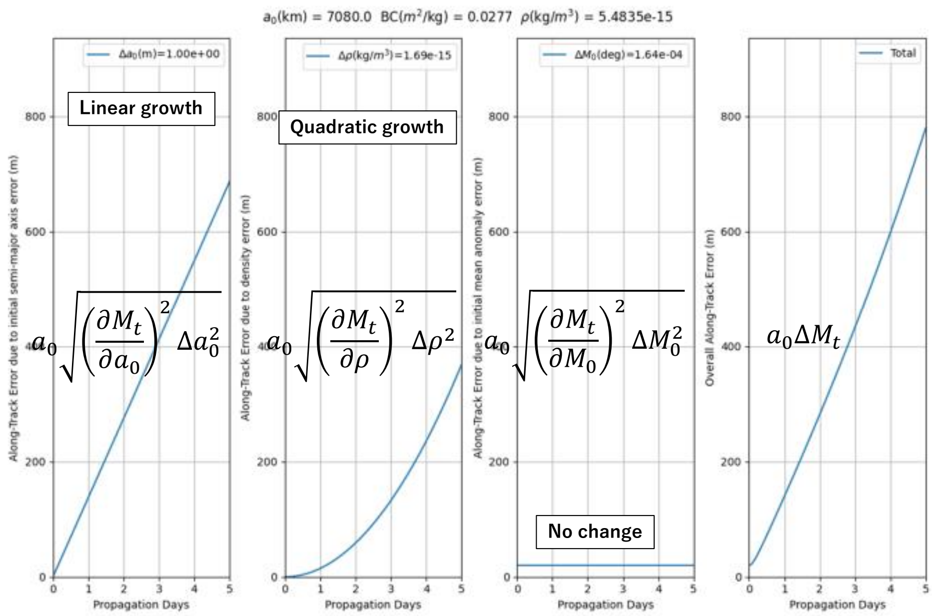
Conditions:
- a: 7080 km
- ρ: 2.256×10^{-14} kg/m^3
- Δa: 1 m
- ΔM_0: 1.637×10^{-4} degree
- $\Delta\rho$: 6.859×10^{-15} kg/m^3



Demonstrations

Low Solar Activity

Conditions:
- a: 7080 km
- ρ: 5.483×10^{-15} kg/m^3
- Δa: 1 m
- ΔM_0: 1.637×10^{-4} degree
- $\Delta\rho$: 1.689×10^{-15} kg/m^3



Application#1

How much do uncertainties change of initial orbit and density affect on OP?

Let us define an uncertainty reduction rate in OP as $\varepsilon_{\Delta\rho}$:

When a density uncertainty reduces from $\Delta\rho_A$ to $\Delta\rho_B$, an uncertainty reduction rate in density is defined by

$$\varepsilon_{\Delta\rho} = \frac{\Delta\rho_A - \Delta\rho_B}{\Delta\rho_A}$$

Then, an uncertainty reduction rate in propagated mean anomaly is given by

uncertainty of density — reduced uncertainty of density

$$\varepsilon_{\Delta M_t} = \frac{\Delta M_t(a_0, \rho, \Delta a_0, \Delta M_0, \Delta\rho_A, t) - \Delta M_t(a_0, \rho, \Delta a_0, \Delta M_0, \Delta\rho_B, t)}{\Delta M_t(a_0, \rho, \Delta a_0, \Delta M_0, \Delta\rho_A, t)}$$

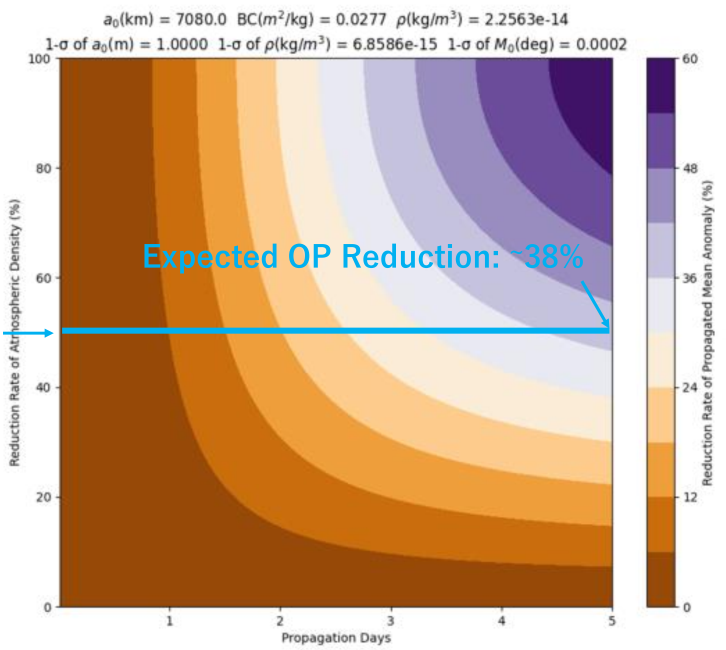
Uncertainty Reduction Rates

High Solar Activity

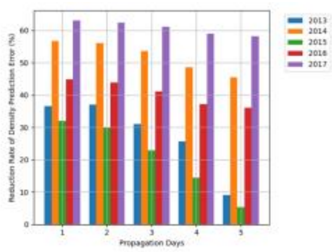
PATHFINDER:
Atmospheric density model under development at JAXA

Goal of Density Reduction Rate

50%



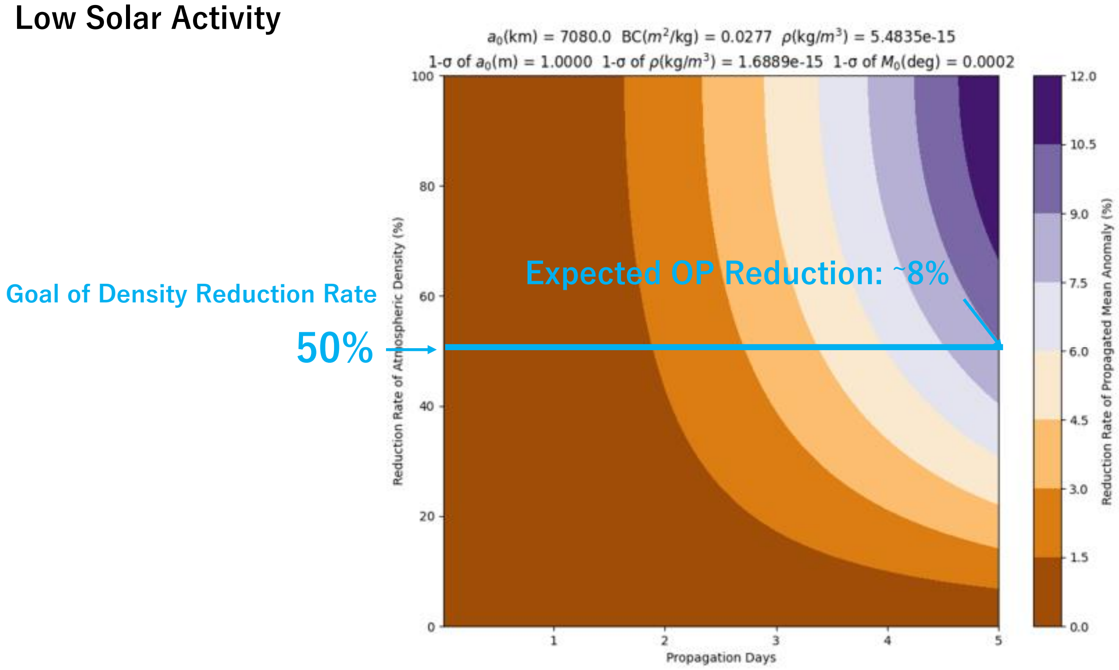
Current prediction capability



PATHFINDER: Prediction of ATmospheric drag enHanced by Flight data INversion for Dynamical Equation Reconstruction

Uncertainty Reduction Rates

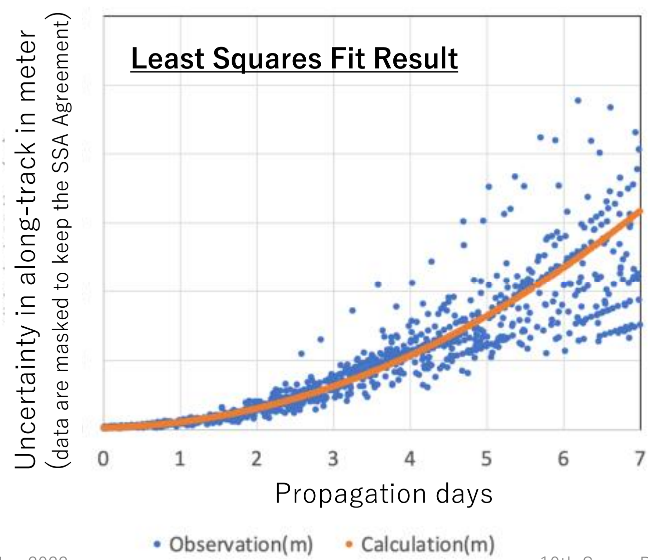
Low Solar Activity



Application#2

Mean Anomaly's Uncertainty Propagation Models:

"I receive tons of conjunction data messages. Can I do something interesting with these?"



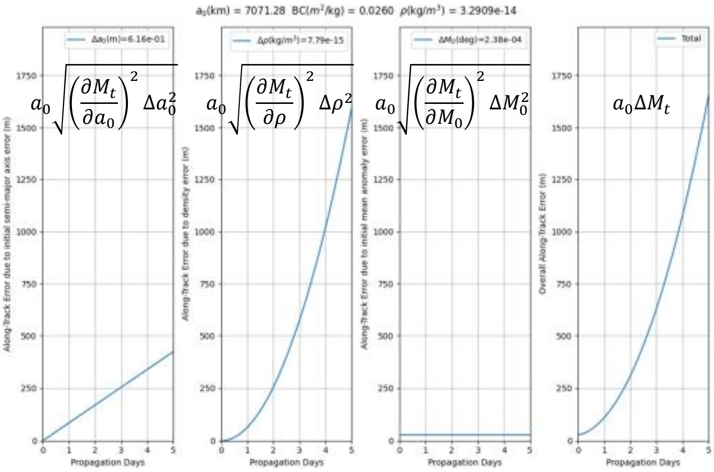
Fitted Parameters

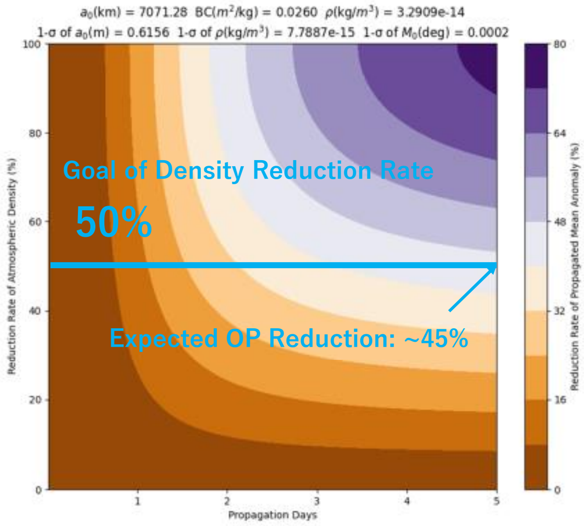
CDM period	1 Apr 2022 – 24 May 2022
$\hat{\delta}$	2.596×10^{-2} m^2/kg *1
$\hat{a}$	7071 km
$\hat{\rho}$	3.291×10^{-14} kg/m^3
$\Delta\hat{a}$	62 cm
$\Delta\hat{\rho}$	23%
$\Delta\widehat{M}_0$	2.376×10^{-4} degree (29m)

*1) Reference value: 2.770×10^{-2} m^2/kg

Application#2

Uncertainty Propagation and its Reduction Rates Using Estimated Parameters:





Summary

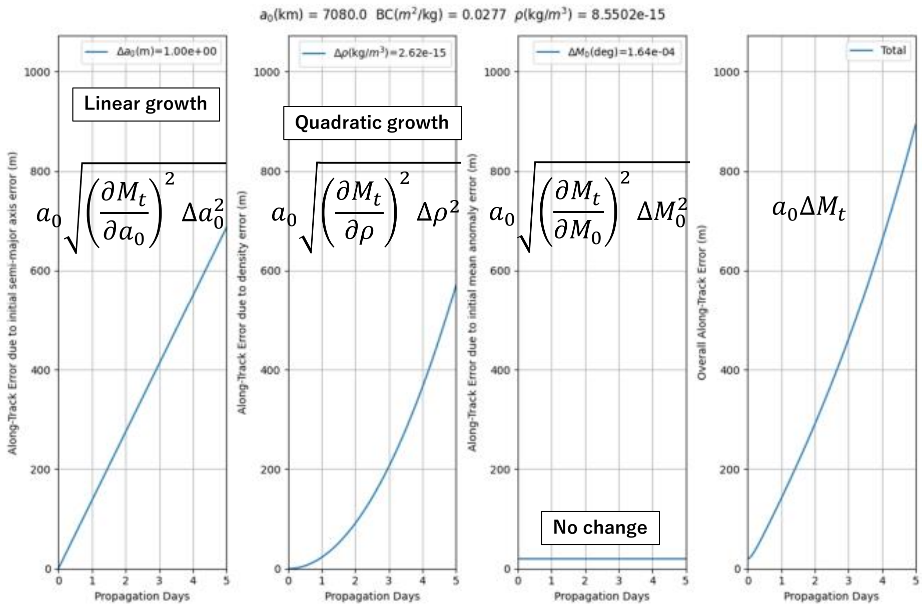
- A complete analytical method was proposed to model uncertainty of orbit propagation in along-track due to initial orbit and atmospheric density uncertainties.
- The proposed method was demonstrated to show uncertainty growth in different solar activities.
- Orbit propagation's uncertainty reduction rates are provided in different solar activities.
- Parameters in the proposed method can be estimated when you have enough CDMs.
- **A Conjunction assessment operator can model an uncertainty growth and a reduction rate in orbit propagation and recalculate an expected uncertainty in orbit propagation when a density reduction rate is given.**

- Backup

Demonstrations

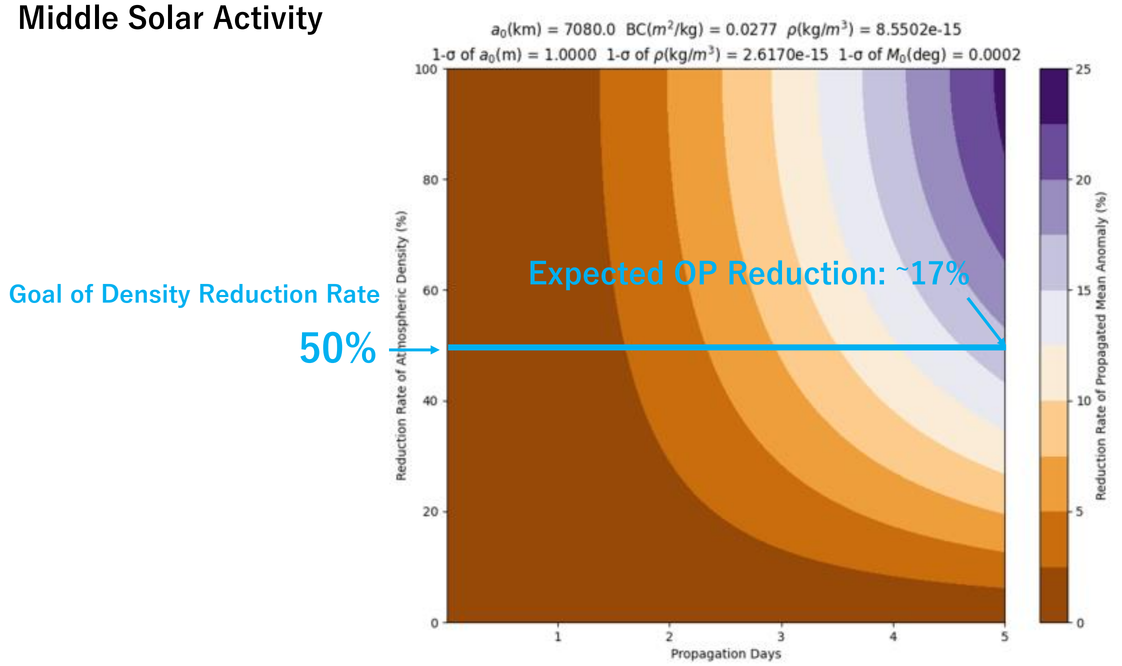
Middle Solar Activity

Conditions:
- a: 7080 km
- ρ: 8.550×10^{-15} kg/m^3
- Δa: 1 m
- ΔM_0: 1.637×10^{-4} degree
- $\Delta \rho$: 2.617×10^{-15} kg/m^3



Uncertainty Reduction Rates

Middle Solar Activity



A11

スターシグナルソリューションズが取り組む接近情報の改良方法に関する概要

Overview of Conjunction Data Enhancement by Star Signal Solutions

○日南川英明（JAXA 追跡ネットワーク技術センター），岩城陽大（JAXA 経営企画部），秋山恭平（JAXA 第一宇宙技術部門衛星測位システム技術ユニット），柳沢俊史（JAXA 研究開発部門第二研究ユニット）
○HINAGAWA Hideaki (JAXA Space Tracking and Communications Center),
IWAKI Akihiro (JAXA Management Division, Strategic Planning and Management Department),
AKIYAMA Kyohei (JAXA Space Technology Directorate I, Satellite Navigation Unit),
YANAGISAWA Toshifumi (JAXA Research and Development Directorate, Research Unit II)

地球周辺の宇宙空間は混雑化が進み, 衛星事業者は CSpOC 等の組織から日々大量の物体接近情報（CDM）を受け取っており，その対応の負荷が大きく，年々受信件数は著しい増加傾向にある．さらに，今後 10 年間には新たに数万もの人工衛星が打上げられると言われており，地上観測に強く依存した宇宙監視・追跡（SST）に基づいた衝突回避の仕組みはいずれ限界を迎えると考えられる．一方，軌道上観測は 1 機あたり 100 億円程度と高価であり，SST に組み込むためには莫大な予算が必要になる．そこで，本発表では，姿勢決定を目的として衛星に搭載されるスタートラッカをデブリ等の観測に用い，その取得データと CDM を組み合わせることで，従来よりも高精度な CDM を生成する手法の概要及びシミュレーション結果を報告する．

Space environment around the Earth is getting more congested and contested more than ever. Satellite operators receive, filter, and analyze tons of conjunction data messages every day, which is a heavy burden to the operators.　In addition, the number of data is drastically increasing every year.　To make matters worse, tens of thousands of satellites are planned to be launched, and current Space Surveillance and Tracking (SST) framework could get stuck near future because most of the SST highly depend on ground observations.　Although some dedicated space-based observation satellites are operational, it may cost more than 10 billion yen to develop a new one.　Star Signal Solutions (SSS) aims to provide a solution for conjunction assessment and collision avoidance using conjunction messages enhanced by star tracker’s images and our own algorithm.　This presentation explains overview of our research activity and presents simulation results.


STAR SIGNAL SOLUTIONS
Overview of Conjunction Data Enhancement
by Star Signal Solutions
Hideaki Hinagawa* (JAXA Space Tracking and Communications Center)
Akihiro Iwaki (JAXA Management Division, Strategic Planning and Management Department)
Kyohei Akiyama (JAXA Space Technology Directorate I, Satellite Navigation Unit)
Toshifumi Yanagisawa (JAXA Research and Development Directorate, Research Unit Ⅱ)
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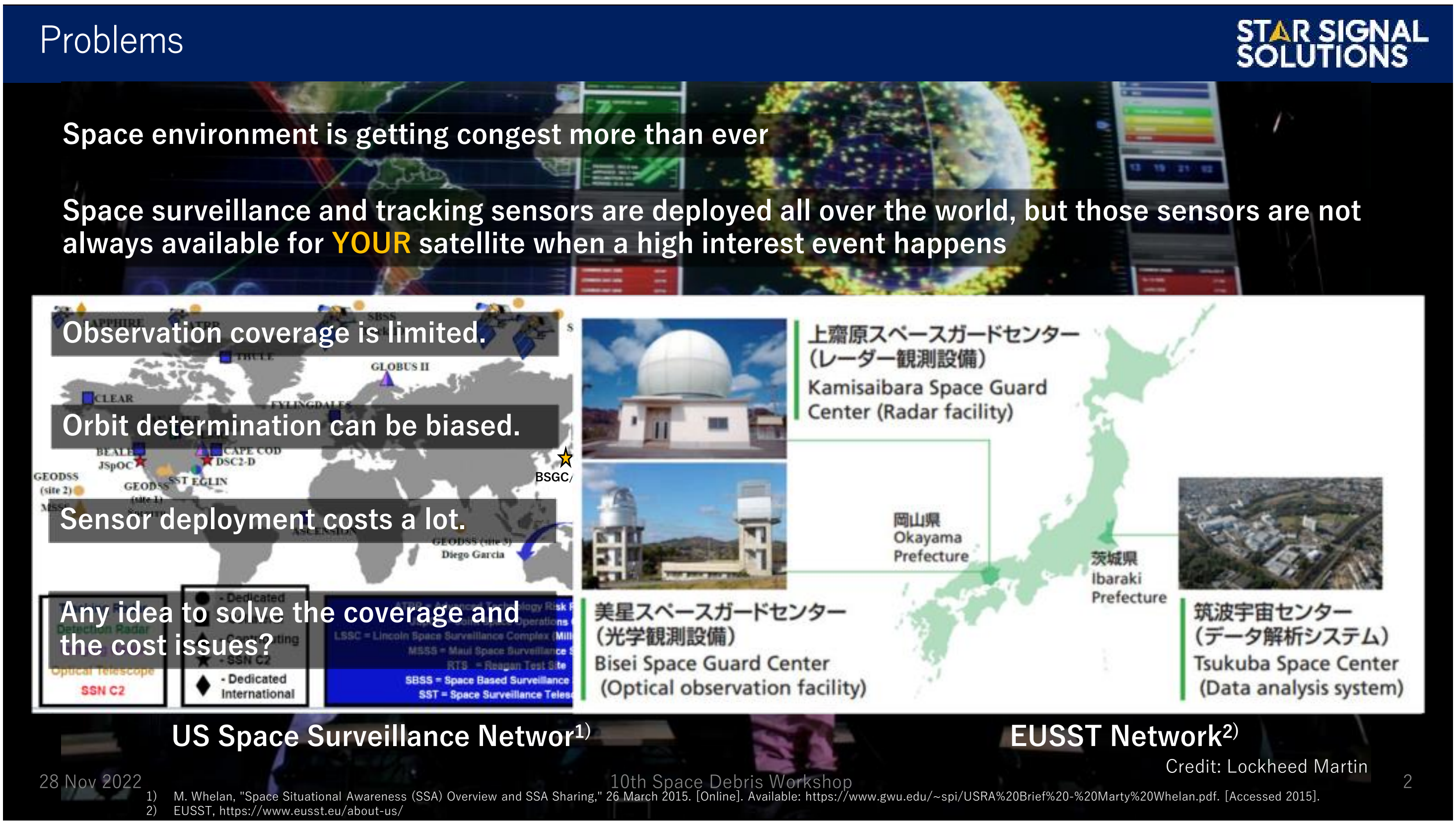
Problems
STAR SIGNAL SOLUTIONS
Space environment is getting congest more than ever
Space surveillance and tracking sensors are deployed all over the world, but those sensors are not always available for YOUR satellite when a high interest event happens
Observation coverage is limited.
Orbit determination can be biased.
Sensor deployment costs a lot.
Any idea to solve the coverage and the cost issues?
上齋原スペースガードセンター
(レーダー観測設備)
Kamisaibara Space Guard Center (Radar facility)
岡山県
Okayama Prefecture
茨城県
Ibaraki Prefecture
美星スペースガードセンター
(光学観測設備)
Bisei Space Guard Center
(Optical observation facility)
筑波宇宙センター
(データ解析システム)
Tsukuba Space Center
(Data analysis system)
US Space Surveillance Networ1)
EUSST Network2)
Credit: Lockheed Martin
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1) M. Whelan, "Space Situational Awareness (SSA) Overview and SSA Sharing," 26 March 2015. [Online]. Available: https://www.gwu.edu/~spi/USRA%20Brief%20-%20Marty%20Whelan.pdf. [Accessed 2015].
2) EUSST, https://www.eusst.eu/about-us/

What Does Star Signal Solutions Propose?

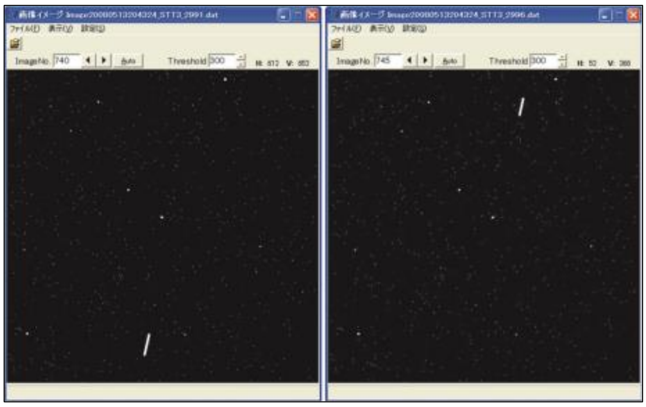
Space-based observation by a star tracker (STT) and enhanced CDM generation

An STT, a sensor for attitude determination, sometimes happens to detect a resident space object in an image (Iwata et al, 2014). However, the Image is usually discarded after it is processed, and not downlinked to ground.

The SST has a potential to be a on-orbit sensor for space situational awareness.

Advantages:
- Frequent observation opportunity, depending on relative position between a space sensor and a target
- No need to launch a dedicated satellite as a space sensor

Disadvantages:
- Reprogramming of onboard software may be required to downlink images
  - This feasibility is out of scope in this presentation
- Setup of an STT for imaging such as exposure time may not be appropriate
  - The blink stacking method can be applicable
- Shorter duration of observation than ground-based obs.
  - STT-only orbit determination could be inaccurate due to the small amount of data. To deal with this issue, a priori information can be used from a conjunction data message

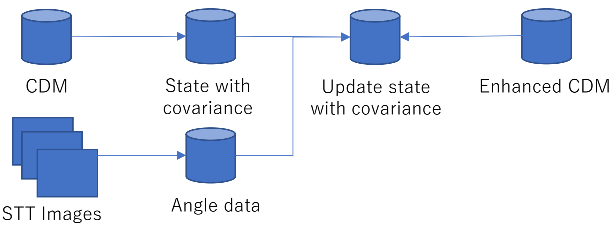


STT Images, Iwata et al (2014)

What Does Star Signal Solutions Propose?

Star Signal Solutions provides:
- An updated CDM with enhanced orbital information by processing an existing CDM and SST-/ground-based observations
- Collision avoidance navigation to owners and operators

Data Flow For Updating CDM generation



What This Presentation Reports:
- Simulations of orbit determination using pseudo SST observations and a CDM

What This Presentation Does NOT Reports (Out-of-Scope):
- Overview of our activity, which is presented by Iwaki in previous session in this workshop
- Image processing, which is conducted by Yanagisawa

Simulations - Setup

STAR SIGNAL SOLUTIONS

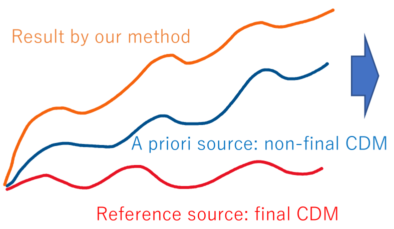
Measurement and Orbital Dynamics Models:

Measurement Model	
measurements	Space-based topocentric RA and Dec in J2000
data correction	Light aberration and light time delay are considered
ground observer	Siding Spring Observatory (SSO)（WGS84：149.064 E, 31.2733 S, 1126.19m）
space observer	Star Signal Solutions Satellite A-series (S4A)-1,2,3,4：a: 7178.14km/i:98.6029deg, Dawn-Dusk orbits spaced every 90 degrees. Star Signal Solutions Satellite B-series (S4B)-1,2,3,4：a: 6978.14km/i: 97.7875deg, Dawn-Dusk orbits spaced every 90 degrees each other and spaced by 45 degrees with S4A.
measurement noise in ground observation	$\sigma_{RA} = 4$ arcsec $\sigma_{Dec} = 4$ arcsec
measurement noise in space observation	$\sigma_{RA} = 40$ arcsec $\sigma_{Dec} = 40$ arcsec
sampling rate for ground/space observer	1 Hz
Orbital Dynamics Model	
gravity model	EGM2008, 10x10
tides	Solid tide
atmospheric density model	User choice from Jacchia-Roberts, NRLMSISE-00, MSIS-2.0, Jacchia Bowman 2008, **SEDR**
third bodies	Sun and Moon (JPL DE430)
coordinate transformation	IAU76/FK5 theory
Estimation Conditions	
Estimator	Weight batch least squares estimator considering a priori states and drag consider parameter extracted from CDM
states to be estimated	Position and velocity in J2000

Simulations – Ground-based Observation

STAR SIGNAL SOLUTIONS

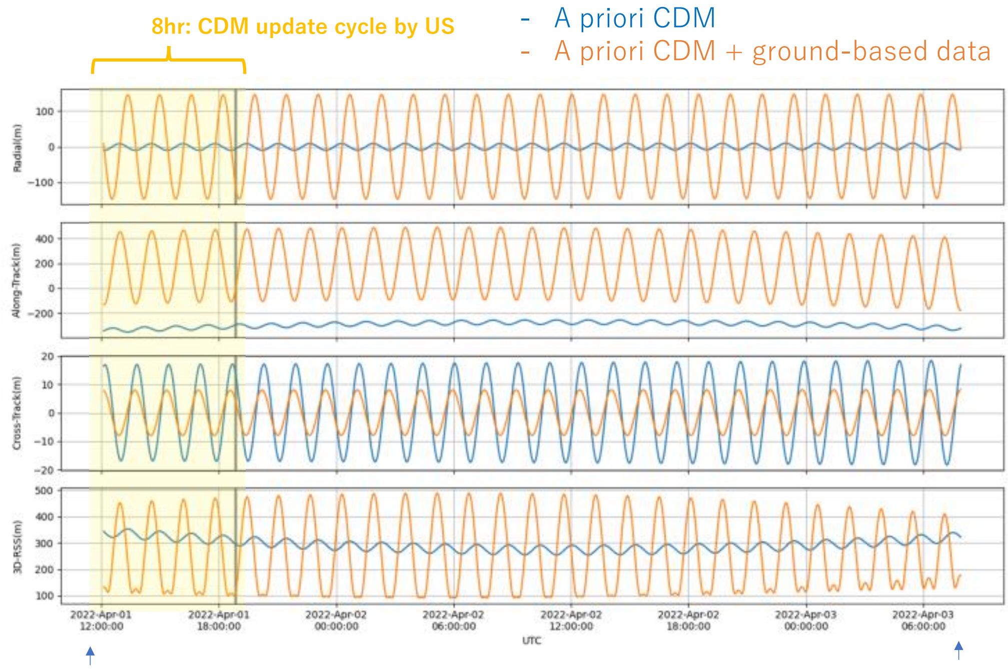
Ephemeris Comparison



1 pass found

Ground-based obs. pass
- 2022-04-01 18:48:49~18:53:46UTC
- Max Ele. 33.5 deg

Additional single pass makes a radial component worse. This could be due to lack of sensitivity in range direction of angle measurement.



CREATION_DATE of a priori

TCA

Simulations – Space-based Observation

STAR SIGNAL SOLUTIONS

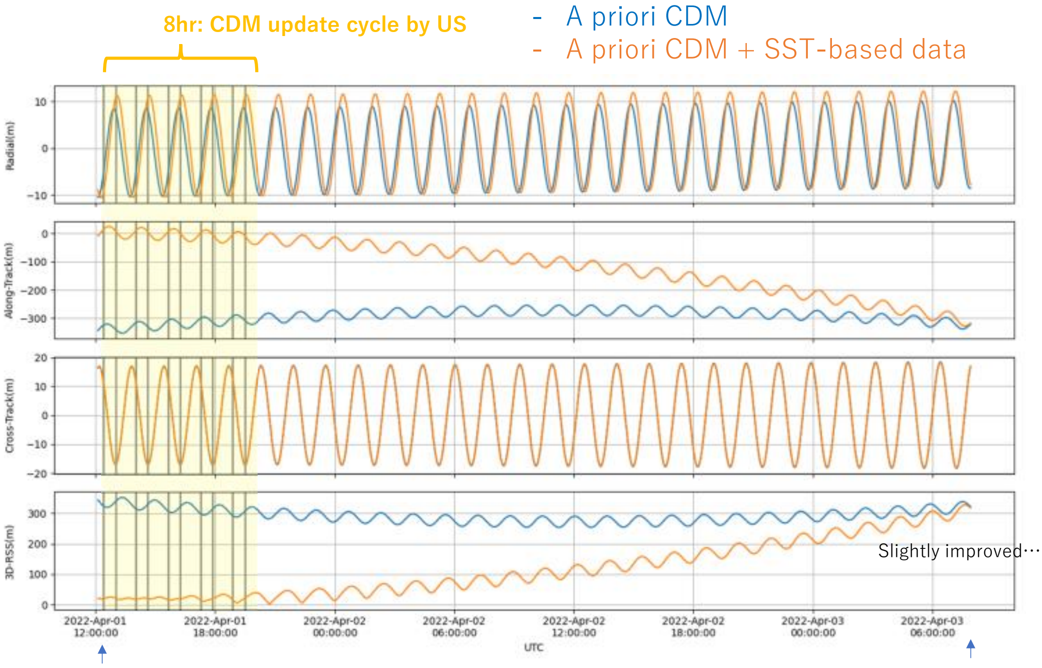
Ephemeris Comparison

10-pass found

Space-based obs. pass
S4B satellite#1
- 2022-04-01 12:25:17~12:25:34UTC
- 2022-04-01 14:02:18~14:02:34UTC
- 2022-04-01 15:39:19~15:39:34UTC
- 2022-04-01 17:16:20~17:16:35UTC
- 2022-04-01 18:53:21~18:53:35UTC

S4B satellite#1
- 2022-04-01 13:01:24~13:01:33UTC
- 2022-04-01 14:38:24~14:38:34UTC
- 2022-04-01 16:15:24~16:15:35UTC
- 2022-04-01 17:52:25~17:52:36UTC
- 2022-04-01 19:29:37~19:29:37UTC

Orbital position differences at observation epochs are improved, but difference at TCA are not improved so much. This issue could be solved by adding a drag parameter to a state to be estimated although there are some important points….



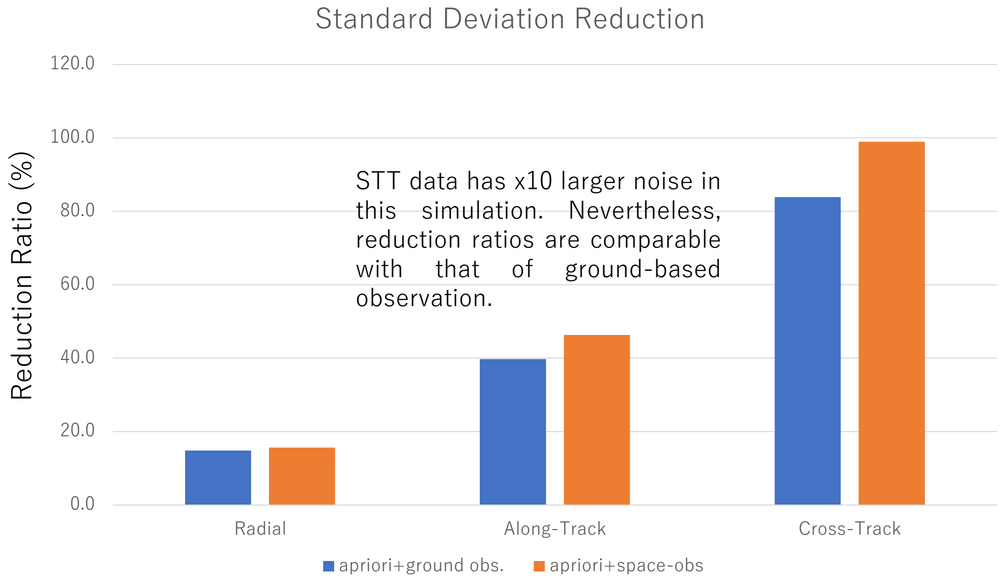
Simulations

STAR SIGNAL SOLUTIONS

Covariance Analysis

Reduction Ratio

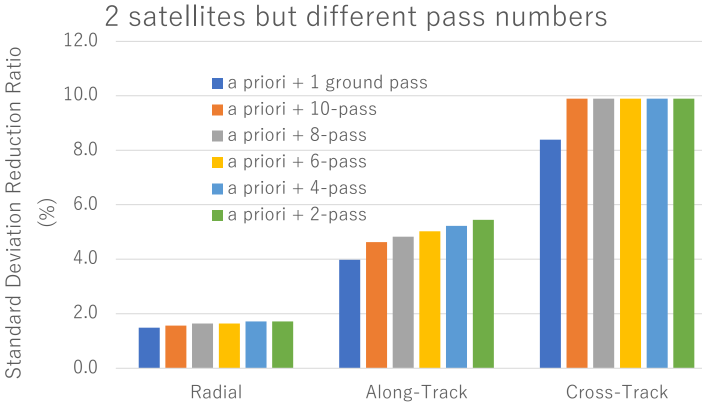
$$\frac{\textit{updated standard deviation}}{\textit{a priori's standard deviation}} \times 100$$

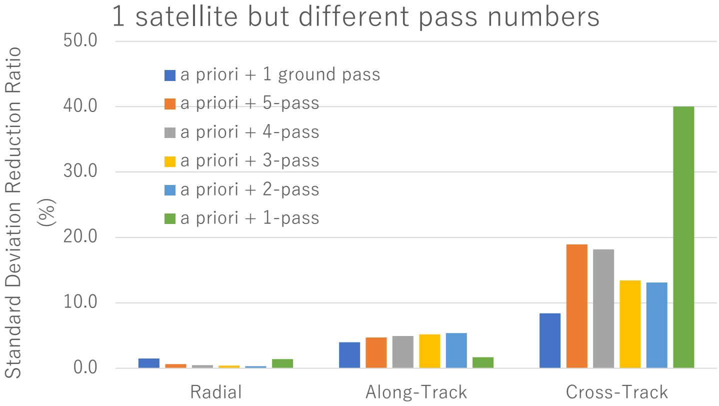


Simulations

STAR SIGNAL SOLUTIONS

Additional Covariance Analysis as Preliminary Study on Satellite Numbers and Visible Passes





When 2 satellites are available, the number of passes could not be dominant to covariance reduction. However, if the number of available satellite is 1, results are different with used pass. Especially, 1 pass by 1 satellite made the result degraded. This indicates that use of 2 satellites would be advantageous in terms of geometrical position between an observer satellite and a target object. We plan to run additional simulations to understand the characteristics more.

Summary

STAR SIGNAL SOLUTIONS

- Star Signal Solutions (SSS) aims to provide a solution for conjunction assessment and collision avoidance operation using conjunction messages enhanced by star tracker's images and our own algorithm
- Overview and simulation results are presented assuming ground-/space-based observations to enhance an existing CDM
- Simulations showed effectiveness of our method in terms of both of accuracy and precision. SSS plans to run more simulations to update and confirm the effectiveness of our method
- Additional consider parameters such as an observer position's uncertainty will be incorporated
- SSS plans to validate our approach using actual space-based observations soon

A12

UMAによるSSA解析能力の向上
Improving SSA Analysis with UMA

〇ティモシー・グリンスキー（LSAS Tec）
〇Timothy Glinski (LSAS Tec)

近年ますます増加傾向にある宇宙物体の軌道を正確に把握することは宇宙ミッションの安全を維持するために非常に重要な課題である。宇宙物体の軌道を正確に把握するには地上の観測センサとそのセンサで得られたデータを用いた軌道決定が重要になる。
Starlink衛星に代表されるメガコンステレーションの大量の衛星群を軌道決定する、あるいは、SSAシステムで観測された多数の未知物体を軌道決定する、といった行為は、運用者や解析者がデータ処理を行う際に試行錯誤を伴ったり、それによって軌道決定に関する高度な専門知識を必要としたりすることがあり、効率よく運用するには課題がある。
我々LSAS Tec社は、宇宙業界で広く使われているAGI ANSYSのODTK及びSTKを活用し、宇宙ミッション解析に有用なUMA（Unified Mission Analysis）を開発した。この製品は、運用者や解析者による軌道決定をはじめとする各種軌道解析を効率的に行うツールである。UMAは未知物体であっても軌道決定処理の自動化と軌道決定精度向上を実現した。特に大量物体や未知物体を処理するSSAシステムでの運用の効率化に寄与できる能力を持ち、経験や軌道決定の深い専門知識を有しない運用者でも解析可能なツールとして期待できる。本ワークショップでは、当社が開発したUMAの機能、能力、有用性について紹介する。

Built on top of AGI ANSYS's proven STK and ODTK technology, LSAS Tec's newly developed UMA (United Mission Analysis) tool allows for improved accuracy high speed orbital determination. This results in improved SSA (space situational awareness) analysis and thus allows the operator to make quick decisions based on accurate data.
With the addition of mega constellations like SpaceX's Starlink, the need for quick and efficient orbital determination that maintains accuracy has risen sharply. However, there are not enough highly skilled orbital analysts to fill such a role and so lowering the barrier to entry to fill said role is required if a full grasp of the space domain is to be maintained. UMA manages to accomplish this by simplifying and automating the most difficult parts of orbital determination.
With the initial orbit determination (IOD) process being fully automated, orbital determination of newly tracked objects has become possible for operators with little to no experience. This has also allowed for quick reevaluation of continuous solutions, which combined with the simplified UMA orbital determination workflow, allows for quick and accurate analysis on the numerous satellites that need to be tracked daily.
Through automation and simplification, UMA allows for quick and accurate orbital determination for operators of all levels, allowing for large scale SSA analysis to be maintained.

LSAS Tec

UMAによるSSA解析能力の向上

Improving SSA analysis with UMA

Unified Mission analysis Automation Tool

LSAS Tec株式会社

ティモシー・グリンスキー
Timothy Glinski

2022年11月28日　第10回スペースデブリワークショップ　講演資料

目 次

LSAS Tec

1．SSAにおける軌道解析の課題

➢ 宇宙物体の増加

・メガコンステに代表される宇宙事業者の増加、ASAT、ブレークアップ…
・観測センサー網の発達と性能向上　⇒　小さいデブリまで見えるように

The number of objects being tracked is constantly increasing

➢ 宇宙活動の安全確保

・大量の宇宙物体の正確な軌道の継続的な把握が重要

Precise and accurate orbital data must be continuously produced for safety of flight

➢ 正確な軌道の継続的な把握＝**軌道決定**

・大量の宇宙物体の軌道決定ではうまく処理できない物体も多々あり、
軌道決定のエキスパートによる手動での解析など効率化が大きな課題

In order to process all data, the workflow needs to be improved as to reduce manual operation by orbital analysts->UMA

軌道のエキスパートでなくても快適に運用・解析できるようにしたい
⇒　UMA開発のモチベーション

LSAS Tec

2．UMAの目的と特長

・ANSYS/AGI社の民製品「STK」や「ODTK」を利用した統合運用ツールを開発
・宇宙ミッションの運用や運用解析のワークフローを自動化、運用者や解析者の作業効率を高める
・オープンソースのCesiumを利用したWebブラウザによる可視化エンジンを搭載

Built on top of proven AGI Ansys technology

ODTK : Orbit Determination Tool Kit
STK : Systems Tool Kit

Ansys
GOVERNMENT INITIATIVES (AGI)

LSAS Tec

3．UMAによる軌道決定処理の自動化

➢ **軌道決定処理の自動化**

軌道決定のエキスパートの介在が無くても短時間で軌道決定が自動的に実行できることを目的に開発

Automized OD

➢ **主な特長**

・**AUTO IOD** ： 初期軌道決定の自動化

先見情報の無い宇宙物体の初期軌道決定を自動化

・**AUTO CALIBRATION** ： 地上局の自動校正

様々な地上局の観測データに含まれるバイアス誤差等の校正処理を自動化

Algorithms to automize and assist in initial orbit determination, tracker calibration, and both precision and force model refinement

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4．軌道決定の自動化による効果の検証

➢ **検証方法**

Used simulated data from SEG to test results

・米国COMSPOC社製品のSEG（Space Event Generator）を用い、静止軌道帯での人工衛星のブレークアップを模擬

・軌道決定のエキスパートによるODTKを用いた手動軌道決定と、UMAの自動実行について、処理時間と軌道決定精度を比較

➢ **想定シナリオ**

・静止衛星が何等かの異常により5つの物体に分離したと想定
・分離した物体が光学センサーにより観測されたと想定
・その観測データを用いて軌道決定を実施

Scenario: Debris event with 5 well separated GEO objects being tracked by optical sensors, with obs association already accurately completed

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4. 軌道決定の自動化による効果の検証

➢ 軌道決定処理の流れ

・数パス分の観測データを使った初期軌道決定
光学センサーのため、Gooding Angles Only法を採用
Use Gooding Angles Only algorithm to get an initial state

⬇

・最小二乗法による軌道初期値の改良
今回、残差率が3σを上回り調整と再実行が必要なケースを模擬
Refine the initial state with a least squares algorithm

⬇

・カルマンフィルター/スムーザによる最終軌道決定
Karlman Filter -> smoother processing for full orbital determination results

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4. 軌道決定の自動化による効果の検証

➢ 処理時間の比較

Result Time comparison

ケース	1物体の処理時間	5物体の処理時間
エキスパートによるODTKの手動実行 Experienced orbit analyst	平均14分 Average of 14 minutes	70分 Total of 70 minutes
UMAの自動実行 UMA Automatic processing	**平均3分** Average of 3 minutes	**15分** Total of 15 minutes

⇒ エキスパートによる手動操作と比較して4倍以上の時間短縮

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4．軌道決定の自動化による効果の検証

➢ 軌道決定誤差の比較

・エキスパートが手動実行した場合　：　約2km
・UMAで自動実行した場合　：　最大約0.2km

⇒ 試行錯誤的に実行した結果より短い時間で高い精度の軌道決定を実現

UMA resulted in a maximum uncertainty of 200 meters versus the manual results of 2000 meters in this study

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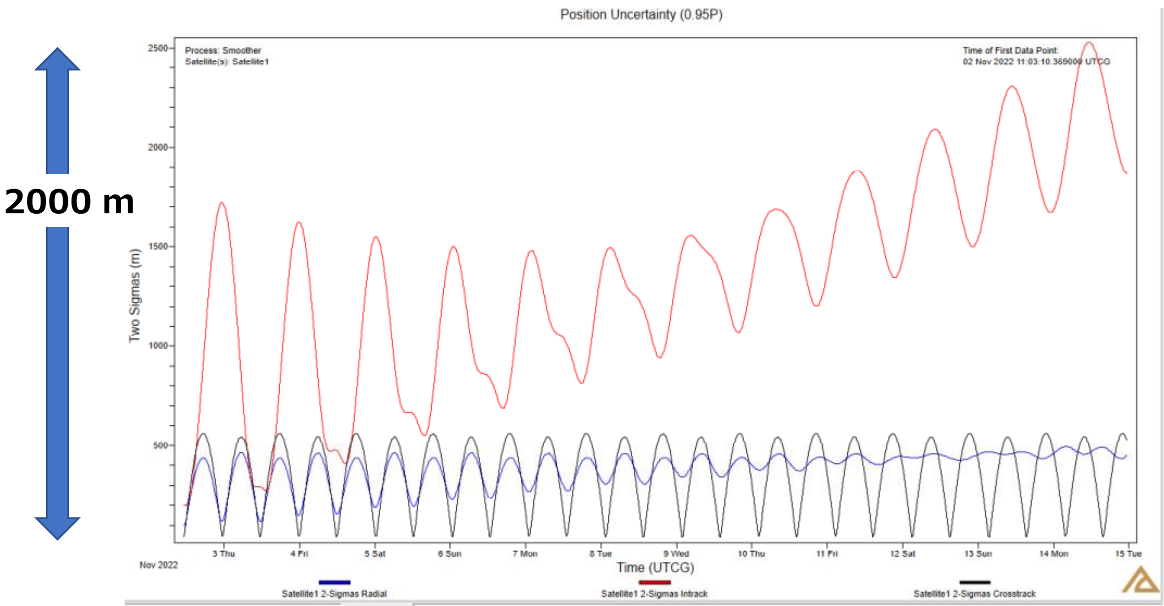
4．軌道決定の自動化による効果の検証

➢ エキスパートによる手動実行時の軌道決定精度

⇒ 位置で約2kmの誤差　　Manual ODTK Results



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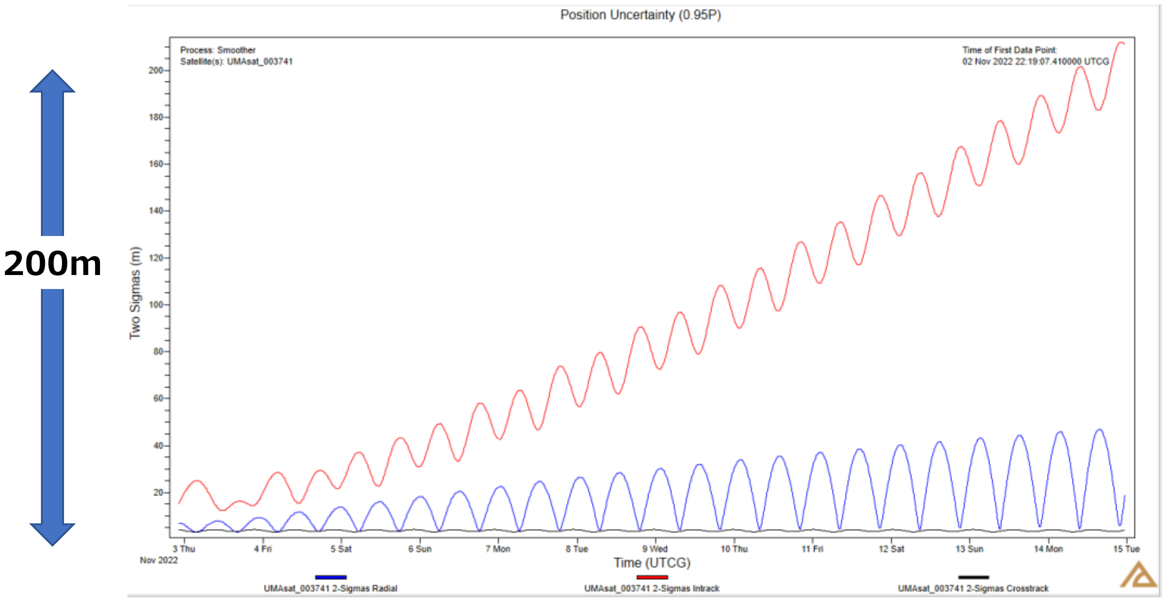
4．軌道決定の自動化による効果の検証

➢ **UMAによる自動実行時の軌道決定精度**
 ⇒ **最大0.2km程度の誤差　UMA Automatic Results**



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4．軌道決定の自動化による効果の検証

➢ **まとめ**

・UMAは、エキスパートが介在せず、自動的に宇宙物体の軌道決定が効率的かつ高い精度で実行可能であり、有用性が評価できた。

With UMA inexperienced operators can produce high accuracy orbital data through the automized tools

・実際のブレークアップでは、はるかに多い物体が発生する。例えば、50物体が発生した場合、今回の検証では、手動で11時間40分を要し、かつ、軌道決定のエキスパートの介在が必要となる。
一方、UMAの場合、処理時間が2時間半程度と大幅に短縮でき、かつ高い精度を実現でき、エキスパートの介在も不要となる。

Assuming a more realistic debris event of up to 50 objects tracked, what could take a full day for an orbit analyst can be reduced to under 2 hours for even an inexperienced operator

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5．今後の展開

- UMAは今後もSSAや衛星事業者の運用に役立つ製品として継続的に開発を進め、宇宙活動の安全に貢献していく。

Future Development plans: Version 2 at the end of fiscal year 2023

- ***UMA Ver2***：2023年度末リリース予定
  - ❑ OA(Observation Association)の自動化
  - ❑ UCT(Un-Correlated Track)の推定機能の強化
  - ❑ 衛星の軌道制御検知の自動化
  - ❑ 衛星の軌道制御履歴による特性把握支援
  - ❑ 宇宙物体の力学モデルの校正機能によるさらなる高精度化
  - ❑ RPO運用シミュレーション機能　など

Planned Features:
Automated observation association and UTC processing,
Automated maneuver detection and characterization,
Automated force model calibration
RPO planning

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UMA Ver1の構成

UMAの構成		機能の概要
FD	軌道決定モジュール	宇宙物体の軌道決定を行う。 軌道決定を自動的に行う機能を具備する。
OT	運用解析者支援ツール	・地上局解析機能 ・相対運動解析機能 ・UMAワークフロー以外の自動化支援機能
CA	接近解析ツール	・接近解析を行い、結果をCSVやCDMに出力
RE	再突入解析ツール	再突入予測を行い、落下予測領域のヒートマップ表示を行う。
VZ	状況可視化ツール	Cesiumプラットフォームに軌道や地上局の可視化を行う。

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A13 Invited Lecture

Space Traffic Management as a Necessity for Future Orbital Operations
A French perspective

〇Christophe Bonnal (CNES)

Based on several decades of activities in the domain of Space Debris, CNES, together with its classical partners at IADC level is proactive in the elaboration of recommendations, requirements, standards or even law in the field of Long Term Sustainability of Space.
After a brief recall of the situation underlining the need to take measures to improve safety of space operations with short and long term perspectives, the presentation will focus on the activities led by a dedicated Working Group on Space Traffic Management and Space Traffic Coordination, in preparation to international discussions and standardization. This presentation provides an analysis of the main identified challenges to be addressed by space traffic management (STM) and an overview of a set of actions considered to tackle those challenges.
The complementarity of political guidelines, regulation, standardization and operational capabilities is discussed, taking into account the need to combine the expected efficiency of the proposed actions with European industry competitiveness and also national and European security constraints.

Space Traffic Management as a necessity for Future Orbital Operations

A French perspective

Christophe Bonnal
CNES Strategy Directorate, Paris, France
French delegate to IADC, ECSS, ISO
Co-Chair IAA Space Debris Committee & IAF Space Traffic Management Committee

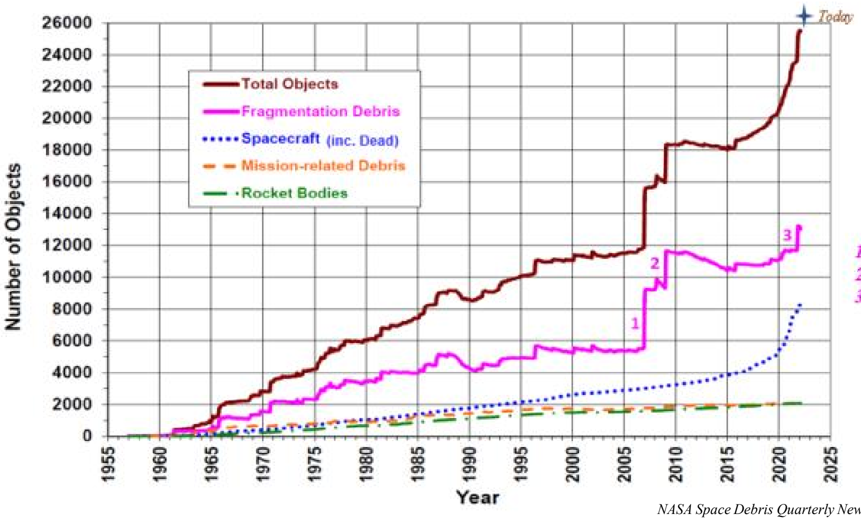
10th JAXA Space Debris Workshop – Chofu, 28 November 2022

cnes

Introduction

cnes

- **The number of artificial satellites put into Earth orbit drastically increases over the years**
  - Number of active satellites: 994 Jan. 1st, 2012 – 7,035 Nov. 27, 2022 (x7)
  - Number of active satellites in Low Earth Orbit LEO: 469 Jan. 1st, 2012 – 5,929 Nov. 27, 2022 (x13)
  - Number of debris has doubled in 15 years
  - 97.5% of the debris in LEO come from USA – Russia – China (France ≅ 0.6%, Japan ≅ 0.4%)



1 Feng Yun 1C ASAT
2 Iridium33 - K2251
3 K1804 ASAT

NASA Space Debris Quarterly News - https://orbitaldebris.jsc.nasa.gov/quarterly-news/

Introduction

- **Space activities, mainly in LEO are Fundamental and Strategic for Environment, Scientific, Commercial, Defence or Educational purposes**

↳ Need to take measures to improve safety of space operations and to contribute to Long-Term Sustainability of outer space activities

- ⇨ Action at French level to provide an analysis of the main identified challenges to be addressed by Space Traffic Management (STM)
- ⇨ Coordinated at International level, IADC-ECSS-ISO and National Agencies
- ⇨ Overview of a set of actions considered to tackle those challenges

- **Complementarity of Political guidelines, Regulations, Standardization and Operational capabilities, taking into account the balance between:**
  - efficiency of proposed actions,
  - industry competitiveness
  - National and European security constraints

Risks

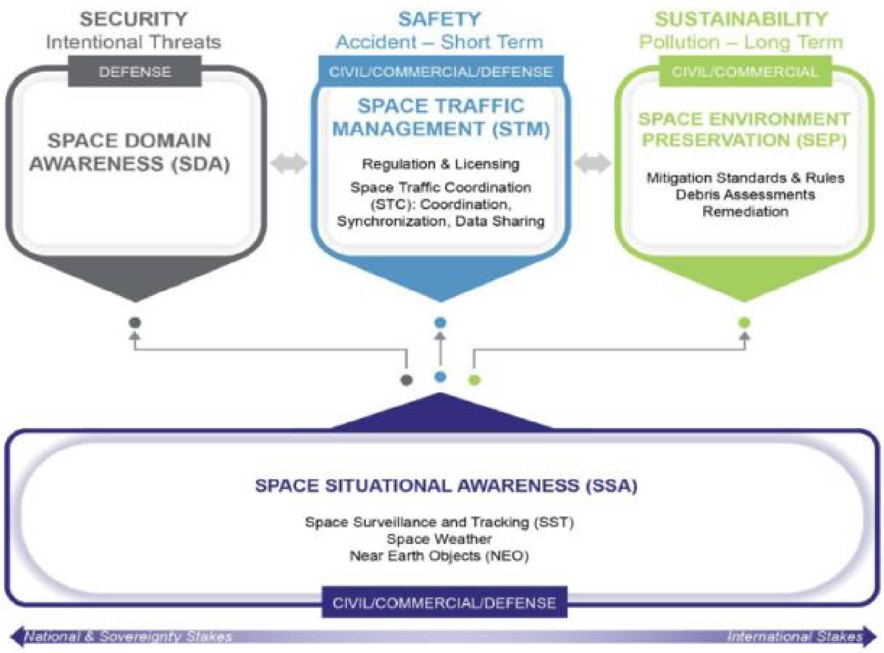
- **Public and Private satellites are exposed to risks and threats that can temporarily or permanently affect their proper functioning and thus their ability to provide their services:**
  - **Risks of natural origin:**
    - On Earth (floods, earthquakes…) affecting the ground control segments,
    - In space (solar flares, collision with a meteorite…) affecting the satellite.
  - **Technological risks:**
    - Collision in orbit with a debris,
    - Collision in orbit with an operational satellite.
  - **Intentional threats:**
    - Resulting from a third party's desire to disrupt or neutralize the service provided by the space system through physical of cyber attacks,
    - Ambiguous behaviors (close approach) or destabilizing behaviors (ASAT action) can also represent threats.

General framework (1/3)

- **Space Traffic Management is primarily a Civilian and Safety issue:**
  - With implications in the field of Security (e.g. data sensitivity),
  - With consequences on military activities.
- **Natural and Technological risk management shall be considered separately from Threat management.**
- **Freedom of access and action for the military must be preserved.**
- **In order to control and reduce the risk, concept of Space Traffic Management:**
  - Appeared within the international space community,
  - Is subject of numerous reflections or initiatives [1]
- **Definition of STM is not yet agreed at international level, nor completely at EU level:**
  - Variants considering Space Traffic Coordination (STC) instead,
  - Ongoing work at ECSS level and International Standardization Organization ISO level [2],
  - Proposals at IAA-IAF-IISL level [3]

[1] *"CNES technical considerations on Space Traffic Management" – Acta Astronautica 167 (2020) 296-301*
[2] *ISO/TC 20/SC 14 N2164 - ISO/CD 9490 - ISO/TC 20/SC 14 N2164 (under elaboration)*
[3] *"Cooperative initiative to develop comprehensive approaches and proposals for STM – The IAF-IAA-IISL initiative" – Special Session IAC 2022*

General framework (2/3)



[1] *Space traffic management terminology – M. Skinner, D. Oltrogge et al. - Journal of Space Safety Engineering 9 (2022) 644–648*

General framework (3/3)

- **Three complementary pillars:**

1. Pillar composed of space surveillance capabilities and operational services to prevent collision risks, enabling to coordinate operators among themselves.
   - Coordination of Space Traffic is based on knowledge (SSA) and surveillance (SST),
   - EU SST is the main European platform.

2. Regulatory and Normative Pillar: set of best practices and/or standards collectively defined and implemented to coordinate space traffic, avoid collisions in space concerning maneuvering satellites, and eventually frame industrial and commercial activities
   - Could imagine regulation and obligations at European level…
   - At national level, countries regulate operations through flight authorization delivery (e.g. French Space Operations Act),
     - ⇨ However, USA-Russia-China represent 90% of orbital population, and 97.5% or orbital debris in LEO
     - ⇘ To develop an effective international regulatory framework, equivalent and reciprocity must be reached!

3. Pillar of coordination and promotion of European positions in international fora, and of dialogue between the actors to optimize the effectiveness of the two previous pillars
   - Progress in the field of STM shall be part of a rise in strategic autonomy of France and EU to give credibility to our positions
   - Security issues must be taken into account
     - ⇨ For instance, an approach based on complete transparency could prove harmful to National and European interests in absence of reciprocity from the other major Space powers
   - We welcome the EU initiative (European Commission note, Sep. 17 2021) enabling to avoid that non-EU standards become reference
   - French authorities consider that EU must remain the forum in Europe where STM is coordinated, in addition to the National level.

Capability and Operational pillar (1/2)

- **France is a founding partner of EU SST**
  - Today: 7 EU member states; expected to raise to 15 member states before end of 2022
  - Objective is to provide EU with ability to Detect, Track, Catalog and Predict the movements of space objects
  - Networking State and Commercial sensors
  - CNES represents France in the consortium, and holds the presidency (experience of CAESAR alert service over the past 15 years…)

- **Three services already provided:**
  - Fragmentation analysis (FG)
  - Re-entry monitoring (RE)
  - Collision Avoidance (CA) (inherited from CNES experience, now provided to EU SST by France and Spain)

- **France: dual use capability based on TAROT civilian telescopes and military SATAM and GRAVES radars**

⇘ **To be influential on STM: fundamental to be credible on technical, capability and operational points of view**
- Main objectives: to develop in an incremental way a European strategic autonomy in Space Surveillance:
  - In LEO all objects larger than 10 cm and if possible most objects larger than 7 cm by 2028
  - Cataloguing of small centimetric objects (1-10 cm) medium term objective, EU 2028-2034 financial framework
  - In high orbits MEO-GEO, all objects larger than 35 cm by 2028.

Capability and Operational pillar (2/4)

Numerous SST means at European level (Space Surveillance & Tracking)

- EU SST between 7 – 15 European Member States
- Numerous private systems: Share My Space, Look-up-Space, SpaceAble, Infinite Orbits…
- Experimental systems under development, not yet operational (Laser, satellites…)

↳ Some examples (non exhaustive…)

ShareMySpace

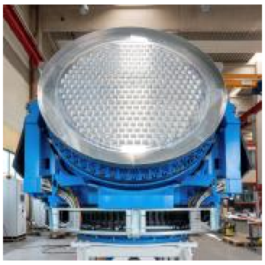
S3TSR

Wetzell - Graz

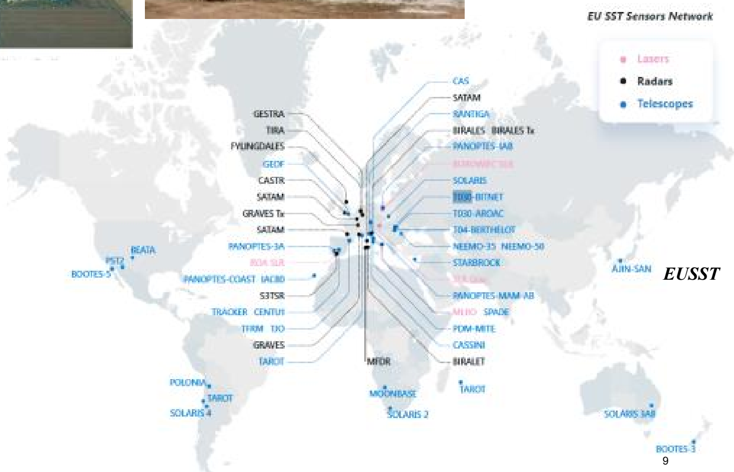
Aiub - Unibe

Birales

SLR - Potsdam



GESTRA



EUSST

Capability and Operational pillar (3/4)

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SST means at French level

Capability and Operational pillar (4/4)

- **Development of capabilities and extension of EU SST services rely on ground-based sensors and space-based infrastructures (space based SSA in the frame of the Connectivity constellation)**
  - Based on an increased openness to innovation of the European commercial sector
  - 6 proposals made by French presidency of EU SST to boost innovation and use of commercial solutions
  - Should encourage consolidation of an industrial ecosystem and startups in the SSA/SST domain
  - In France:
    - Emerging and promising startups: e.g. Share-My-Space, Space Able, Infinite Orbits, Look-up-Space
    - Space Industry with high quality SSA sensors and services: Safran Data Systems, ArianeGroup, Thales Alenia Space, Airbus Defence and Space…)

- **Development of EU SST capabilities and services**
  - Based on the discussions undertaken within the “European Union Industry and Startups Forum” (EUISF), established April 2022, chaired by European Commission, co-chaired by EU SST
  - Promotion of additional commercial services, complementing public services, to EU SST users
    - Certification of these commercial services shall be studied
  - French Presidency of the European Union (PFUE 2022) significantly contributed to raise awareness of the need for Union to invest massively in space surveillance capabilities through EU SST
    - ↳ Objective could be to aim for at least 1 billion Euros in the 2028-2034 financial framework
  - Possible creation of a legal entity to develop an autonomous assessment of the space situation
    - Will have to preserve the duality of the program taking into account the security dimension and sensitivity of data

Regulatory and Normative pillar (1/2)

- **Preliminary remark:**
  - Article 189 of the “Treaty on the Functioning of the European Union” (TFEU) excludes “any harmonization of the laws and regulations of the Member States” in the Space field
  - Moreover, several European States do not have any regulation concerning the management of space activities
    - ↳ A legally binding European regulation on STM is not an obvious path…
    - ⇨ Convergence of national frameworks would allow a better coherence at European level

- **It could be proposed to adopt a set of high-level STM principles and guidelines:**
  - Discussed in the Council’s Space Working Party, Agreed at EU level
    - ⇨ Proposal for a EU tool-box and group on standardization could be supported,
    - ⇨ Leading to more homogenous European framework
  - Potentially promoted at international level
  - Implementation of regulations by the European partners should be of high interest,
    - Potentially benefiting from French Space Law
  - Several conditions:
    - Analysis of benefits and risks to European industry, strategic autonomy of EU and Long-term sustainability of Space
    - Non-binding instruments not beyond what is prescribed in the French Space Operations Act

Regulatory and Normative pillar (2/2)

- **Main objectives of the Regulatory and Normative pillar:**
  - Limit to the strict minimum the production of space debris over the entire life cycle of a space system
    ↳ France signed the "Net zero Space" initiative during the 4th Paris Peace Forum
  - Ensure that satellite operators are informed of the risk of in-orbit collisions

- **At European level, several initiatives exist:**
  - Definition of a set of technical standards in the framework of future group on standardization, in connection with ECSS
  - Follow-up of European legislation project on STM pushed by the Commission, some Member States, and some European Members of Parliament aiming at a binding legislation by end of 2024

- **France has supported a debris mitigation strategy for orbital systems and launchers since several decades**
  - First priority: efficient operational behavior and conception choices aiming at reducing debris footprint of missions
  - Second priority: shared "rules of the road" between space actors
    - Collaboration and Coordination between operators through Space Traffic Coordination STC

  ↳ Gradual evolution of the French LOS technical regulations is underway [1]

- **EU may develop its own Technical Regulations applicable to EU space objects:**
  - Not systematically applicable to satellites from EU Member States
    ↳ Remain subject only to National authorization procedures of each Member State

[1] *"The French Space Operations Act Technical Regulations…" – IAC-2022- A6.4.11 presented 20 Sept. 2022*

Dialogue and International regulations pillar

- **No official forum on STM at international level:**
  - Not within the mandate of IADC (not yet?...)
  - UNCOPUOS 21 Long Term Sustainability Guidelines (LTS) part of the international STM framework
  - Principle of a comprehensive international regulation does not appear feasible in the current political context of international discussions
  - French position is to keep the management of space traffic within responsibility of States, as it involves their security
  - Defining an international STM regulatory framework that would not be respected by USA-Russia-China would not be a sustainable solution to the problem of space traffic growth.

- **France adopts a pragmatic attitude:**
  - Based on adoption of guidelines, best-practices, norms of behavior, transparency and confidence-building measures
    ↳ Much more within the reach of international space community

- **In COPUOS the LTS initiative is the only one which offers prospects for concrete progress**
  - France supports timely implementation of the 21 LTS Guidelines
  - Sharing and reviewing best practices on practical implementation will enhance communication, international cooperation, and capacity building, as well as preserving the outer-space environment for future generations
  - France has submitted a very extensive document detailing its implementation of the 21 LTS
  - Should new guidelines be discussed within the new Working Group LTS 2.0, France is ready to contribute and share its priorities

Conclusions - Priorities

- **Deal with today's situation**
  - Consolidation of international regulations
    - ① **We shall share the current regulations at international level, based on the 21 LTS COPUOS**
    - ② **Consolidate our action at international level ECSS, IADC, ISO, COPUOS**
  - Specificities of "New-Space": a very high reactivity is mandatory in order not to be always "one war late"
    - ③ **Very dynamic evolution of current regulations is compulsory: Current action at LOS level ongoing**

- **Mitigate the consequences from yesterday**
  - Kessler syndrome between 700 and 1,100 km altitude mainly linked to operations in the years 70-90
  - Necessity to retrieve largest and most dangerous debris, otherwise naturally diverging
  - No significant action ongoing today at international level
    - ④ **It is fundamental to start as soon as possible Active Debris Removal operations**

- **Prepare for tomorrow**
  - Take all necessary actions to guarantee Long Term Sustainability, despite large constellations
  - Drastic improvement of Collision Avoidance processes: STC – STM
    - ⑤ **It is fundamental to coordinate at international level to share the same rules (ECSS – ISO)**
  - Improvement of the knowledge of orbital environment: priority to Space Surveillance & Tracking (SST)
    - ⑥ **It is mandatory to improve tracking and cataloging of orbital objects**
  - Preserve the "inhabitable" zone 380 – 430 km: density of objects there has increased by a factor 18 in 10 ans
    - ⑦ **It is important (but hard to imagine…) to define a preserved zone for inhabited space stations**

A14 Invited Lecture

Update on CNES Space Debris Activities

〇Vincent RUCH (CNES)

This presentation will provide an update on the CNES Space debris activities. CNES is contributing to the safety, security and sustainability of space operations, from detection of RSO, cataloguing, operational service provision and research and development activities.

UPDATE ON CNES SPACE DEBRIS ACTIVITIES

10TH JAXA SPACE DEBRIS WORKSHOP

November 28th, 2022
Chofu, Japan

Vincent RUCH - CNES

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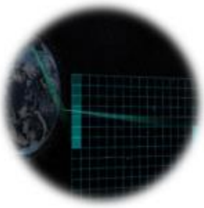
CNES Space Surveillance Office

The CNES Space surveillance office contributes to the **Safety**, **Security** and **Sustainability** of space operations

- Safety deals with natural and technological risks
- Security deals with intentional threats
- Sustainability deals with the preservation of Space Environment



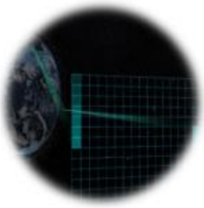
Observation

Data processing

Services

Sustainable Environment & Regulation

UPDATE ON CNES SPACE DEBRIS ACTIVITIES – NOVEMBER 28TH 2022 – 10TH JAXA SPACE DEBRIS WORKSHOP



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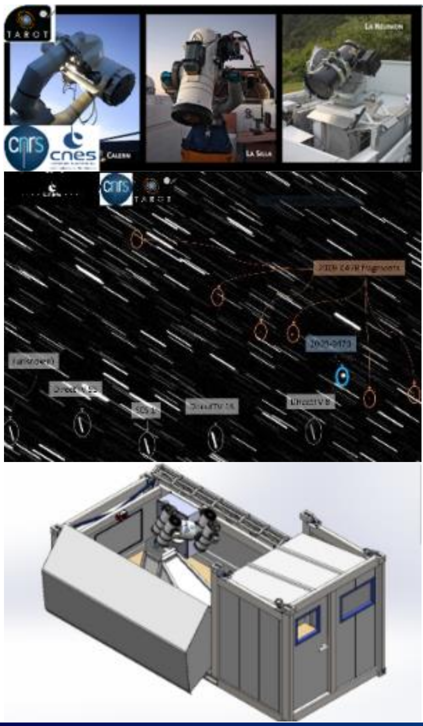


TAROT telescopes network

- CNES operates the **TAROT telescope network**:
  - 3 telescopes owned by CNRS in Calern, Chili, La Réunion
  - **1 telescope owned by CNES in New Caledonia (2023)**
- Tasking and image processing using CNES software
- TAROT network provides full coverage of the Geostationary ring and access to all orbital regimes

Other sensors

- CNES collects data from military sensors of the French Ministry of the Armed Forces:
  - Surveillance radar GRAVES
  - Three tracking radars SATAM
  - Tracking radar on MONGE ship
- **CNES is able to collect and share operational data from multiple actors, considering relevant security constraints**

Graves Radar

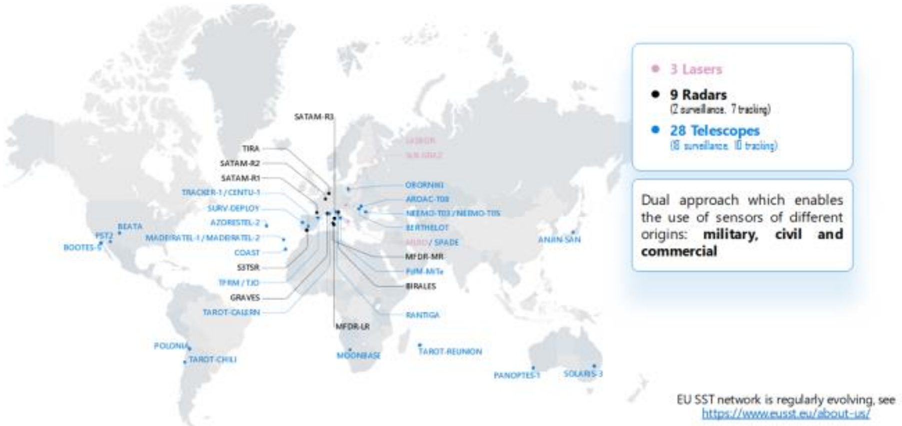
SATAM Radars

Monge Radar

Observation is the key to understanding

Measurements are crucial to **ensure safe operations and space sustainability**

Need to increase the number of observations, in particular through **cooperation**,



40+ Sensors distributed worldwide and covering all orbital regimes from LEO to GEO:

- **Radars (Surveillance and Tracking)**
- **Telescopes (Surveillance and Tracking)**
- **Lasers**

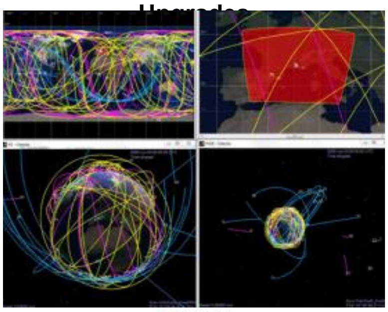
Figures from EUSST Service Portfolio (https://www.eusst.eu/services/)

Preparing the future

Measurements are crucial to **ensure safe operations and space sustainability**

Need to plan the **evolutions of the system**, to maximize the performance of the system,

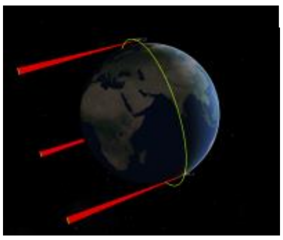
Prioritization of the **Sensor Upgrades**



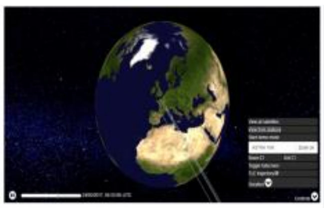
BAS³E

Definition of the **upgrading path**, to maximize the performance of the system. Evaluation of performance in terms of **cataloguing and Service Provision**.

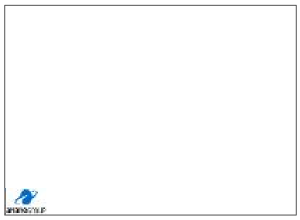
Developing **New Sensors**, using innovative concepts and technologies, in **cooperation with Industry and Academia**



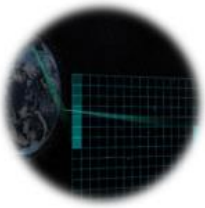
SBSS Constellation Design in complement of ground SST system (EUSST R&D studies with AIRBUS Defense and Space, HEMERIA, Thales Alenia Space)



Use of Passive Radio Frequency sensors to observe and catalogue active – highly maneuverable satellites from VLEO – GEO (EUSST R&D with SAFRAN Data Systems)



LEO to GEO optical observation and daylight Infra-red and laser observation of space debris (EUSST R&D with Ariane Group)



Observation

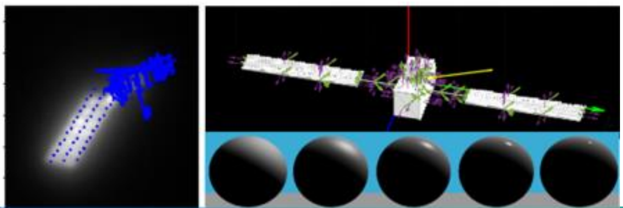
Data processing

Services

Sustainable Environment & Regulation

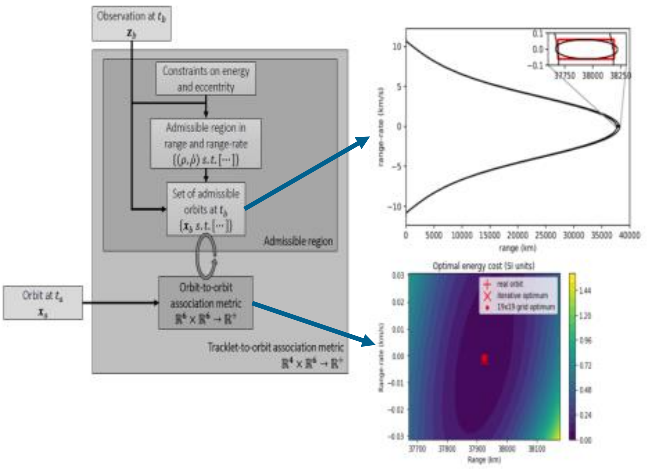
Data fusion

- Maintaining a global picture of the operational space situation
  - Detection: What is orbiting?
  - Surveillance and Tracking: Keeping custody of the orbits
  - Identification: Recognizing the mission of each object (maneuvers, station keeping, magnitude, …)
- CNES is in charge of computing the **national catalogue** through the data fusion of all the measurements collected from the sensors
- The national catalogue is automatically computed 24/7 on all orbital regimes
- R&D activities on attitude determination through data fusion

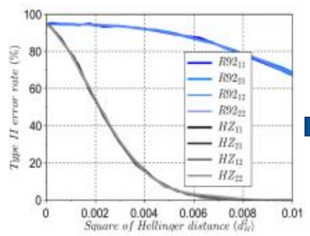


R&D activities

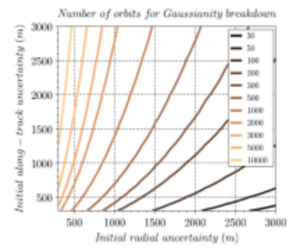
Numerous R&D activities related to data, for example on the **quantification and propagation of uncertainties**, or the **processing of measurements**



Serra R., Yanez C., Frueh C. Tracklet-to-Orbit Association for Maneuvering Space Objects using Optimal Control Theory.
Acta Astronautica. https://doi.org/10.1016/j.actaastro.2021.01.026



Statistical tests requires Monte Carlo Evaluations, and are therefore computationally Costly



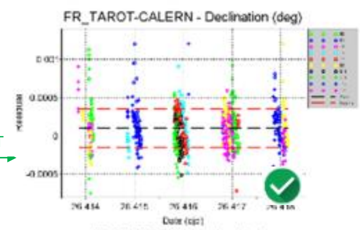
It is possible to use a similarity metric, based on Hellinger Distance d_H, instead of the statistical tests to characterize the departure from Gaussianity

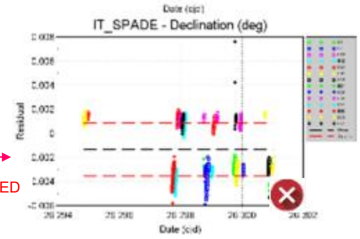
$$d_H(p,q) = \left[\frac{1}{2}\int_{\Upsilon}(p(x)^{\frac{1}{2}} - q(x)^{\frac{1}{2}})^2 dx\right]^{\frac{1}{2}}$$

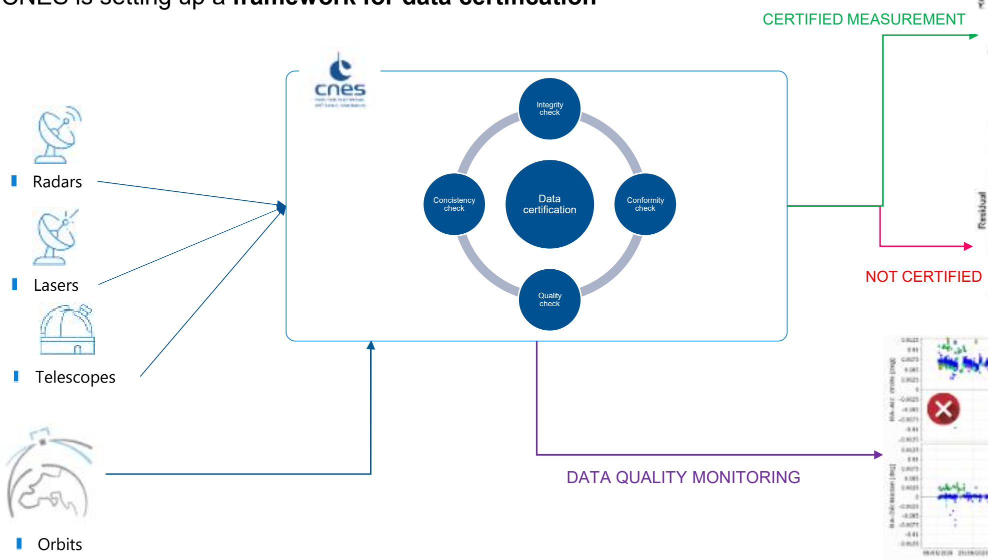
Yanez C. et al. On the Gaussianity validity time for orbital uncertainty propagation. 70th International Astronautical Conference. 21 – 25 Octobre 2019. Washington D.C.

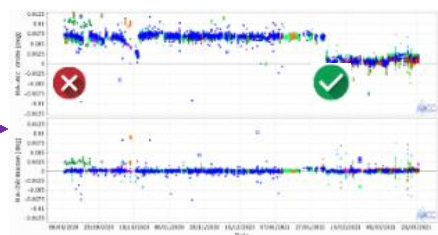
Data calibration and certification

- As data are coming from multiple sources, trusting the data *a priori* is not an option
- CNES is setting up a **framework for data certification**



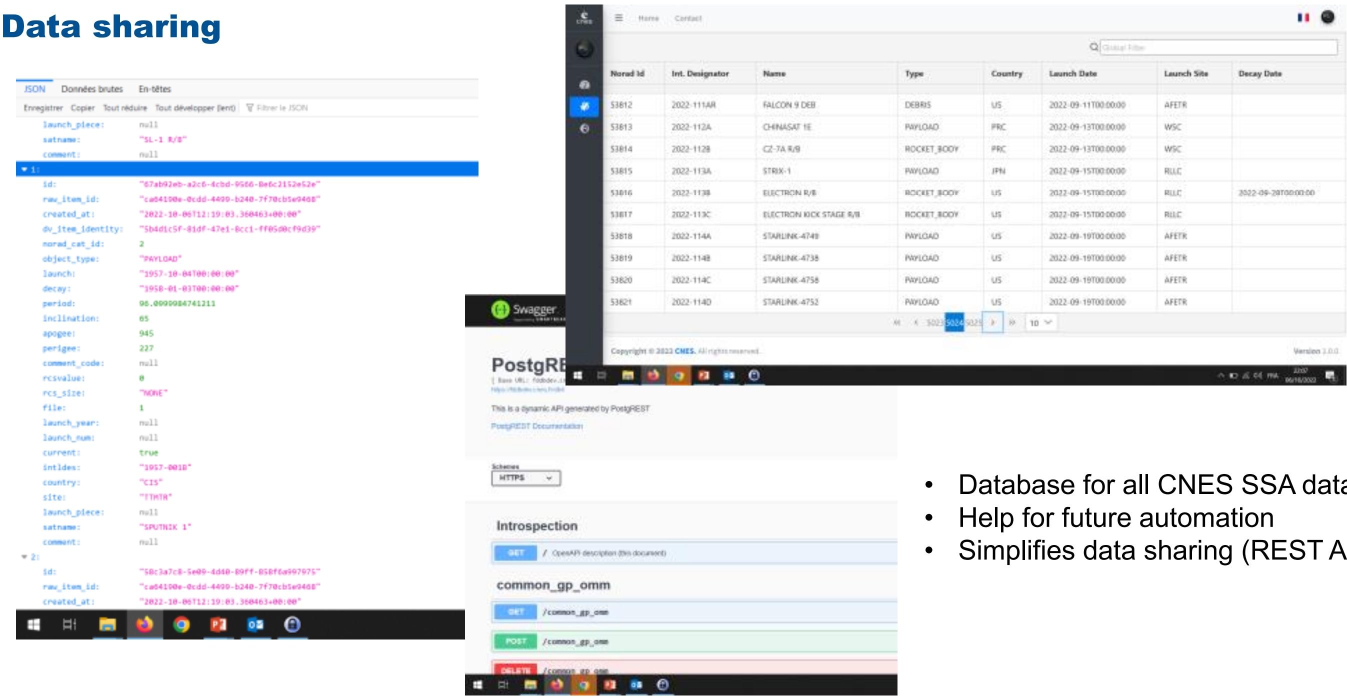






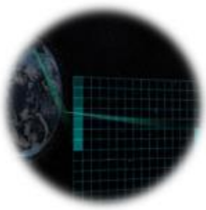
40TH IADC - WG2 - 2022-10-10

Data sharing



- Database for all CNES SSA data
- Help for future automation
- Simplifies data sharing (REST API)

UPDATE ON CNES SPACE DEBRIS ACTIVITIES – NOVEMBER 28TH 2022 – 10TH JAXA SPACE DEBRIS WORKSHOP



Observation

Data processing

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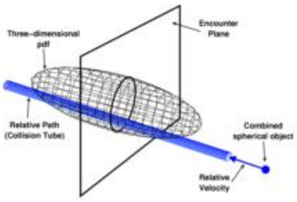
Collision avoidance service

- **CAESAR** is the CNES operational collision avoidance service
  - 3 on-calls teams to monitor the fleet on a 24/7 basis
- EU SST rely on CNES and CDTI to provide a free of charge collision avoidance service to all European satellite operators (~300 satellites)

Collision Avoidance | 293 Satellites | 42 ORGS



- Statistics in 2021 :
  - 2,7 millions CDM managed (7400+ a day)
  - 17 avoidance manoeuvers
- Strong collaboration with the US on data (CDM from JSpOC/18th SPCS) and methods
- Strong relation with industry and academia : R&D activities to improve the methods (in non-standard cases such as constellations, low relative velocities…) or optimize the maneuvers

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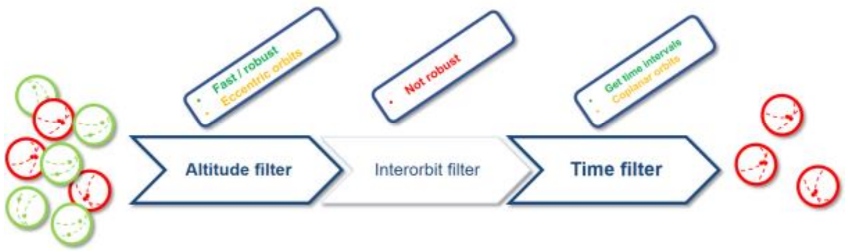
Screening methods: FilteringLib

“Classical” Hoots filters

→ Series of filters to identify pairs at risk in on-orbit object catalog

→ Done:
- → Implemented in ***FilteringLib***
- → Calculation time improved
- → Robust implementation
- → Understand limits of algorithms



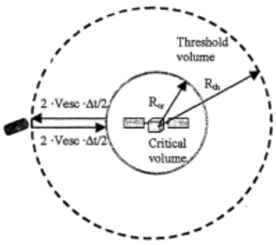
“Smart Sieve” filter

→ Relative velocity between two on-orbit objects is always less than twice escape velocity v_{esc}

→ So, if initial distance to a critical area is higher than $v_{esc}\Delta t$, the object can't go in and out the threshold volume

→ Done : implemented in ***FilteringLib***, first tests show a robust behavior and fast calculation

→ To do: tests on operational data

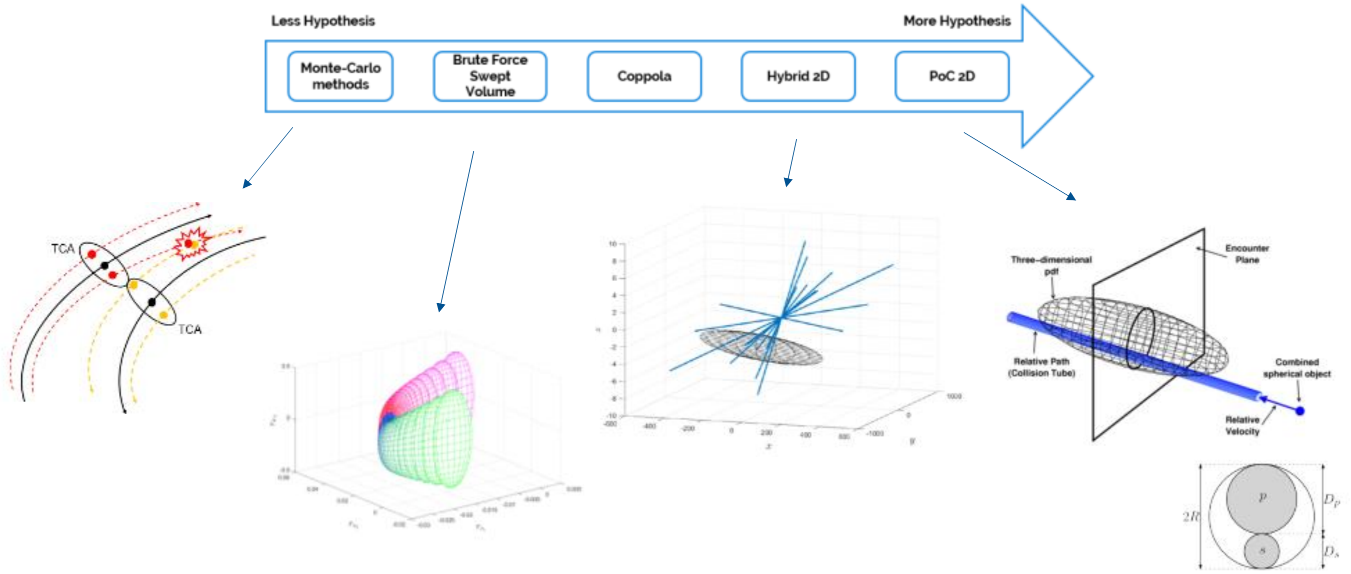


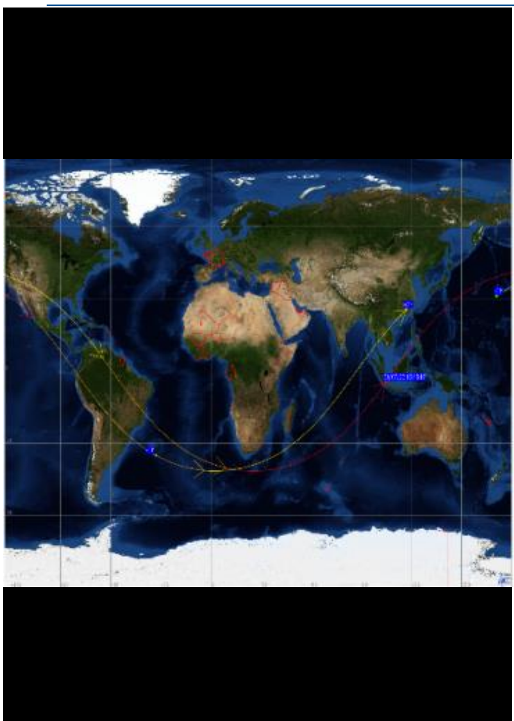
Runtimes	1 cœur	4 cœurs
Geometric filter	711.739	240.623
Smart sieve filter	329.144	97.180
Altitude filter	7.428	8.150
Legacy altitude filter	8.763	10.654
Orbit path filter		
Time filter		
Modified time filter	866.451	322.028
Altitude filter + Time filter		
Altitude filter + Modified time filter	426.517	176.440
Altitude filter + Smart sieve filter	258.790	95.721

Computation time (in seconds) example
on a catalog of 8000 objets, ~32M pairs, D=50 km, T=1 jours

Hoot & al, « *An analytic method to determine future close approaches between satellites* », 1984
Rodriguez & al, « *Collision risk assement with a Smart Sieve method* », 2002

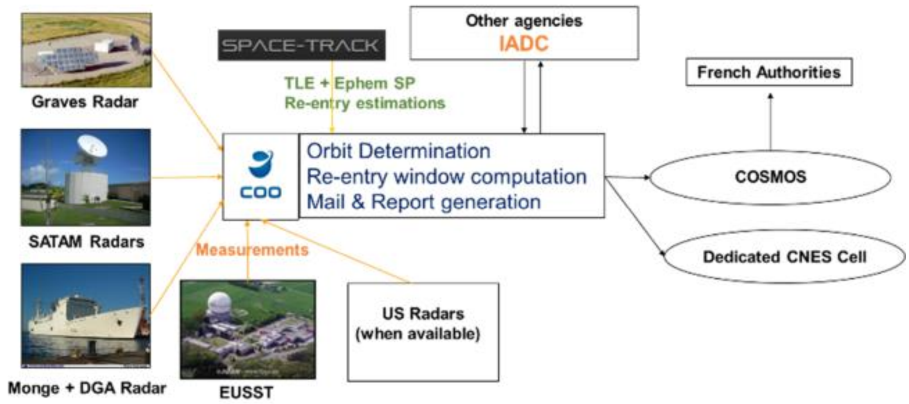
PoC Estimaton in non-standard contexts





Atmospheric re-entry monitoring service

- CNES follows the risky atmospheric re-entries, in collaboration with the COSMOS (French armed forced)



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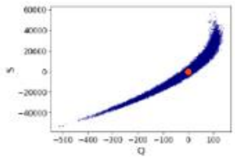
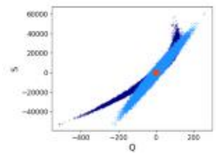
Mission support service

- **Quantification of the statistical collision risk** over mission duration
  - Estimation of the number of manoeuvers and related fuel consumption
  - Risk threshold selection
- **Support for on-board image processing**
  - Ground vs Board trade-off
  - Identification of objects
- **Quantification of maneuver uncertainty**





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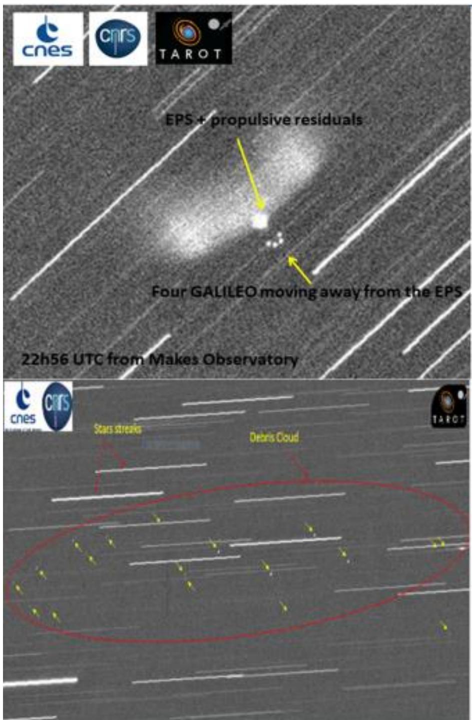
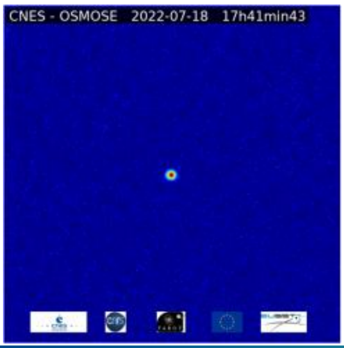
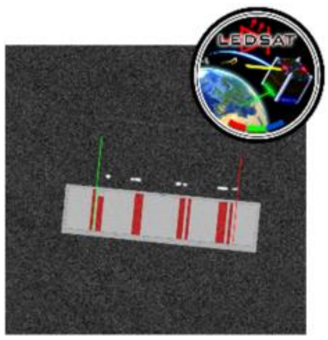


Special event follow-up service

- On demand, CNES can activate the tasking of it's sensors and provide expertise to **monitor special events** :
  - Launch and early orbit / deorbit phases (e.g. electric propulsion, graveyard orbits). Satellite localization when the orbit is approximatively known (MT-CUBE2 / CELESTA) ; confirm the deployment of solar wind ; evaluate the tumbling rate…
  - Close proximity operations (e.g. Astroscale experiment, MEV operation)
  - Fragmentation detection and follow-up (e.g. ASAT test)





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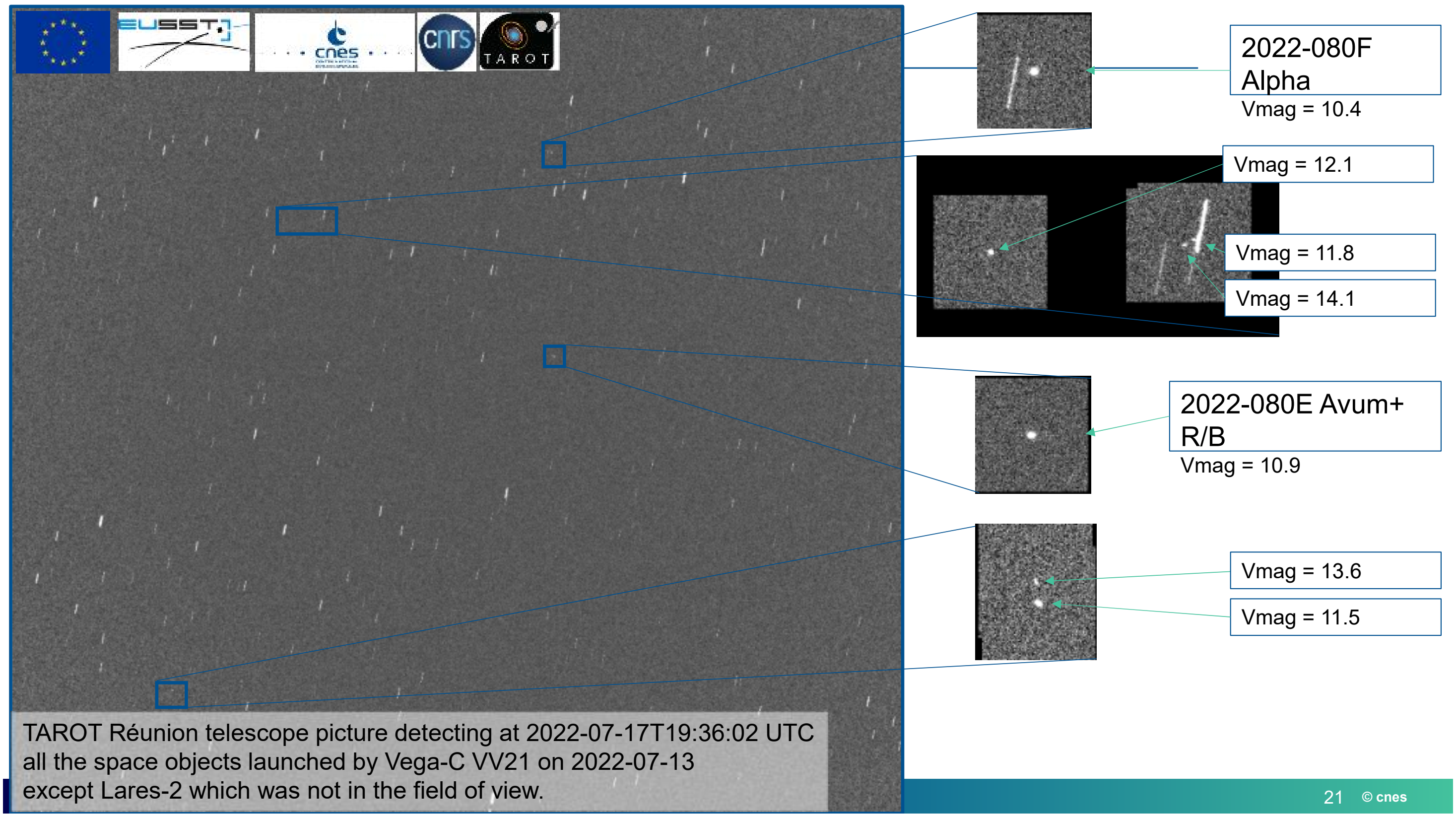
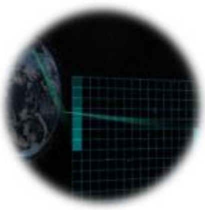


TAROT Réunion telescope picture detecting at 2022-07-17T19:36:02 UTC all the space objects launched by Vega-C VV21 on 2022-07-13 except Lares-2 which was not in the field of view.



Observation

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Services

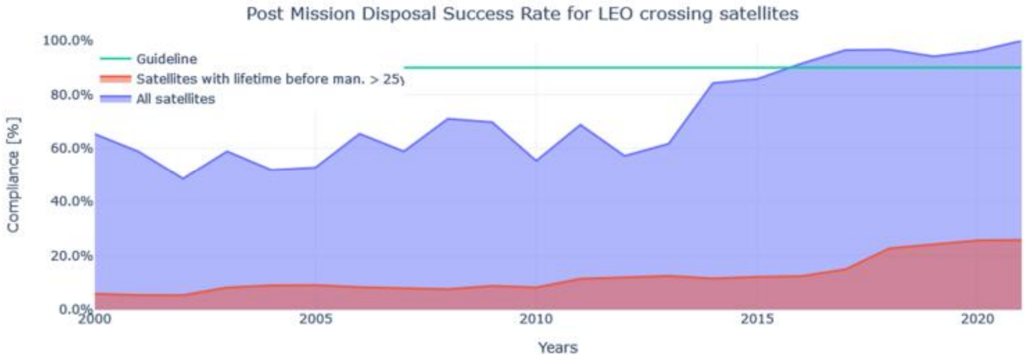
Sustainable Environment & Regulation

UPDATE ON CNES SPACE DEBRIS ACTIVITIES – NOVEMBER 28TH 2022 – 10TH JAXA SPACE DEBRIS WORKSHOP

Monitor the growth of Non-Active Objects on the Environment

Since late 90ˢ Several Guidelines, Standards and Laws has been put in place to limit the proliferation of space debris in orbit

- **2002: IADC Space Debris Mitigation Guidelines**
- **2006: European Code of Conduct**
- **2007: UN – COPUOS Outer Space Mitigation Guidelines**
- **2010: French Space Operation Act (First National Space Law incl. requirements from international guidelines)**
- **2019: U.S. Orbital Debris Mitigation Standard Practices (Update)**



Progress on the global compliancy of Post Mission Disposal Success rate, in particular by selection of operational orbit (i.e. naturally compliant with the 25 years rule)

UPDATE ON CNES SPACE DEBRIS ACTIVITIES – NOVEMBER 28TH 2022 – 10TH JAXA SPACE DEBRIS WORKSHOP

Evaluate the Criticality of Space Objects to the Environment

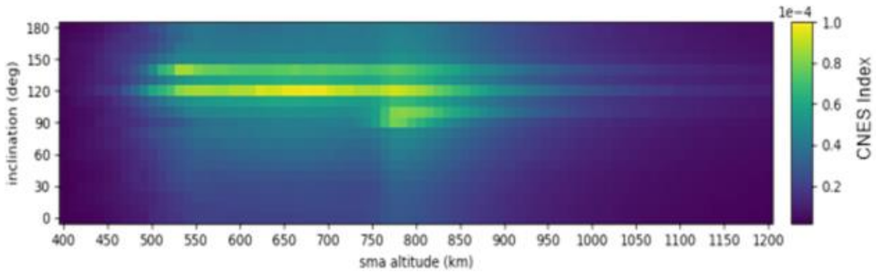
The criticality of Space Objects to the environment, shall be used

- **On the certification process**
- **To decide about the premature End of Mission of a given Space Object**
- **To prioritize remediation operations**

Environmental Indexes have been developed for years at International level

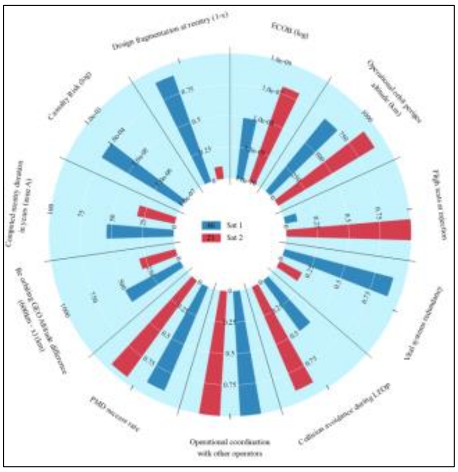
Different Indexes for different purposes (e.g. regulatory, footprint of mission on the environment, ,,,)

The Capability of an object to generate debris in the event of a fragmentation, may be just an « ingredient » of the Indexes



Example of CNES Environmental Index Evaluation Tool – INDIGENE

Qualitative Output Example

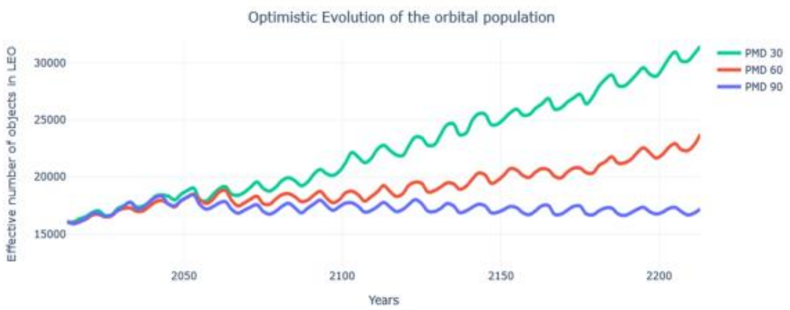


UPDATE ON CNES SPACE DEBRIS ACTIVITIES – NOVEMBER 28TH 2022 – 10TH JAXA SPACE DEBRIS WORKSHOP

Evaluate the efficiency of current guidelines and behaviors

Numerous uncertainties:

- Initial population → Which source? Size?
- Dynamics → Space weather, models…
- Assumptions (PMD, launch traffic, …) → Future behaviors/trends



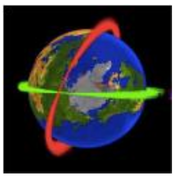
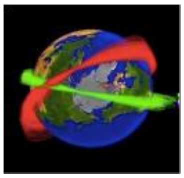
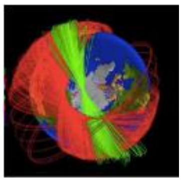
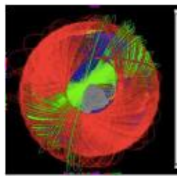
Is the catalog relevant to capture the evolution beyond a few decades?

UPDATE ON CNES SPACE DEBRIS ACTIVITIES – NOVEMBER 28TH 2022 – 10TH JAXA SPACE DEBRIS WORKSHOP

Long-term risk evaluation of an orbital break-up: problem

Should we propagate a cloud of debris as many individuals?

- **Initial conditions** of break-up are **unknown**: number *and* states (position, size, etc.) of debris are *both* uncertain
- **Long-term evolution** relies on models with **limited fidelity**:
  - Predictive information on individual states is hardly actionable, beyond a few months
  - Population dynamics (future fragmentations, re-entries, etc.) are uncertain at best

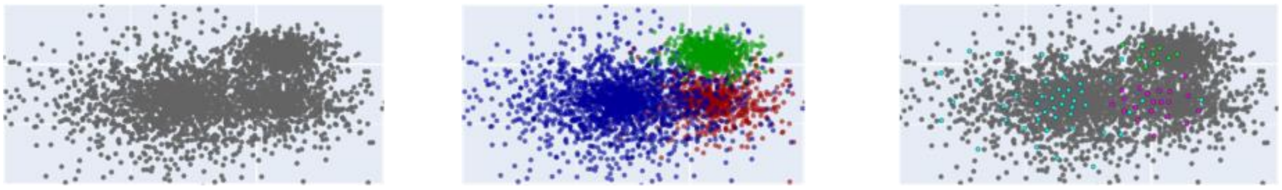
- **We care about the overall long-term risk induced by a cloud, not the number and states of debris!**

→ **Sampling** and **propagating** a full cloud is **costly**, **unrealistic**, and **overdescriptive** for the problem at hand

UPDATE ON CNES SPACE DEBRIS ACTIVITIES – NOVEMBER 28TH 2022 – 10TH JAXA SPACE DEBRIS WORKSHOP

Long-term risk evaluation of an orbital break-up: trying a holistic approach

- **Initial cloud of debris** described by a **point process**, a population with random size *and* elements, to match *statistical NASA* break-up model
- **Moment statistics** on point process yield **population statistics** about cloud as a whole (e.g. average number of debris on a given orbit), **not individual statistics on** debris (e.g., mean state of a given debris)
- Orbital motion model is applied to point process, yielding population statistics at desired epoch



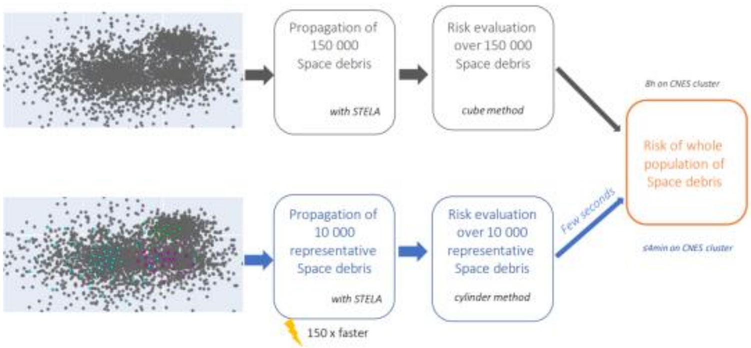
- **Risk evaluation metrics** (e.g. mean number/stdev of collisions) derived[1] from **population statistics**

➡ **Individual** level is dropped *on purpose* from population description, towards a more realistic - and easier to handle - representation of long-term predictions

[1] *Reference: A. Narykov, E. D. Delande, and D. E. Clark. A Formulation of the Adversarial Risk for Multiobject Filtering. Aerospace and Electronic Systems, IEEE Transactions on, 57(4):2082–2092, (2021).*

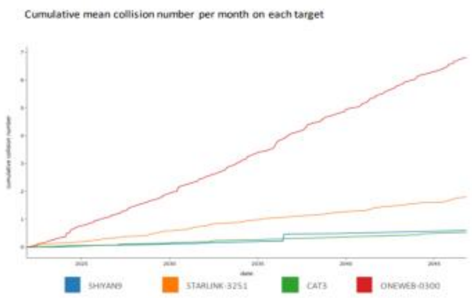
40TH IADC - WG2 - 2022-10-10

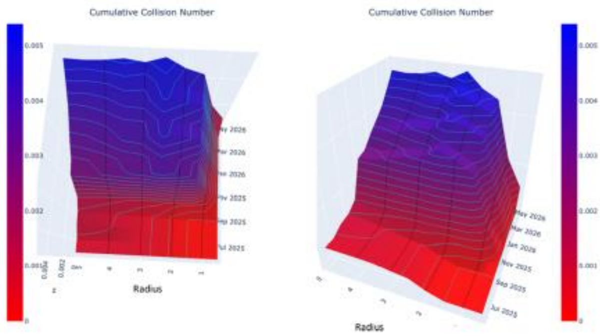
Long-term risk evaluation of an orbital break-up: encouraging results

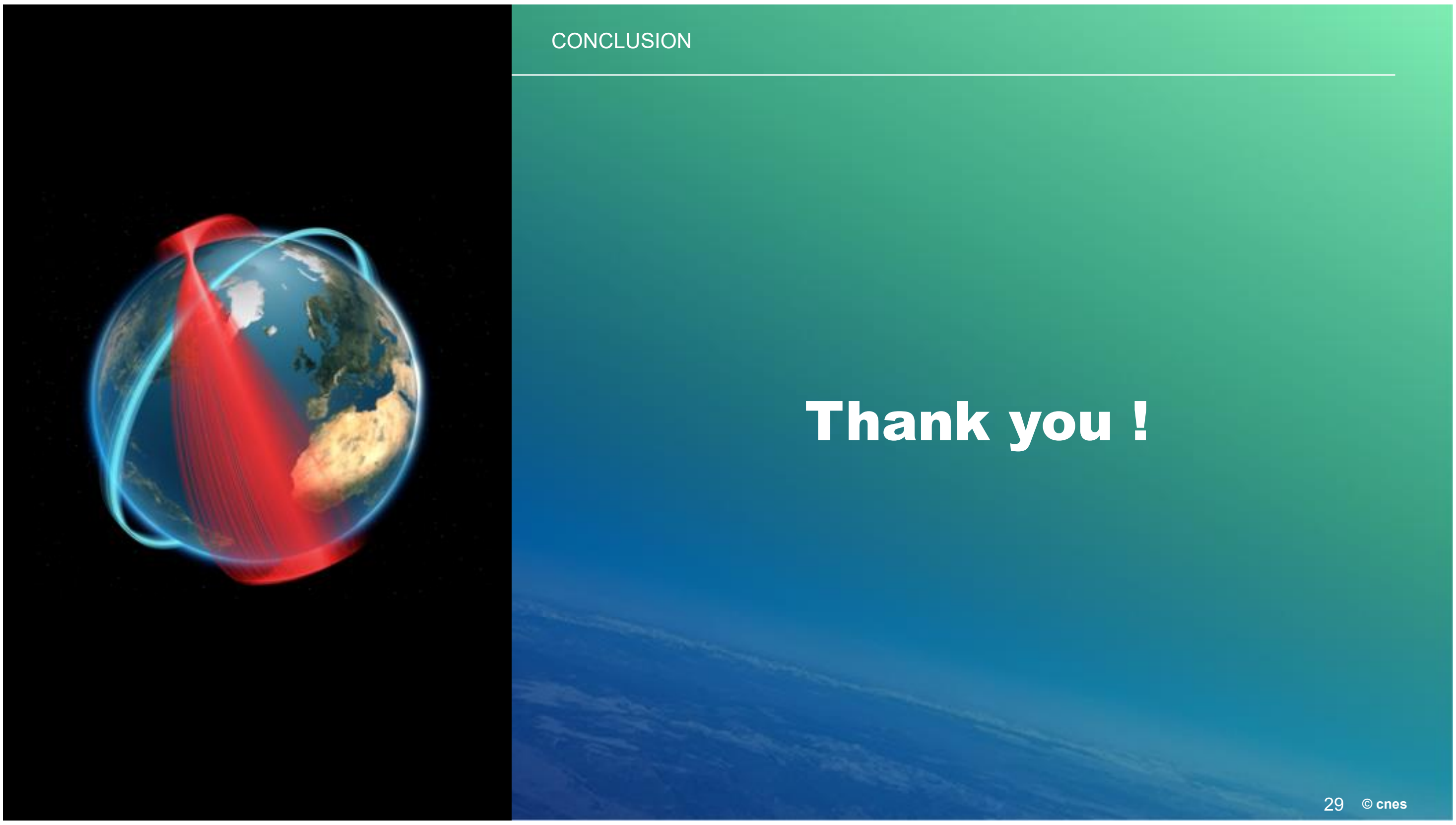


Ongoing work on :

- Population statistics approach applied to fragmentation events
- Fast evaluation of collision number






CONCLUSION
Thank you !
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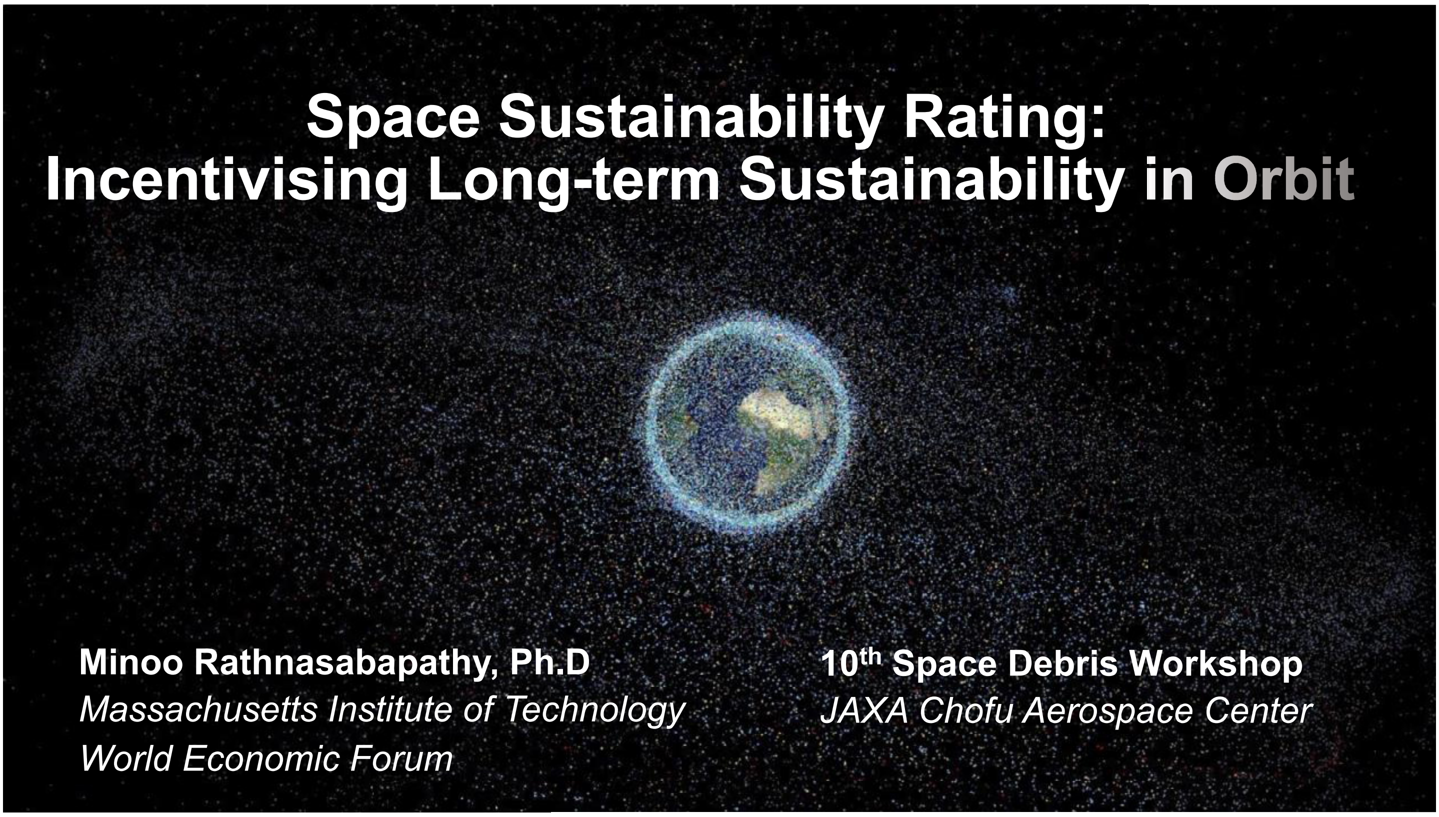
B01 Invited Lecture

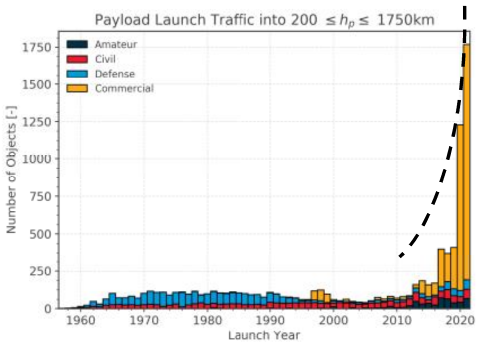
Space Sustainability Rating: Incentivising Long-term Sustainability in Orbit

〇Minoo Rathnasabapathy, Danielle Wood (MIT), Adrien Saadaa, Emmanuelle David,
Florian Micco, Jean-Paul Kneib (eSpace), Dennis Weber, Francesca Letizia, Stijn Lemmens (ESA),
Moriba Jah (University of Texas at Austin), Simon Potter (BryceTech),
Nikolai Khlystov (World Economic Forum)

The Space Sustainability Rating (SSR) was first conceptualised within the World Economic Forum Global Future Council on Space, and is being designed by an international and transdisciplinary consortia including the World Economic Forum, Space Enabled Research Group at Massachusetts Institute of Technology (MIT) Media Lab, European Space Agency, University of Texas at Austin, and Bryce Space and Technology. With the increasing awareness of the rapidly growing number of objects in space, and new space actors, the implementation of a rating system, such as the SSR, provides an innovative way to address the orbital challenge by incentivising industry to design missions compatible with sustainable and responsible operations, and operate missions considering potential harm to the orbital environment and impact on other operators.
This presentation will detail the current status of the SSR, and SSR evaluation for range of missions (LEO, GEO, constellation, CubeSat, etc.) will be presented. In addition, the presentation will provide an overview of design and operational decisions that can be taken by an operator to increase the SSR score of a mission. The presentation further explores how the SSR contributes to existing mechanisms (eg. UN long-term Sustainability Guidelines, IADC Space Debris Mitigation Guidelines) in supporting long-term space sustainability. The presentation will conclude with an overview of the perception of the SSR by a range of actors including government, space agencies, academia, and industry.

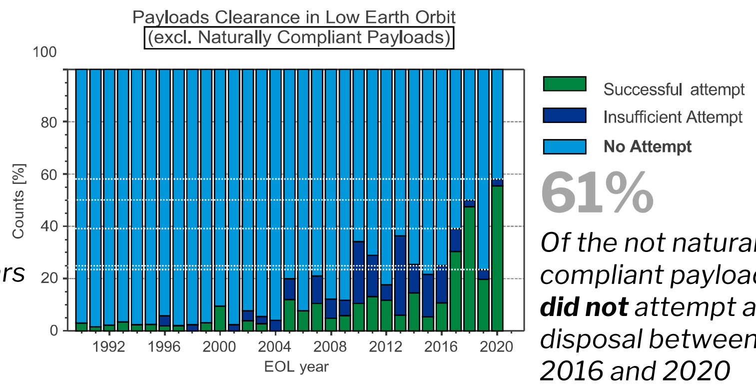


Why a Space Sustainability Rating?



x10

In 10 years



61%

*Of the not naturally compliant payloads **did not** attempt a disposal between 2016 and 2020*

Encouraging space actors to design and implement sustainable & responsible space missions to ensure the long-term sustainability of the space environment

Source: ESA's Annual Space Environment Report, 2022

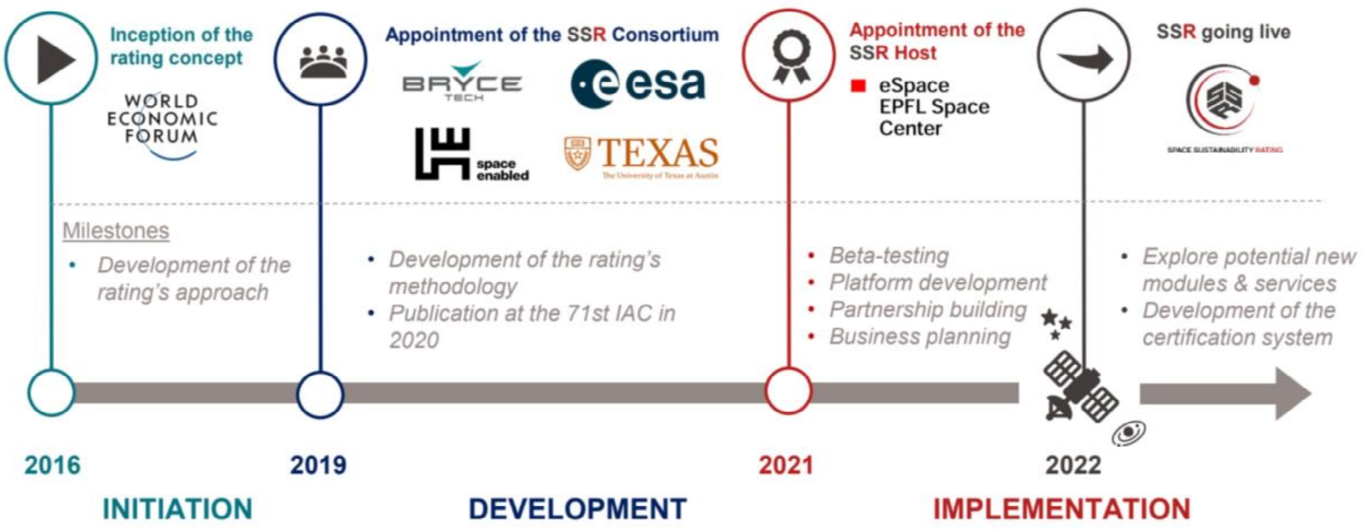
Space Sustainability Rating (SSR)

- Main objective: create an **incentive** to
  - **design** missions compatible with sustainable operations
  - **operate** missions considering not only mission objectives & service quality, but also the potential harm to the orbital environment and the impact on other operators

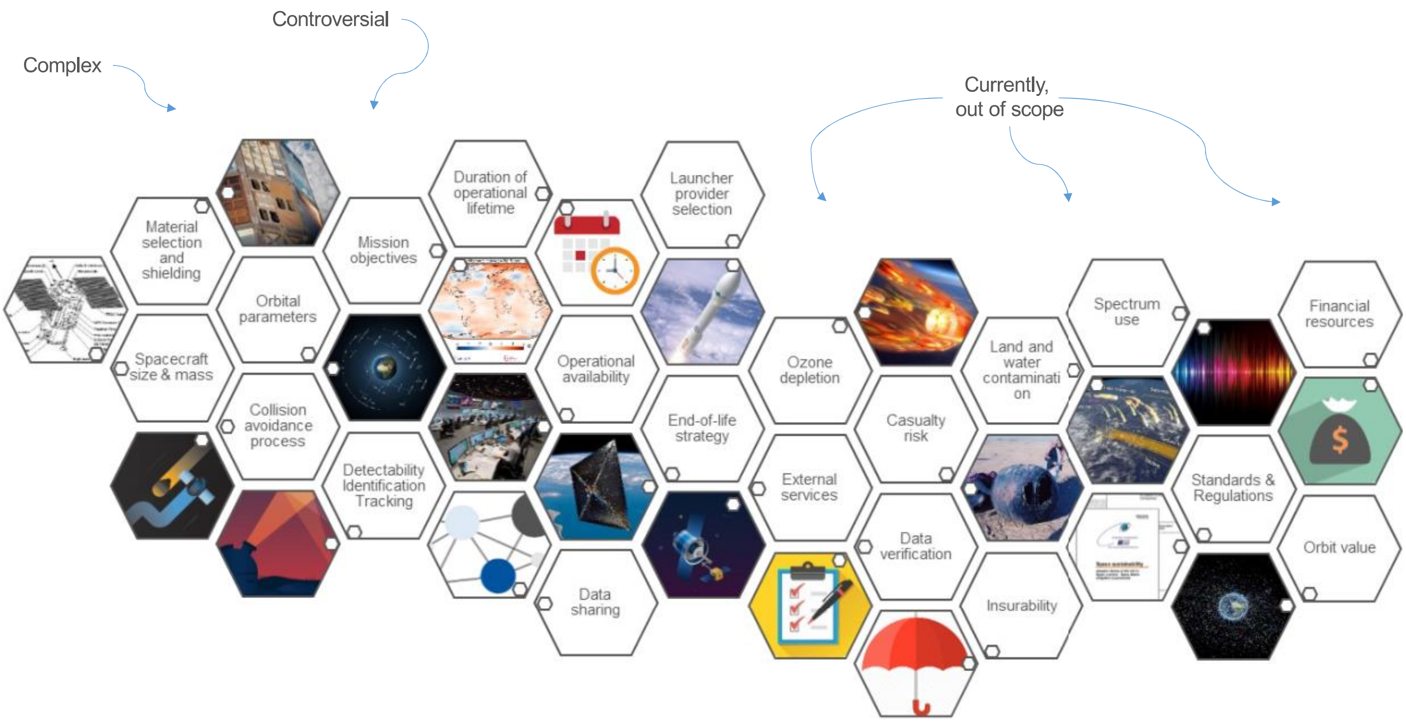
SPACE SUSTAINABILITY RATING

eSpace EPFL Space Center · esa · The University of Texas at Austin · World Economic Forum · space enabled · Bryce Tech

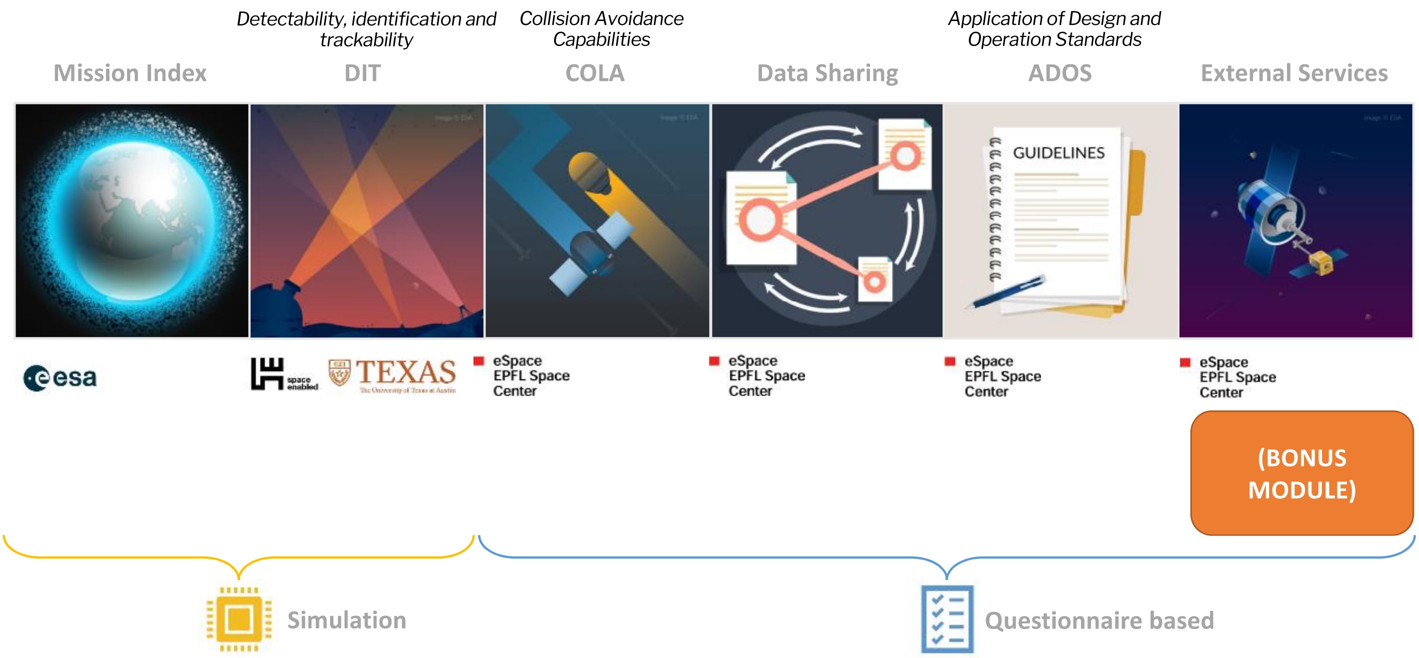
SSR Timeline



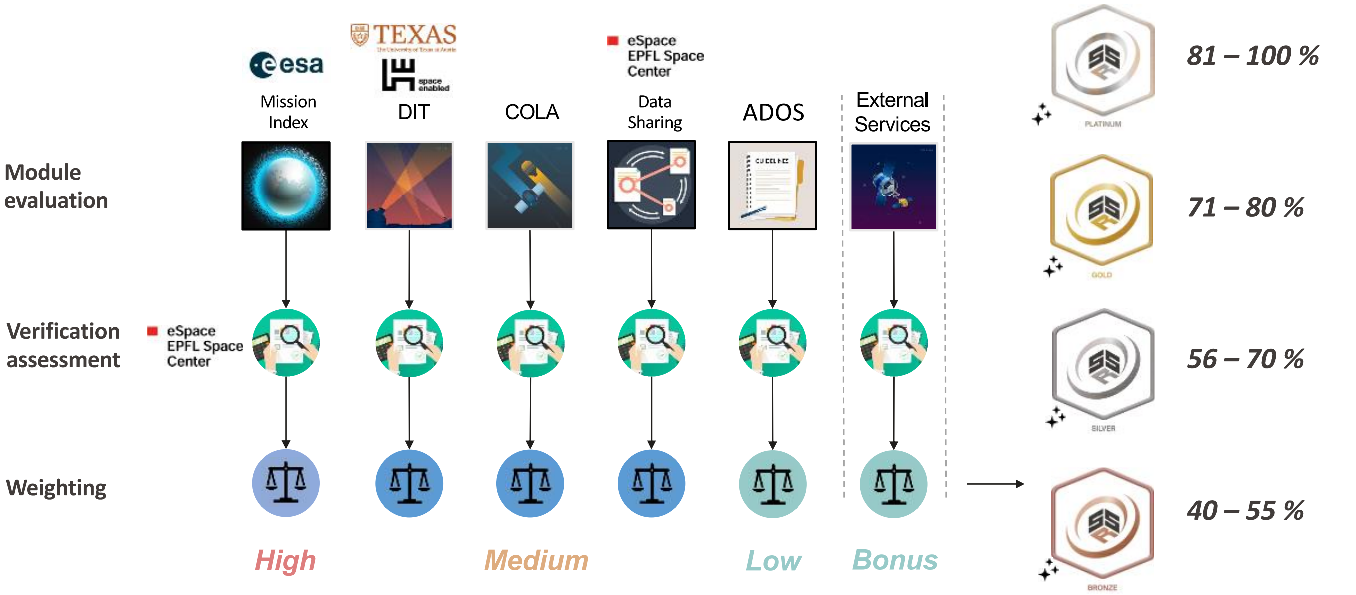
Potential scope



SSR Modules



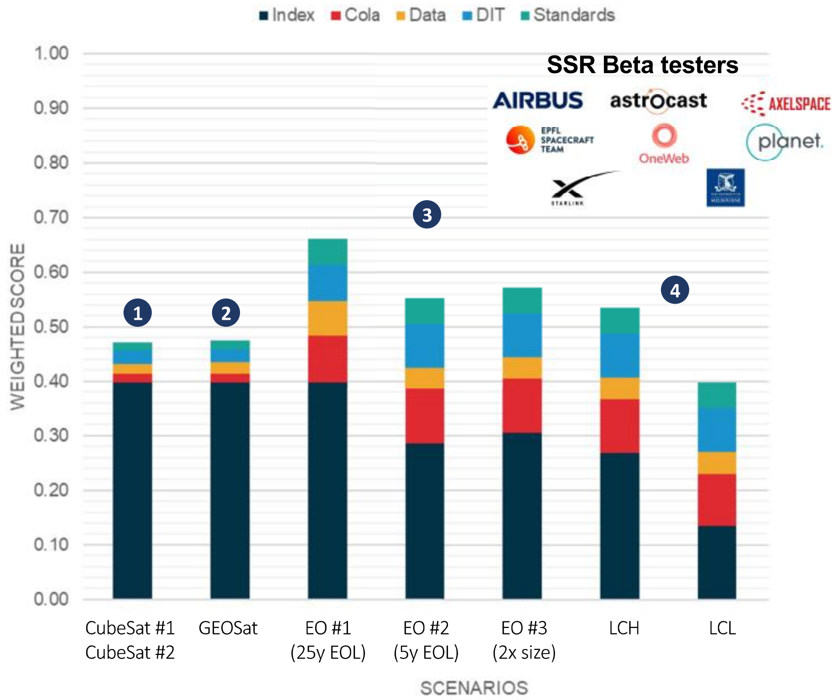
SSR Scoring and Tiers



Example of mission evaluations

GEO missions benefit from reduced risk metric with respect to LEO missions 2

1 CubeSat missions have low associated risk, but are penalised by the lack of collision avoidance capabilities

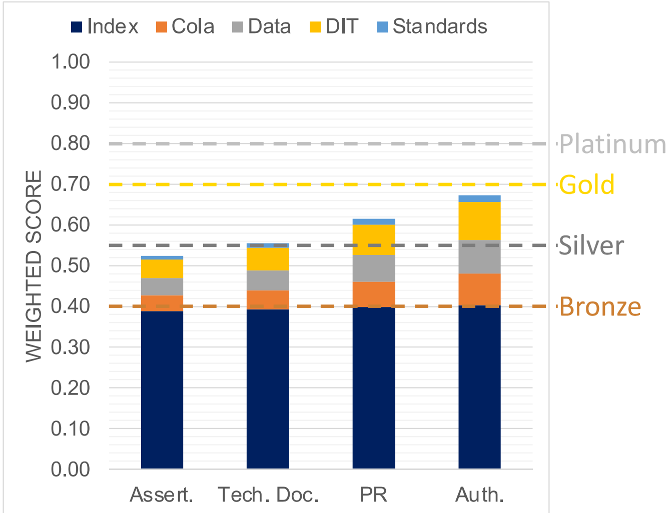


Variations on an Earth Observation mission to assess the sensitivity to operator choices (e.g. disposal) and to design features (e.g. size) 3

4 Large LEO Constellations cases at High and Low altitude. Significant risk contribution.

EPFL Data Verification Process

Level of verification	Factor
Assertion Affirmative statement by the applicant is provided, without supporting documentation	0.5
Technical documentation supporting the assertion Supporting technical documentation on the mission design is disclosed to the SSR entity	0.6
Public release of the technical documentation Supporting technical documentation is submitted to a government or non-profit available for public review	0.8
Authority – independent technical review An independent technical review or confirmation of compliance by a third-party technical expert is provided	1



Saada et al., "The Space Sustainability Rating: An operational process incentivizing operators to implement sustainable design and operation practices". 73th International Astronautical Congress, 2022

EPFL Test case definition (simplified)





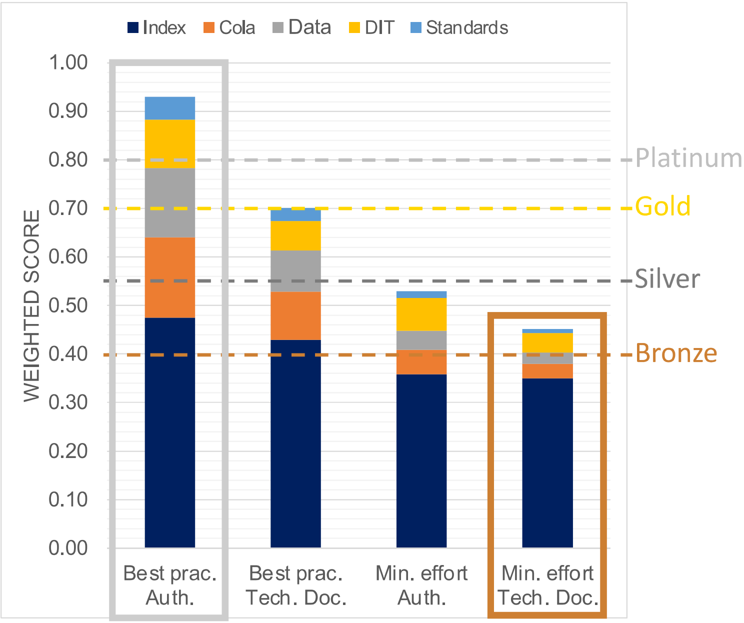
	Mission Index	COLA	DIT	Data Sharing	ADOS
"Best practices"	Perigee lowering **100km** (PMD success rate **99%**)	Orbital state knowledge maintained **(<1km)**	Satellite is detectable and trackable	Most inputs shared with SSA providers, other operators upon request, network of operators, and public	**Total compliance** to space debris mitigation guidelines
		Routine conjunction assessment system	Custody of the operated spacecraft is maintained within 1 day of deployment and thereafter		Explosion risk is characterized and kept under **1e-3**
	Mitigated collision risk **90%**	**Documented procedure** for collision screening, assessment, and mitigation	Radiometric and photometric data are shared with the SSR issuer		Spacecraft is **passivated**
					Payload is registered within the UN register of object launched into outer space
"Minimal effort"	Altitude lowering to comply with the IADC **25 years** rules (PMD success rate **90%)**	**Third party SSA** provider used for state information	Operators rely **on third party public SSA** providers	Most inputs are shared with **SSA providers only**	**Partial compliance** to space debris mitigation guidelines
		Ability to coordinate in response to **emergencies only**			Explosion risk is not characterized
	No collision avoidance envisioned as part of the operations	**No dedicated process** for conjunction screening, assessment, or mitigation			Spacecraft is **not passivated**

Saada et al., "The Space Sustainability Rating: An operational process incentivizing operators to implement sustainable design and operation practices". 73th International Astronautical Congress, 2022

Single satellite mission

Modules	Test cases			
	Best practises	Best practises Tech. doc	Minimal effort	Minimal Effort Tech. Doc.
Tier	93,0%	70,1%	52,9%	45,2%
	Platinum	Gold	Bronze	Bronze

- **Large score variability**
- **Platinum to Bronze score range**

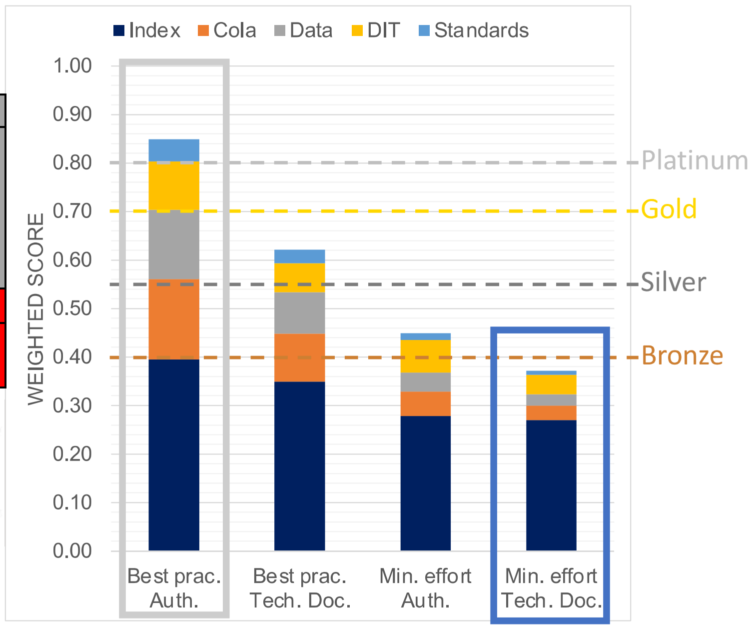


Saada et al., "The Space Sustainability Rating: An operational process incentivizing operators to implement sustainable design and operation practices". 73th International Astronautical Congress, 2022

100 satellites mission

Modules	Test cases			
	Best practises	Best practises Tech. doc	Minimal effort	Minimal Effort Tech. Doc.
Tier	85,0%	62,1%	44,9%	37,2%
	Platinum	Silver	Bronze	None

- Best effort still able to secure platinum
- **Minimal effort scenario fails to score**



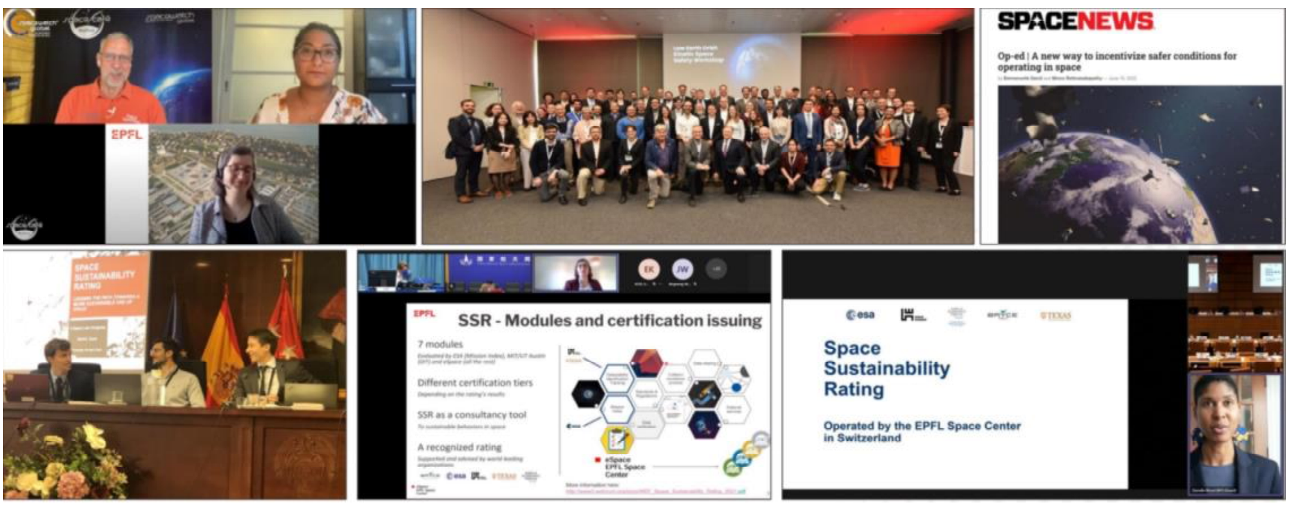
Saada et al., "The Space Sustainability Rating: An operational process incentivizing operators to implement sustainable design and operation practices". 73th International Astronautical Congress, 2022

Research into new SSR modules

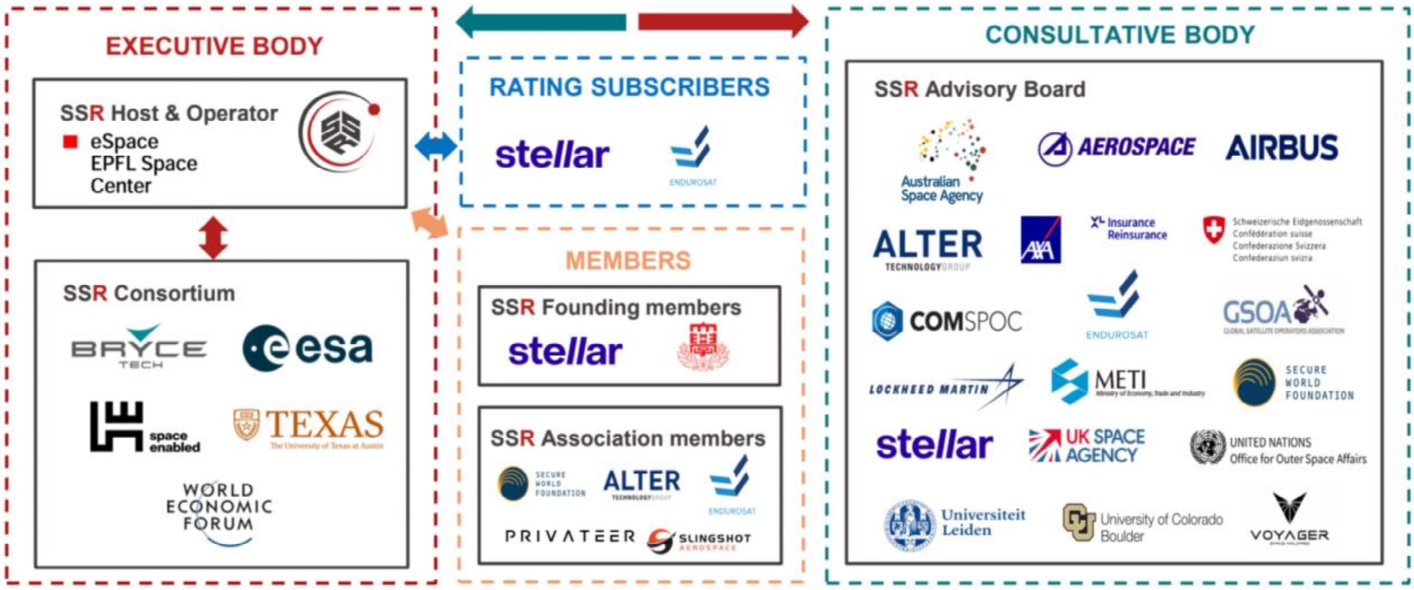
Impact on Astronomical Observation

- Intern to join in July
  - Literature review
  - Key criteria identification
  - Rating methodology formulation
  - SSR integration proposition
- SSR/eSpace to join discussion within the CPS as a member
- Discussion opened on developing such a module in collaboration with CPS

Building momentum



Working with industry partners, governments and space agencies



SSR in Japan

Establishment of a regional SSR hub in Japan

Nihon University SSR Founding Member

SSR documents translated into Japanese

Work with Japanese partners, METI and Nihon University

METI
Ministry of Economy, Trade and Industry

4 SSR モジュール

Figure 4: SSR を構成するモジュールの概要

SSR を構成する主なモジュールは以下の通りである。（最終スコアの重みづけが重くなると予想される順）:

0. *前提条件となる質問(Prerequisite Questions):* これらの質問は、SSR を達成するためにオペレータが実行しなければならない最低限の基準について示している。これには、ミッション後の廃棄(PMD)、安全化処置、意図的なデブリの発生防止、デブリ削減計画の策定のための国際機関間スペースデブリ調整委員会（IADC）のガイドライン遵守が含まれる。また、ミッションのライフタイムを通じて、ベースラインの宇宙機の情報を SSR 発行者と共有する意思がオペレータにあるかどうかの質問も含まれている。これらの質問に対して準拠出来ないオペレータ、または SSR 発行者に必要な情報を提供しようとしないオペレータは、他のカテゴリで高いパフォーマンスを発揮できるとしても、低いランクの格付けに制限される、もしくはレーティングを拒否される可能性がある。

1. *宇宙交通フットプリント算出のためのミッション指標(Mission Index to*

Get involved

The SSR Association as a non-profit organization to ensure a fair & independent rating system, relevant and practical for operators

- Establishing a **platform for engagement** involving all space actors & stakeholders with an interest in space sustainability, **centred on the rating**
- Developing and exchanging on **best practices** for sustainable & responsible behaviour in space
- Foster **action-focused collaboration** across the global space ecosystem to maximize the impact of sustainability incentives

Thank you

minoo@mit.edu

spacesustainabilityrating.org

B02

Making Spaceflight Safer

〇Siamak Hesar (Kayhan Space)

The idea for our session focuses on addressing the growing orbital debris issue in Lower Earth Orbit (LEO). It is estimated that there are more than one million pieces of debris orbiting Earth moving at speeds up to 10 kilometers per second and more than 11,000 satellites have been launched into LEO since the 1950s. We propose that the solution to congestion in LEO requires not only changes in international policy but the widespread adoption of autonomous and coordinated collision avoidance software for all satellite operators. The future of satellite maneuvers and coordination lies in the development of advanced software algorithms that are capable of generating feasible maneuver instructions consistent with the physics-based and operational constraints of the spacecraft and operators. Our speaker will be Dr. Siamak Hesar, who is the co-founder and CEO of Kayhan Space. He holds a Ph.D. in Aerospace Engineering Sciences from the University of Colorado, Boulder, with a focus on precise orbit determination. He has supported NASA missions in the past, including the OSIRIS-REx asteroid sample return mission.

kayhan.
space

Kayhan Space

Making Spaceflight Safer

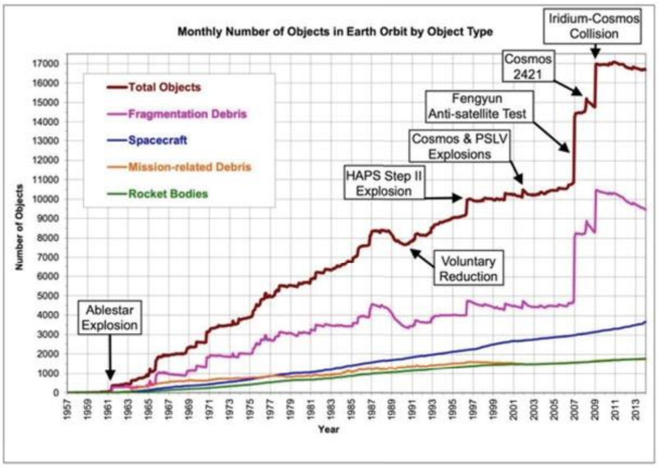
Nov 2022

Dr. Siamak Hesar — Co-founder, CEO
siamak@kayhan.space

A HISTORICAL OVERVIEW

Major collisions/breakups

- 2007, break up of China's Fengyun-1C Weather satellite in an anti-Satellite (ASAT) test
- 2008, the U.S. ASAT test at an altitude of 240 km
- 2009, collision of the Iridium 33 communication satellite and Russia's Cosmos s/c.
- 2013, collision between a Fengyun-1C debris and Russia's BLITS laser ranging satellite.
- 2019, India's ASAT weapon test that destroyed an Indian Microsat-R satellite
- 2021, Russia's ASAT test generated 1,500 trackable debris objects.
- There are many other examples like this …



UNOOSA Committee on the Peaceful Uses of Outer Space Report, A/AC.105/C.1/2017/CRP.12

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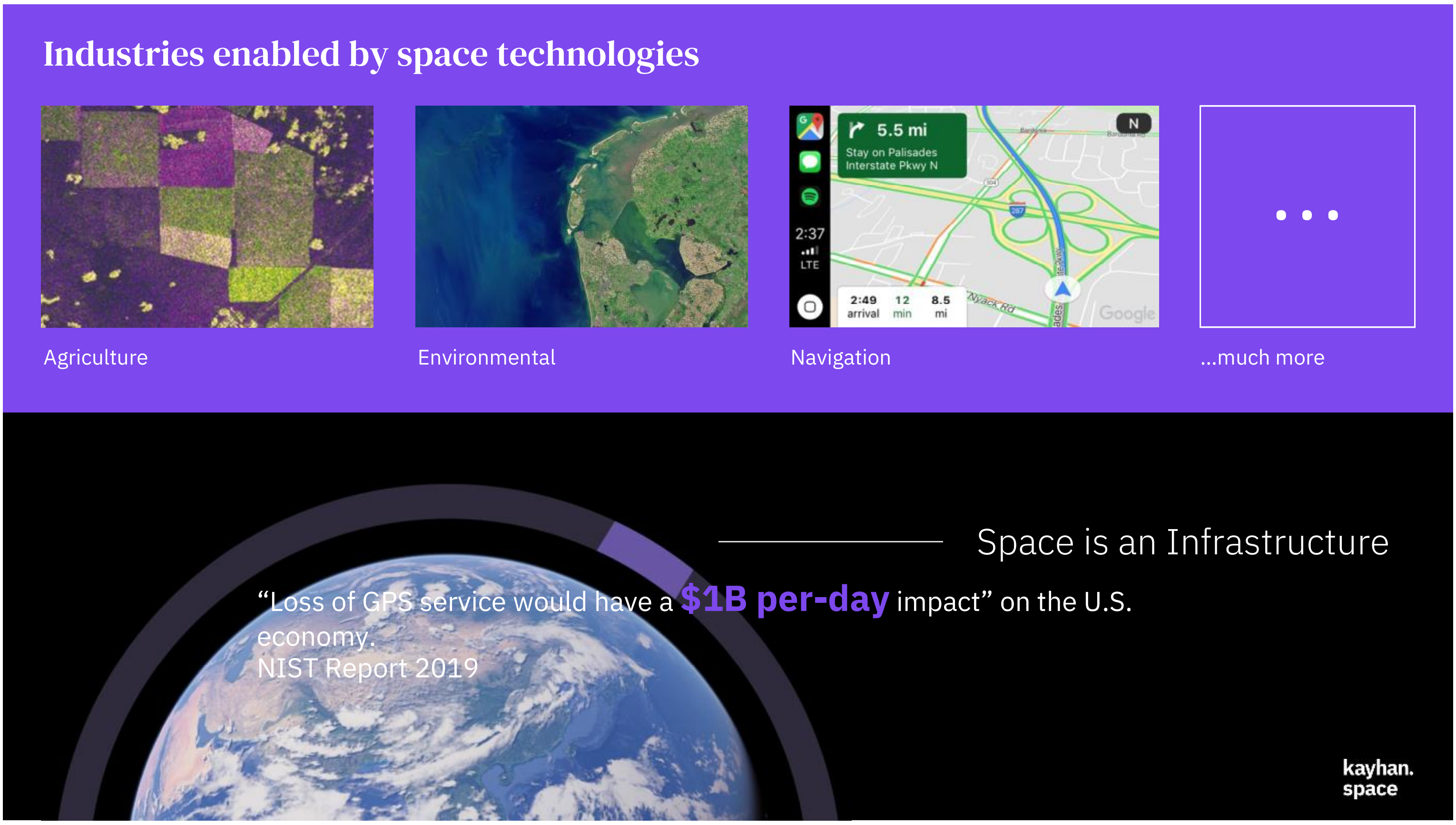
Industries enabled by space technologies
Agriculture
Environmental
Navigation
...much more
5.5 mi
Stay on Palisades Interstate Pkwy N
Space is an Infrastructure
"Loss of GPS service would have a $1B per-day impact" on the U.S. economy.
NIST Report 2019
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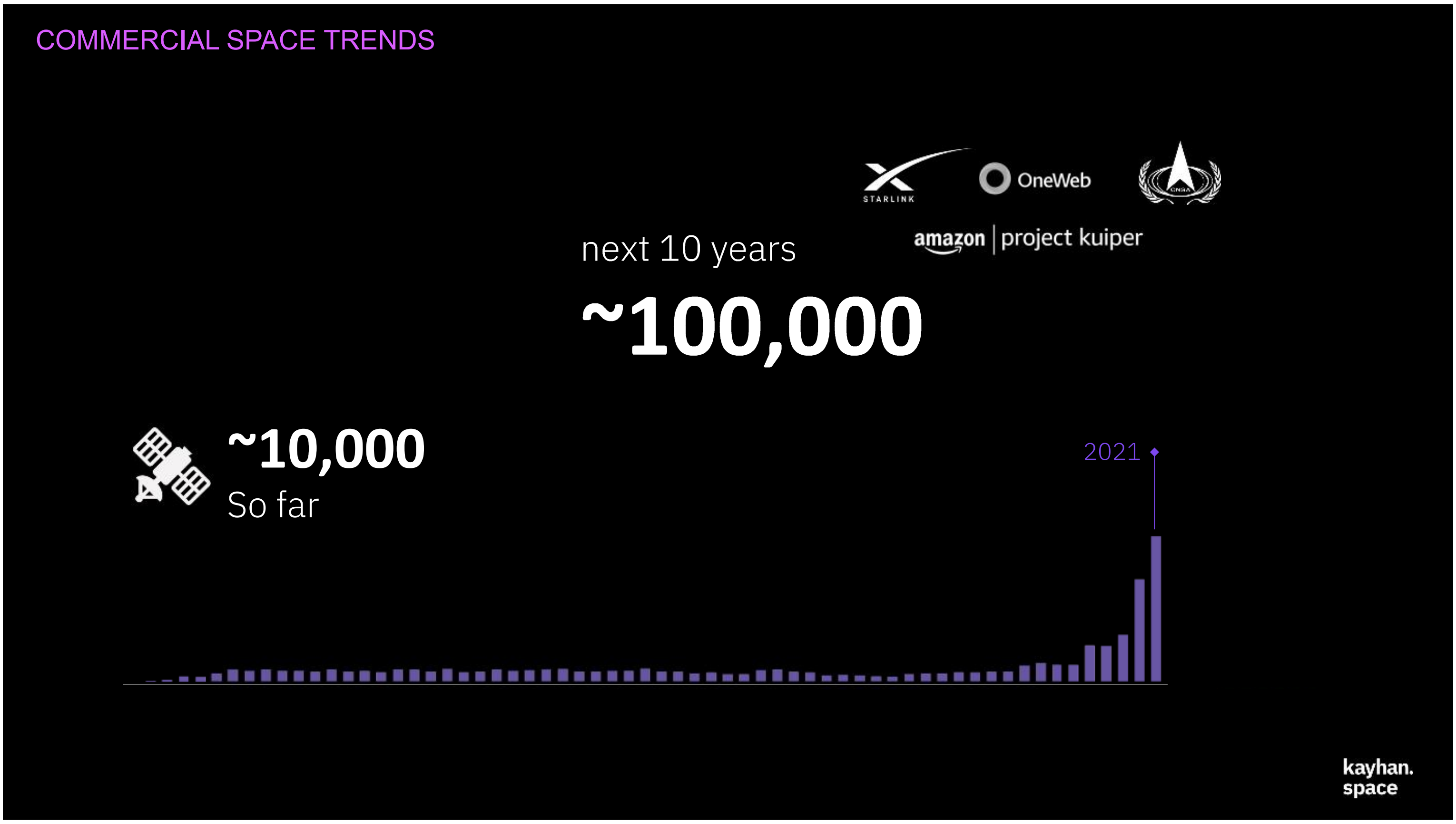
COMMERCIAL SPACE TRENDS
STARLINK
OneWeb
amazon | project kuiper
next 10 years
~100,000
~10,000
So far
2021
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PROBLEM

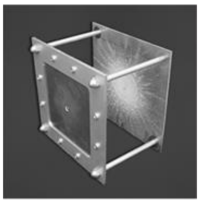
Processes that are used today to ensure spaceflight safety are not scalable; they are prone to human errors and delays.

Satellite operators need help!

TECHNOLOGICAL SOLUTIONS

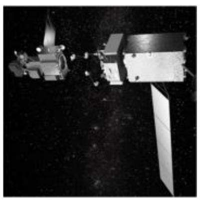
Improved Tracking

NASA SPACE FORCE LEO LABS



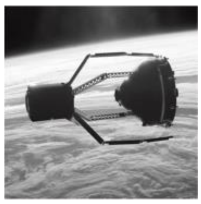
Hyper-Velocity Impact Shielding

NASA



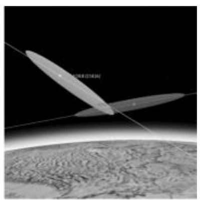
Mission Extension

NORTHROP GRUMMAN ORBITFAB



Active debris removal

esa JAXA Astroscale



Autonomous Decision Support

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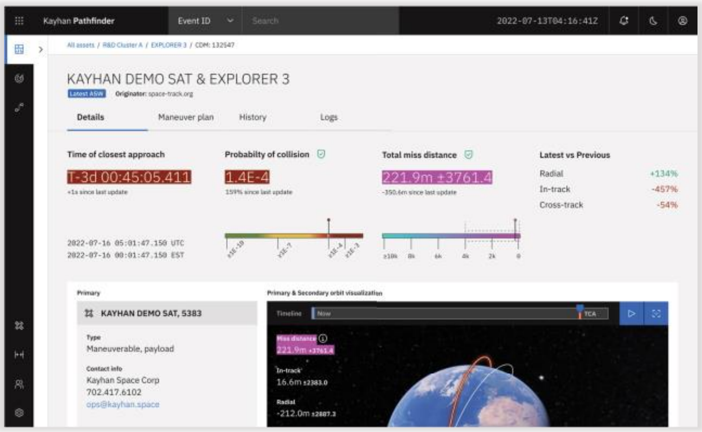
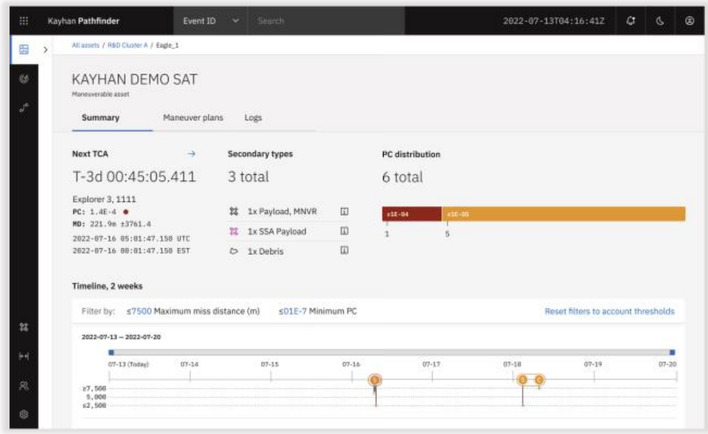
KAYHAN PATHFINDER

Autonomous & coordinated satellite collision avoidance solution

Reducing the response time to potential collisions by 95%





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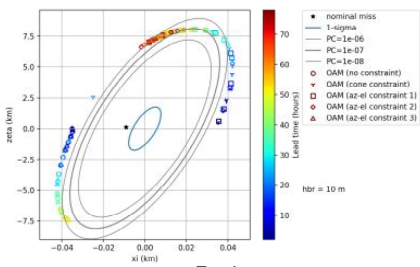
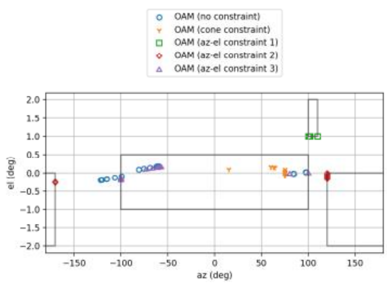
KAYHAN AUTONOMOUS AVOIDANCE MANEUVERS

- An advance set of algorithms for generating autonomous optimal avoidance maneuvers that are
  - Ready to execute
    - Meet both the ***physics-based*** and ***operational*** constraints of satellite operators
  - Safe
    - Screened for safety of flight
- Coordinated Autonomous Avoidance Maneuvers
  - The rate of operational vs. operational satellite conjunctions is increasing
  - Efficient rule-based procedure to enable autonomy



B-plane



DV direction

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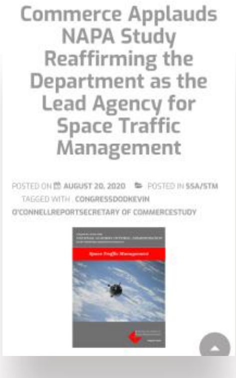

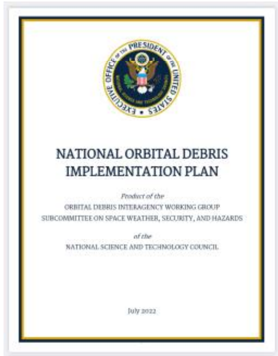

REGULATORY SOLUTIONS

Technology can't solve it alone

U.S. Government has a critical role…

Initiatives

- Space Policy Directive-3
- Department of Commerce – Office of Space Commerce
- Open Architecture Data Repository (OADR)
- National Orbital Debris Implementation Plan

However, this is just in the U.S. …

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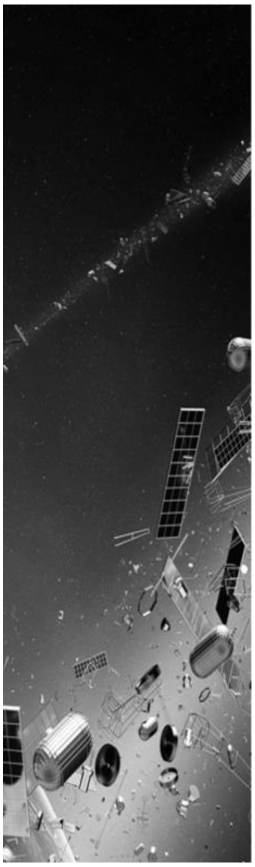
space

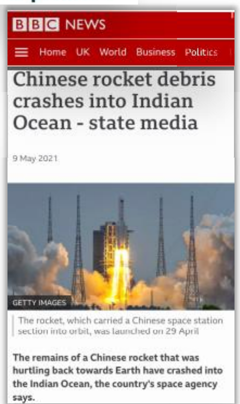


INTERNATIONAL COOPERATION IS KEY

Space does not belong to any one nation

There needs to be an internationally cooperative approach to achieve space sustainability.

- ASAT WEAPONS TEST BAN
  U.S., Canada, New Zealand, Japan, Germany, UK, South Korea, and Australia
- UNITED NATIONS, OFFICE FOR OUTER SPACE AFFAIRS
  Space Debris Mitigation Guidelines
- Russia and China should be part of the dialog



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space

Air Traffic Control Analog

"In the United States, after some mid-air collisions of commercial aircraft, a consortium of airliners began to monitor the operation of their own flights." ... "The Department of Commerce then assumed the control of the operations and, shortly after, opened eight more units in order to cover the United States airspace."

https://www.usca.es/

We are at an inflection point, and I hope we make the right set of decisions to continue a sustainable space exploration.

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space

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space

Thank you

Dr. Siamak Hesar — Co-founder, CEO
siamak@kayhan.space

B03

Would the Introduction of a Space Environment Tax Be Effective in Balancing Space Activities and the Space Environment?

宇宙環境税の導入は宇宙活動と宇宙環境の両立に有効か？

○MINATO Nobuaki (Ritsumeikan University), KOHTAKE Naohiko, OTSUKA Akiko (Keio University),
FUSE Testuhito (Kyushu Institute of Technology)
○湊宣明（立命館大学），神武直彦，大塚聡子（慶應義塾大学），
布施哲人（九州工業大学）

When external diseconomies such as environmental pollution by companies occur, the introduction of an environmental tax is considered as a means of controlling environmental impact while maintaining economic activity. This study focuses on the concept of a space environmental tax as a mechanism to autonomously balance space development activities with space environmental protection. Previous studies have pointed out the positive and negative effects of introducing an environmental tax, and it is thus necessary to assess the systematic and long-term effects of the policy intervention. This study aims to model space activities and the associated increase or decrease in debris as an ecosystem and to examines whether the introduction of a space environmental tax can promote space activities by companies while preserving the space environment. A model was built using system dynamics to reproduce the interaction between spacecraft launches and debris generation, and a 30-year simulation was performed. The results suggest that, by setting an appropriate space environment tax rate, the number of spacecraft and the number of debris could be balanced at a constant level in the long term and sustainable space environment protection could be achieved.

企業等による環境汚染等の外部不経済が発生する場合、経済活動を維持しつつ環境負荷を抑制する手段として、環境税の導入が検討される。本研究は、企業等による宇宙開発活動と宇宙環境保全を自律的に均衡させる仕組みとして「宇宙環境税」の概念に着目する。先行研究では環境税の導入に正負の効果が指摘されており、体系的かつ長期的な影響を評価する必要がある。本研究は、宇宙開発活動とそれに伴うデブリの増減を生態系システムとして捉えてモデル化し、宇宙環境税の導入により、宇宙環境保全を図りつつ、企業による宇宙開発活動を促進させることが可能かを検証する。システム・ダイナミクスを用いて宇宙機の打上とデブリ発生の相互作用を再現したモデルを構築し、30 年間のシミュレーションを実行した。結果、宇宙環境税率を適切に設定することで、宇宙機の数とデブリの数を長期的に一定水準に均衡させ、持続可能な宇宙環境保全を達成できる可能性が示唆された。

RITSUMEIKAN Keio University 国立大学法人 九州工業大学

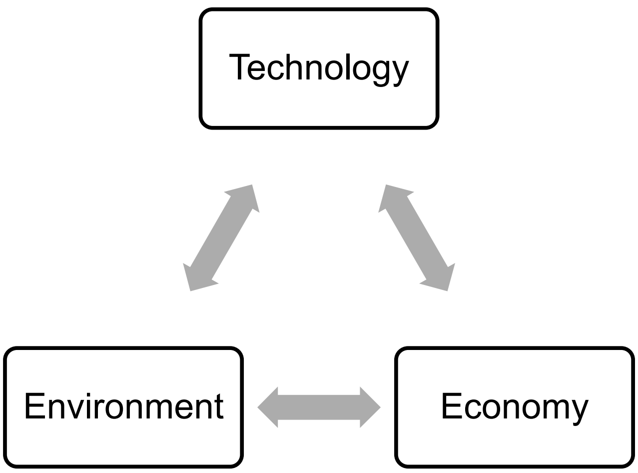
Would the introduction of a space environment tax be effective in balancing space activities and the space environment?

Nobuaki MINATO (Ritsumeikan University)
Naohiko KOHTAKE, **Akiko OHTSUKA** (Keio University)
Tetsuhito FUSE (Kyushu Institute of Technology)

November 28th – 30th
10th Space Debris Workshop @ Japan Aerospace Exploration Agency

Issue

- **Economic Kesler Syndrome** (Adilova et al, 2020)
  - The phenomenon of increased debris and then the increase of debris collision probability influence the cost of spacecraft development and operation and makes commercial space activities unprofitable.



Purpose

- Adilova et al. (2020) suggest that a high taxation on space debris may reduce the debris generation rate.
  - Pros and Cos of environment taxation
    - Creating financial resources for the environmental protection activities and Inducing voluntary measures by the private companies (Xiao et al., 2021)
    - A high tax rate may inhibit economic activities (Mardones and García, 2020)
- This study aims to examine the concept of a space environmental tax (SET) as a mechanism to autonomously balance space development activities with space environment conservation.

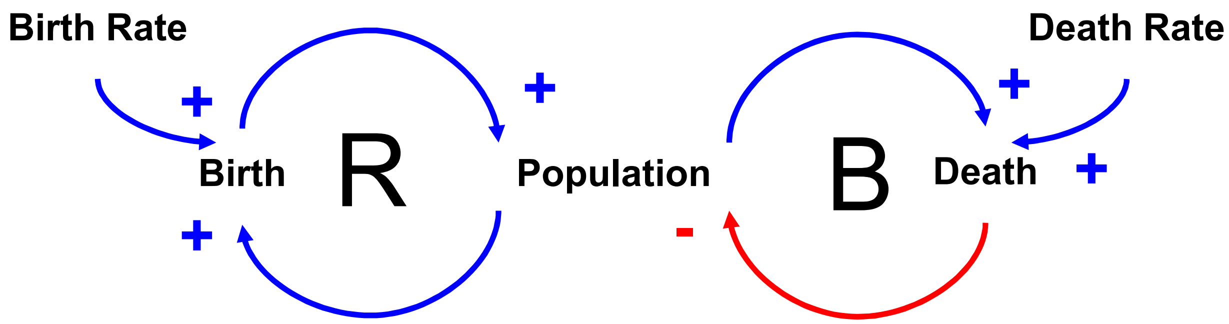
Research Question

Would the introduction of a space environment tax be effective in balancing space activities and the space environment?

3

Method

- **System Dynamics** (SD)
  - is a method to simulate the dynamic behavior of a system over time by reproducing the feedbacks among the system elements.[8]
  - causal loop diagram (CLD) is used to identify feedback loops that influence the system behavior.



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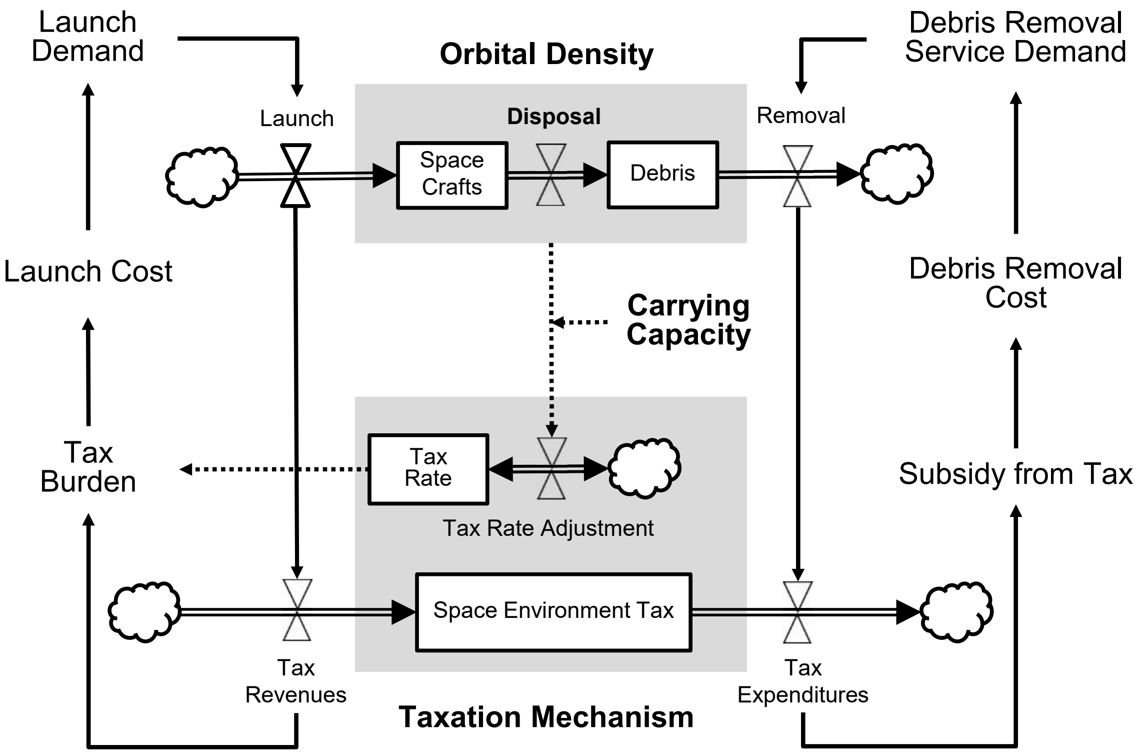
Method

- **Stock Flow Diagram** (SFD)
  - Consists of a stock representing the accumulation of material or information in the system, an inflow into the stock, and an outflow from the stock, clouds are unlimited resource containers.

  - Integral calculation of the difference between the in-flow (t) and out-flow (t) per unit time accumulated in the stock, adding the initial value (t_0) of the stock, and estimating the stock's state at time (T) .

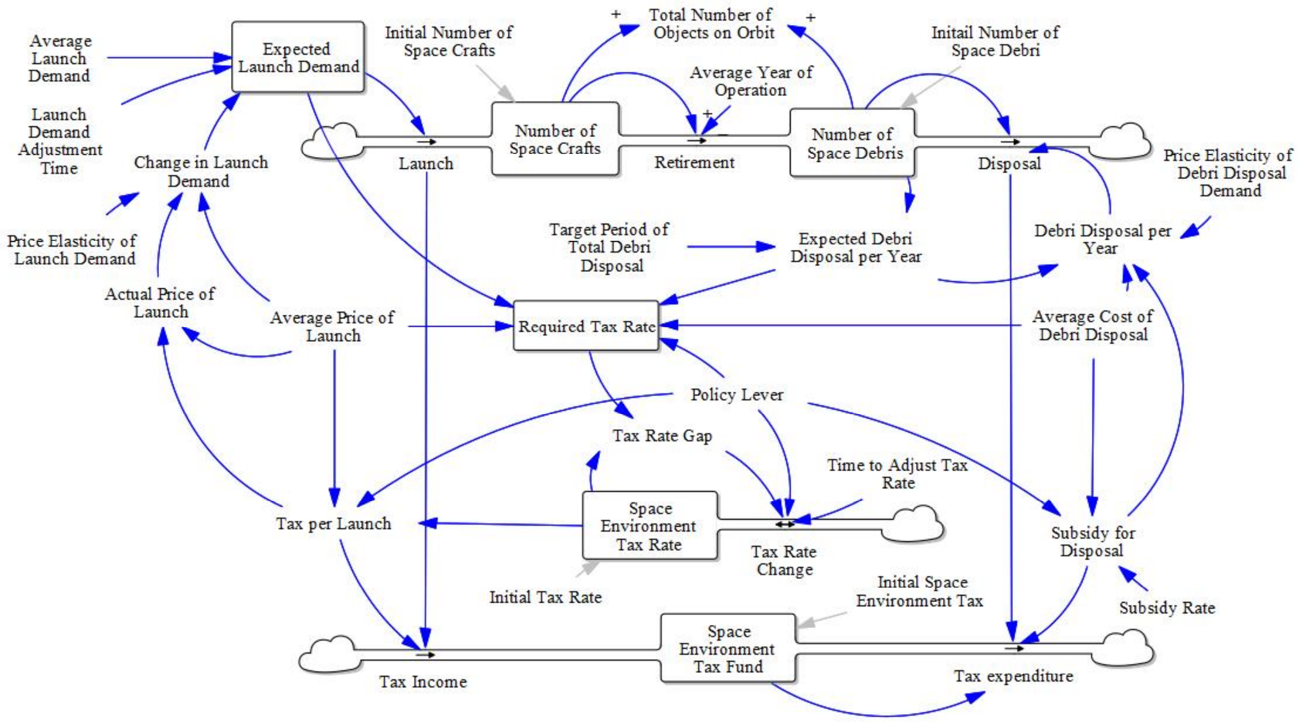
$$Stock(T) = \int_{t_0}^{T} [Inflow(t) - Outflow(t)]dt + Stock(t_0)$$

Model Design



Model Design in Stock and Flow Diagram

Model Building



Space Environment Tax Simulation Model (VENSIM 9)

7

Simulation

- Simulation Condition
  - Assumed a single orbit
  - Simulations run for 30 years, with 2 scenarios
    (1) “without” SET and (2) “with” the SET
  - SET is paid by the operators according to the launch price and the tax rate varies according to the orbit density.
  - 90% of the debris removal cost is compensated from the SET.

Name of Variable	Value
Initial Number of Space Crafts	100
Initial Number of Space Debris	100
Average Demand of Launch	10/year
Average Years of Operation	10 years
Average Price of Launch	$100 million
Average Price of Debris Disposal	$10 million
Subsidy Rate	0.9
Price Elasticity of Launch Demand	0.9
Price Elasticity of Debris Disposal	0.9

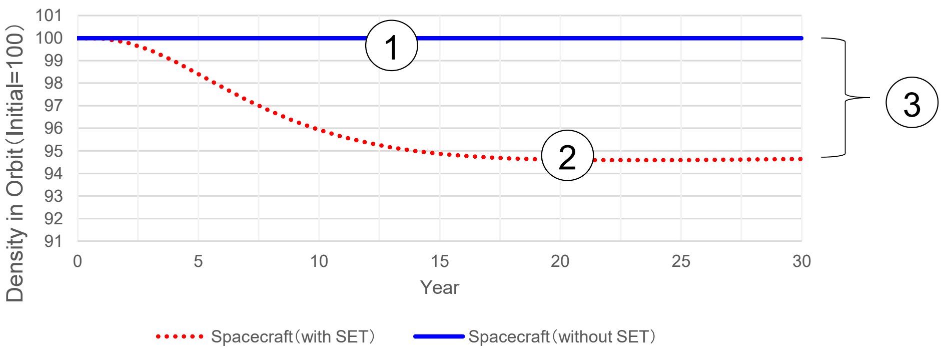
8

Results (Spacecraft)

① In the scenario without space environment tax, the number of spacecraft is unchanged from 100 because launch demand is assumed to be constant.

② On the other hand, in the scenario with the space environment tax, the tax burden increases the launch price, and the price elasticity reduces the demand for launches, so the observed impact is a decrease in the number of spacecraft.

③ However, the decline rate will be limited to a maximum of 5% and will move toward equilibrium over the long term.



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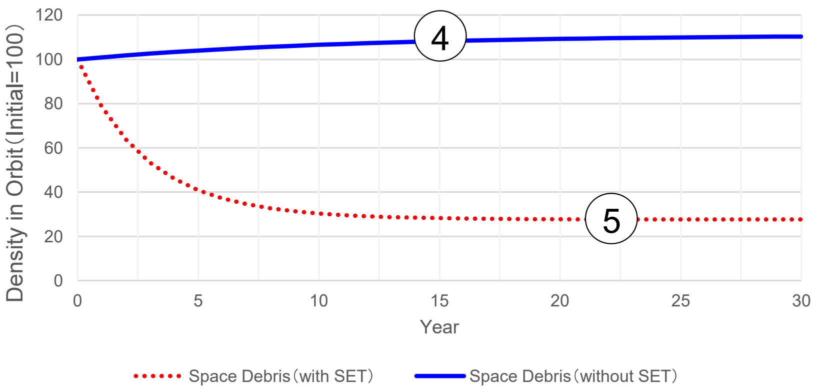
Results (Space Debris)

④ In the scenario without the space environment tax, the number of debris showed a slight increase (solid line: blue)

⑤ In the scenario with the space environment tax, a significant decrease in the number of debris was observed (dotted line: red).

– This is because the tax burden reduced the launch demand and suppressed debris generation, at the same time subsidizing the cost of debris disposal and encouraging operators to promote the disposal.



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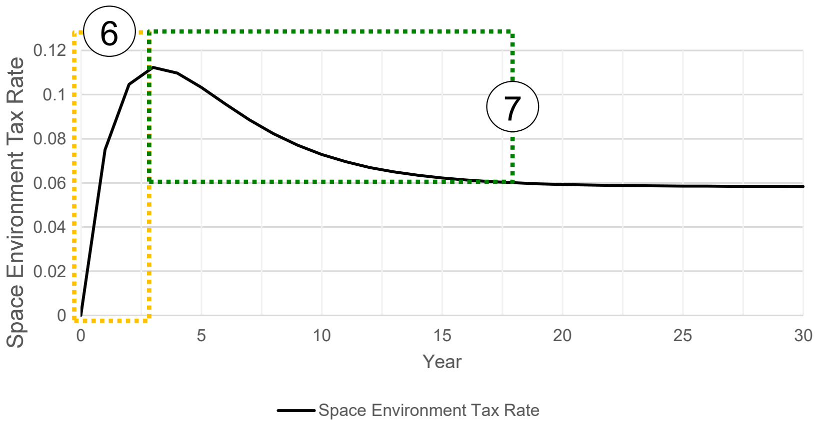
Discussions

- The space environmental tax rate changed adaptively in response to orbital space density, possibly moderating the overall impact.
  - Initially, the space environmental tax rate increases due to the high spatial density (⑥), which suppresses the increase in debris, and then the space environmental tax rate decreases toward equilibrium with the debris processing capacity (⑦).
  - Suggests that the optimal design of the taxation mechanism may keep the economic impact within a certain range



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Summary

- Summary
  - A 30-year simulation was performed using system dynamics to examine the interactive behaviors between spacecraft launches and debris generation.
  - Concluded that introduction of the SET would enable the maintenance of a certain level of space density in orbit by adoptively changing the tax rate.

- Future works
  1. Model validation based on space debris database
  2. Risk evaluation model on debris collision
  3. Legal issues on the taxation right on space debris

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B04

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

〇Manuel Cegarra Polo, YANAGISAWA Toshifumi, KUROSAKI Hirohisa (JAXA),
SAKO Shigeyuki (University of Tokyo), Tomo-e Gozen Team

In this work we will present the first results of the previously developed streaks detection algorithm in astronomical images, after its installation in the processing pipeline of the Tomo-e Camera of the 1M Telescope at Kiso Observatory. We developed an improved version of this algorithm, now capable to process images in real-time, that is, faster than the image are produced, through an heterogeneous computing paradigm. For the firsts tests, we used a 64 CPU cores with 2 Nvidia RTX A6000 GPUs machine to process half of the Tomo-e camera full frame, which will be installed during September 2022. The system is capable to automatically detect non-catalogued objects in LEO that are imprinted as streaks in astronomical images, down to an apparent magnitude of ~11.3. In this work we will explain the working principle of the detection system, based in a variation of the so-called stacking method, previously developed by some of the authors of the present work. We will also describe the heterogeneous computing architecture capable to reach real-time performance and we will present the results of the first observation campaign that will be carried out after its installation during September 2022.

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Manuel Cegarra Polo
Toshifumi Yanagisawa
Hirohisa Kurosaki
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Japan Aerospace Exploration Agency (JAXA)
University of Tokyo

10th Space Debris Workshop
28-30 November 2022, Tokyo, Japan

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Heterogeneous Computing

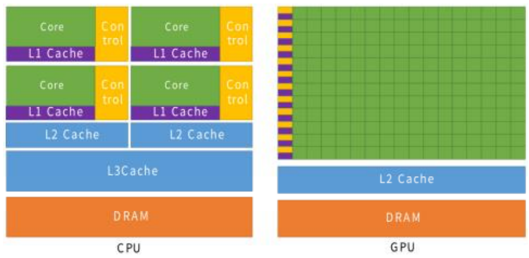
PARALLEL COMPUTING. HETEROGENEOUS COMPUTING
- Many processes are executed concurrently ≠ multi-tasking (time-sharing single CPU).
- Nowadays multi-core/multi-GPU are very common.
- Hardware accelerators:
  - GPU (Graphics Processing Unit).
  - FPGA (Field Programable Gate Array).
- **Heterogeneous computing: Systems that use more tan one type of processor or core**.

GPU
- GPU appeared in the 70's as specialized graphic circuits to aid the CPU.
- GPU dedicated to graphics rendering, specially for the gaming industry.
- GPGPU (General Purpose GPU) appeared in 2000.
- GPGPU perform parallel computation in application traditionally handled by CPU.
- Processing pipelines for graphics processing were found to fit other fields needs. such us scientific computing, encryption/decryption or physics calculations.

JAXA WORKSTATIONS FOR HETEROGENEOUS COMPUTING

GDEP DLEARNING BOXII
- 4 x NVIDIA QUADRO RTX8000
- 4 x **4608 CUDA cores**
- 4 x 40 GB GPU Memory
- CPU Intel i9-10940x 3.30 Hz
- **28 CPU cores**
- 128 GB RAM Memory

GDEP DPLEARNING BOX ALPHA
- 2 x NVIDIA RTX A6000
- 2 x **10752 CUDA cores**
- 2 x 48 GB GPU Memory
- CPU AMD Epyc 7502 2.5 GHz
- **64 CPU cores**
- 128 GB RAM memory



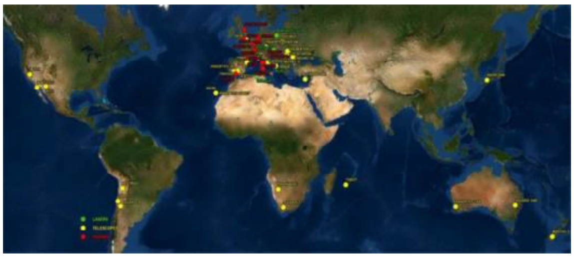
Hardware architecture CPU vs GPU (source: NVIDIA CUDA C++ Programming Guide)


JAXA Workstations for Heterogeneous Computing: BOXII (left), BOX ALPHA (right)

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

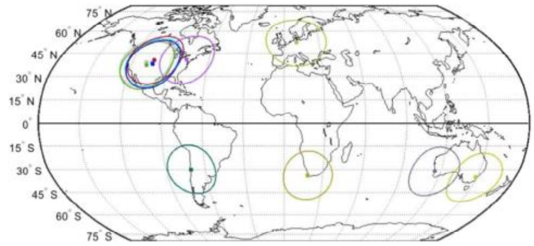
Why Heterogeneous Computing? 1st Scenario: Massive datasets of images and large image sensors

- Telescopes of national and international SST networks produce large datasets of images.
- Tomo-e camera at Kiso Observatory produces **~30 Tbytes of data per night.**
- Nowadays larger, faster and more sensitive sCMOS/CMOS image sensors.
- **Short processing time is very convenient in previous scenarios.**

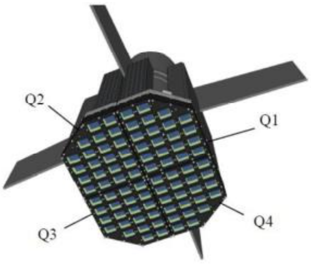


Global distribution of EU SST sensor network (P. Faucher et al. JSSE 2020)

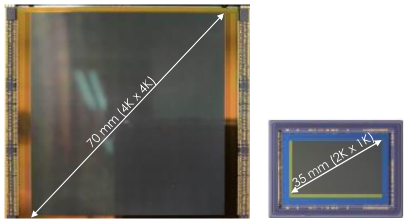
JAPAN SST sensor network (http://www.jaxa.jp/projects/ssa/)



Field coverage of FTN Network for LEO (F. Chun et. al. PASP 2018)



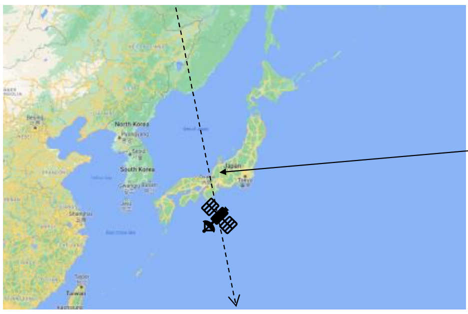
84 image sensor array of Tomo-e camera in 1 M Schmidt Telescope at Kiso Observatory (Japan). (S. Sako et al. SPIE, Texas, US, 2018)



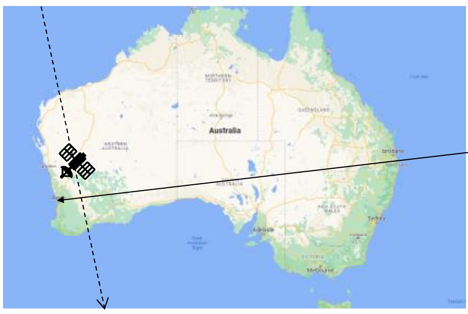
ANDOR BALOR sensor 4K x 4K (left) vs. CANON FXDXS (BITRAN BH-60) 2K x 1K (right)

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Why Heterogeneous Computing? 2nd Scenario: Follow-up observations of objects in LEO



KISO Observatory (U. Tokyo)



ZADKO Observatory (JAXA)

Detection of uncatalogued object in Kiso Observatory

⇩

Detection of streak ends RA/Dec coordinates and time stamps

⇩

Circular orbit element calculated from observed coordinates

⇩

Calculate next pass coordinates

⇩

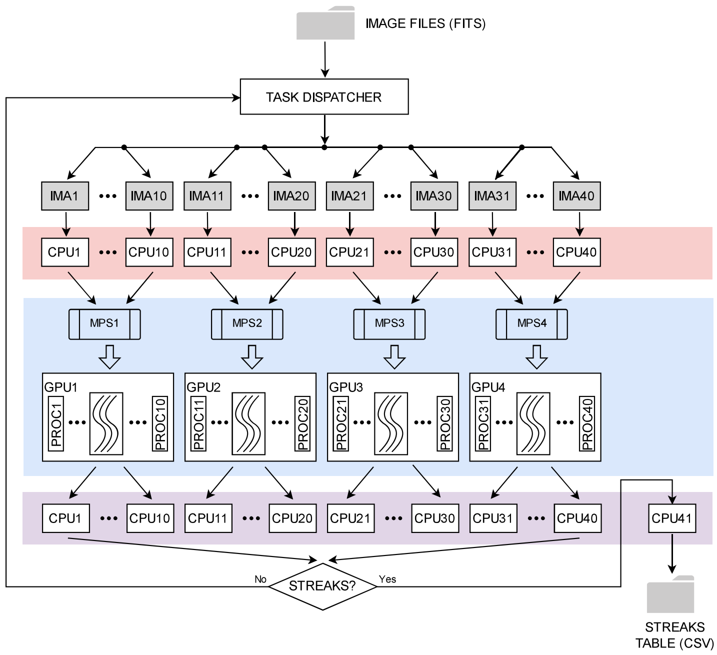
Follow-up observation in Zadko Observatory

⇩

Precise Orbital Determination

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Detection of LEOs (streak-shaped) through the Stacking Method in multi-GPU/CPU system. Hardware Architecture



PROCESS FOR 41 CPU CORES / 4 GPUs

PREPROCESSING

- Image files (FITS files) are stored continuously in a folder as they are produced.
- The "Task Dispatcher" assigns image files as they arrive to available CPUs (1-40).
- **Each CPU processes 1 image file in parallel with the rest**.

DETECTION

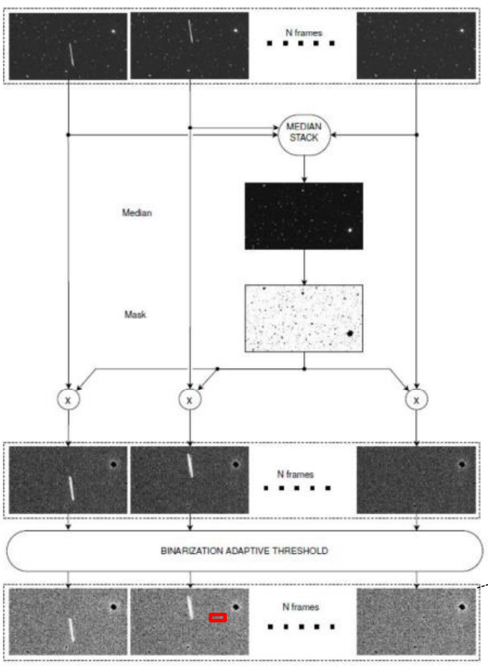
- 4 MPS (Multi-Process Service) instances are executed in each GPU respectively.
- **MPS allows concurrency of processes in GPU**, which increase GPU utilization.

POSTPROCESSING

- If streaks are detected a background process that run postprocessing tasks is executed in parallel with the rest of CPUs (CPU41).
- If streaks are not detected the corresponding CPU(1-40) is released and ready to be assigned to another image.

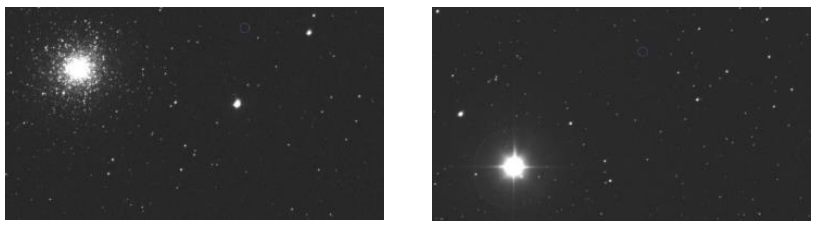
Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Detection of LEOs (streak-shaped) through the Stacking Method in multi-GPU/CPU system. Preprocessing



PREPROCESSING OF 3D N x 1128 x 2000 pixels FITS file

- **Removal of stars**: (variation of star removal method*) to avoid detection of false positives of streaks created by diffraction spikes of bright stars or other astronomical objects.



Diffractions spikes of bright stars and other astronomical objects are removed to avoid false positives streaks detection (Tomo-e camera images)

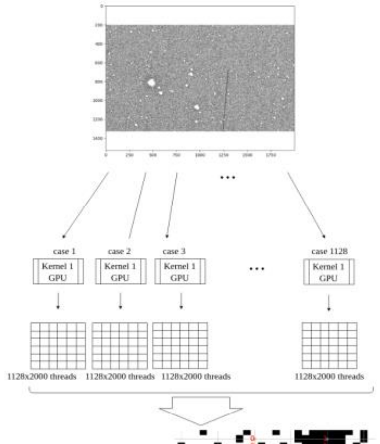
- **Binarization**: global or local (adaptive thresholding).

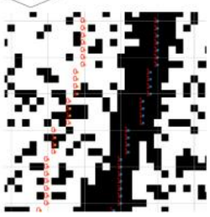
Magnification region (in red) of 2nd binarized image

* Automatic Detection Algorithm for Small Moving Objects, Yanagisawa T. et al, Publ. Astron. Soc. Japan, 57, 399–408, 2005

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

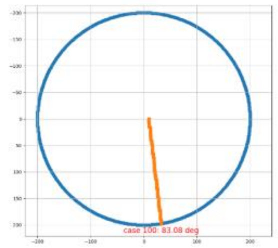
Detection of LEOs (streak-shaped) through the Stacking Method in multi-GPU/CPU system. Detection

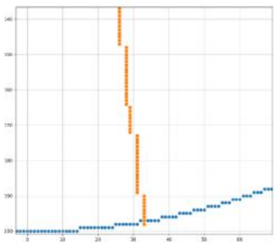




Case	Pixel	It
42	162000	130
42	162001	131
42	162002	130
42	162003	138
42	162004	140
42	162005	141

raw output: case, pixel and value over threshold

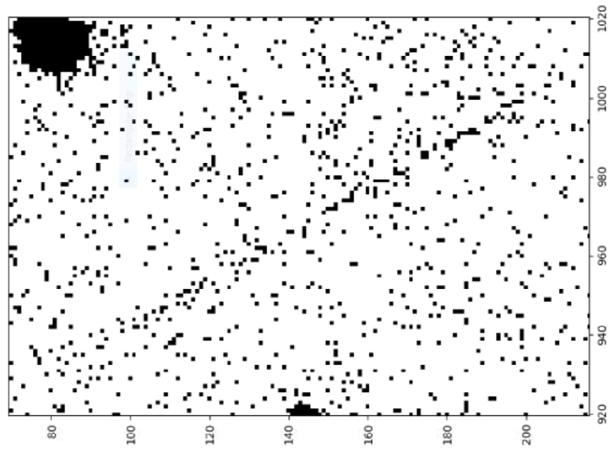




Generation of casefile

PARAMETERS

- Pixel binary values (0/1) are accumulated over segments of length 200/100/50 pixels
- Casefile includes 1128 possible directions generated through a casefile
- **Cases over threshold (130/200 66/100 33/50) are considered candidates of streaks**

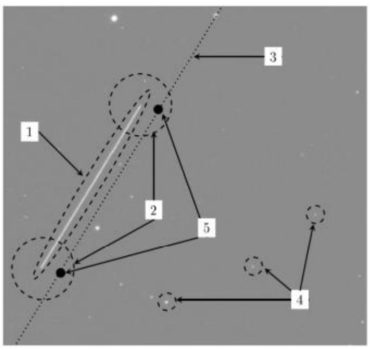


Faint streak after binarization

* Detection of Small GEO Debris by Use of the Stacking Method", Yanagisawa T. et al, T. Japan Soc. Aero. Space Sci., V.44, No. 146, pag. 190-199, 2005

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Detection of LEOs (streak-shaped) through the Stacking Method in multi-GPU/CPU system. Postprocessing



1. **Elliptical area** surrounding the detected streak to compute the total brightness.
2. Circular areas surrounding both ends of the detected streak, that defines the **error with the TLE database** of objects comparison.
3. **Trajectory of real object** in the database obtained through the propagation of its TLE data with SGP4 algorithm.
4. **photometric stars** for differential photometry.
5. **(RA,Dec) coordinates** of object from database corresponding to the timestamps of start and end of camera integration time. if these points are encompassed by the circular areas (2), the streak is associated with the candidate object.

SUBSTAGES

ASTROMETRY

- Obtention of astronomical coordinates (RA, Dec) of each streak end.
- Python subprocess calls to xy2sky library*
- Compute RA, Dec of each object in UTC timestamp + (0.5s x n_subframe)**

IDENTIFICATION

- coordinates ends are compared with those of known objects of a space-track.org database of ~29,000 entries, based in the SGP4 orbital propagation or their initial TLE coordinates.
- Download TLE file of ± 12 hours FITS file UTC timestamp with query

DIFFERENTIAL PHOTOMETRY

- Calculated through the sum of all bright pixels of the detected streak.
- To characterize system sensitivity, not intrinsic to the object.

* http://tdc-www.harvard.edu/software/wcstools/xy2sky/ XY2SKY WCSTools 3.9.5, 30 March 2017
** Skyfield: Brandon Rhodes. https://ui.adsabs.harvard.edu/abs/2019ascl.soft07024R

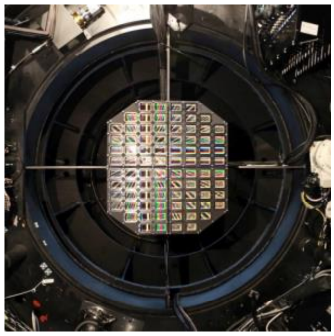
Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Detection of LEOs (streak-shaped) through the Stacking Method in multi-GPU/CPU system. Experimental Setup

TOMO-E CAMERA AT 1M SCHMIDT TELESCOPE AT KISO OBSERVATORY

FITS files:	18 consecutive frames of 0.5 s exposure time 2000 x 1128 x 18 ~ 40.61 Mpixels ~ 162.4 Mbytes
Data rate:	~ 1.7 Tbytes / hour
Sensor model:	Canon 35MMFHDXM
Sensor type:	CMOS Front illuminated
Pixel size:	19 µm/pixel
Pixel scale:	1.198 arcsec/pixel
No. sensors:	84

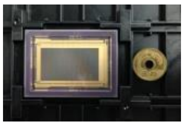
Kiso Schmidt telescope
Wide-field telescope (D_{eff} = 1.05 m, f/3.1)
(source: https://tomoe.mtk.ioa.s.u-tokyo.ac.jp/)



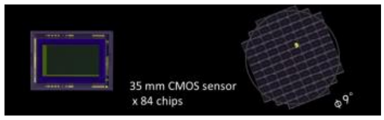
Tomo-e Gozen camera
Wide-field CMOS camera covering 20 deg2 sky.
(source: www. https://tomoe.mtk.ioa.s.u-tokyo.ac.jp/)

OBSERVATION CAMPAIGN SEPTEMBER-OCTOBER 2022

We made a **5 days observation campaign** to test the system, perfect the processing pipeline.
Each night we processed data **during 2 hours after sunset.**



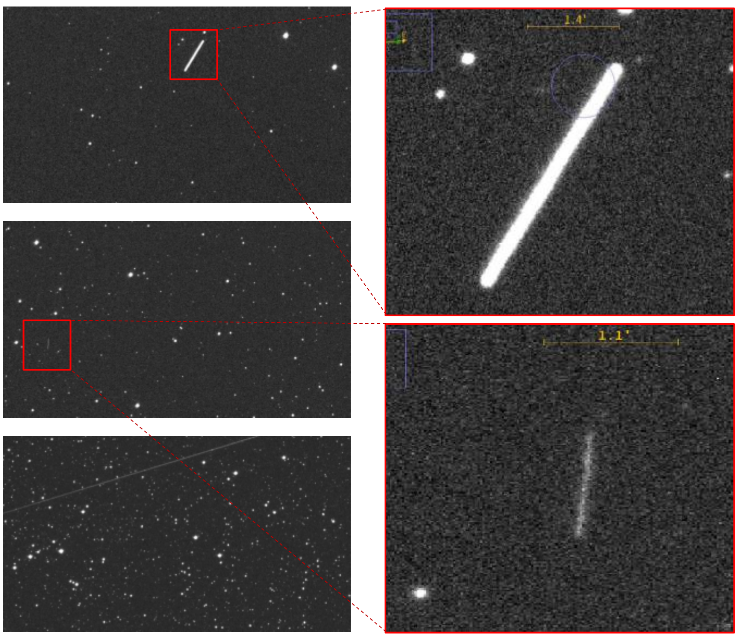
35 mm Full HD 2000 x 1128 pixels
(source: www.ioa.s.u-tokyo.ac.jp/tomoe)



Layout of CMOS sensors in Tomo-e Gozen camera. 1.198 arcsec/pix
(source: www.ioa.s.u-tokyo.ac.jp/tomoe)

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Detection of LEOs (streak-shaped) through the Stacking Method in multi-GPU/CPU system. Detection Rates



5 nights observation campaign:
10,000 -15,000 FITS files each night

⇩

Detected streaks in
~2-3% of the FITS files

⇩ ⇩

Streaks across several sensors **60%**

Streaks within 1 sensor bounds **40%**

⇩ ⇩

Streaks not-identified **25%** (as short as ~1arcmin and App Mag as low as ~ +12)

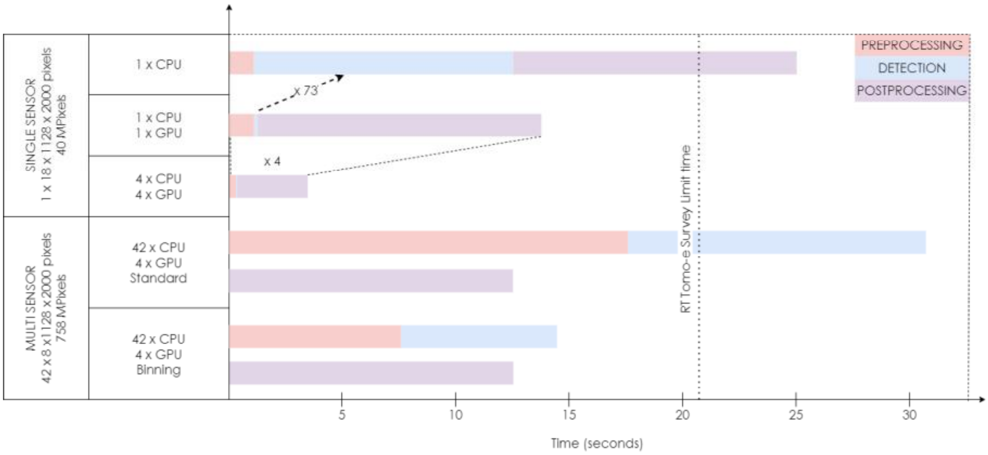
Streaks NORAD ID identified **75%**

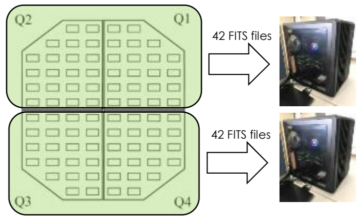
⇩

SUMMARY
We can detect **~30 non catalogued objects** (not included in the daily space-track.org official database) in this 2 hours period of time.

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Detection of LEOs (streak-shaped) through the Stacking Method in multi-GPU/CPU system. Timing Performance





SINGLE SENSOR

- Use of GPU instead of GPU in the Detection process is x73 times faster.
- This process is scalable with the number of CPU-GPU pipelines.

MULTI SENSOR

- Through Heterogeneous Computing, we can process 42 image sensors of Tomo-e camera (1/2 of the FOV) in Real-Time (binning mode)

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Detection of LEOs (streak-shaped) through the Stacking Method in multi-GPU/CPU system. Output table

file_name	positives	min_x	min_y	max_x	max_y	min_RA	min_Dec	max_RA	max_Dec	UTC_begin	UTC_end	TLE_candidate	NORAD ID	Dif_Time_Epoch	mag	residuals
rTMQ220221102008077126_0.fits	189004	1902	18	1987	42	16:49:57.350	+26:55:54.66	16:50:04.866	+26:55:24.03	221102 09:21:46.53	221102 09:21:47.03	STARLINK-4137	53031	-0.140110358	near edge	near edge
rTMQ2202211020080771532_10.fits	2946730	414	138	764	914	16:49:49.767	+23:40:23.08	16:50:18.385	+23:24:50.42	221102 09:22:51.92	221102 09:22:52.42	no match	no match		9.92	1.79
rTMQ2202211020080771531_14.fits	3430631	1510	141	1859	924	16:51:18.953	+22:51:46.56	16:51:47.219	+22:36:05.47	221102 09:22:52.92	221102 09:22:53.42	no match	no match		8.62	0.52
rTMQ2202211020080771524_2.fits	2843521	1444	72	1826	927	16:46:44.172	+25:18:41.28	16:47:16.394	+25:01:37.17	221102 09:22:49.92	221102 09:22:50.42	no match	no match		8.77	0.58
rTMQ2202211020080771621_14.fits	3176632	504	377	478	760	17:15:31.881	+15:23:15.33	17:15:29.567	+15:15:39.93	221102 09:23:24.05	221102 09:23:24.55	no match	no match		9.97	0.05
rTMQ2202211020080773012_16.fits	1288345	28	338	262	410	17:11:27.368	+38:53:38.63	17:11:51.112	+38:52:09.33	221102 09:28:37.34	221102 09:28:37.84	no match	no match		near edge	near edge
rTMQ2202211020080773023_4.fits	360614	757	297	1014	721	17:18:21.376	+39:40:55.72	17:18:46.730	+39:32:23.98	221102 09:28:34.34	221102 09:28:34.84	no match	no match		9.88	0.08
rTMQ2202211020080773623_14.fits	341564	10	447	155	927	18:02:50.186	+39:14:18.22	18:03:03.983	+39:04:44.00	221102 09:30:59.65	221102 09:31:00.15	no match	no match		near edge	near edge
rTMQ2202211020080774731_0.fits	2301	1895	14	1888	86	18:06:01.100	+22:53:57.03	18:06:00.335	+22:52:31.64	221102 09:34:59.10	221102 09:34:59.60	COSMOS 1054	11131	0.026271264	near edge	near edge
rTMQ2202211020080774733_12.fits	864	1335	908	-1	-1	18:05:22.167	+24:12:28.55	18:03:27.649	+24:31:04.63	221102 09:35:02.09	221102 09:35:02.59	no match	no match		near edge	near edge
rTMQ2202211020080774733_14.fits	3085	1263	423	1280	661	18:05:16.920	+24:22:07.24	18:05:17.903	+24:17:23.78	221102 09:35:02.59	221102 09:35:03.09	no match	no match		10.13	0.3
rTMQ2202211020080774733_16.fits	2534	1207	20	1208	163	18:05:12.880	+24:30:07.97	18:05:12.671	+24:27:17.92	221102 09:35:03.09	221102 09:35:03.59	no match	no match		near edge	near edge
rTMQ2202211020080774732_4.fits	2537	1670	864	1665	924	18:05:45.526	+23:25:13.22	18:05:44.952	+23:24:02.06	221102 09:35:00.10	221102 09:35:00.60	no match	no match		11.12	0.29
rTMQ2202211020080774732_6.fits	8703	1607	393	1627	628	18:05:41.190	+23:34:35.16	18:05:42.367	+23:29:55.16	221102 09:35:00.60	221102 09:35:01.10	no match	no match		10.08	0.29
rTMQ2202211020080774732_8.fits	3823	1548	22	1554	125	18:05:36.951	+23:41:58.06	18:05:37.230	+23:39:55.43	221102 09:35:01.10	221102 09:35:01.59	COSMOS 1054	11131	0.026242335	near edge	near edge
rTMQ2202211020080775024_0.fits	4073	1861	920	-1	-1	17:50:46.029	+18:00:30.49	17:48:11.463	+18:19:08.36	221102 09:36:09.34	221102 09:36:09.84	ONEWEB-0282	49000	-0.334731919	near edge	near edge
rTMQ2202211020080774941_12.fits	32514	795	554	861	776	18:00:24.606	+15:41:32.84	18:00:29.644	+15:37:07.22	221102 09:35:51.73	221102 09:35:52.23	no match	no match		10.24	0.16
rTMQ2202211020080774941_14.fits	37373	657	91	726	325	18:00:14.058	+15:50:46.84	18:00:19.329	+15:46:06.86	221102 09:35:52.23	221102 09:35:52.73	no match	no match		10.15	0.16
rTMQ2202211020080775032_12.fits	41657	299	12	348	138	17:53:02.027	+16:41:52.48	17:53:05.895	+16:39:21.72	221102 09:36:12.34	221102 09:36:12.84	no match	no match		near edge	near edge
rTMQ2202211020080775032_14.fits	218593	547	593	670	881	17:53:21.673	+16:30:16.73	17:53:31.405	+16:24:31.74	221102 09:36:12.84	221102 09:36:13.34	no match	no match		10.38	1.24
rTMQ2202211020080775514_0.fits	22810	918	438	883	559	17:52:36.629	+10:21:06.93	17:52:33.717	+10:18:43.40	221102 09:38:01.02	221102 09:38:01.52	COSMOS 706	7625	-0.007347296	10.06	2.71
rTMQ2202211020080775514_2.fits	2515	978	210	944	328	17:52:41.637	+10:25:37.44	17:52:38.807	+10:23:17.48	221102 09:38:01.52	221102 09:38:02.02	COSMOS 706	7625	-0.007347296	10.49	2.71
rTMQ2202211020080775514_4.fits	12772	1038	16	1021	82	17:52:46.621	+10:29:27.48	17:52:45.201	+10:28:09.19	221102 09:38:02.02	221102 09:38:02.52	COSMOS 706	7625	-0.007353082	near edge	near edge
rTMQ2202211020080775515_16.fits	44118	1514	769	1486	883	17:53:26.203	+11:02:34.81	17:53:23.875	+11:00:19.42	221102 09:38:05.02	221102 09:38:05.52	no match	no match		11.39	4.87
rTMQ2202211020080775713_2.fits	25245	132	482	115	724	18:19:03.074	+02:30:33.23	18:19:01.670	+02:25:45.46	221102 09:38:52.84	221102 09:38:53.34	COSMOS 521	6206	0.026103945	9.79	0.62
rTMQ2202211020080775713_4.fits	16776	163	72	155	232	18:19:05.627	+02:38:40.63	18:19:04.956	+02:35:30.44	221102 09:38:53.34	221102 09:38:53.84	COSMOS 521	6206	0.026103945	10.26	0.62
rTMQ2202211020080775811_0.fits	252757	27	877	81	922	18:16:40.633	+00:46:52.72	18:16:44.912	+00:45:59.16	221102 09:39:13.16	221102 09:39:13.66	STARLINK-4143	53029	-0.15222992	near edge	near edge
rTMQ2202211020080775715_16.fits	20065	475	750	465	913	18:19:32.158	+04:01:34.41	18:19:31.298	+03:58:20.57	221102 09:38:56.34	221102 09:38:56.84	no match	no match		10.53	0.45
rTMQ2202211020080775915_0.fits	111835	67	796	164	878	18:16:47.586	+03:36:35.02	18:16:55.259	+03:34:57.03	221102 09:39:33.99	221102 09:39:34.49	GLOBALSTAR M045	25676	-0.074896606	8.67	0.47
rTMQ2202211020080775714_8.fits	5577	292	890	-1	-1	18:19:16.162	+03:10:44.68	18:18:53.452	+03:28:27.22	221102 09:38:54.34	221102 09:38:54.84	no match	no match		near edge	near edge
rTMQ2202211020080775714_10.fits	23956	334	385	316	627	18:19:19.821	+03:20:45.05	18:19:18.236	+03:15:57.31	221102 09:38:54.84	221102 09:38:55.34	no match	no match		10.08	0.7
rTMQ2202211020080775714_12.fits	4377	358	49	359	114	18:19:21.946	+03:27:24.61	18:19:21.983	+03:26:07.26	221102 09:38:55.34	221102 09:38:55.84	no match	no match		near edge	near edge
rTMQ2202211020080776321_0.fits	24537	11	607	133	727	19:04:52.331	-06:57:55.61	19:05:02.121	-07:00:17.59	221102 09:41:09.28	221102 09:41:09.78	GLOBALSTAR M045	25676	-0.075999473	near edge	near edge
rTMQ2202211020080776321_2.fits	766	349	927	349	927	19:05:19.453	-07:04:14.18	19:05:19.453	-07:04:14.18	221102 09:41:09.78	221102 09:41:10.28	GLOBALSTAR M045	25676	-0.075999473	11.08	0.4

FITS file name (subframe) — XY coordinates of streak ends — RA/Dec coordinates of streak ends — UTC time start and stop subframe — Matches with Space-track.org — Time diff. TLE — Photometry (if not near edge)

Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory

Conclusions. Future work. Acknowledgements

CONCLUSIONS

- **Heterogenous computing can dramatically improve timing performance** when processing massive number of images.
- We have developed a real-time processing system to detect and identify objects as streaks, based in heterogenous computing (mixed multi CPU-GPU), in two variants (standard and high sensitivity), with **Real-Time performance (images processed faster than they are produced).**
- We have installed the system in **Kiso Observatory** with good results after the 1st observation campaign.
- Currently we can fast-process all ranges of unresolved objects, from **dot-shaped to streak-shaped**.
- GPU-based streaks process can detect a **percentage of non-catalogued objects** (space-track database): **~30 objects in 2 hours time after sunset.**

FUTURE WORK

- Accuracy in streak end coordinates in **very faint streaks**.
- Streaks **across several sensors**.
- **Automated pipeline** between observations sites.
- Increase performance with **cloudy weather**.

ACKNOWLEDGEMENTS

- Part of this research is funded by **JSPS** (Japan Society of Promotion of Science) under the Fellowship Program.
- Astronomical images for the case study were kindly provided by the **Tomo-e Gozen Team of University of Tokyo.**

B05

China’s Role in the International Framework for Space Debris Mitigation

〇Tao Yangzi (Keio Univ.)

The long-term sustainability of space activities has been compromised by the increasing amount of space debris. Along with carrying out space activities, states are aiming at advancing space debris mitigation (SDM) measures. The UN COPUOS Guidelines for the Long-term Sustainability of Outer Space Activities is one of the instructive examples of the relatively few international rules that are currently in place for SDM, yet only 21 of which have currently obtained unanimous consensus while the guidelines concerning active debris removal (ADR) have not. The representatives of China and other countries suggested a working group be formed under the COPUOS to carry on the negotiations in this regard. China, a major spacefaring nation, advocates for an international regulatory framework for SDM measures and the formation of ADR procedural standards, which is also reflected in its 2021 Space White Paper. This paper presents SDM-related perspectives and related developments in this white paper in order to analyze China's role in the future international framework for SDM.

China’s Role in the International Framework for Space Debris Mitigation

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China’s Space Program: A 2021 Perspective

- Released every 5 years
- Introduces China's purposes, principles, policies, measures and cooperative mindset in space activities

China's Space Program: A 2021 Perspective

- China has strengthened international exchanges on space debris, long-term sustainability of outer space activities, and other issues through mechanisms such as the Space Debris Work Group of China-Russia Space Cooperation Sub-committee and the Sino-US Expert Workshop on Space Debris and Space Flight Safety.
- China supports the activities of international organizations such as the International Telecommunication Union, Group on Earth Observations, Inter-Agency Space Debris Coordination Committee, Consultative Committee for Space Data Systems, International Space Exploration Coordination Group, and the Interagency Operations Advisory Group.

3

China's Space Program: A 2021 Perspective

Experiments on New Technologies

In the next five years, China will focus on new technology engineering and application, conduct in-orbit tests of new space materials, devices and techniques, and test new technologies in these areas:

- Smart self-management of spacecraft;
- Space mission extension vehicle;
- Innovative space propulsion;
- In-orbit service and maintenance of spacecraft;
- Space debris cleaning.

4

China’s Space Program: A 2021 Perspective

Space Environment Governance

- With a growing database, China's space debris monitoring system is becoming more capable of collision warning and space event perception and response, effectively ensuring the safety of in-orbit spacecraft.
- In compliance with the Space Debris Mitigation Guidelines and the Guidelines for the Long-term Sustainability of Outer Space Activities, China has applied upper-stage passivation to all its carrier rockets, and completed end-of-life active deorbit of the Tiangong-2 and other spacecraft, making a positive contribution to mitigating space debris.
- Progress has been made in the search and tracking of near-earth objects and in data analysis. A basic space climate service system is now in place, capable of providing services in space climate monitoring, early warning, and forecasting, and is providing broader applications.

5

China’s Space Program: A 2021 Perspective

Space Environment Governance

In the next five years, China will continue to expand its space environment governance system. It will:

- Strengthen space traffic control;
- Improve its space debris monitoring system, cataloging database, and early warning services;
- Conduct in-orbit maintenance of spacecraft, collision avoidance and control, and space debris mitigation, to ensure the safe, stable and orderly operation of the space system;
- Strengthen the protection of its space activities, assets and other interests by boosting capacity in disaster backup and information protection, and increasing invulnerability and survivability;
- Study plans for building a near-earth object defense system, and increase the capacity of near-earth object monitoring, cataloging, early warning, and response;
- Build an integrated space-ground space climate monitoring system, and continue to improve relevant services to effectively respond to catastrophic space climate events.

6

China's Space Program: A 2021 Perspective

Developing and Expanding Space Application Industry

To serve the economy and society, China has promoted public and commercial applications of space technology.

New business models for upscaling the space economy, including debris removal, will be developed to expand the industry.

Under UNCOPUOS Framework

Space Debris Mitigation Standards Compendium

- National mechanisms

Recommendations on SDM, such as the UN Guidelines and the European Code of Conduct, have been incorporated into national legislation, creating obligations to be followed by entities under national jurisdiction when carrying out space activities.

COPUOS: Committee on the Peaceful Uses of Outer Space

Under UNCOPUOS Framework

Space Debris Mitigation Standards Compendium

- States that have not established national mechanisms
  - ➢ conducting space activities within the framework of the ESA
  - ➢ emerging spacefaring nations
  - ➢ do not yet possess space technology

9

Soft Law

- Shortcoming: lack of legally binding force
- Advantage: flexibility
- a transitional form between non-binding rules and customary international law

10

Advocate international dialogue and establish procedural rules for SDM measures

- The difficulty of promoting SDM activities on a large scale

➢ unorganized state of SDM

➢ lack of international rules

➢ the fact that cooperation mostly takes the form of bilateral agreements

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Advocate international dialogue and establish procedural rules for SDM measures

- China is currently leading the way in the development of international rules in this field

➢ China could use its position as a permanent member of the UN to advocate the establishment of a data-sharing center for the monitoring of space debris

➢ UN should be responsible for the continuous supervision of the SDM activities so as to ensure transparency, thus avoiding the use of removal activities for military purpose

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International cooperation

- China has always emphasized the importance of international cooperation in space exploration
  - ➢ signed multiple space cooperation agreements or memorandums of understanding with other national space agencies and international organizations, including cooperation projects on space debris
  - ➢ China should cooperate with western space powers (e.g., space debris data sharing agreements) to strengthen the construction of space situational awareness systems and enhance the ability to obtain information as well as the ability to forecast technological needs.

Commercial Space Industry

- The influx of capital into the commercial spaceflight sector provided financial support for China's commercial space industry
- Circular of the State Administration of Science, Technology and Industry for National Defense and the Central Military Commission Equipment Development Department on **Promoting the Standardized and Orderly Development of Commercial Launch Vehicles:** In the launch license and special examination application materials, commercial rocket enterprises shall give key explanations on space debris mitigation
- By creating a domestic environment for commercial actors, China is also putting peer pressure on the global commercial space sector, forcing other spacefaring nations to strengthen technical control over their commercial actors, thus promoting competition in the governance of SDM.

B06

Current Status for S&MA Leadership on Sustainable Space Activities and Mission Security TF under the Trilateral Safety and Mission Assurance Meeting

三極安全・ミッション保証会議の下での持続可能な宇宙活動とミッションセキュリティ TF に関する S&MA リーダーシップの現状

〇NITTA Kumi, KITAZAWA Yukihito, TAURA Shinichiro (JAXA Safety and Mission Assurance Department)
〇仁田工美、北澤幸人、田浦伸一郎（JAXA 安信部）

The current status of efforts for sustainable space utilization under the S&MA (NASA/ESA/JAXA) trilateral meeting, especially the current recognition and methods for small debris, breaking down from "what to do" to "how to do" will be introduced.

S&MA3 極（NASA/ESA/JAXA）会合下で実施されている持続可能な宇宙利用にむけての取り組みの現状、特に What to do から How to do にブレークダウンした small debris に係る現状認識と、手法等を紹介する。

Current Status for S&MA leadership on sustainable space activities and mission security TF under the Trilateral Safety and Mission Assurance Meeting

Kumi NITTA
Japan Aerospace Exploration Agency
System Safety and Space Operations Safety Unit

Introduction

How is NASA/ESA/JAXA S&MA meeting ?

The purpose of the meeting is to exchange opinions and promote cooperation on common issues related to safety and mission assurance among Japanese, European, and U.S. space agencies.

★Current Status of Meetings

The first meeting was held in 2006, and meetings are held every 1.5 years on a rotating basis. Since 2010, the Trilateral Safety and Mission Assurance Conference (TRISMAC), an open symposium including related companies, has been held every three years in conjunction with the trilateral meetings.

★Main Activities and Major Achievements

①Sharing of materials

S&MA-related materials are exchanged for the purpose of sharing the past knowledge of the trilateral parties, recognizing the differences among them, and utilizing the materials in international cooperation missions.

②Comparison of S&MA standards

S&MA standards are compared in order to deepen mutual understanding of S&MA requirements and to support smooth implementation of project activities in international cooperation projects

③Sharing of Alerts

In order to share information on defects that can be disclosed among the trilateral parties, activities to exchange new alerts and the annual alert list have been conducted since 2016.

3極S&MA活動／Space Sustainability Task Forceの概要

1. Space Sustainability TF

(1) 契機

2021/5月のTRISMACにて、スペースデブリ急増に伴う軌道環境悪化に対して、「三極S&MAの枠組みで何かできないのか」との意見あり。
対策協議を目的とするTFの設置に三極合意。

(2) TF Charter

2021/10月に第1回会議を開催。

何度かの会議／認識合わせを経て、2022/3月にTF Charterにサインアップ。

(3) 認識及び目的等（Charterの骨子）

(a)タイトル＝"Sustainable Space" Task Force (from S&MA perspective)

(b)軌道上の人工物、特にSpace Debris増加は、Outer SpaceのSustainability、特に有人・無人宇宙機のリスクを増しており、重要な課題と
認識されている。そうであるがゆえに、UNやISO、IADC等の国際機関・フォーラムや各国は、Space Sustainability保持を目的とする多くの法規やガイドラインを制定している。

(c)しかし、これら法規・ガイドラインは、宇宙機及びその運用に対する要求＝「何をなすべきか」（What to Do）を定義するが、その実現方法（How to Do）は必ずしも共有されていない。法規・ガイドラインに適合させるアプローチを構築し、これを共有することは全ての宇宙関連組織のニーズに
合致すると考える。

(d)本TFでは、3極が保有する知見（文書・ツール・設備及び人的ネットワーク）を整理、宇宙開発・利用に従事する組織（民間含む）と共有し、
もってSpace Sustainability実現の一助とすることを狙う。

TF Activity Report Contents

1. Introduction to the "Space Sustainability TF

(1) Background and History

(2) TF Charter Outline

(3) Expected Outcome

2. Phase 1 Achievement

(1) Plan vs. Achievement

(2) Output

- Information Package: Standard Content
- Information Package Example
- Initial User Feedback

3. Recommendation

(1) Recommendation from the Team

(2) Phase 2 Plan Outline

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TF Activity Report Contents

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1. Introduction to the SSTF – (1) Background and History

(1) Background

- An opinion was raised by a participant upon continuous Space Debris increase that; "Isn't there anything Trilateral S&MA could do against the worsening orbit situation?" (TRISMAC 2021; May 2021)
- We all agreed to form a TF dedicated to "Space Sustainability" (Trilateral Summit; June 2021)

(2) History

- Kickoff meeting held in Oct. 2021
- Participants agreed on the understanding of the situation and the TF mission;
  - ✓ Requirements ("What to Dos") are available in various doc's but NOT properly implemented as expected
  - ✓ S&MA are the ones to provide "How to Dos" to realize "Space Sustainable" products/ services
  - ✓ Selected UNCOPUOS LTS Guideline as "Starting Point" as it brings a comprehensive agenda for Space Sustainability
  - ✓ TF to develop "Information Packages (IP)" to be used in development frontlines
- TF Charter was signed in Mar. 2022
- Developed an IP example and started (or "about to start") user feedback collection

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1. Introduction to the SSTF – (2) TF Charter Outline

(1)"Sustainable Space" Task Force (from S&MA perspective)

Adobe Acrobat Document

(2)Important Notes

(a) Many regulations, guidelines, and recommendations related to space sustainability (including space debris mitigation) have been issued, and "What to Do" for Space Actors is becoming more apparent.

(b) However, consistent compliance with the regulatory framework above continues to be problematic. It is in the common interest of all Space Actors to establish and share possible approaches to meet the full intent of policy related to space sustainability.

(3)TF Mission

(a) S&MA will provide "How to Do" support to the operators (projects and businesses) inside and outside each agency by utilizing its accumulated technology, knowledge, and various networks.

(b) Specifically, we provide helpful information and technical support to assist operators to "implement" the requirements and recommendations (Shall, Should, Recommend) specified in various guidelines, ISO, and standard documents of each agency into their products, design, manufacturing, and operation technologies.

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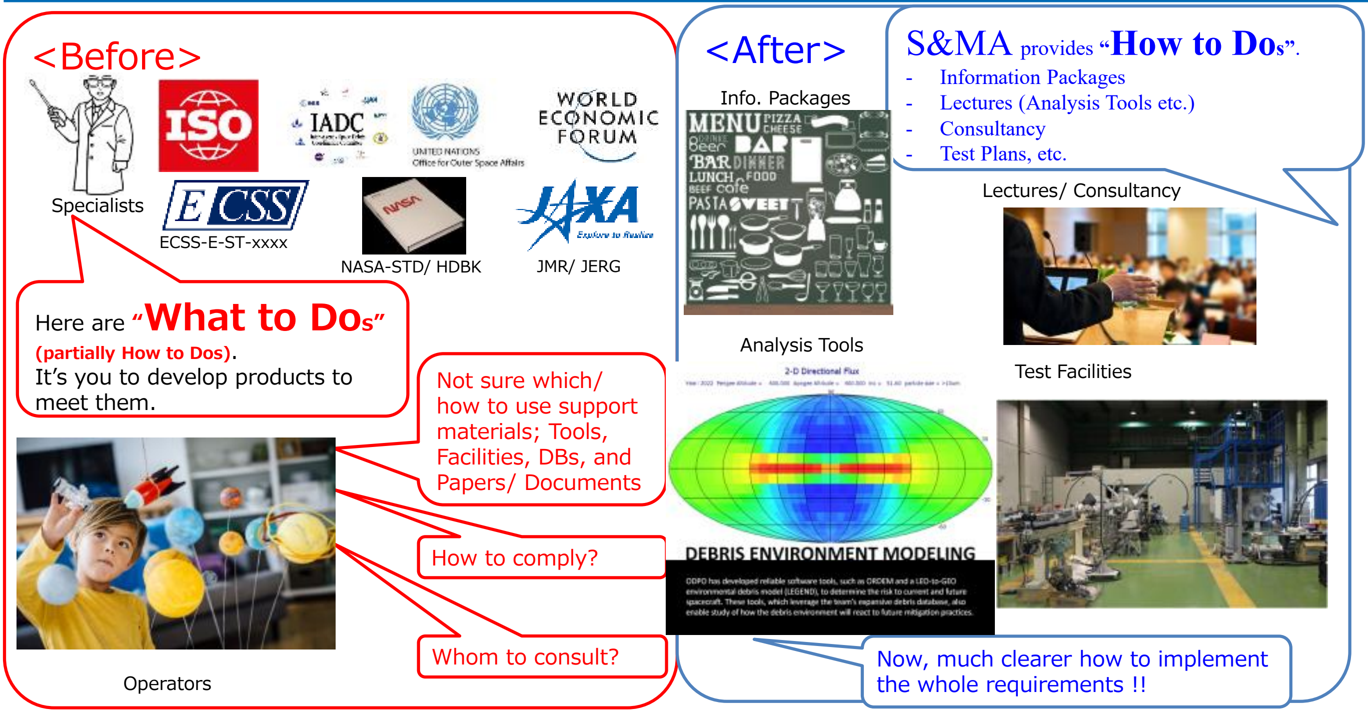
1. Introduction to the SSTF – (3) Expected Outcome



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TF Activity Report Contents

1. Introduction to the "Space Sustainability TF
   (1) Background and History
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   (3) Expected Outcome
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   (1) Plan vs. Achievement
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3. Recommendation
   (1) Recommendation from the Team
   (2) Phase 2 Plan Outline

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2. Phase 1 Achievement – Output

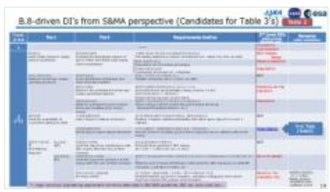
Starting from LTS B.8 high-level requirements, extracted technical keywords (Discussion Items; DI) for which "How to Dos" should be developed and shared.
Table 3s in the "Information Package" provide comprehensive information from three agencies.

Step 1
Extract LTS B.8 Full Statements that require measures

→ **Step 2**
"Table 1"
Select High-Priority 1st Level DI's

→ **Step 3**
"Table 2"
Select 2nd Level DI's (Technical Keywords)

→ **Step 4**
IP incl. "Table 3s"
Arrange available resources for the selected DI



Standard IP Contents (Template)

Example Table 3 for "Small Debris"

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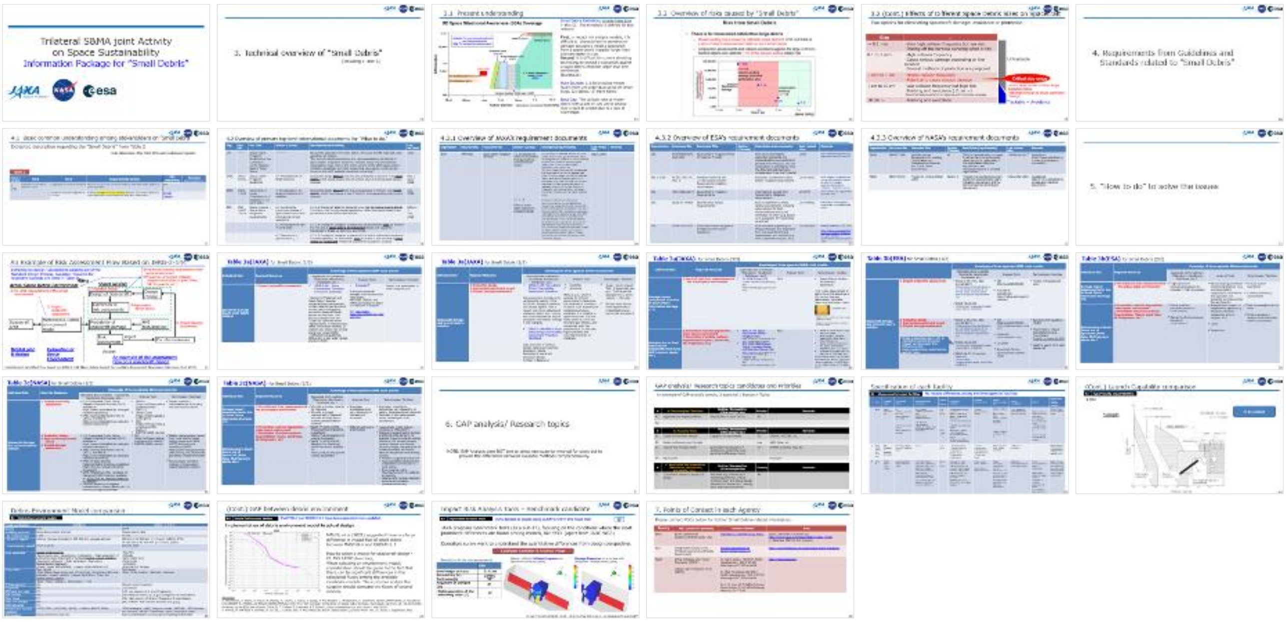
Example IP for Small Debris



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2. Phase 1 Achievement - Summary

Thanks to TF participants' cooperation, now we're ready to listen to potential users.
We could develop better packages upon their voice and expand coverage along with the TF purpose.

Planned Actions (from Charter)	Achievements	Comments
1. Develop useful Knowledge Base (1) Applicable documents and Websites (Standards, Handbooks, databases, etc.) (2) Owned tools (3) Available technologies and facilities	(1) Broke down LTS B.8 to extract technical keywords (DIs), which require comprehensive IPs (2) Took "Small Debris" as a DI example and developed the draft IP (3) Completed standard contents of IP (4) Completed an example draft IP for Small Debris	(1) Draft IP comprehensively summarized required information (2) Collecting feedback from potential users (JAXA)
2. Develop the way of informing the operators	Not yet completed	Too early to publicize; need multiple IPs before informing
3. Develop action plan forward	TF agreed on the Phase 2 plan outline	

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2. Phase 1 Achievement – Initial Feedback

We need User feedback

JUST NOW

TF Activity Report Contents

1. Introduction to the "Space Sustainability TF
   - (1) Background and History
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   - (1) Plan vs. Achievement
   - (2) Output
     - Information Package: Standard Content
     - Information Package Example
     - Initial User Feedback
3. From the Team
   - (1) From the tham
   - (2) Phase 2 Plan Outline

3. From the Team

1. The team believes the activity itself and the "Information Package" are worthwhile;
   (1) shows fully supportive attitude of the three agencies
   (2) comprehensive information
   (3) TBD

2. On the other hand, the achievement to date is limited;
   (1) Just started users' voice on the Draft IP; subject to refinement
   (2) Only one DI has been covered; more DIs should be covered
   (3) Yet to be shared with public users

3. The team strongly recommends continuing the TF, along with the Charter.

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3. Phase 2 Plan Outline

"Phase 2" = Jan. 2023 until the next TRISMAC in 2024 (1.5 years)

Target outcome, Action, and Deliverables for Phase 2 will be defined in the updated Charter.

1. Develop IPs for 'How to Do'

(1) Small Debris (completed)
(2) Re-entry Risk
(3)Others (To be Confirmed)

Main Stream

2. Publish/ Announcement

(1) HP sites (internal & trilateral S&MA community reviews expected)
(2) Presentation at the next TRISMAC, announcing new HP sites for users
(3) Others

User Feedback

(Note) example for Small Debris; different approaches might be appropriate for other IPs

Input

Out-of-TF activities (upon agreement)

(1) Comparison Test
(ex. Hypervelocity impact facilities)
(2) Benchmark Evaluation
(ex. Impact Risk Analysis Tools)
(3) Design Guideline comparison
(ex. Protection Design)

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3. Phase 2 Plan Outline – User communication

(1) Target Outcome

(a) List all the DI Packages in the respective Agency HP site
(b) FAQs accessible for each DI
(c) Request form available for users
(d) Link to the other Agency DI sites

(2) Steps to proceed

(a) Complete the Small Debris package with agency-internal users' review
(b) Complete several DI packages with the same level of maturity (through internal users' review)
(c) Introduce to the public in the next TRISMAC in 2024
(d) Open the sites both to internal and public after the TRISMAC

(Note) Details to be discussed

B.8 Analysis (Extract Discussion Issues out of B.8 requirements and recommendations)

Table 1 (Note) Cat.1=Priority High / (Cat.)=Out of S&MA scope; lower priority

Chapt. of B.8	Excerpts that requires actions	Priority as S&M(P)A	Remarks	Discussion Issues as S&M(P)A (1st Level DI)
1	promote design approaches that increase the trackability of space objects	Category 1 Within the scope of 'design support' while including R&D factors		Improve Trackability
	facilitate the accurate and precise determination of their position	Cat.3 Tracking & Control agency/ section is responsible	Collaboration/ Integration with the sections is important in terms of Trackability	N/A
2	design such objects to limit the long-term presence of space objects in protected regions of outer space ↑ To be broken down into technical issues (Table2)	Cat.1 Break-up prevention/ de-orbit on/ from the protected orbit are the major purposes; various Design supports are effective to improve 'assurance'	Quantitative targets, sharing/ publicizing technical requirements/ information that comply with each organization's standard (and IADC, ISO) is meaningful. (UN Space Debris Mitigation guideline lacks quantitative targets.)	Major technical/ engineering items commonly described in various standards and guidelines ↑ Select as 1st Level DI
	share their experiences and information on the operation and end-of-life disposal of space objects	Cat.2 Sharing technical experiences should be effective	Collaboration with T&C section should be important	N/A
3	the implementation of the present guideline supports the development of space pro-grammes (for developing countries and emerging spacefaring countries, due to the importance of small-size space object)	(Cat.2) Publicizing activities assuring 1&2 above could bring significant influence	International Affairs, Public Affairs, and Education Center are responsible; collaboration is important	N/A

B.8-driven DI's from S&MA perspective (Candidates for Table 3's) Table 2

Chapt. of B.8	Tier1		Tier2	Requirements Outline	2nd Level DI's (High-priority keywords only)	Remarks (other candidates)
1				−−−	Trackability improvement	
2 (*1)	発生抑止 Limit debris released during normal operations		部品等放出抑制 Avoiding the intentional release of space debris into Earth orbit during normal operations	分離後に軌道に残る恐れのある締結具等の放出防止 Preventing unintended release of fasteners etc. which may stay on orbit	Non-release design	
				剥離、脱落等の防止 Separation and Desertion prevention	Material selection	
				燃焼排出物等の抑制 Combustion Emissions etc. mitigation	Slag debris	
	軌道上破砕の防止 Minimize break-ups during operational phases		破壊行為禁止 Avoid intentional destruction and other harmful activities	軌道上で宇宙システムを破壊しない。 Prohibit destroying space system on orbit.	N/A	
			運用中の事故 Minimize the potential for break-ups during operational phases	運用中の偶発的破砕発生率を0.001以下とする。 Accidental break-up probability during mission <0.001 破砕の兆候を検知して、破砕を防ぐ。 Monitor Break-up signs to prevent it.	Reliability during operation	
			残留推薬放出等 Minimize potential for post-mission break-ups resulting from stored energy	運用終了後の破砕を防ぐため残留エネルギを排除する。 Stored energy release to prevent post-mission break-up. （Residual Propellant Release, etc.）	Passivation	
	衝突対策 Limit the probability of accidental collision in orbit		大型物体衝突回避 Large Objects Collision Avoidance	他の宇宙物体と衝突する可能性を検知し、衝突を回避する。 Monitor, evaluate collision probability with other space objects to avoid a collision.	N/A	
			小型物体衝突対策 Small Objects Anti-Collision Measures	デブリとの衝突で（廃棄処置が不可能になる）不具合を防ぐ。 Prevent disorder (disables post-mission disposal) due to collision with Small Debris.	Small Debris	First Topic (Table3)
	運用終了後の処置 Post-Mission Disposal	静止軌道 GEO	保護域からの排除 Limit the long-term interference with GEO region after the end of their missions	静止軌道保護域から退避する。 Evacuate from protected GEO region. $\Delta H = 235 + 1{,}000 \times CR \times A / m$ [km]	N/A	
		低高度軌道 LEO	保護軌道域からの排除 Limit the long-term presence in LEO region after the end of their missions	運用終了後は軌道寿命の短縮、制御再突入等の処分により保護軌道域との干渉を最小限に抑える。 Minimize post-mission interference with protected GEO region by on-orbit life reduction, controlled re-entry, etc.	De-orbit design	
			再突入時の地上被害回避 Re-entry Safety	落下危険度（傷害予測数）を予測し、要すれば破片落下区域 Evaluate fall risk (projected casualty), announce anticipated area where fragment reaches the ground when required.	Re-entry risk (casualty risk)	溶融解析の比較照合 （B. 9へも貢献） Melting Analysis comparison (also contribute to B.9)

*1 major technical/ engineering requirement commonly described in UN/ IADC guidelines, ISO, etc. (based on Kato, 2021)

2. Phase 1 Achievement – Standard contents for each DI

Contents	Notes
1. Discussion Issue	Description of the Discussion Issue using simple words.
2. Definition	A simple definition of the issue. The definition is recommended to refer to international documents. (ex. ISO24113, IADC guideline, etc.)
3. Technical overview of the DI 3.1 Present understanding 3.2 Overview of risks caused by the DI	A brief description of the present knowledge.
4. Requirements from Guidelines and Standards related to the DI 4.1 Basic common understanding among stakeholders (ESA, NASA, JAXA, and manufacturers/ operators) 4.2 Lists of International documents	4.1 Extracts of description regarding the DI of Table 2 4.2 Extracts of requiems regarding the DI
5. "How to do" to solve the issues 5.1 Overview of technical background (optional) 5.2 "Table 3"s	5.1 Brief overview of contents of Table3s if necessary 5.2 Tables summarizing each agency's resources
6. GAP analysis/ Research topics (Optional)	Issues that S&MA should or under research so that documents, analysis tools, equipment, etc., will be more helpful to users (accuracy, usability, etc.)
7. Points of Contact in each Agency	Provide POCs to consult with.

Trilateral S&MA joint Activity on Space Sustainability

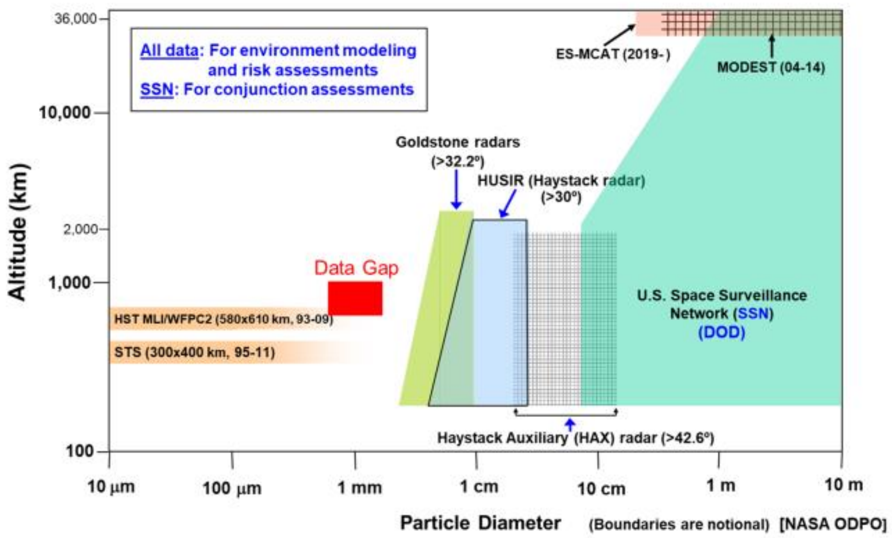
Information Package for “Small Debris”

3. Technical overview of “Small Debris”

(Including 1. and 2.)

3.1 Present understanding

OD Space Situational Awareness (SSA) Coverage



Small Debris Definition: smaller than 1cm in this DI. The threshold is defined for two reasons.

First, in impact risk analysis models, it is difficult to characterize the penetrative damage accurately inside a spacecraft from a space debris impactor larger than one centimeter in size.
Second, it is difficult for current shielding technology to protect a spacecraft against a space debris impactor larger than one centimeter.
[ISO16126]

Main Sources: (1) Solid rocket motors (SRM) from µm-order dust up to cm-order slugs, (2) Ejects, (3) Paint flakes

Data Gap: The collision rate of micro-debris with a size of 100 µm to several mm is hard to predict due to a lack of knowledge.

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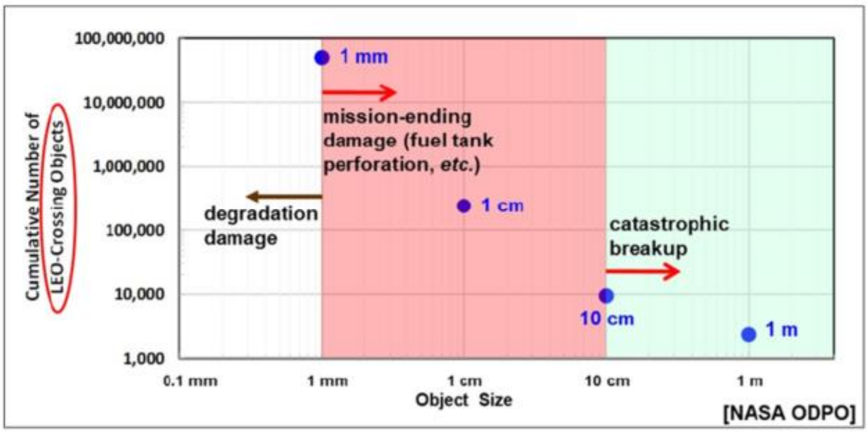
3.2 Overview of risks caused by "Small Debris"

Risk from Small Debris

- **There is far more small debris than large debris**
  - Mission-ending risk is driven by millimeter-sized debris in LEO, but there is a lack of direct measurement data on such small debris
  - Conjunction assessments and collision avoidance against the large (≥10 cm) tracked objects only address <1% of the mission-ending impact risk



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3.2 (Cont.) Effects of Different Space Debris Sizes on Spacecraft

Two options for eliminating spacecraft damage: avoidance or protection

Size	--
～ 0.1 mm	･Very high collision frequency but low risk ･Peeling off the harness covering when it hits
0.1 to 1 mm	･High collision frequency ･Cause serious damage depending on the location ･Several methods of protection are proposed
1 mm to 1 cm	･Middle collision frequency ･Potential to cause serious damage
1 cm to 10 cm	･Low collision frequency but high risk ･Tracking and avoidance (2 cm ～) ･Note that High uncertainty in tracking and incomplete coverage
10 cm ～	･Tracking and avoidance

Untrackable

Critical size range

･much more numerous than larger trackable debris
･still large enough to cause significant damage

Trackable = Avoidance

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4. Requirements from Guidelines and Standards related to “Small Debris”

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4.1 Basic common understanding among stakeholders on "Small Debris"

Extracted description regarding the "Small Debris" from Table 2

Note: Stakeholders = ESA, NASA, JAXA, and manufacturers/ operators

Table 2

Chapt. of B.8	Tier1	Tier2	Requirements Outline	DI's (High-priority keywords only)	Remarks (other candidates)
2 (*1)	Prevention of accidental collision in orbit	Large Objects Collision Avoidance	Monitor and evaluate collision probability with other space objects to avoid a collision.	N/A	
		Protection for Small Objects Anti-Collision	Prevent damage to critical systems (disables post-mission disposal) and catastrophic hazard due to collision with Small Debris.	Small Debris	

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4.2 Overview of primary top-level international documents for "What to do."

Org.	Doc. No.	Doc. Title	Section (Clauses)	Description (requirements)	Last rev./date
UN	―――	Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space	―――――	No specific description for small debris. However, the UN endorsed IADC guidelines as follows. "For more in-depth descriptions and recommendations pertaining to space debris mitigation measures, Member States and international organizations may refer to the latest version of the IADC space debris mitigation guidelines and other supporting documents, which can be found on the IADC website (www.iadc-online.org)"	2010
IADC	IADC-02-01	Space Debris Mitigation Guidelines	5.4 Prevention of On-Orbit Collisions	Spacecraft design **should** also limit the probability of collision with **small debris** which could cause a loss of control, thus preventing post-mission disposal.	Rev. 3 June 2021
IADC	IADC-15-03	Statement on Large Constellations of Satellites in Low Earth Orbit	3. Considerations for large constellations of satellites	Spacecraft design **should** limit the consequences of collision with **small debris**, which could cause a loss of control, thus preventing post-mission disposal.	July 2021
ISO	ISO 24113 :2019	Space systems — Space debris mitigation requirements	6.1 Avoiding the intentional release of space debris into Earth orbit during normal operations	6.1.1.1 Spacecraft **shall** be designed so as **not to release space debris** into Earth orbit during normal operations, other than space debris from pyrotechnics and solid rocket motors.	Edition : 3 July 2019
			6.2 Avoiding break-ups in Earth orbit	6.2.3.4 During the design of a spacecraft an assessment **shall** be made of the risk that a **space debris or meteoroid** impact will cause the Spacecraft to break-up before its end of life.	
			6.3 Disposal of a spacecraft or (…)	6.3.1.2 During the design of a spacecraft for which a disposal manoeuvre has been planned, an assessment **shall** be made of the risk that a **space debris or meteoroid** impact will prevent the successful disposal	

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4.3.1 Overview of JAXA's requirement documents

Organization	Document No.	Document Title	Section (Clauses)	Description (requirements)	Last revised date	Remarks
JAXA	JMR-003D	Space Debris Mitigation Standard	5.1.2 Limitation of combustion products from pyrotechnics and solid rocket motors 5.3.1.1.8 Effect of space debris impact and protection design	(1) Pyrotechnic devices, except for solid rocket motors and igniter devices, shall be designed and used so as not to release combustion products and fragments larger than 1 mm in their largest dimension into Earth orbit. (2) Solid rocket motors shall be designed and operated so as not to release slag sized 1 mm or larger into GEO protected region and LEO protected region. It is evaluated on a case-by-case basis when the effect on GEO protected region by released products is limited due to its trajectory such as the moon, planetary and other missions with a highly elliptical orbit. Probability of the loss of disposal functions shall be calculated against impacts by space debris and meteoroid. Critical components and cables shall be in the calculation then protection measures, redundancy and layout change should be considered if the risk is unacceptable. The acceptable criteria shall be defined for each mission taking into account for the technical maturity of collision risk calculation and protection methods. Refer to "Micro-debris Impact Survivability Assessment Procedure (JERG-2-144)" about the collision risk calculation and protection design.	Sep.9, 2020	

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4.3.2 Overview of ESA's requirement documents

Organization	Document No.	Document Title	Section (Clauses)	Description (requirements)	Last revised date	Remarks
ESA	ESA/ADMIN/IPOL(2014)2	Space Debris Mitigation Policy for Agency Projects		ESA policy defining the applicable standards, the implementation and verification procedure for Projects, and the certification of compliance from the ESA Technical Authority (independent from the Projects)	2022	https://technology.esa.int/page/space-debris-mitigation
ESA / ECSS	ECSS-U-AS-10C, Rev. 1	Adoption Notice of ISO 24113: Space systems - Space debris mitigation requirements		European standard for Space Debris Mitigation requirements	2019/12/03	https://ecss.nl/standard/ecss-u-as-10c-adoption-notice-of-iso-24113-space-systems-space-debris-mitigation-requirements-2/
ISO	ISO 24113:2019	Space Debris Mitigation Requirements		International standard for Space Debris Mitigation requirements	2019/07	https://www.iso.org/standard/72383.html
ESA	ESSB-ST-U-004	ESA Re-entry Safety Requirements		ESA standard for re-entry safety requirements, including requirements for both uncontrolled re-entry and controlled re-entry (e.g. based on 5 successful ATV controlled re-entries)	2017/04/12	Distribution upon request: (space.debris.mitigation@esa.int)
ESA	ESSB-HB-U-002	ESA Space Debris Mitigation Compliance Verification Guidelines		ESA handbook explaining to Project Manager and Engineers how the requirements are implemented and verified (e.g. how to perform analysis, etc.)	2015/02/19	Issue 2 expected in Q3 2022 https://technology.esa.int/page/space-debris-mitigation (or upon request: space.debris.mitigation@esa.int)

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4.3.3 Overview of NASA's requirement documents

Organization	Document No.	Document Title	Section (Clauses)	Description (requirements)	Last revised date	Remarks
NASA	NPR 8715.6B	NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments	All	This is a top-level policy document. It defines the purpose of orbital debris mitigation, applicability of the orbital debris mitigation requirements, and roles/responsibilities of affected organizations.	16 February 2017	Available at: https://www.orbitaldebris.jsc.nasa.gov/reference-documents/
NASA	NS 8719.14C	Process for Limiting Orbital Debris	Section 4	This technical standard document establishes detailed orbital debris mitigation requirements and the technical rationale behind each requirement.	5 November 2021	Available at: https://www.orbitaldebris.jsc.nasa.gov/reference-documents/

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5. "How to do" to solve the issues

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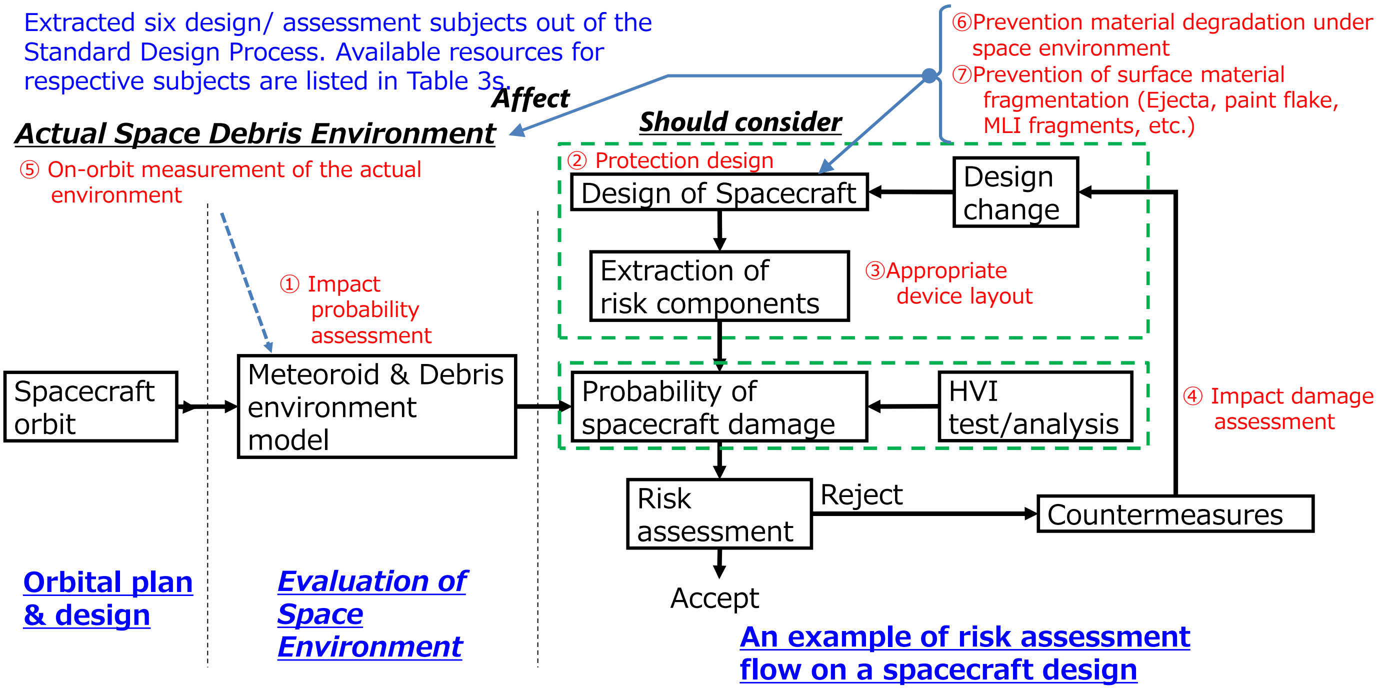
An Example of Risk Assessment Flow Based on JERG-2-144



Modified and simplified flow based on JERG-2-144 Micro-debris Impact Survivability Assessment Procedure (Kitazawa,*et al.*,2016) 33

Table 3a(JAXA) for Small Debris (1/3)

Individual Risk	Required Measures	Knowledge of three agencies S&MA could provide		
		Applicable doc's/websites (Standards, Handbooks, Databases, etc.)	Analysis Tools	Technologies／Facilities
Spacecraft damage due to small debris collision	**① Impact probability assessment**	✓ JERG-2-141 Space Environment Standard (written in Japanese) <Section 10 "Meteoroid and Space Debris" describe meteoroid/debris environment models, selection procedures of models, and those applying process to spacecraft design phases are explained. This process coincides with ISO 14200:2012 (Process-based implementation of meteoroid and debris environment models). In addition, ISO 14200 was revised, and a new version of ISO 14200:2021 was published. JERG-2-141 is also under revised proses in 2022.>	✓ TURANDOT It analyzes spacecraft damages from collisions with space debris. MASTER8、ORDEM3 and MEM3 are handled for debris flux database in analyses. Ref: http://astro-muse.com/contents_en_products.html	Impact risk assessment is done using the tool

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Table 3a(JAXA) for Small Debris (2/3)

Individual Risk	Required Measures	Knowledge of three agencies S&MA could provide		
		Applicable doc's/websites (Standards, Handbooks, Databases, etc.)	Analysis Tools	Technologies／Facilities
Spacecraft damage due to small debris collision	② Protection design ③ Appropriate equipment layout ④ Impact damage assessment	✓ JERG-2-144 Micro-debris Impact Survivability Assessment Procedure the assessment procedure for verifying the validity of the protection design of satellites and probes against risks of impact with micro-debris and meteoroid which are 1 mm or less in size and whose impact probability and impact damage is not negligible ✓ JERG-2-144-HB001 Micro-debris Impact Survivability Assessment Procedure Handbook Data provision of Various Impact Tests and numerical simulation results. Examples of spacecraft protection design (written in Japanese)	✓ LS-DYNA ✓ Autodyne Using E.O.S., which is suitable for collision phenomena to determine the penetration threshold of debris such as protection materials and space materials, it is possible to approximate not only the liquid phase but also the solid and gas phases, and sometimes even the plasma state, to simulate highly dynamic and nonlinear behavior of materials.	✓ Hyper velocity impact Test: 2-stage-light gas gun: ISAS projectile diameter 0.3-3.2mm velocity ~ 7km/sec ✓ Ballistic limit derived from hypervelocity impact testing and hydrocode simulations

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Table 3a(JAXA): for Small Debris (3/3)

Individual Risk	Required Measures	Knowledge of three agencies S&MA could provide		
		Applicable doc's/websites (Standards, Handbooks, Databases, etc.)	Analysis Tools	Technologies／Facilities
Damage impact assessment error due to Small Debris information shortage (*2)	⑤ On-orbit real-time measurement of the actual space environment	✓ On-Orbit Impact DB (Under recovery coordination; Ref: https://matdb.jaxa.jp/main_e.html)	N/A	✓ Space Debris Monitor for onboard Spacecraft <For in-situ measurement of debris flux in the size range of 100 um to a few mm. Measurement parameter: Debris size and Impact time>  ©JAXA,IHI,iQPS https://www.kenkai.jaxa.jp/eng/pickup/sdm.html https://www.kenkai.jaxa.jp/pickup/kasper.html
Pollution due to Small Debris out of Spacecraft (Paint flake, MLI fragment, ejecta, etc.)	⑥ Prevention material degradation under space environment ⑦ Prevention of surface material fragmentation (Ejecta, paint flake, MLI fragments, etc.)	✓ JERG-2-143 Space Environment Effects Mitigation; Ref: https://sma.jaxa.jp/en/TechDoc/Docs/E_JAXA-JERG-2-143.pdf ✓ JMR-003D-HB001 Space Debris Prevention Design and Operation Manual; Ref: https://sma.jaxa.jp/TechDoc/Docs/JAXA-JMR-003-HB001.pdf ✓ Material DB (Under recovery coordination; Ref: https://matdb.jaxa.jp/main_e.html)	N/A	✓ Material characteristics test data for space environment; Material degradation due to AO, UV, Electron ✓ Hyper velocity impact test for ejecta assessment based on ISO11227:2012 ✓ Space environment testing facilities at TKSC facilities https://jaxa.repo.nii.ac.jp/?action=repository_action_common_download&item_id=2565&item_no=1&attribute_id=31&file_no=1

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Table 3b(ESA) for Small Debris (1/2)

		Knowledge of three agencies S&MA could provide		
		Applicable doc's/websites (Standards, Handbooks, Databases, etc.)	Analysis Tools	Technologies／Facilities
Spacecraft damage due to (small) debris collision	① Impact probability assessment	✓ ECSS-U-AS-10C / ISO 24113:2019 (https://ecss.nl/standard/ecss-u-as-10c-adoption-notice-of-iso-24113-space-systems-space-debris-mitigation-requirements-2/) ✓ ESSB-HB-U-002 ✓ (https://technology.esa.int/page/space-debris-mitigation)	✓ ESA DRAMA/ARES/MIDAS ✓ MASTER-8 available at: https://sdup.esoc.esa.int/master/	✓ Models computational tools
	② Protection design ③ Appropriate equipment layout ④ Impact damage assessment Unable to download; sign-in with an organization account is required. Instead, can download it from; https://www.iadc-home.org/documents_public/view/page/2/id/120#u	✓ ECSS-U-AS-10C / ISO 24113:2019 (https://ecss.nl/standard/ecss-u-as-10c-adoption-notice-of-iso-24113-space-systems-space-debris-mitigation-requirements-2/) ✓ ESSB-HB-U-002 (https://technology.esa.int/page/space-debris-mitigation) ✓ IADC-04-03 (Protection Manual) (https://iadc-home.org/documents_public/view/id/81#u)	✓ ESA DRAMA/ARES/MIDAS (https://sdup.esoc.esa.int/drama/) ✓ ESABASE2 (https://esabase2.net/) ✓ LS-DYNA ✓ Smoothed-Particle Hydrodynamics (SPH) codes	✓ Ballistic Limit Equations (BLEs) ✓ Hypervelocity impact tests/facilities (e.g. Fraunhofer) English - Fraunhofer EMI ✓ Lessons learnt from past spacecraft

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Table 3b(ESA) for Small Debris (2/2)

Individual Risk	Required Measures	Knowledge of three agencies S&MA could provide		
		Applicable doc's/websites (Standards, Handbooks, Databases, etc.)	Analysis Tools	Technologies／Facilities
Damage impact assessment error due to Small Debris information shortage (*2)	⑤ On-orbit real time measurement of the actual space environment	✓ Flight operation manuals/procedures to manage in-flight anomalies	✓ Housekeeping parameter monitoring/analysis (e.g. unit parameters degradation recorded by the Operator and assessed during Anomaly Review Boards)	✓ Ground station operations ✓ Collision probability assessments
Pollution due to Small Debris out of Spacecraft (Paint flake, MLI fragment, ejecta, etc.)	⑥ Prevention material degradation under space environment ⑦ Prevention of surface material fragmentation (Ejecta, paint flake, MLI fragments, etc.)	✓ Space qualified processes/products (https://ecss.nl) ✓ Design/product assurance standards (https://ecss.nl)	✓ Analysis with respect to degradation agents (e.g. radiation, thermal, outgassing, atomic oxygen, etc.) ✓ Tests ✓ Inspection	✓ Best knowledge/practice basis ✓ Orbit propagation analysis from identified debris cloud events

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Table 3c(NASA) for Small Debris (1/2)

Individual Risk	Required Measures	Knowledge of three agencies S&MA could provide		
		Applicable doc's/websites (Standards, Handbooks, Databases, etc.)	Analysis Tools	Technologies／Facilities
Spacecraft damage due to (small) debris collision	① Impact probability assessment	✓ U.S. Government Orbital Debris Mitigation Standard Practices (2019), available at: https://www.orbitaldebris.jsc.nasa.gov/reference-documents/ ✓ NASA Technical Standard 8719.14C (2021), available at: https://www.orbitaldebris.jsc.nasa.gov/reference-documents/	✓ ORDEM (https://software.nasa.gov/software/MSC-25457-1) ✓ ORDEM Cloud (https://ordem.appdat.jsc.nasa.gov/) ✓ DAS (https://software.nasa.gov/software/MSC-26690-1) ✓ BUMPER (NASA internal)	✓ Impact probability assessments are done using the tools listed to the left
	② Protection design ③ Appropriate equipment layout ④ Impact damage assessment	✓ U.S. Government Orbital Debris Mitigation Standard Practices (2019), available at: https://www.orbitaldebris.jsc.nasa.gov/reference-documents/ ✓ NASA Technical Standard 8719.14C (2021), available at: https://www.orbitaldebris.jsc.nasa.gov/reference-documents/ ✓ NASA TP-2003-210788, Meteoroid/Debris Shielding, available at: https://hvit.jsc.nasa.gov/reference-documents/ ✓ NASA TM-2009-214785, Handbook for Designing MMOD Protection, available at: https://hvit.jsc.nasa.gov/reference-documents/ ✓ DebriSat database for fragment characterization (shape, density, etc.) to improve damage assessments	✓ DAS (https://software.nasa.gov/software/MSC-26690-1) ✓ BUMPER (NASA internal)	✓ Ballistic limit equations derived from hypervelocity impact testing (primarily at NASA WSTF) and hydrocode simulations (WSTF: https://www.nasa.gov/centers/wstf/testing_and_analysis/hypervelocity_impact/home.html) ✓ Failure criteria defined by missions or hypervelocity impact testing/simulations

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Table 3c(NASA): for Small Debris (2/2)

Individual Risk	Required Measures	Knowledge of three agencies S&MA could provide		
		Applicable doc's/websites (Standards, Handbooks, Databases, etc.)	Analysis Tools	Technologies／Facilities
Damage impact assessment error due to Small Debris information shortage (*2)	⑤ On-orbit real time measurement of the actual space environment	✓ On-orbit anomalies reported by operators ✓ On-orbit anomalies documented in Spacecraft On-orbit Anomaly Report (SOAR) database (NASA internal)	✓ Anomalies: investigation tools vary, depending on the nature of anomalies	✓ Anomalies: investigation technologies vary, depending on mission requirements and resources ✓ Dedicated in-situ measurement sensor technologies under development
Pollution due to Small Debris out of Spacecraft (Paint flake, MLI fragment, ejecta, etc.)	⑥ Prevention material degradation under space environment ⑦ Prevention of surface material fragmentation (Ejecta, paint flake, MLI fragments, etc.)	✓ NASA TP-2003-210788, Meteoroid/Debris Shielding, available at: https://hvit.jsc.nasa.gov/reference-documents/ ✓ NASA TM-2009-214785, Handbook for Designing MMOD Protection, available at: https://hvit.jsc.nasa.gov/reference-documents/	✓ Different testing and analysis tools	✓ Hypervelocity impact testing (primarily at NASA WSTF) ✓ Space environment testing facilities at different NASA Centers. For example, the environmental testing facilities at JSC include vibration, vacuum, thermal, and thermal-vacuum chamber test operations for human spaceflight and robotic missions and provide the following services: ▪ Materials outgassing evaluations ▪ Accelerated Electrical/Electronic components burn-ins and life cycle testing ▪ Environmental cycling (thermal/humidity) for materials survivability ▪ Materials and hardware testing in extreme environments (manned/unmanned)

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6. GAP analysis/ Research topics

NOTE: GAP Analysis does NOT aim to select one superior method for users but to provide the differences between available methods comprehensively.

GAP analysis/ Research topics candidates and Priorities

An example of GAP analysis (among 3 agencies) / Research Topics

#	A. Technologies／Facilities	Outline/ Perspective of the comparison	Priority	Remarks
A1	Hypervelocity impact facilities	Specification of each facility	#1	
A2				

#	B. Analysis Tools	Outline/ Perspective of the comparison	Priority	Remarks
B1	Debris Environment Models	Capability of each model	#2	ORDEM, MASTER, etc.
B2	Meteoroid Environment Models		Low	MEM, Grün, etc.
B3	Impact Risk Analysis Tools	Quantitative comparison in condition(s) where the most significant differences found	#3	DRAMA, Turandot, DAS, etc.
B4	Hydrocodes			Autodyne

#	C. Applicable doc's/websites (Standards, Handbooks, Databases, etc.)	Outline/ Perspective of the comparison	Priority	Remarks
C1	Documents related to protection design	Are there any differences in estimating/defining" Critical minimum size" and actual design methods for "Protection " among each applicable documents	#4	

Specification of each facility

A1 Hypervelocity impact facilities No notable differences among the three agencies' facilities

#	Org.	Location (Site)	Accelerator Type	Single Projectile Size Range	Velocity Range	Diagnostics Available	Velocity Measurement	Target Accommodations	Target Capabilities	Others	Bibliography and/or website address
1	JAXA	ISAS (Sagamihara)	Ex. 7/30mm horizontal Two-stage light gas gun (PAI) 4.7/15mm vertical Two-stage light gas gun (PAI)	0.3 -7.0mm (Ability of projectile sizes) 0.03-0.5mm (Multiple particles) 1.0 -4.8mm (single particle) (Ability of multiple shots (ex. Using sabot) also mentioned)	0.5-7.0 km/s 0.8-7.0 km/s	+High-Speed Video Camera -HPV-X (Shimadzu) -HPV-1 (Shimadzu) -Phantom V2512 (Vision Research) -KIRANA (Specialized Imaging) -Fast M3K (Telops) +spectrograph -maya2000 (Ocean) -Time-resolved spectrum system (Hamamatsu)	- laser-photodetector system	100cm×200cm or 45cm×30cm (Size and/or Capacity of target chamber) 100cm×200cm or 45cm×30cm	- 1Pa (Ability to pressurize and/or heat/cool targets)	-Optical, laser, electron microscopes and laser profiler for target inspection -Compression testing machine -Sound velocity measurement system	https://stage.tksc.jaxa.jp/pairg/spf/
2	ESA (collaboration example)	EMI Fraunhofer (Freiburg, Germany)	Two-stage light gas gun (different sizes)	100 g	7.8 km/s	- Accelerometers - Pressure gauges - High-speed spectroscopy - High-speed photo/video	- Laser vibrometers - Flash/impact light detectors - X-ray film track	5.5m x 3.5m x 3.5m (target chamber)	1 GPa max pressure		https://www.emi.fraunhofer.de/en/business-units/space/equipment.html
3	NASA	White Sands Test Facility	Horizontal Two-stage light gas guns	Projectile shapes range from spheres, cylinders, disks, and cubes to multiple projectile "shotgun" shots. Single projectiles range in diameter from 25.4 mm down to 0.4 mm. Multiple projectiles down to 0.05 mm.	Up to 7 km/s	High speed data acquisition (100 million samples per second) and imaging systems (up to 200 million frames per second) capture projectile, environment, and target data for results analysis.	Laser break-beam stations Photo diode flash detectors	Target chambers range from 107 cm diameter x 213 cm long to 274 cm diameter x 914 cm long, accommodating targets with different dimensions	Ability to pressurize and/or heat/cool targets	Laser microscope for target inspection Ultra-high-speed imaging system cameras to capture projectiles in flight immediately prior to impact	https://www.nasa.gov/centers/wstf/testing_and_analysis/hypervelocity_impact/index.html

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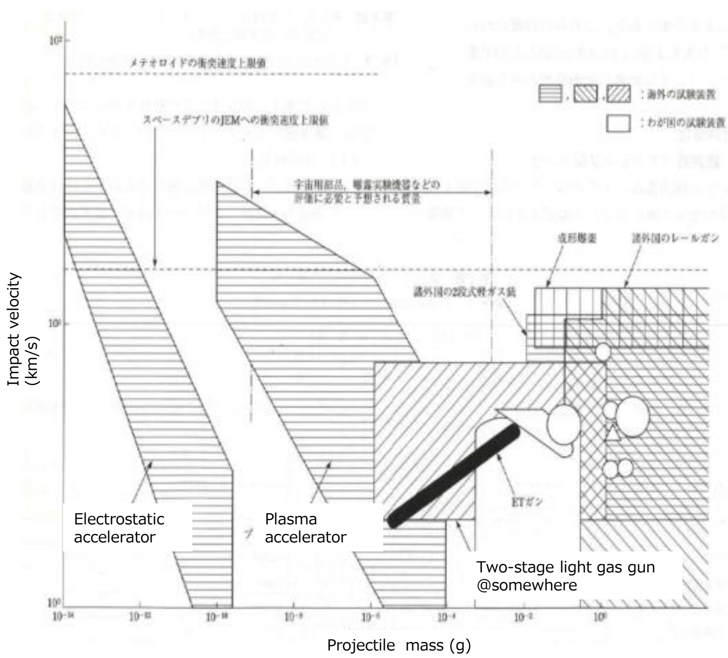
(Cont.) Launch Capability comparison

A1 Hypervelocity impact facilities

★TBD

Sample



To be updated

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Debris Environment Model comparison

B1 Debris Environment Models

Model specification	MASTER-8	ORDEM 3.1(3.2)
Source	ESA	NASA
Modelling approach	Semi deterministic analysis	Measurement data
a) minimum size	1 µm	10 µm
b) orbital regime	186 km (perigee altitude) to 500 000 km (apogee altitude)	100 km to 40 000 km (> 10 µm) (LEO to GTO) 34 000 km to 40 000 km (> 10 cm) (GEO)
c) evolutionary period	1957 to 2036	2015 to 2050
Input parameter	Target orbit scenario: -Semi-major axis ,-Eccentricity, -Inclination, - Right ascension of ascending node,-Argument of perigee Inertial volume scenario: -Geocentric distance, ,-Right ascension, -Declination Spatial density scenario: -Lower/ upper altitude limit, -Lower/ upper decline Limit	-Apo/Peri -Altitude -Semi-major axis -Eccentricity -Inclination -Argument of perigee
Output data	Flux versus -Size,-Mass,-Semi-major axis,-Eccentricity, -Inclination,-Altitude,-Latitude ,-Impact velocity, -Impact declination,-Time, etc. Spatial density versus -Size, -Mass, -Altitude , -Declination, -Time	Flux versus -Size, -Orbit position, -Altitude, -Latitude
TLE background	Yes	(Density discrimination)
Fragments	Yes	(IN) Intacts
SRM dust and slag	Yes	(LD) Low-density (1,4 g/cc) fragments
NaK droplets	Yes	(MD) Medium-density (2,8 g/cc) fragments & microdebris
Paint flakes	Yes	(HD) High-density (7,9 g/cc) fragments & microdebris
West ford needles	Yes	(NK) RORSAT NaK coolant droplets (0,9 g/cc)
MLI fragments	Yes	
Primary data source/ validation	-LDEF,-CME, -HST (SM1, SM3B), -EuReCa,-PROOF 2009	-SSN catalogue, -LDEF, -Haystack radar, -HST-SA., -STS window and radiator, -MOSEZT telescope, -HAX, -Goldstone radar
Web address	https://sdup.esoc.esa.int/	https://orbitaldebris.jsc.nasa.gov/modeling/ordem.html

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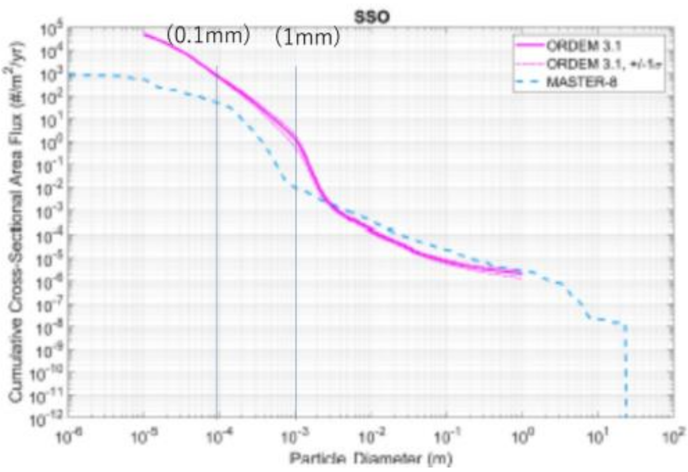
(Cont.) GAP between debris environment

B1 Debris Environment Models MASTER-8 and ORDEM 3.1 have been assessed when updated.

Implementation of debris environment model to actual design.



MANIS, et al.(2021) suggested there is a large difference in impact flux of small debris between MASTER-8 and ORDEM 3. 1

How to select a model for spacecraft design?
Cf. ISO 14200 describes;
When selecting an environment model, consideration should be given to the fact that there can be significant differences in the calculated fluxes among the available candidate models. The customer and/or the supplier should compare the fluxes of several models.

Reference
A. Horstmann, A. Manis, V. Braun, M. Matney, A. Vavrin, D. Gates, J. Seago, P. Anz-Meador, C. Wiedemann, S. Lemmens, FLUX COMPARISON OF MASTER-8 AND ORDEM 3.1 MODELLED SPACE DEBRIS POPULATION, Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)
A. MANIS, M. MATNEY, A.VAVRIN, D. GATES, J. SEAGO, AND P. ANZ-MEADOR ,NASA Orbital Debris Quarterly News Vol. 25, Issue 3, September 2021

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Impact Risk Analysis Tools – Benchmark candidate

B3 | Impact Risk Analysis Tools JAXA decided to assess using GCOM-C within this Fiscal Year.

JAXA proposes Benchmark Tests (as a sub-TF), focusing on the conditions where the most prominent differences are found among models, like SSO. (apart from IADC WG3)

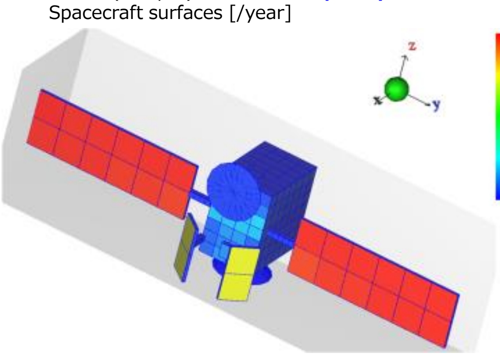
Operators surely want to understand the quantitative differences from design perspective.

Candidate Condition & Analysis Image

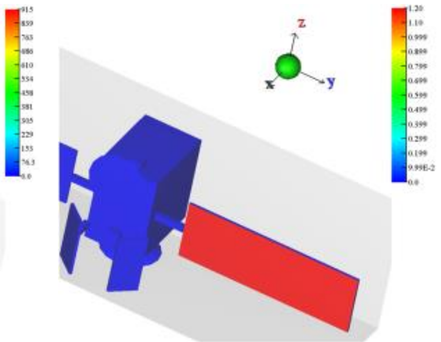
Simulation for the risk assessments.

	SSO
Semi-major axis (*a*)	**7171km**
Eccentricity (*e*)	**0.0001**
Inclination(*i*)	**98°**
Argument of perigee (ω)	**0°**
Right ascension of the ascending node (Ω)	**0°**

Debris (>10μm) **Collision Frequency** on Spacecraft surfaces [/year]



Damage Frequency on a surface with designated Damage Mode [/year]



(1-year from 2018/01/01 Orbit : SMA 7187㎞, ECC 1.0e-3, Inc 98deg Earth-pointing)

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7. Points of Contact in each Agency

Please contact POCs below for further Small Debris-related information.

Agency	POC (section or persons)	Contact Address	Note
JAXA	S&MA Department System and Orbit Safety Unit	Sustainability_SpaceDebris@ml.jaxa.jp	Space Debris HP is available at; https://www.jaxa.jp/projects/debris/index_j.html (in Japanese ONLY at this moment)
ESA	Independent Safety Office (Product Assurance and Safety Department)	Rosario.Nasca@esa.int Sergio.Ventura@esa.int	https://technology.esa.int/page/space-debris-mitigation
NASA	Office of Safety and Mission Assurance (OSMA) Orbital Debris Program Office (ODPO)	Dr. Frank Groen, HQ 5F87, NASA Headquarters, 300 E ST SW, Washington,DC,20546-0001 Dr. Matt Forsbacka, HQ 5F87, NASA Headquarters, 300 E ST SW, Washington,DC,20546-0001 Dr. J.-C. Liou, XI-5, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058	https://sma.nasa.gov/

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B07

大型 CMOS センサを利用した低軌道デブリ観測

LEO Debris Observation Using Large CMOS Sensors

○柳沢俊史、セガーラポロマヌエル、黒崎裕久（JAXA 研開部門）
○YANAGISAWA Toshifumi, Cegarra Polo Manuel, KUROSAKI Hirohisa
(JAXA Research and Development Directorate)

JAXA 研開部門では宇宙デブリの観測技術を長年開発してきている。近年は高速で天球を移動する低軌道デブリの観測に適した大型の CMOS センサの入手が容易になり、それとともに GPU 計算機が普及して解析速度の高速化が可能になってきている。これらの資源を有効に利用することにより低軌道デブリの観測技術を向上させることが可能である。我々は豪州に CMOS カメラを利用した遠隔観測施設を 2 局設置して低軌道デブリの観測及び解析体制を構築した。また、東京大学の大型 CMOS カメラ、Tomo-e Gozen のデータから低軌道デブリを抽出するパイプラインを構築している。これらの観測装置から得られるデータを利用して未カタログデブリを含む多くの低軌道デブリの検出及び軌道決定が可能である。

Observation technologies has been developed at the research and development directorate of JAXA for long times. The large CMOS sensors that is suitable for fast moving LEO objects become available recently. On top of that, GPU machines which enable us to analyze the data on real time basis are also available. Observation technologies fore LEO objects will be enhanced using these items. Two remote observation sites using CMOS sensors have been established for LEO debris observation. The data analysis pipeline for Tomo-e Gozen camera, which contains 84 CMOS sensors and installed at Kiso Observatory, are also being developed. Detections and orbital determinations of LEO objects including un-cataloged objects will be possible using the data from these observation sensors.

10th Space Debris Workshop Nov 29th 2022

LEO debris observation using large CMOS sensors

Japan Aerospace Exploration Agency(JAXA)
Research and Development Directorate

T.Yanagisawa, M.CegarraPolo, and H.Kurosaki

University of Tokyo

S.Sako and Tomo-e Team

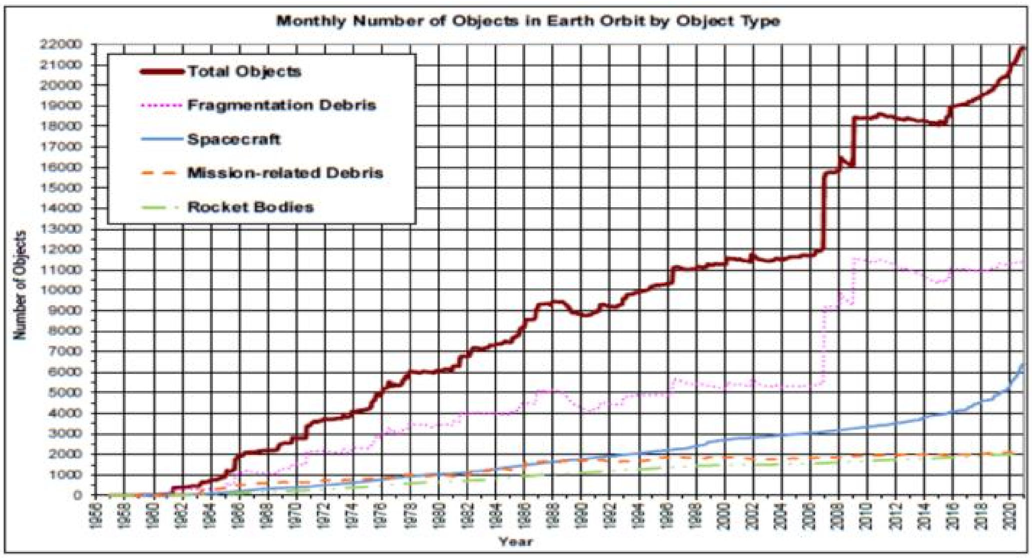
1

Abstract

Observation technologies has been developed at the research and development directorate of JAXA for long times. The large CMOS sensors that is suitable for fast moving LEO objects become available recently. On top of that, GPU machines which enable us to analyze the data on real time basis are also available. Observation technologies for LEO objects will be enhanced using these items. Two remote observation sites using CMOS sensors have been established for LEO debris observation. The data analysis pipeline for Tomo-e Gozen camera, which contains 84 CMOS sensors and was installed at Kiso Observatory, are also being developed. Detections and orbital determinations of LEO objects including un-cataloged objects will be possible using the data from these observation sensors.

2

Background

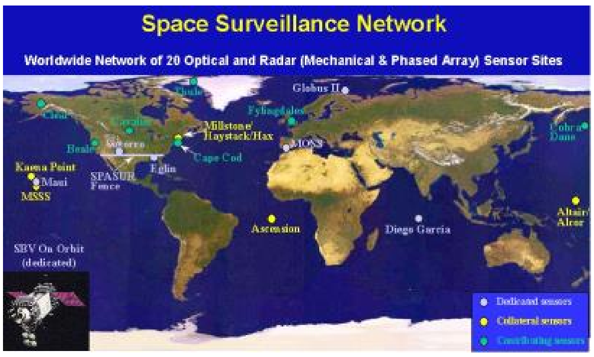


- Space environment is deteriorated with space debris especially in LEO region recently.
- Dead zone problem. (a few mm to 10cm)
- Inaccuracy of TLE

Observation ability of space objects must be reinforced.

3

Background



ISON network of Russia

Observation methods of LEO objects

①Radar observation: SSN of USA. 24-hour and 365-day observation is possible. Enormous cost is needed to construct and maintain.

②Optical observation: ISON network of Russia. Observable time is limited by lighting condition of the sun and weather. Very cost effective.

- Optical Sensors(CCD, CMOS) are improving
- PC performances are improving
- Position accuracy of optical sensor is much better than radar

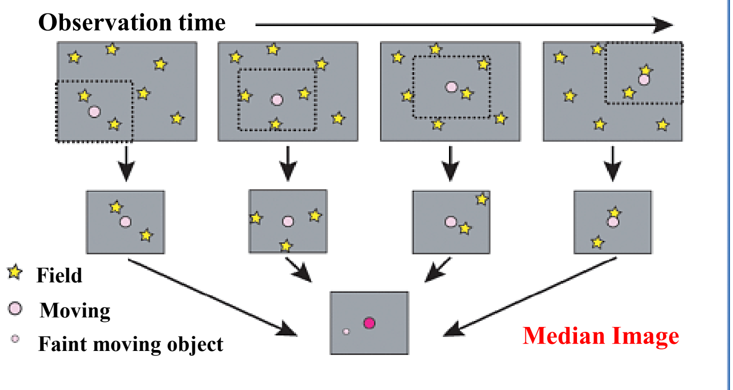
Cost-effective ground-based optical observation system of LEO objects which is used for SSA will be possible.

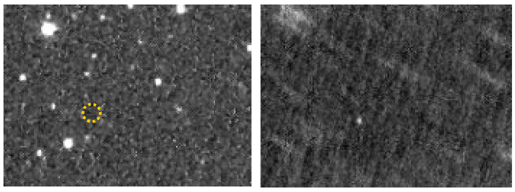
4

Image-processing technology : Stacking method

The stacking method uses multiple images to detect very faint objects that are undetectable on a single image.

Concept of the stacking method





An asteroid detect with the stacking method. One CCD image (left) and the stacked image (right).

Sub-images are cropped from many images to follow the presumed movement of moving objects. Faint objects are detectable by making the median image of these sub-images.

Image-processing technology : Stacking method

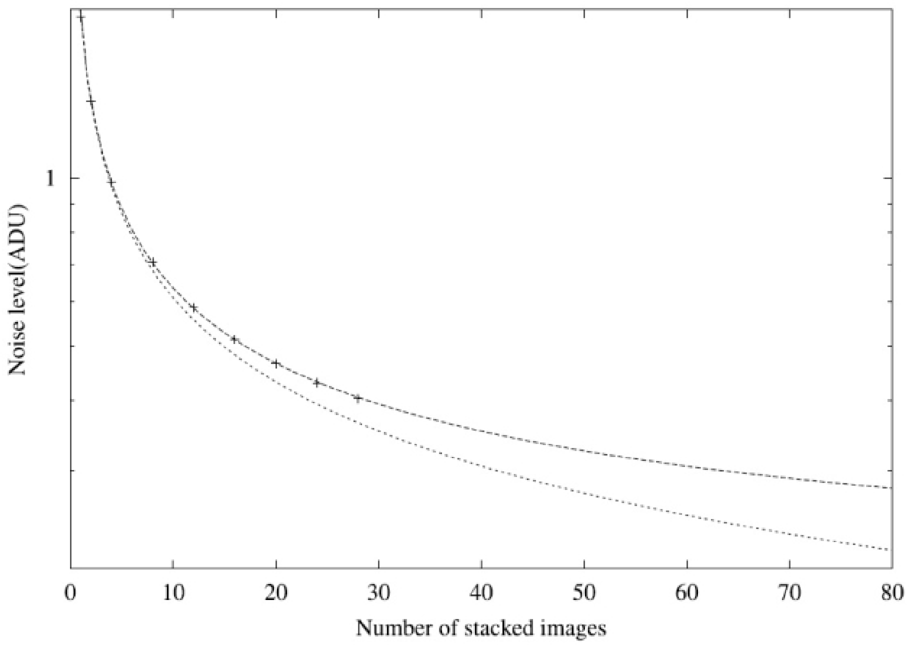
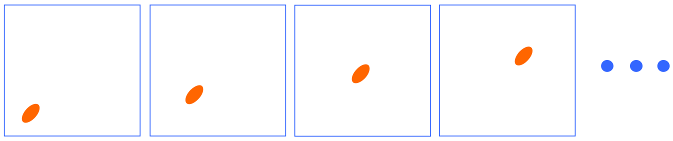
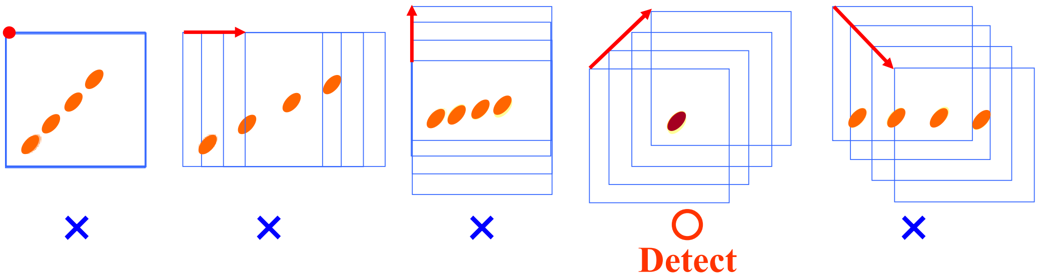


Image-processing technology：Stacking method

The weak point of the method is taking time to analyze the data in case of detecting unseen object whose movement is not known, because various movements of the object have to be presumed.



Many CCD image are taken with telescope-fixed mode.



Images are stacked in many ways, as various shift values are presumed. Once a object is detected, its movement is also determined.

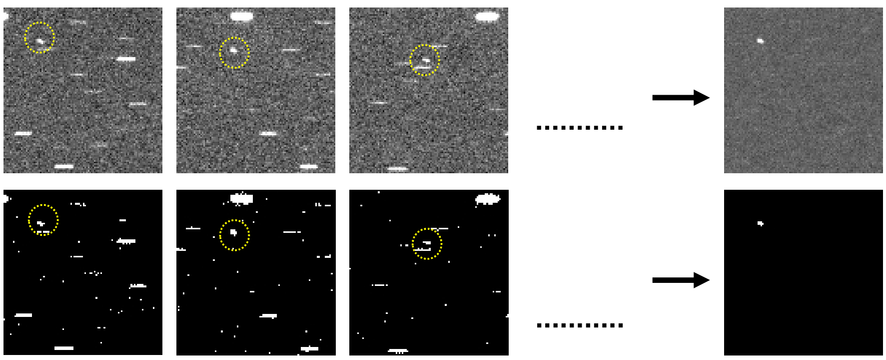
Analysis time for 65536 processes of 32 1024×1024-pixel frames which are intended to detect objects moving within 256×256 pixels is about 280 hours using 1 normal PC.

Development of the new algorithm

Calculating median is complicated and time-consuming process as compared with calculating average.

Simple calculation process like average that contains the advatage of median is required.

Binarization solves the problem!!



Deference between the original algorithm of the stacking method (upper) and the new algorithm using binarized images.

Analysis time is reduced to one 60th.

Development of the new algorithm

●The new algorithm is installed to the FPGA board for further speed-up.

FPGA board, EXpresso A5 manufactured by soliton systems

The analysis time became 1/20.
Total reduce rate became 1/1200.
280 hours → 14 minutes

●GPU machine also reduces analysis time more.

GDEP DLEARNING BOX II

- 4 x NVIDIA QUADRO RTX8000 GPU
- 4 x 4608 CUDA cores
- 48 GB GPU Memory
- NVLink

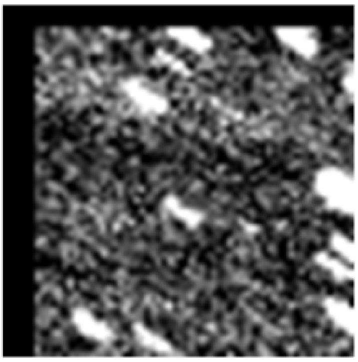
- Intel i9-10940X CPU 3.30 GHz
- 28 CPU cores
- 128 GB RAM Memory

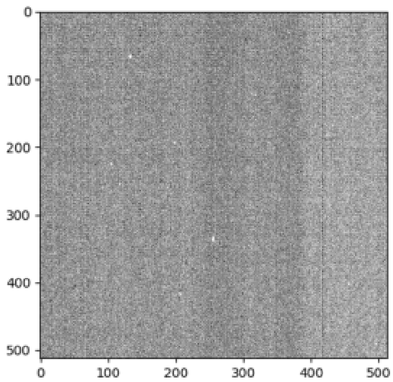
Analysis time became 4 secs which is available for LEO objects detections.

9

Development of the new algorithm

Frame acquisition rate for various objects





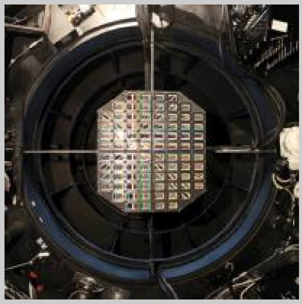
- **32 frames / 15 minutes for Near Earth Objects**
- **32 frames / 5 minutes for GEO objects**
- **32 frames / 2 seconds for LEO objects**

FPGA (Near Earth Objects, GEO objects)
GPU (LEO objects)

10

LEO debris observation using optical sensors

Tomo-e Gozen Camera
(Kiso Observatory)

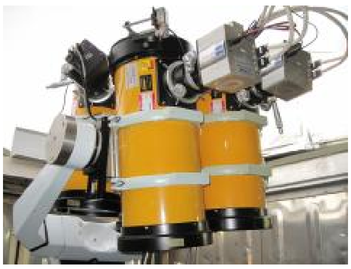


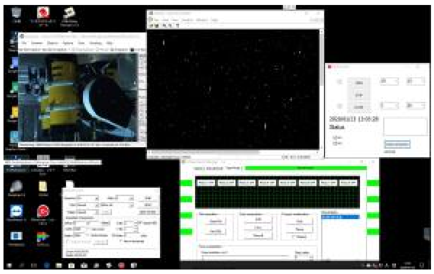
Remote observation site #2
(Zadko Observatory)

Remote observation site #1
(Siding Spring Observatory)

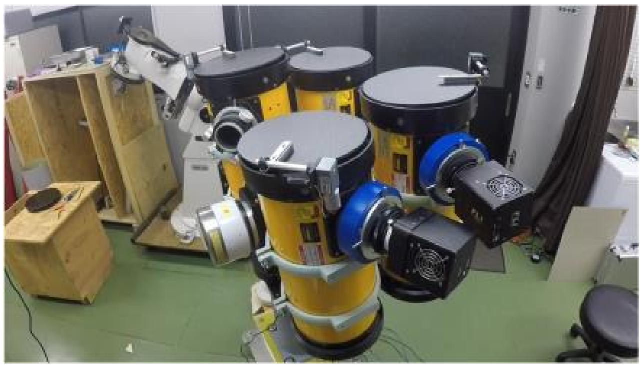
LEO debris observation using optical sensors

Remote observation site in Australia





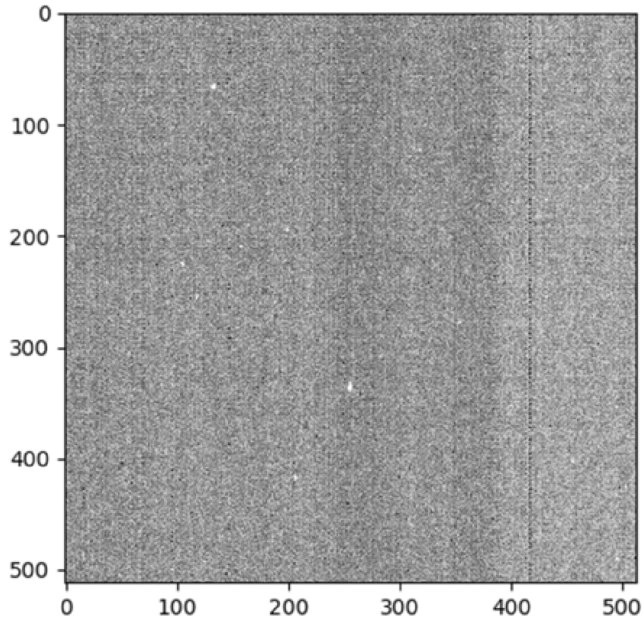
Remote observation site was developed at Siding Spring Observatory in Australia. Four sets of the 18cm telescope and the large CMOS camera were installed.



Test scene in Japan

The FPGA machine and the multi-core PC for the analysis

LEO debris observation using optical sensors



A LEO object detected in the survey. 6.1-magnitude (4m in size).
500×500 pixels around the object. Played with 10-time speed.

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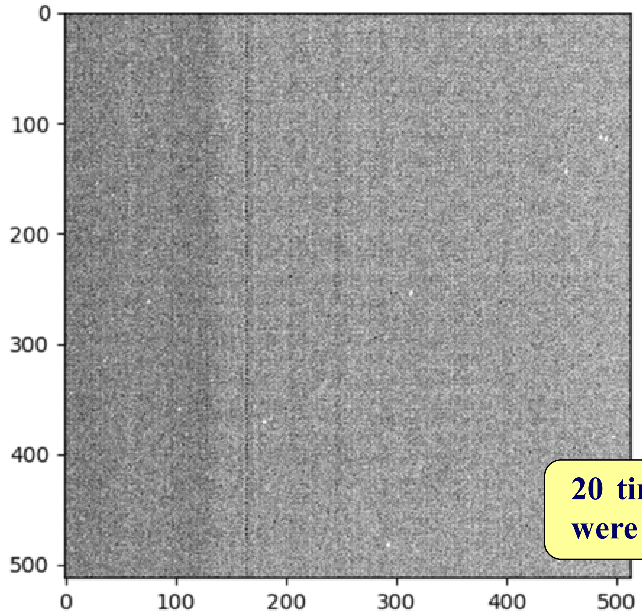
LEO survey using CMOS sensor



20 times fainter objects were detectable.

A LEO object detected in the survey. 9.7-magnitude (60cm in size).
500×500 pixels around the object. Played with 10-time speed.

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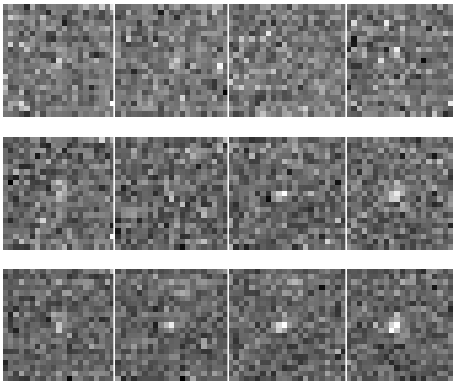
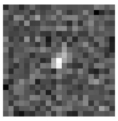
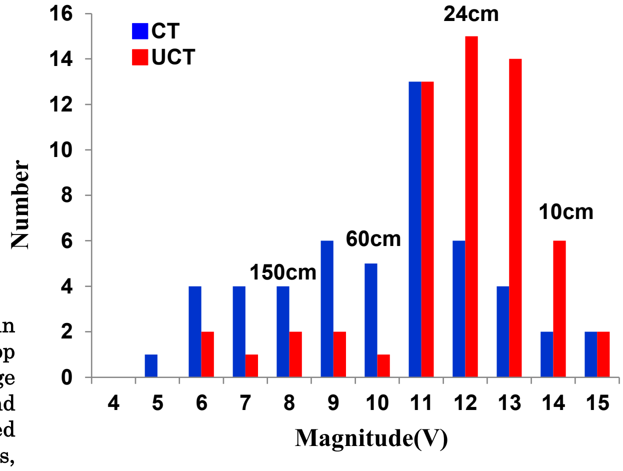
LEO survey using CMOS sensor

109 LEO objects were detected. 58 of them (53%) were un-cataloged.





The faintest object (about 7cm in diameter) detected in this study. Top figure shows the original image around the detected object. The second and the third images are the stacked images using 4 and 8 frames, respectively. The bottom image is the final stacked image .



A large amount of data taken by the CMOS camera became to be analyzed using the multi-core PC, the FPGA machine and the GPU machine in almost real time basis.

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LEO debris observation using optical sensors

Result file of LEO survey observation

1	221114	10.532545	7189.554	0.0000	89.611	1.108	0.0000	329.020	11.4	B1-0	2	000053	000054	195.67	245.29	21529	SCOUT G-1 DEB
2	221114	10.872545	7260.124	0.0000	101.961	358.417	0.0000	328.322	12.7	B1-11	2	000665	000666	78.41	58.38	N/A	N/A
3	221114	10.990600	7348.820	0.0000	65.091	23.561	0.0000	325.454	6.9	B1-14	3	000877	000879	13394.53	14915.41	13175	COSMOS 1365
4	221114	10.991155	7256.428	0.0000	34.170	125.332	0.0000	246.107	13.6	B1-15	3	000877	000881	24.65	31.84	N/A	N/A
5	221114	11.148655	7237.177	0.0000	81.230	14.774	0.0000	328.680	12.4	B1-16	2	001162	001163	150.34	58.64	38271	METEOR 2-5 DEB
6	221114	11.318655	7612.217	0.0000	64.795	174.514	0.0000	214.543	5.6	B1-19	4	001467	001470	47630.42	49556.69	26550	DNEPR 1 R/B
7	221114	10.543655	7145.688	0.0000	98.129	356.506	0.0000	328.683	9.9	B1-2	2	000073	000074	946.35	840.31	23344	RESURS 01 DEB
8	221114	11.337270	7595.282	0.0000	87.914	190.291	0.0000	210.900	8.0	B1-21	3	001501	001503	5847.40	5766.07	48214	ONEWEB-0218
9	221114	11.551430	7414.912	0.0000	65.852	178.367	0.0000	214.367	11.8	B1-25	2	001887	001888	176.08	140.83	18507	COSMOS 1375 DEB
10	221114	11.568380	7637.125	0.0000	66.217	29.522	0.0000	325.827	8.9	B1-26	3	001917	001919	2343.30	2243.48	48541	SL-12 DEB
11	221114	11.669210	7842.196	0.0000	74.054	25.047	0.0000	327.704	9.1	B1-28	4	002098	002101	1894.13	1795.39	12642	COSMOS 1293
12	221114	11.713930	7519.646	0.0000	65.476	31.996	0.0000	325.553	11.9	B1-29	3	002179	002181	135.18	148.32	10415	COSMOS 839 DEB
13	221114	10.561155	7876.164	0.0000	82.542	177.257	0.0000	211.131	5.4	B1-3	5	000103	000107	59388.80	53883.46	44905	GONETS M 14 (M24)
14	221114	11.812820	7595.328	0.0000	102.920	9.718	0.0000	328.144	11.9	B1-31	3	002357	002359	204.54	106.46	N/A	N/A
15	221114	11.830600	7627.831	0.0000	63.693	180.339	0.0000	215.037	12.4	B1-33	2	002389	002391	85.49	100.32	N/A	N/A
16	221114	10.585600	7377.528	0.0000	144.527	304.631	0.0000	297.616	8.3	B1-4	5	000147	000151	3540.24	3630.63	02124	OV1-4 R/B
17	221114	12.272545	7800.976	0.0000	82.542	197.822	0.0000	211.429	6.3	B1-43	4	003184	003187	29856.74	24211.34	22188	SL-14 R/B
18	221114	12.375600	7819.470	0.0000	73.996	193.897	0.0000	212.553	10.4	B1-45	5	003369	003373	674.13	670.63	15002	COSMOS 1563
19	221114	10.612545	7166.197	0.0000	86.391	180.152	0.0000	211.066	5.0	B1-5	3	000197	000198	74262.83	84217.56	24944	IRIDIUM 29
20	221114	10.692265	7849.591	0.0000	74.026	173.320	0.0000	212.207	8.7	B1-7	5	000339	000343	2740.75	2668.38	11693	COSMOS 1158
21	221114	10.754490	7677.225	0.0000	65.790	168.658	0.0000	214.150	12.3	B1-8	3	000452	000454	94.97	91.04	03932	THOR ABLESTAR DEB
22	221114	10.516990	7351.096	0.0000	82.887	177.648	0.0000	211.219	7.0	B2-0	2	000025	000026	10781.79	10587.29	22307	COSMOS 2230
23	221114	10.583380	7378.493	0.0000	144.537	304.599	0.0000	297.133	8.3	B2-1	3	000144	000146	3119.35	3399.06	02124	OV1-4 R/B
24	221114	11.082270	7247.174	0.0000	100.075	194.848	0.0000	211.502	11.5	B2-10	3	001042	001044	93.68	125.18	N/A	N/A
25	221114	11.153655	7304.072	0.0000	106.115	199.571	0.0000	212.312	12.3	B2-12	2	001171	001172	83.94	95.40	N/A	N/A

Circular orbital element calculated from the observed coordinates

Identification with TLE

Tracking observation using Zadko Observatory → **Precise orbital determination**

These data are also used for space debris modelling

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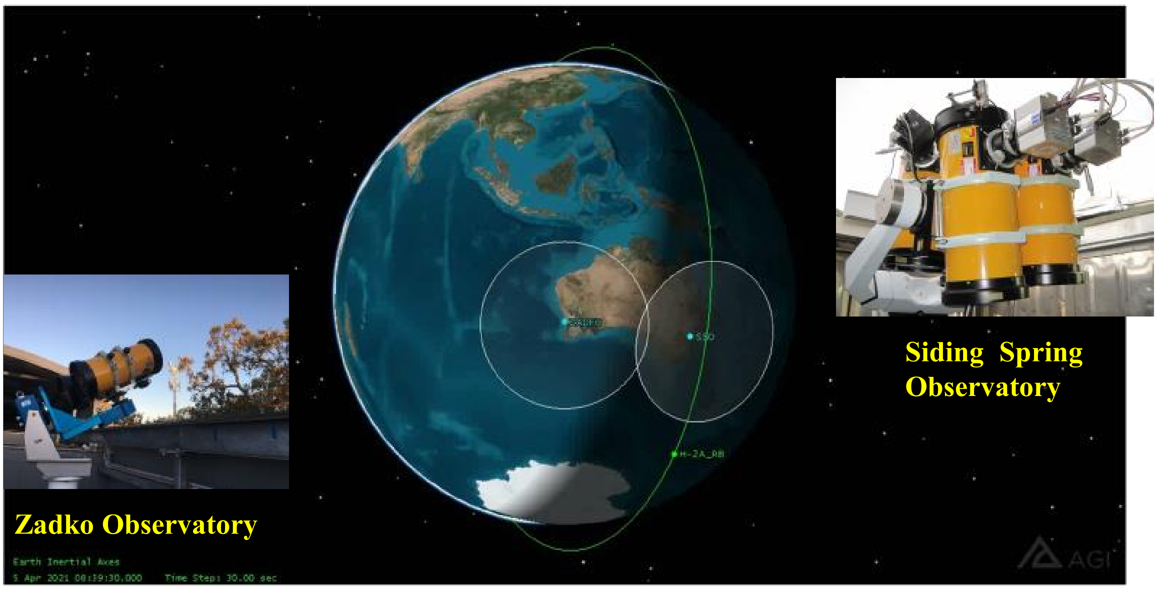
LEO debris observation using optical sensors

Precise orbital determinations using two remote sites in Australia

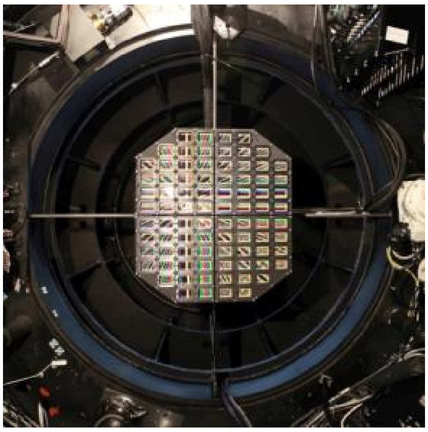


LEO debris observation using optical sensors

LEO observation using Tomo-e Gozen camera

University of Tokyo has developed a large CMOS camera, Tomo-e Gozen, which is for 105cm Schmidt telescope at the Kiso observatory, the University of Tokyo. The Tomo-e Gozen camera is the world's first wide-field CMOS camera. The entire focal plane area of the Kiso Schmidt telescope, 9 degrees in diameter, is covered by 84 chips of 35 mm full HD CMOS image sensors.

Kiso 105cm Schmidt telescope

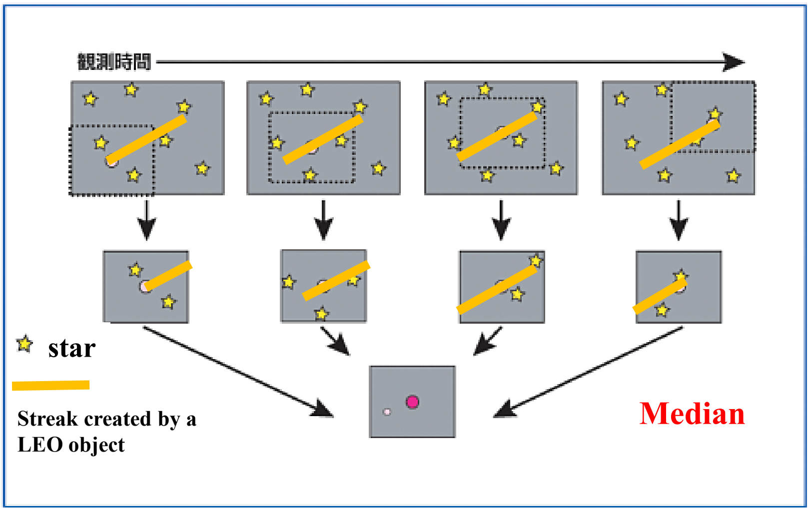


Tomo-e Gozen camera

LEO debris observation using optical sensors

We applied the stacking method to detect the streaks created by LEO objects on the images of Tomo-e Gozen camera. The pipe-line using GPU machine was developed to analyze large amount of data almost real time basis.

Streak detections using the stacking method



GDEP DLEARNING BOX II
- 4 x NVIDIA QUADRO RTX8000 GPU
- 4 x 4608 CUDA cores
- 48 GB GPU Memory
- NVLink
- Intel i9-10940X CPU 3.30 GHz
- 28 CPU cores
- 128 GB RAM Memory

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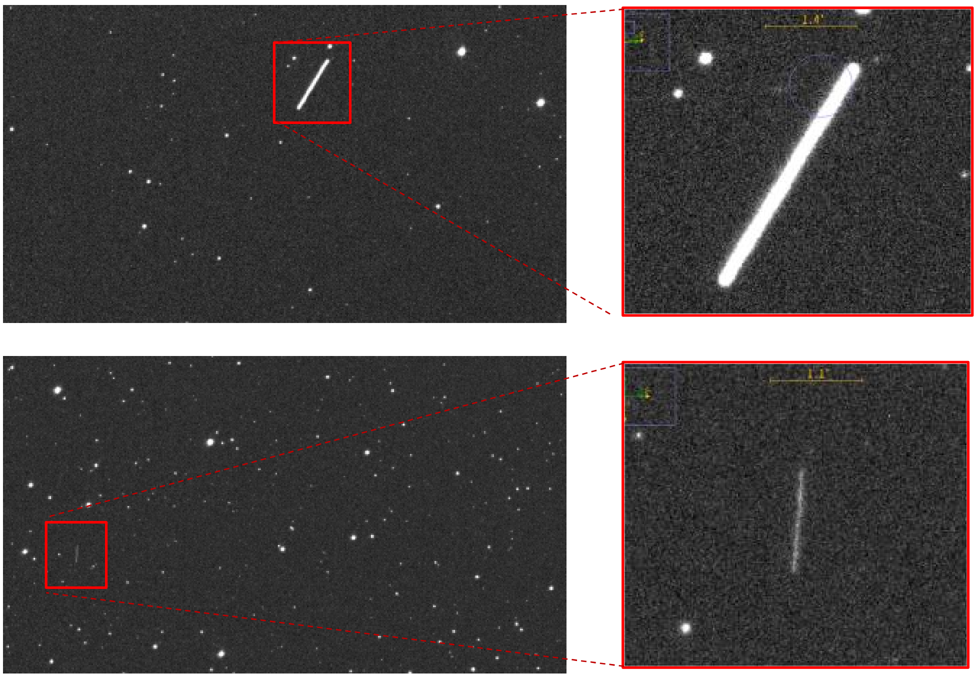
LEO debris observation using optical sensors



Detected streaks by the pipe-line

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LEO debris observation using optical sensors

Result file of the streak detections

subframe	file_name	positives	max_x	max_y	min_x	min_y	max_RA	max_Dec	min_RA	min_Dec	UTC_begin	UTC_end	TLE_candidate	NORAD ID
7	rTMQ1202010180038009611_7.fits	386984	1675	1055	1702	988	17:48:08.792	-07:10:54.57	17:48:10.992	-07:09:35.11	2020-10-18 09:22:34.165882	2020-10-18 09:22:34.665786	SATCOM K2 R/B(PAM-D2)	16295
8	rTMQ1202010180038009611_8.fits	694382	1720	983	1768	740	17:48:12.434	-07:09:29.32	17:48:16.424	-07:04:40.70	2020-10-18 09:22:34.665786	2020-10-18 09:22:35.165690	SATCOM K2 R/B(PAM-D2)	16295
9	rTMQ1202010180038009611_9.fits	1109989	1759	780	1823	508	17:48:15.680	-07:05:28.20	17:48:20.963	-07:00:05.25	2020-10-18 09:22:35.165690	2020-10-18 09:22:35.665594	SATCOM K2 R/B(PAM-D2)	16295
10	rTMQ1202010180038009611_10.fits	888185	1817	545	1884	286	17:48:20.461	-07:00:49.21	17:48:25.970	-06:55:41.79	2020-10-18 09:22:35.665594	2020-10-18 09:22:36.165498	SATCOM K2 R/B(PAM-D2)	16295
11	rTMQ1202010180038009611_11.fits	1914	1878	406	1889	200	17:48:25.418	-06:58:04.44	17:48:26.421	-06:53:59.56	2020-10-18 09:22:36.165498	2020-10-18 09:22:36.665402	SATCOM K2 R/B(PAM-D2)	16295
13	rTMQ1202010180038009611_13.fits	7985	1520	874	1524	433	17:47:56.527	-07:07:17.89	17:47:57.127	-06:58:33.38	2020-10-18 09:22:37.165306	2020-10-18 09:22:37.665210	SATCOM K2 R/B(PAM-D2)	16295
14	rTMQ1202010180038009611_14.fits	1	1567	399	1567	399	17:48:00.582	-06:57:53.33	17:48:00.582	-06:57:53.33	2020-10-18 09:22:37.665210	2020-10-18 09:22:38.165114	SATCOM K2 R/B(PAM-D2)	16295
13	rTMQ1202010180038009612_13.fits	10	1668	1127	1688	1004	17:48:09.131	-06:24:09.55	17:48:10.763	-06:21:43.31	2020-10-18 09:22:37.165306	2020-10-18 09:22:37.665210	SL-24 R/B	27610
8	rTMQ1202010180038009913_8.fits	7	9	505	1860	250	18:13:37.240	-12:24:43.90	18:16:07.676	-12:19:56.09	2020-10-18 09:23:46.185148	2020-10-18 09:23:46.685052	no match	no match
2	rTMQ1202010180038009914_2.fits	543	595	620	372	243	18:14:26.391	-11:39:02.85	18:14:08.548	-11:31:32.63	2020-10-18 09:23:43.185724	2020-10-18 09:23:43.685628	no match	no match
3	rTMQ1202010180038009914_3.fits	193	838	1024	614	622	18:14:45.858	-11:47:05.34	18:14:27.928	-11:39:05.36	2020-10-18 09:23:43.685628	2020-10-18 09:23:44.185532	no match	no match
13	rTMQ1202010180038010044_13.fits	332788	1597	407	1464	200	18:02:32.141	-11:56:49.87	18:02:21.646	-11:52:41.15	2020-10-18 09:24:09.086756	2020-10-18 09:24:09.586660	no match	no match
14	rTMQ1202010180038010044_14.fits	1676705	1940	953	1740	635	18:02:59.216	-12:07:46.06	18:02:43.423	-12:01:23.83	2020-10-18 09:24:09.586660	2020-10-18 09:24:10.086564	no match	no match
15	rTMQ1202010180038010044_15.fits	99026	18	1121	1897	855	18:00:23.118	-12:10:27.45	18:02:55.858	-12:05:48.60	2020-10-18 09:24:10.086564	2020-10-18 09:24:10.586468	no match	no match
8	rTMQ1202010180038010215_8.fits	22816	1781	1016	1990	985	18:25:08.817	-03:33:27.09	18:25:25.428	-03:32:51.57	2020-10-18 09:24:55.598711	2020-10-18 09:24:56.098615	no match	no match
8	rTMQ1202010180038010825_8.fits	235	540	245	747	200	18:07:40.656	+03:43:30.63	18:07:57.109	+03:44:24.10	2020-10-18 09:27:07.480134	2020-10-18 09:27:07.980038	no match	no match
4	rTMQ1202010180038011014_4.fits	11	375	1061	324	1018	18:23:12.382	+10:29:09.58	18:23:08.275	+10:30:00.77	2020-10-18 09:27:54.495094	2020-10-18 09:27:54.994998	no match	no match

Coordinates at the beginning

Coordinates at the end

Observation times (beginning and end)

Precise orbital determination ⇐ Tracking observation using remote sites in Australia ⇐ Circular orbits

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Summary

Observation technologies has been developed at the research and development directorate of JAXA for long times. The large CMOS sensors that is suitable for fast moving LEO objects become available recently. On top of that, GPU machines which enable us to analyze the data on real time basis are also available. Observation technologies for LEO objects will be enhanced using these items. Two remote observation sites using CMOS sensors have been established for LEO debris observation. The data analysis pipeline for Tomo-e Gozen camera, which contains 84 CMOS sensors and was installed at Kiso Observatory, are also being developed. Detections and orbital determinations of LEO objects including un-cataloged objects will be possible using the data from these observation sensors.

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B08

日豪 2 地点からの低軌道物体光学観測実証（追加検証結果の報告）

Optical Observation Demonstration of LEO Objects from Japan and Australia (The Report of Additional Verification)

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柳沢 俊史，黒崎 裕久（JAXA 研究開発部門第二研究ユニット）
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YANAGISAWA Toshifumi, KUROSAKI Hirohisa (JAXA, Research Unit2, Research and Development Directorate)

近年，宇宙状況監視の需要が高まっている。特に低軌道においては，軌道上物体の数が急激に増加しており，宇宙空間の安定利用のためには，軌道上物体の位置および軌道の把握が重要である。
本研究では，光学観測による宇宙状況監視の実証として，地球上の遠隔 2 地点（JAXA の豪州サイディング・スプリング観測所および，IHI の相生観測所）の観測所から既知の低軌道物体を観測し，その軌道把握を試みた。
本講演では，第 9 回デブリワークショップにて報告した内容に関する追加検証の結果を報告する。特に，同一パスを両観測所で観測して算出した軌道について評価結果を示す。

In recent years, the demand for space situational awareness has been increasing. Especially in low-earth orbit (LEO), the number of objects is rapidly increasing. Therefore, it is important to grasp the positions and orbits of those objects for the stable utilization of space.
In this study, we demonstrated optical observation of LEO objects from two observatories (JAXA Siding Spring Observatory and IHI Aioi Observatory).
In this presentation, we will report the result of additional verification from our presentation in 9th Space Debris Workshop. Particularly, we will discuss about the orbit determination from using two observatories data including same path observaion data.

第10回スペースデブリワークショップ／10th Space Debri Workshop

日豪2地点からの低軌道物体光学観測実証（追加検証結果の報告）

Optical observation demonstration of LEO objects from Japan and Australia (The report of additional verification)

IHI

29th Nov. 2022

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柳沢 俊史（JAXA研究開発部門第二研究ユニット），
Toshifumi Yanagisawa (JAXA, Research Unit2, Research and Development Directorate),

黒崎 裕久（JAXA研究開発部門第二研究ユニット）
Hirohisa Kurosaki (JAXA, Research Unit2, Research and Development Directorate),

目次／Contents

IHI

1. 概要／Abstract

IHI

本研究では，光学観測による宇宙状況監視の実証として，
地球上の遠隔2地点（JAXAの豪州サイディング・スプリング観測所（SSO）および，IHIの相生観測所（IAO））の観測所から既知の低軌道物体を観測し，その軌道把握を試みた。
本講演では，第9回デブリワークショップにて報告した内容に関する追加検証の結果を報告する。

In this study, we demonstrated optical observation of LEO objects from two observatories (JAXA Siding Spring Observatory (SSO) and IHI Aioi Observatory (IAO)).
In this presentation, we will report the result of additional verification from our presentation in 9th Space Debris Workshop.

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2. これまでの研究の成果と課題 Results and Challenges of Previous Research

IHI

成果：　(1) 日豪2地点観測で軌道決定の精度向上を確認した。
　　　　(2) 同日2パス観測データによる軌道の精度がTLEよりも良い結果を得た。

課題：　同日2パス観測データによる軌道精度向上効果の追加検証が必要（評価ケースが1つのみのため）

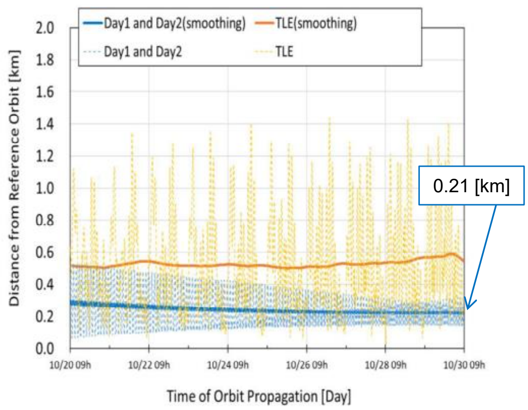
Results: (1) Orbit determination accuracy was improved by using 2 observatories data.
(2) An Orbit determination accuracy using 2 paths observation data was better than TLE.

Challenge: Evaluation of 2 paths observation needs additional verification. (Only 1 case we've got)

研究成果の例／Example of Result of Previous Research

Name	Day 1				Day 2			
SERT 2	1st Pass		2nd Pass		1st Pass		2nd Pass	
NORAD ID	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO
04327	●		●		●	●		

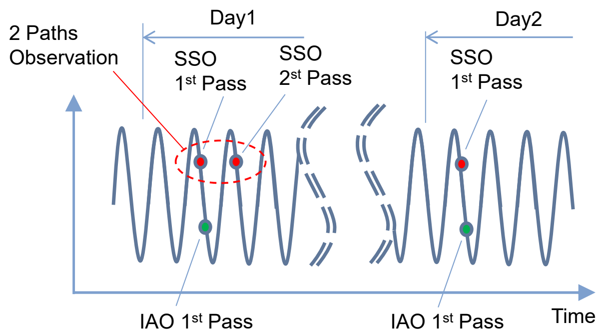
2 paths observation



3. 追加検証
Additional Verification from Previous Research

IHI

観測概略図／Schematics of Observation



	Day 1				Day 2			
	1st Pass		2nd Pass		1st Pass		2nd Pass	
	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO
Example	●	●	●		●	●		

＜本研究の目的／Objective＞

同日2パス観測データを用いた
軌道決定精度向上効果の追加検証

Additional verification of improvement effect of 2 paths observation for orbit determination accuracy

● 観測対象 ／Observation Targets

	NORAD ID	Name	Inclination [deg]	Apogee [km]	Perigee [km]	Eccentricity
1	02436	DELTA 1 Rocket Body	100.99	1484	1382	0.065802
2	03036	DELTA 1 Rocket Body	102.16	1485	1410	0.048160
3	04322	DELTA 1 Rocket Body	101.49	1479	1435	0.028019
4	40303	SL-24 Rocket Body	97.14	1938	484	0.954645

3. 追加検証
Additional Verification from Previous Research

IHI

＜ 観測結果／Observation Results ＞

観測期間／Term: 2021/10/18 ～ 2021/10/29

取得データ数／Total Data Amount
02436 (DELTA 1 Rocket Body)：298
03036 (DELTA 1 Rocket Body)：237
04322 (DELTA 1 Rocket Body)：280
40303 (DELTA 1 Rocket Body)：429

評価用データ／Evaluation Data

	Day 1				Day 2				Data Amount
	1st Pass		2nd Pass		1st Pass		2nd Pass		-
NORAD-ID	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	-
02436		●		●	●	●			84
03036	●		●		●	●			74
04322	●		●				●	●	76
40303			●	●	●		●		92

評価項目／Evaluation item

リファレンス軌道と評価軌道との距離
※リファレンス軌道：取得データをすべて用いて算出した軌道
※評価軌道：評価データを用いて算出した軌道

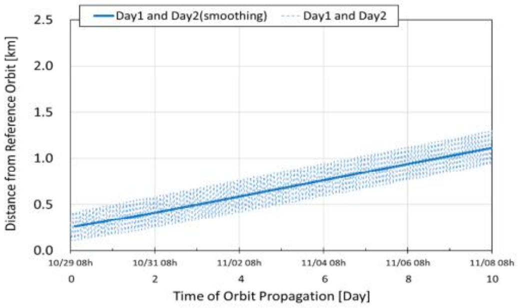
Distance between Reference orbit and Evaluation orbit
*Reference Orbit: Orbit using all obtained data
*Evaluation Orbit: Orbit using evaluation data

3. 追加検証
Additional Verification from Previous Research

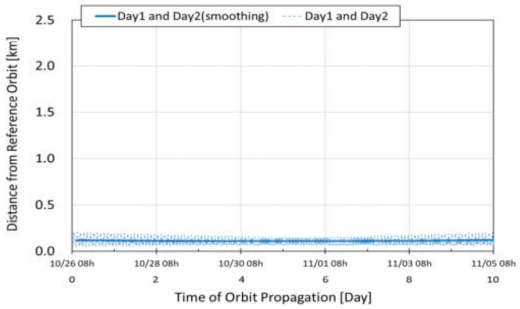
IHI

＜評価結果／Evaluation Result＞

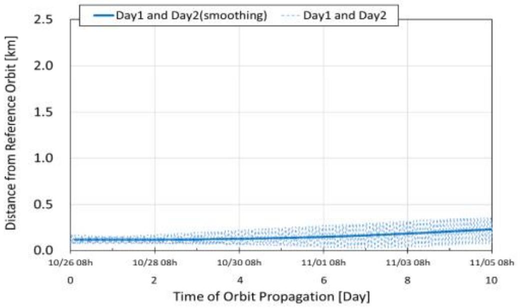
NORAD ID: 02436 (DELTA 1 Rocket Body)



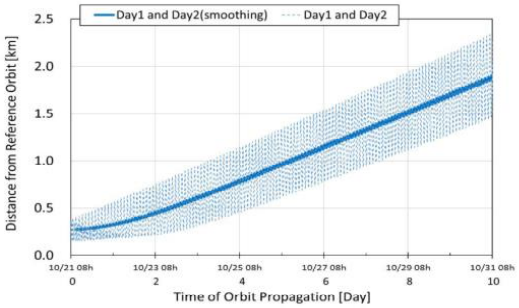
NORAD ID: 03036 (DELTA 1 Rocket Body)



NORAD ID: 04322 (DELTA 1 Rocket Body)



NORAD ID: 40303 (DELTA 1 Rocket Body)



3. 追加検証
Additional Verification from Previous Research

IHI

＜まとめ／Summary＞

	NORAD ID	Name	Distance from Reference orbit After 10days from Epoch[km]
1	02436	DELTA 1 R/B	1.11
2	03036	DELTA 1 R/B	0.12
3	04322	DELTA 1 R/B	0.22
4	40303	SL-24 R/B	1.91

追加検証の結果，同日2パス観測データを用いることで軌道決定精度向上できることを確認した。

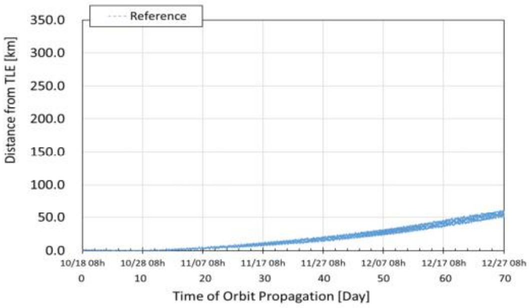
Additional validation shows that, accuracy of orbit determination can be improved by using 2 paths observation data.

4. 軌道寿命評価／Evaluation of Orbit Lifetime

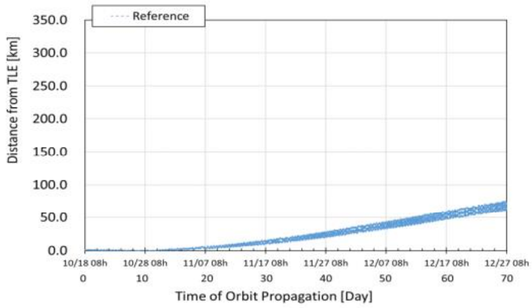
IHI

評価軌道と軌道元期から50日後のTLEを比較した。
Compared with Evaluation Orbit and TLE of 50 days from epoch.

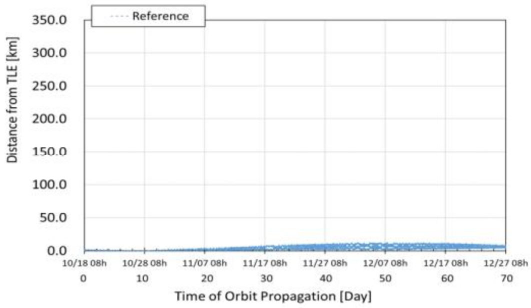
NORAD ID: 02436 (DELTA 1 Rocket Body)



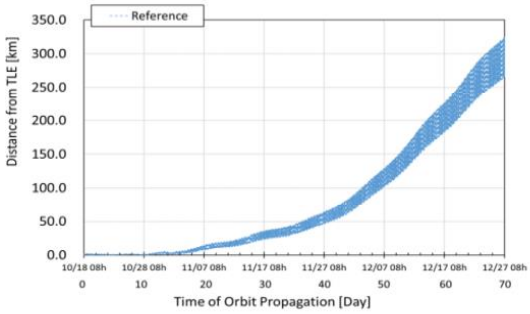
NORAD ID: 03036 (DELTA 1 Rocket Body)



NORAD ID: 04322 (DELTA 1 Rocket Body)



NORAD ID: 40303 (DELTA 1 Rocket Body)



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4. 軌道寿命評価／Evaluation of Orbit Lifetime

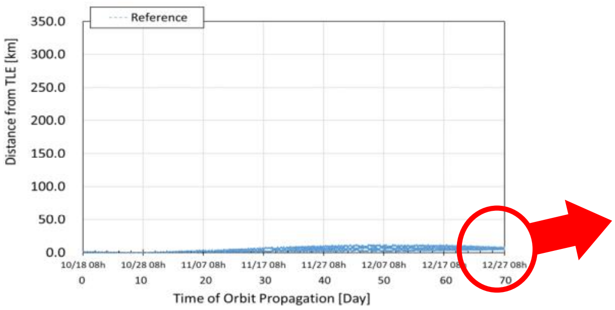
IHI

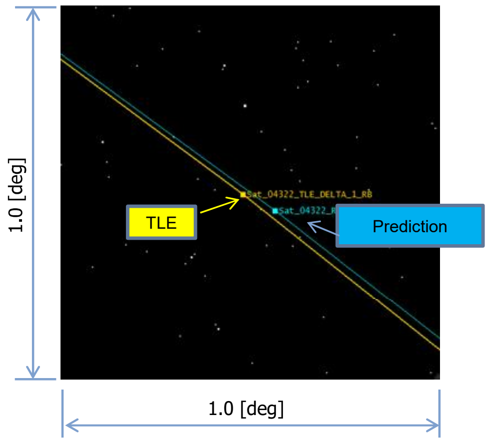
軌道決定から70日後の位置予測／Position Prediction after 70 days from Orbit Determination

今回評価した物体のうち，NORAD ID: 04322については軌道決定から70日後の位置予測結果を用いて観測可能という解析結果を得た。

Among the objects evaluated in this Research, NORAD ID: 04322 was analyzed to be observable using the position prediction results 70 days after the orbit determination.

NORAD ID: 04322 (DELTA 1 Rocket Body)





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4. 軌道寿命評価／Evaluation of Orbit Lifetime

IHI

＜観測結果／Observation Result＞

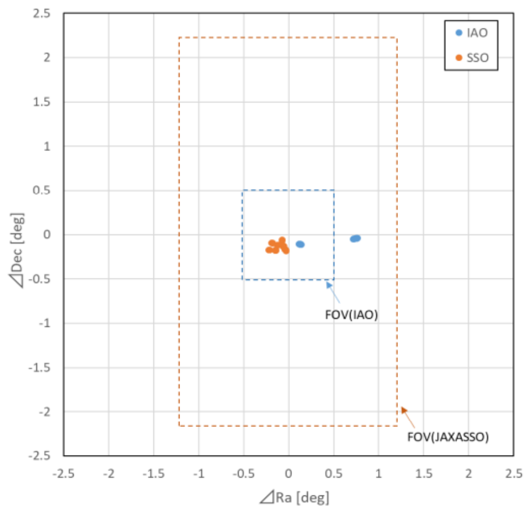
NORAD ID: 04322は，軌道決定から59日後･60日後，64日後，65日後，66日後，71日後に観測成功した。

SSO，IAOどちらの観測所においても，観測位置は予測した位置から±1.0 [deg]以内で観測できた。

NORAD ID: 04322 was successfully observed 59 days, 60 days, 64 days, 65 days, 66 days, and 71 days after orbit determination.

Observed positions were within ±1.0 [deg] from the predicted position at both SSO and IAO observatories.

Difference between Prediction and Observation



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5. まとめ／Conclusion

IHI

(1) 追加検証の結果，同日2パス観測データを用いることで軌道決定精度向上できることを確認した。

(2) 今回の研究では，NORAD ID: 04322において，軌道決定から71日後に位置予測結果を用いて観測成功した。

(1) Additional validation shows that, accuracy of orbit determination can be improved by using 2 paths observation data.

(2) In this research, NORAD ID: 04322 was successfully observed using the position prediction results of 71 days after orbit determination.

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IHI
Realize your dreams

B09

EISCAT レーダー観測データを用いた既知デブリとの相関解析

A Correlation Analysis between Space Debris Detected by an EISCAT Radar and Cataloged Ones

○藤田 浩輝，有吉雄哉（日本文理大），吉村 康広（九州大），小川泰信（国立極地研），
花田 俊也（九州大）
○FUJITA Koki, ARIYOSHI Yuya (Nippon Bunri Univ.), YOSHIMURA Yasuhiro (Kyushu Univ.),
OGAWA Yasunobu (National Institute of Polar Research), HANADA Toshiya (Kyushu Univ.)

レーダー観測により検出された低軌道上の人工物体について，最終的に未知のスペースデブリの同定を目的とした，カタログ上の既知物体との相関解析を行う．特にここでは，EISCAT Svalbard Radar (ESR)と呼ばれる，北欧スバールバル諸島に位置する大気レーダーを用いて 2022 年 3 月の 2 日間，計 14 時間にわたって観測された物体について，軌道情報が既知のカタログ物体（スペースデブリを含む全ての既知物体）から予測される観測データと実観測データ（レンジおよびレンジレート）との間の相関計算を行った結果について述べる．本相関解析でカタログ物体に対して相関の取れた物体は約 60%となった．そこで，実際に相関が得られた物体と得られなかった物体それぞれの高度やサイズや，相関が得られた物体の軌道上の特徴について調べると共に，相関が得られなかった物体の起源や，未知物体の同定における課題について考察を行う．

This paper describes an analysis of radar observation data detecting space objects in low-earth orbit (LEO), which are correlated to cataloged ones. In this work, the objects detected by an atmospheric radar system called EISCAT Svalbard Radar (ESR) are treated. When the objects observed in March of 2022 (totally 14 hours for two days) were applied to the correlation analysis, sixty percent of the observed objects were highly correlated with all the cataloged objects including space debris, which are known and constantly tracked. This paper investigates altitudes and sizes of the correlated and uncorrelated objects, respectively, as well as discusses cause of the lack of correlation and problems how to identify the uncorrelated objects.

B09

A Correlation Analysis between Space Debris Detected by an EISCAT Radar and Cataloged Ones

10th Space Debris Workshop

November 29, 2022

JAXA Chofu Aerospace Center (and Online)

○ FUJITA Koki, ARIYOSHI Yuya (Nippon Bunri Univ.), YOSHIMURA Yasuhiro (Kyushu Univ.), OGAWA Yasunobu (National Institute of Polar Research), HANADA Toshiya (Kyushu Univ.)

日本文理大学 NIPPON BUNRI UNIVERSITY KYUSHU UNIVERSITY NiPR National Institute of Polar Research

Outline

- Background and Objective of this Research
- Observation Campaign with EISCAT Radar in 2021
- A Correlation Analysis between the Detected Objects and Cataloged Objects in LEO
- Comparisons among the Analytical Results of Past Campaigns in 2016-2018
- Discussion
- Conclusions and Future Work

2

Background and Objectives

EISCAT Radars

Operated by **E**uropean **I**ncoherent **SCAT**ter Scientific Association

Main target: Disturbances in the ionosphere and magnetosphere

[redacted]

ESR (= EISCAT Svalbard Radar)

EISCAT HQ

(Common Use in Japan)

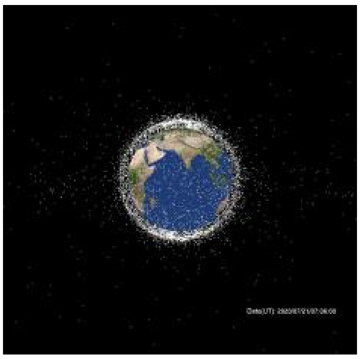
National Institute of Polar Research (NIPR)
Nagoya Univ.(ISEE)

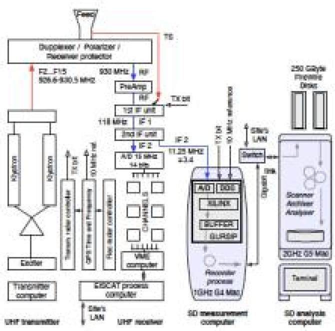
Domestic universities and research organizations

3

Background and Objectives

SD Receiver





Space Debris (SD) Receiver

The Fast Match Function (FMF) Algorithm

J.Markkanen, N.Postila, "REAL-TIME SMALL-SIZE SPACE DEBRIS DETECTION WITH EISCAT RADAR FACILITIES", Final Report of ESOC Contract No.16646/02/D/HK(CS) with EISCAT Scientific Association, Feb., 2005.

Space Object (including Debris) Tracking for Low-Earth-Orbit

4

Background and Objectives (in the past studies)

- Observation campaigns targeting space debris as one of the special programs of EISCAT experiment in Japan (2016 -)

- A special program in FY2019 - FY2021 (PM：Fujita)

"Observation Campaign Aiming at Identification of Space Debris and Validation of an Environment Model for a Specific Breakup Event"

  - FY2019・・・ Observation planning and a (Constrained Admissible Region based) classification analysis for fragmentation debris from 4 different parent objects.
  - FY2020・・・ The same study for fragmentation debris from 5 different parent objects. + A correlation analysis for the cataloged objects

Out of range in this study

5

Background and Objectives (In this study)

- A correlation analysis for the known cataloged objects
  - The analytical results for the campaign in FY 2020
  - 1409 among 7794 objects (18%) were correlated to the cataloged ones
- Another group's results from an EISCAT experiment
  - ESA's Beam Park Observations in 2018 (Vierinen, 2018)
  - 2043 among 2400 objects (85%) were correlated to the cataloged ones
  - The experiment at the same site (ESR) while to the different obs. direction
- The special program in FY 2021
  - An observation campaign focusing on the correlation analysis to the cataloged objects
  - <u>Considering a targeted observation was impossible</u> because of a failure of a gear box of the ESR 32m antenna.

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Observation Campaign with EISCAT Radar in 2021

※ 42m-antenna was used instead of 32m-antenna (used in the past studies)

Table1 Observation conditions in the campaign 2021

Facility	EISCAT Svalbard Radar (ESR) 42m-antenna
Site (geographical lat. and long.)	(78° 09′ N, 16° 03′ E)
Dates	Mar. 3 and 4, 2022 8:00 – 15:00 UTC
Targets	All the cataloged objects in LEO
Observation direction (fixed)	(Az, El) = (180.5deg, 82.1deg)

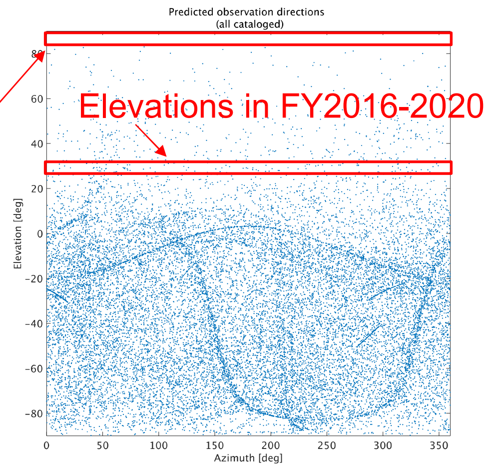

Fig.1 Predicted observation directions of the cataloged objects (10am(UTC), Mar.4, 2022, Site: ESR)

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Observation Campaign with EISCAT Radar in 2021

Table 2. Observation results of the campaign 2021

March 3, 2022		March 4, 2022	
Time slot (UTC)	Counts	Time slot (UTC)	Counts
08:00-09:00	41	08:00-09:00	35
09:00-10:00	58	09:00-10:00	46
10:00-11:00	40	10:00-11:00	87
11:00-12:00	56	11:00-12:00	75
12:00-13:00	52	12:00-13:00	50
13:00-14:00	36	13:00-14:00	33
14:00-15:00	38	14:00-15:00	45
Subtotal	321	Subtotal	371

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Observation Campaign with EISCAT Radar in 2021

- Estimated physical parameters of the detected objects

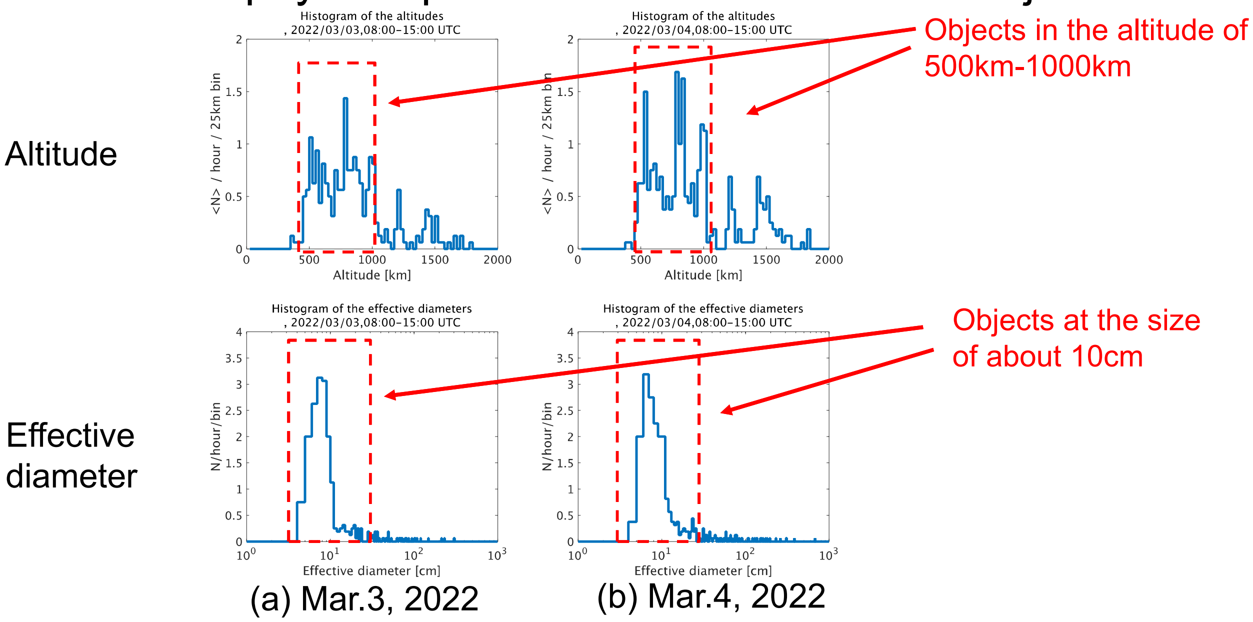
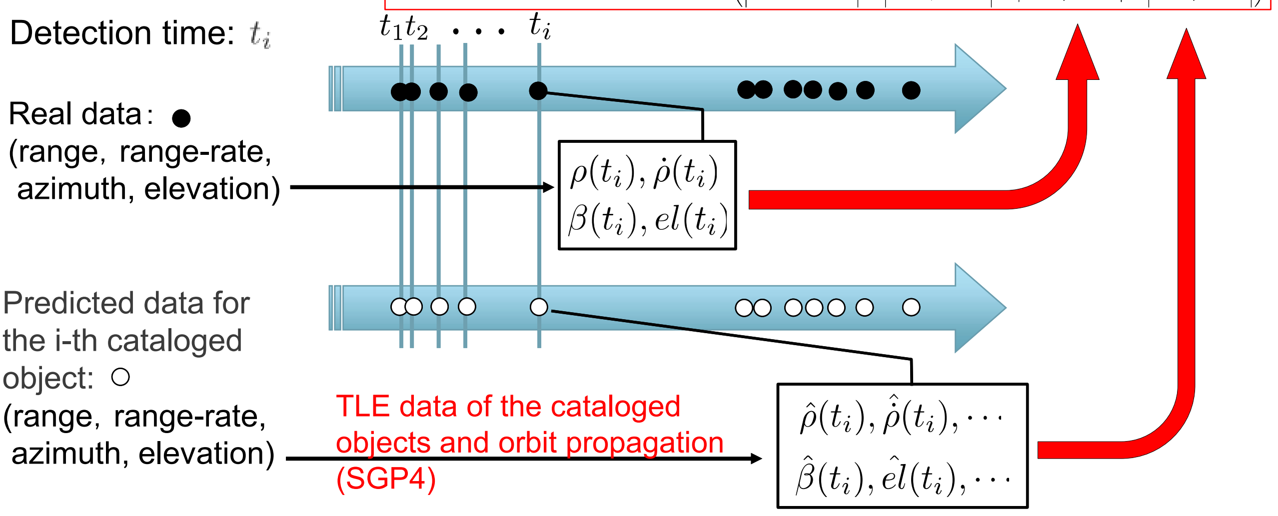


Fig.2 Histograms of the physical parameters' distribution

A Correlation Analysis between the Detected Objects and Cataloged Objects in LEO

- Correlation Analysis

Correlation Function (MAD): $\mathrm{MAD}(i) = \frac{1}{4}\left(\left|\frac{el(t_i)-\hat{el}(t_i)}{el_l}\right| + \left|\frac{\beta(t_i)-\hat{\beta}(t_i)}{\beta_l}\right| + \left|\frac{\rho(t_i)-\hat{\rho}(t_i)}{\rho_l}\right| + \left|\frac{\dot{\rho}(t_i)-\hat{\dot{\rho}}(t_i)}{\dot{\rho}_l}\right|\right)$



$\mathrm{MAD}(i) > 1$: Uncorrelated

$\arg\min_i \mathrm{MAD}(i)$: Correlated to the (i-th) cataloged object

A Correlation Analysis between the Detected Objects and Cataloged Objects in LEO

Table 3. Analytical results (for the campaign 2021)

Mar.3, 2022			Mar.4, 2022		
Time slot (UTC)	Number of the obs. data	Number of the corr. objects	Time slot (UTC)	Number of the obs. data	Number of the corr. objects
08:00-09:00	40	27	08:00-09:00	35	26
09:00-10:00	58	40	09:00-10:00	46	40
10:00-11:00	38	24	10:00-11:00	81	66
11:00-12:00	55	41	11:00-12:00	74	57
12:00-13:00	52	37	12:00-13:00	49	31
13:00-14:00	36	21	13:00-14:00	31	23
14:00-15:00	38	29	14:00-15:00	45	30
Subtotal	317	219(69%)	Subtotal	361	273(76%)

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A Correlation Analysis between the Detected Objects and Cataloged Objects in LEO

Table4. Analytical results (breakdown on the object type)

Mar. 3, 2022		Mar.4, 2022	
Type	Corr. objects	Type	Corr. objects
Fragmentation debris	74	Fragmentation debris	96
R/B	28	R/B	28
The others	117	The others	149
Subtotal	219	Subtotal	273

➡ About half of the correlated objects can be classified as space debris (fragmentation debris and rocket bodies)

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Comparisons among the Analytical Results of Past Campaigns in 2016-2018

FY 2016			FY 2017		
Date and time (UTC)	Obs. data	Corr. objects	Date and time (UTC)	Obs. data	Corr. objects
Jan.13, 2017 02:00-09:00	217	194(89%)	Feb.1, 2018 13:00-20:00	673	382(57%)
Jan.13,2017 14:00-22:00	1035	647(63%)	Feb.2,2018 14:00-20:00	529	262(50%)

FY 2018 -1			FY 2018 - 2		
Date and time (UTC)	Obs. data	Corr. objects	Date and time (UTC)	Obs. data	Corr. objects
Dec.13, 2018 00:00-06:00	467	430(92%)	Dec.13,2018 13:00-14:00	**63**	**1(2%)**
Dec.13,2018 14:00-20:00	309	178(58%)	Range-rates of the 982 objects among 1045 observed ones: NaN → Unanalyzable		

3

➢Discussion

- Conceivable factors for the extremely low rate of the objects correlated to the cataloged ones
  - Spatio-temporal distribution of the objects in orbit for a specific observation direction and time

    - Failure of obtaining range-rate data as well as decreasing analysis precision
  - Uncorrelated (Unidentified) objects

    - Unknown objects outside of the catalogue
  - Characteristic properties of radar observation

    - Accuracy issues on a distance measured from various elevation angles (FY2016-2020: El = about 30deg, FY2021: El = about 82deg, ESA's experiment in 2018: El = 75deg)
    - Issues on detection sensitivity caused from effects of sidelobes

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➢Conclusions and Future Work

[Summary]

- For the campaign in FY 2021, 69-76% of the detected objects were correlated to the cataloged objects in LEO.
- A reason of the extremely low rate of the correlation (as seen in FY 2020) is considered that it may depend on the objects' spatio-temporal distribution for a specific observation direction and time.

[Future work]

- Understanding a relation between the rate of the correlation and number of the observation data for a specific observation direction and time.

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B10

東京大学「トモエゴゼン」の科学観測データを活用した民間宇宙状況監視データプラットフォームの取り組みについて

Leveraging Scientific data by Tomo-e Gozen to a Commercial SSA Data Platform

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益田哲也（デロイトトーマツコンサルティング株式会社），酒向重行（東京大学），
Tomo-e Gozen プロジェクト
○MITSUDA Kazuma, HATTORI Kunihiro (Deloitte Tohmatsu Risk Advisory Co., Ltd.), TANIMOTO Hirotaka,
WAKIMOTO Takuya, MASUDA Tetsuta (Deloitte Tohmatsu Consulting Co., Ltd.),
SAKO Shigeyuki (University of Tokyo), Tomo-e Gozen Project

本公演では東京大学の科学観測データを活用した民間宇宙状況監視(SSA)データプラットフォームの取り組みを紹介する。人工衛星が社会インフラとして機能する中、宇宙ゴミの増加により宇宙空間の持続的な開発・利用へのリスクが高まっている。事業への影響を抑えつつ宇宙ゴミとの衝突を回避するには、宇宙ゴミを含む人工天体の軌道について、高い網羅性と精度のデータが欠かせない。そこで我々は、東京大学の可視光広視野動画カメラ「トモエゴゼン」の全天サーベイに映り込む人工天体を抽出し、軌道などのデータを提供するプラットフォームの開発を計画する。このサーベイでは一晩に平均約900件の移動天体が検出され、その大部分は未カタログを含む人工天体である。広視野動画観測を活かした未カタログの人工天体の発見による網羅性の向上と、カタログ済みのものについては光学観測による精度向上を図る。最初期のプロトタイプでは人工天体の軌道データをTLE形式で提供する計画である。

We are developing a commercial Space Situation Awareness (SSA) data platform leveraging scientific observational data taken by the university of Tokyo. An increasing number of space debris poses a risk for activity of satellites which are a part of the social infrastructure. In order for satellites to avoid collisions with debris while minimizing impact for the business, orbital data of artificial objects including debris with high precision and completeness are crucial. We extract artificial objects from the scientific output obtained in the all sky survey by Tomo-e Gozen at the university of Tokyo, and provide data such as orbital elements on the data platform we are developing. In the survey, on average ~900 moving objects are observed per night, and most of them are supposed to be artificial objects including uncatalogued. We contribute enhancement of completeness by discovering uncatalogued objects utilizing wide-field movie observation as well as that of precision for catalogued ones by adding optical observations. On the prototype of the platform, we plan to provide orbital data of artificial objects in the TLE format.

Deloitte.
デロイト トーマツ

東京大学「トモエゴゼン」の科学観測データを活用した民間宇宙状況監視データプラットフォームの取り組みについて

Leveraging scientific data by Tomo-e Gozen to a commercial SSA data platform

Kazuma Mitsuda (Deloitte Tohmatsu Risk Advisory), Tomo-e Gozen Project, and other 4 authors
Space Debris WS 10, 2022 Nov.

MAKING AN IMPACT THAT MATTERS since 1845

Our project is based on the academic-industrial collaboration research between the University of Tokyo and Deloitte Tohmatsu Risk Advisory

Project Members

Academic-industrial collaboration research

Deloitte

Kazuma Mitsuda
- Deloitte Tohmatsu Risk Advisory, Co. Ltd.
- New Business Development
- Manager
- Ph.D. in Astronomy

Kunihiro Hattori
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The University of Tokyo

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- Institute of Astronomy, School of Science
- Associate Professor

TOMO-E GOZEN

Tomo-e Gozen Project

We are developing a data platform to provide space debris data obtained as contamination in scientific observations

Key Takeaways

Our Missions

- To enhance scientific value of Tomo-e Gozen
- To contribute to sustainable development of space business

Tomo-e Gozen

- Wide FoV (20 deg2), optical, video (2 fps) observation
- All sky survey ≧ 1 per night
- > 1000 artificial objects are detected per night as contamination of NEO

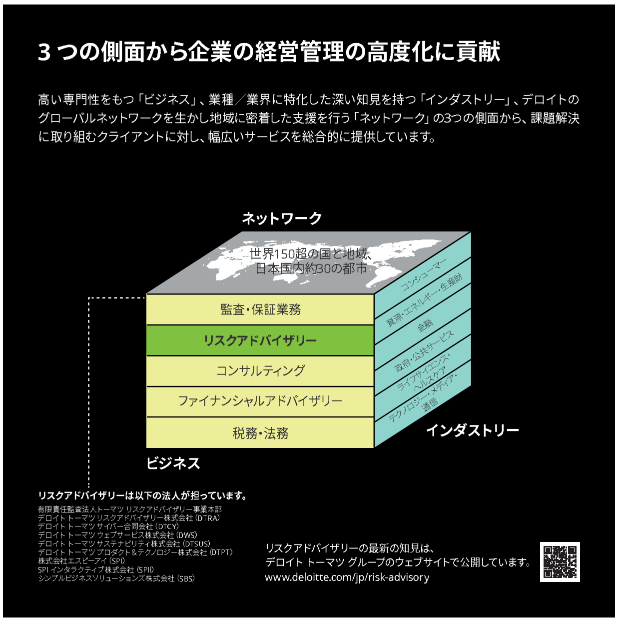
Space Debris Data Platform

- Space debris data are extracted from Tomo-e Gozen's scientific data
- The data and related solutions will be provided on web GUI and API
- A prototype is being developed and going live next year

Why Deloitte Deals with Space Debris

Deloitte offers a wide range of comprehensive professional services to clients who are working on solving their respective issues

Deloitte Tohmatsu Risk Advisory



We offer various services to promote space business

Our Contribution to Space Industry

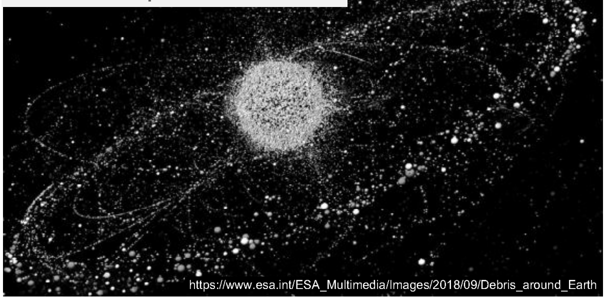
*1: deloitte.com
*2: deloitte.com
*3: deloitte.com

*1: https://www2.deloitte.com/jp/ja/pages/energy-and-resources/solutions/space.html; *2: https://www2.deloitte.com/jp/ja/pages/about-deloitte/articles/d-nnovation/np-space-business-satellite.html;
*3: https://www2.deloitte.com/jp/ja/blog/science-and-technology/2022/space-transportation-system.html

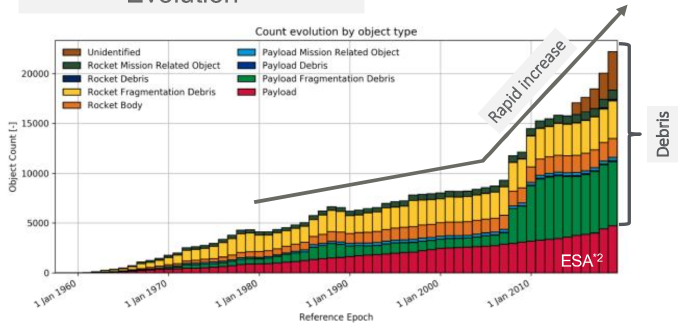
Increasing number of debris is one of the largest concern in space development

Space Debris

Current space situation



Evolution*2



Estimated number of debris*2	Size	Count
	> 10 cm	36,500
	1 -- 10 cm	1,000,000
	< 1 cm	130 million

Space debris can be a significant risk in the future

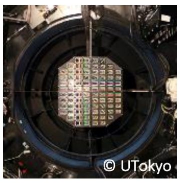
*2: https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers ; *2: ESA: http://www.esa.int/Safety_Security/Space_Debris/About_space_debris

We contribute to sustainable development of space with space debris risk services by leveraging scientific garbage data

Our Solution

The University of Tokyo and Deloitte has carried out collaboration research for more than 2 years

Tomo-e Gozen's scientific data × **Algorithm & Solution by Deloitte**



- Optical
- 1.05-m Schmidt telescope
- Wide FoV (20 deg^2)
- Video (2 fps) observation

- > 1000 artificial objects are detected per night
- Debris data are useless garbage for scientists

Kazuma Mitsuda
- Data scientist in Deloitte
- Observational astronomer
- Development member of Tomo-e Gozen

Space debris risk services for sustainable development of space

Tomo-e Gozen’s Observation

Tomo-e Gozen is a mosaic CMOS camera mounted on the 1.05-m Schdmit telescope at Kiso Observatory, the University of Tokyo

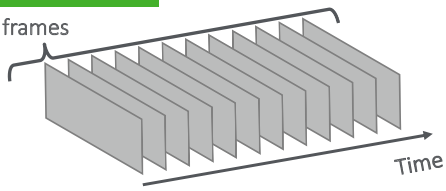
Tomo-e Gozen Overview

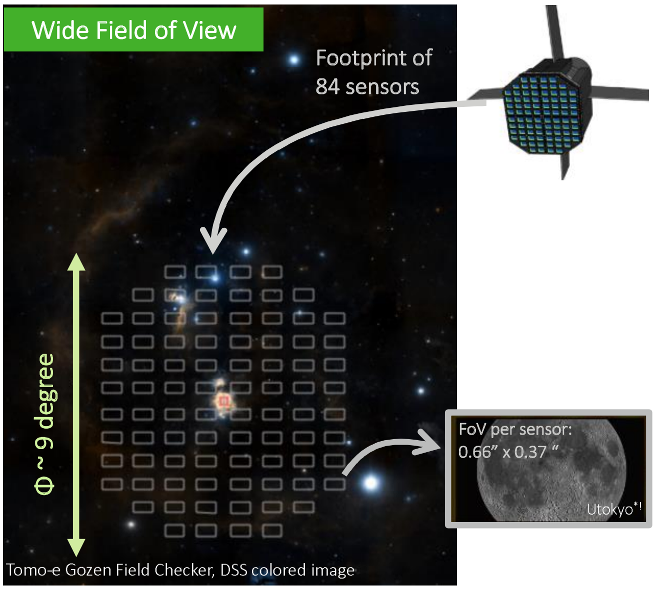
Tomo-e Gozen provides unique opportunities to monitor the sky with wide a field of view (~ 20 deg^2) and 2-fps frame rate

Wide Field-of-view, Optical, Movie Observation

Spec	
Telescope	The 1.05-m Schmidt telescope
Wavelength	Optical (single band)
Field of view	20 deg^2
Sensor	84 high-sensitivity CMOS sensors
Resolution	~3 arcsec FWHM (seeing limit)
Frame rate	2 fps
Limit. mag.	~18th mag (0.5 sec exposure)

Video Observation

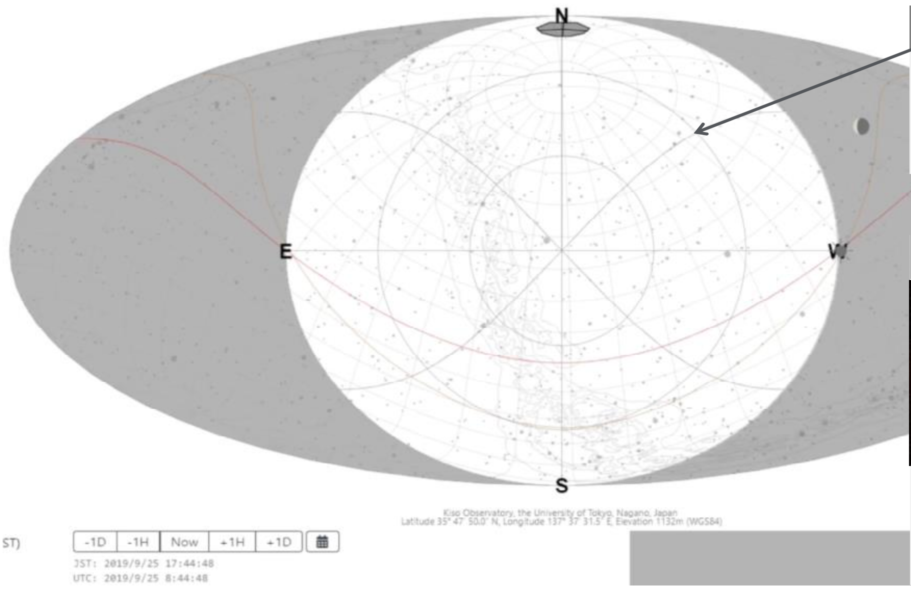




*1: http://www.ioa.s.u-tokyo.ac.jp/kisohp/NEWS/pr20190930/pr20190930.html

Survey observation is carried out every clear night with which the sky visible from the Kiso observatory is monitored > once per night

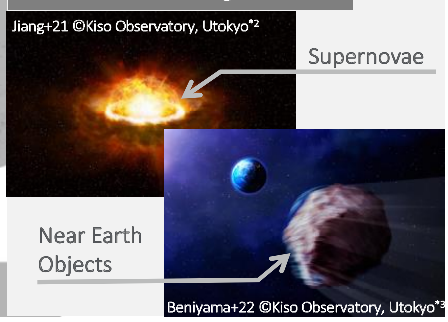
All Sky Survey



Survey Path (example shown*1)

- Determined and tuned automatically
- Depends on conditions
  - Scientific programs
  - Weather

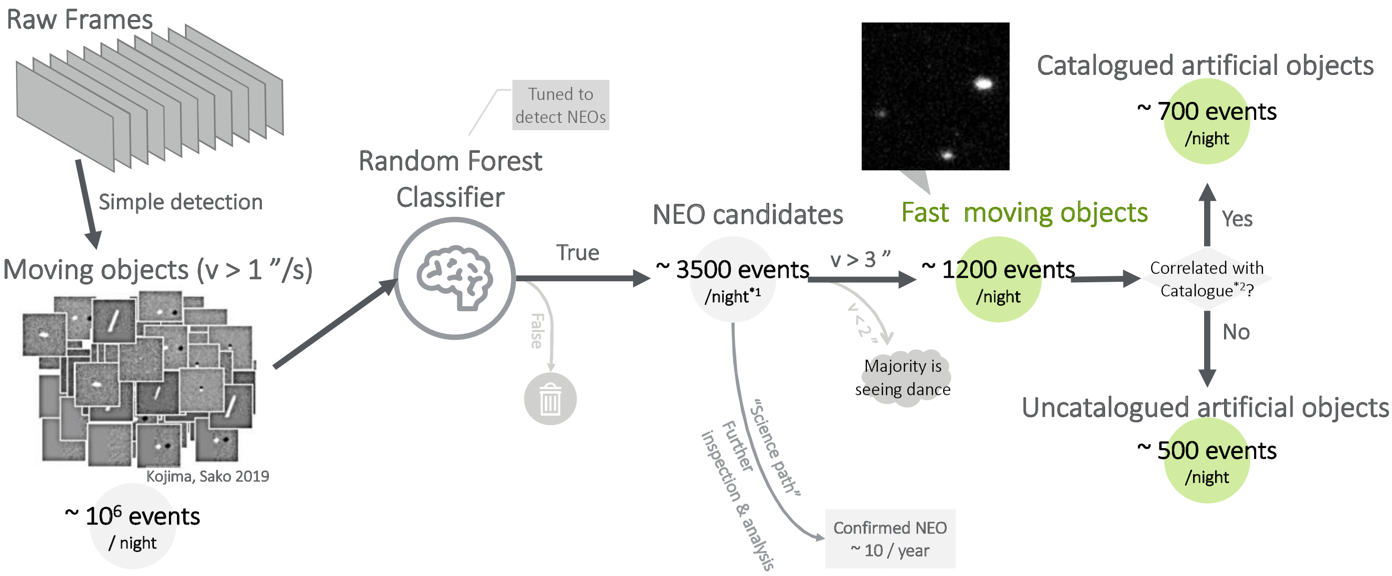
Scientific Targets



*1: http://www.ioa.s.u-tokyo.ac.jp/kisohp/NEWS/pr20190930/pr20190930.html; *2: https://www.s.u-tokyo.ac.jp/ja/info/7665/; *3: https://www.s.u-tokyo.ac.jp/ja/press/2022/7975/;

Artificial objects are detected as contaminations of Near Earth Objects (NEOs)

NEO Detection Algorithm and Artificial Objects in Tomo-e Gozen's Observation

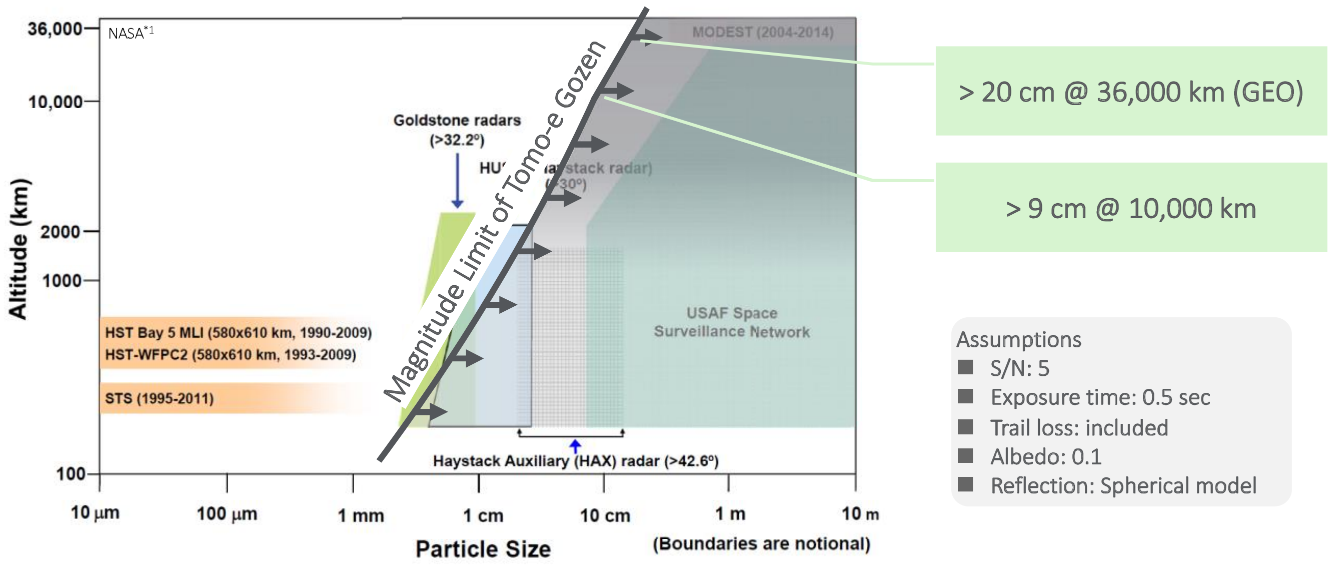


*1: Average of 12 nights (20200614 to 20200617, 20201107 to 20201111, 20220329, 20220330, and 20220401); *2: Space Track (https://www.space-track.org/)

Satellites/Space Debris Observed by Tomo-e Gozen

Optical video observation provides detection capability at high altitude

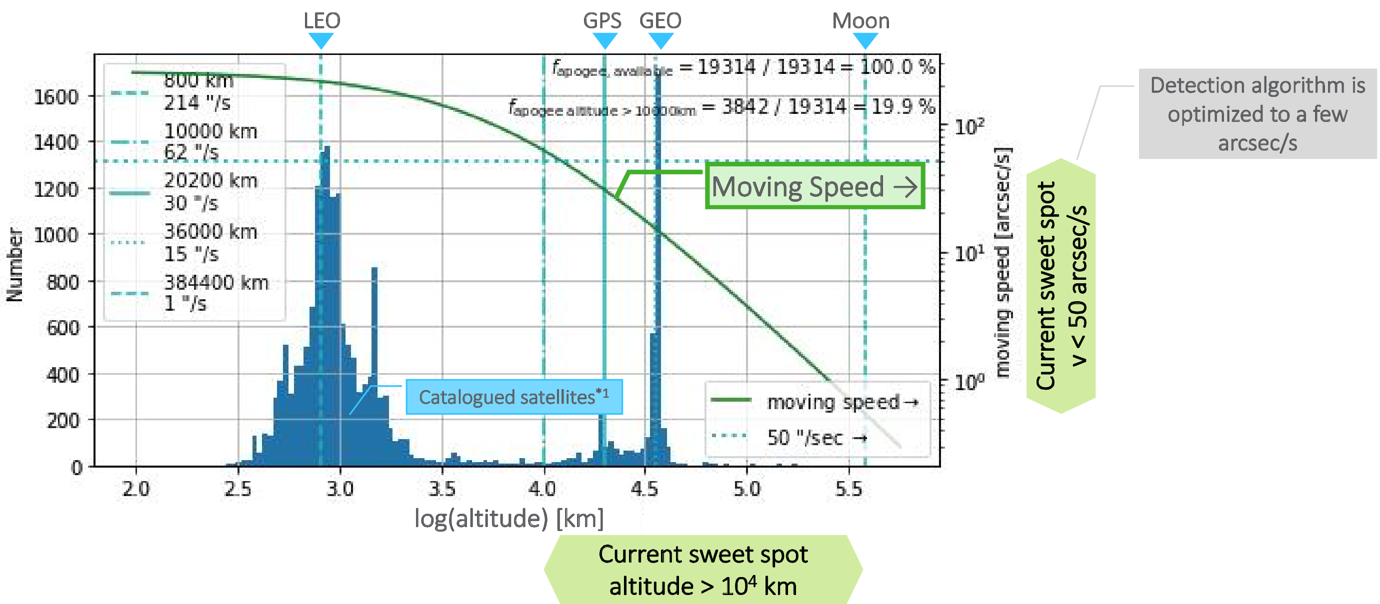
Detection Capability of Tomo-e Gozen



*1: NASA https://orbitaldebris.jsc.nasa.gov/measurements/

At an early stage, we focus on contaminations of NEOs. As the current detection algorithm is optimized to a few arcsec/s, main targets are debris at altitude > 10^4 km

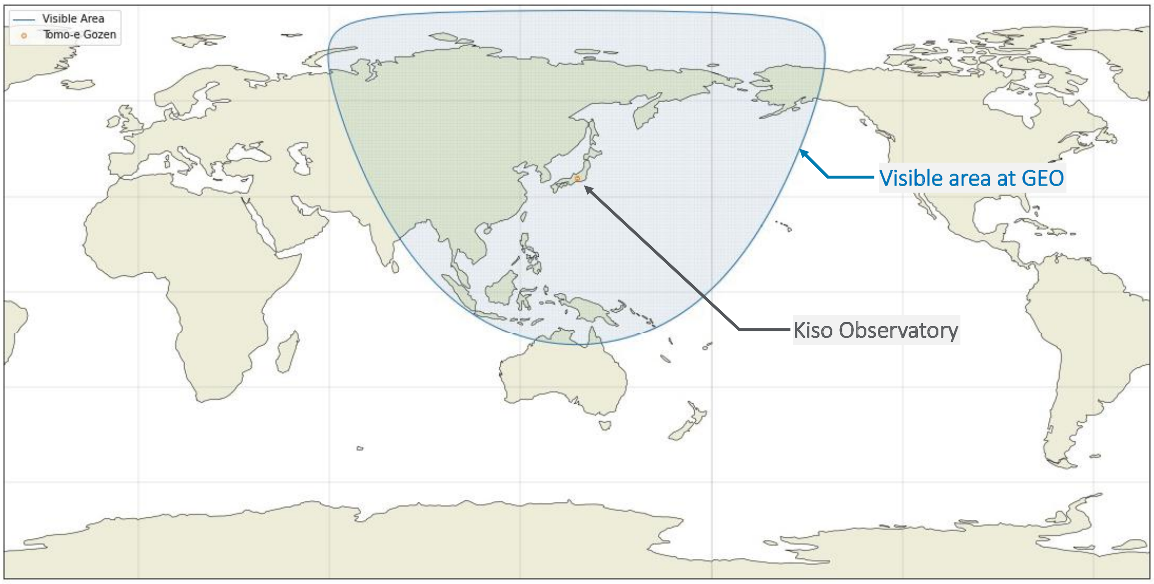
Space Debris as Contaminations of NEO



*1: Space Track (https://www.space-track.org/)

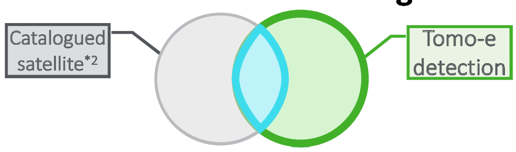
The sky visible from Kiso Observatory with telescope altitude > ~30 deg can be observed in the all sky survey

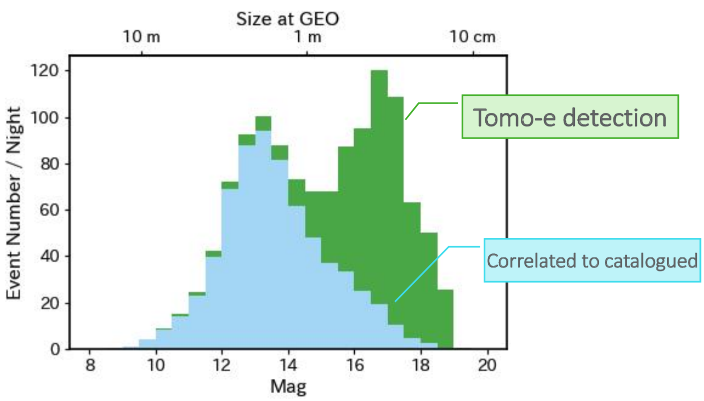
Visibility at GEO

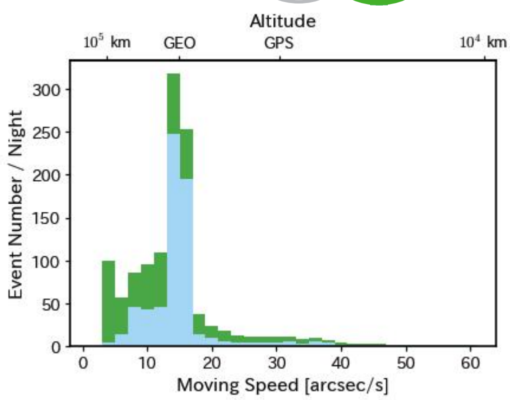


Objects are detected down to ~19th mag with uncatalogued detections in > 15th mag

Statistics from Observational Data*1 -- Tomo-e Detection







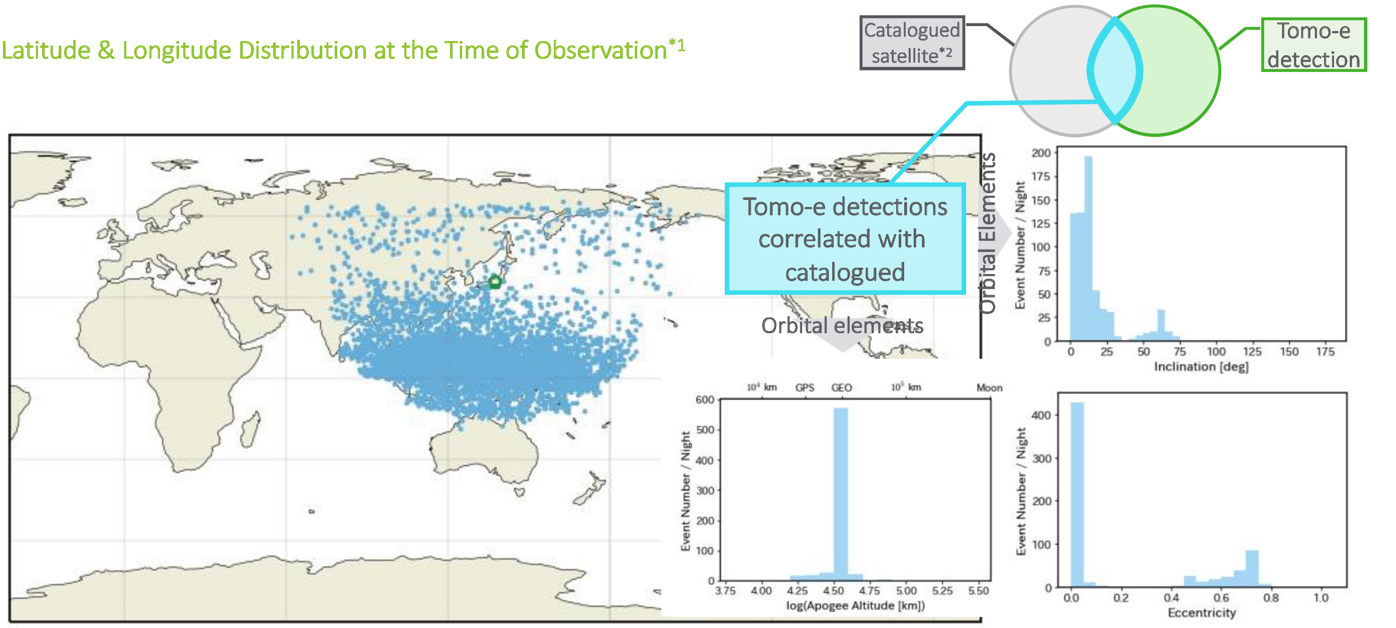
Magnitude distribution
- Objects are detected down to ~19th mag
- Uncatalogued detections in > 15th mag

Moving speed distribution
- Detections mainly in GEO and above
- ~100 uncatalogued detections around GEO

*1: Average of 12 nights (20200614 to 20200617, 20201107 to 20201111, 20220329, 20220330, and 20220401); *2: Space Track (https://www.space-track.org/)

Catalogued satellites/debris detected by Tomo-e Gozen are mainly GEO and highly eccentric orbits

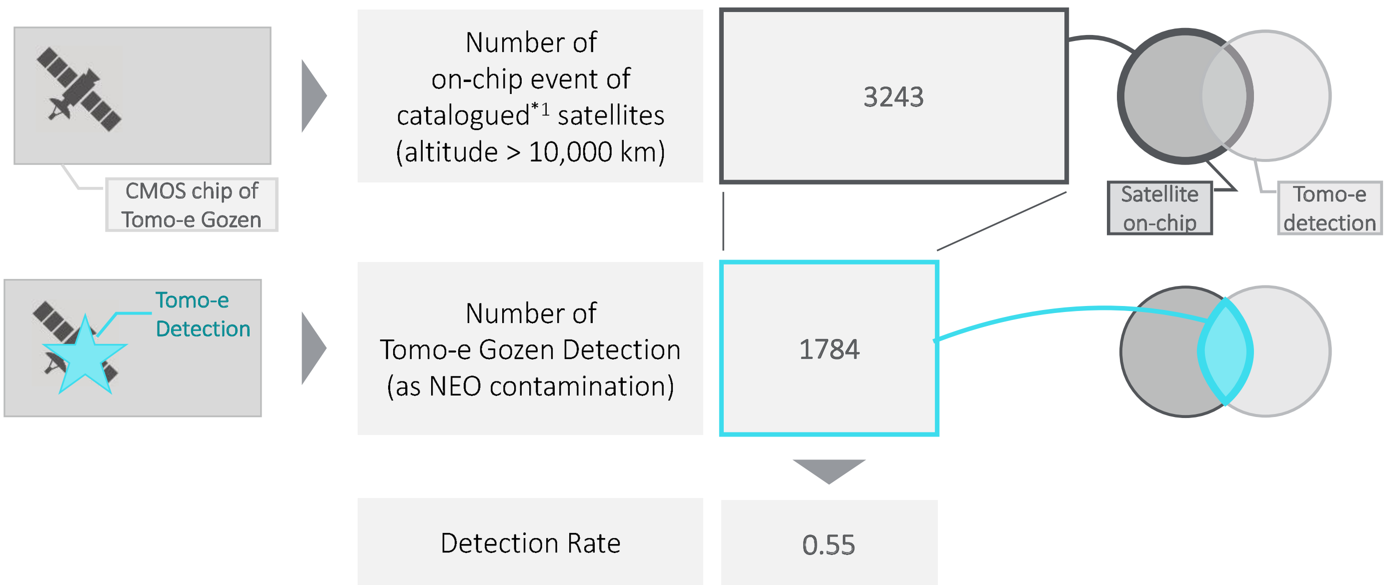
Latitude & Longitude Distribution at the Time of Observation*1



*1: In 12 nights (20200614 to 20200617, 20201107 to 20201111, 20220329, 20220330, and 20220401); *2: Space Track (https://www.space-track.org/)

When a satellite/debri passes on a CMOS chip of Tomo-e Gozen, it is detected as NEO contamination with a ~55 % possibility

Detection Rate of satellites/debris by Tomo-e Gozen (Observations from 20200615 to 20200617)*1

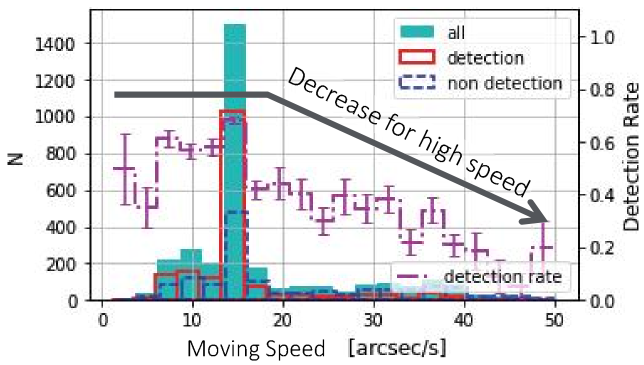


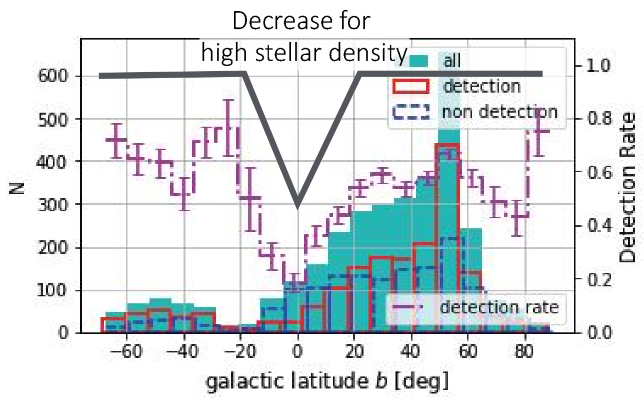
*1: From poster presentation by KM in Space Debris Workshop 9; *2: Space Track (https://www.space-track.org/)

Detection rate of satellites/debris is affected by systematic and random factors such as moving speed and background stellar density

Systematic and Random Effects on the Detection Rate*1

Systematic Effect	▶	Detection rate decreases with increasing moving speed (example)	Random Effect	▶	Detection rate decreases when the background stellar density is high



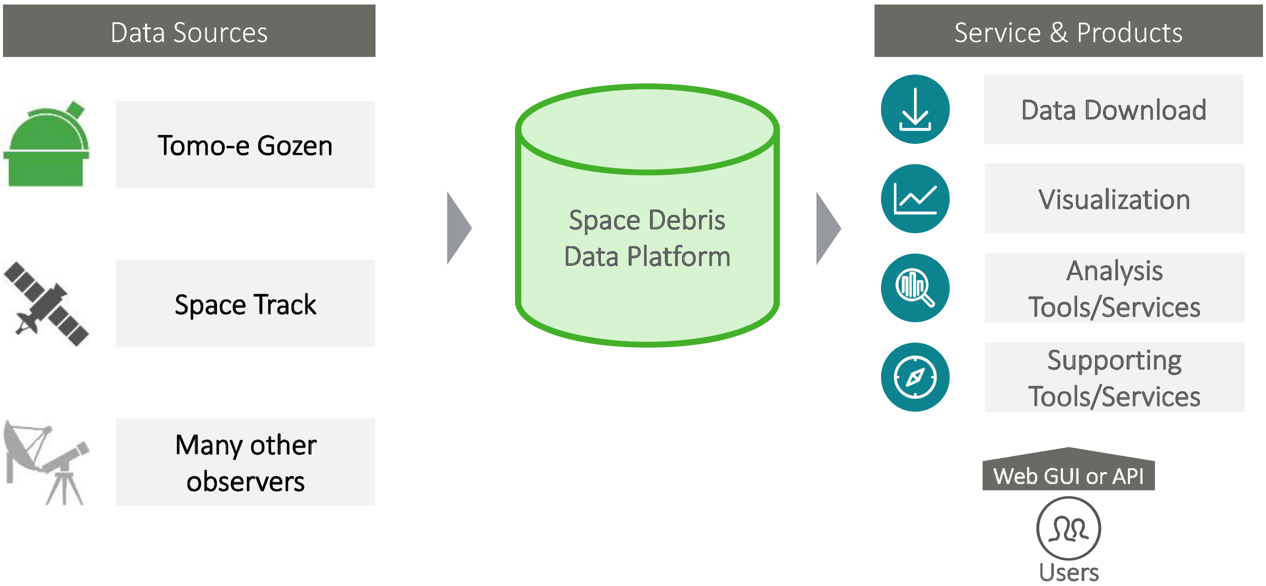


*1: From poster presentation by KM in Space Debris Workshop 9

The Space Debris Data Platform

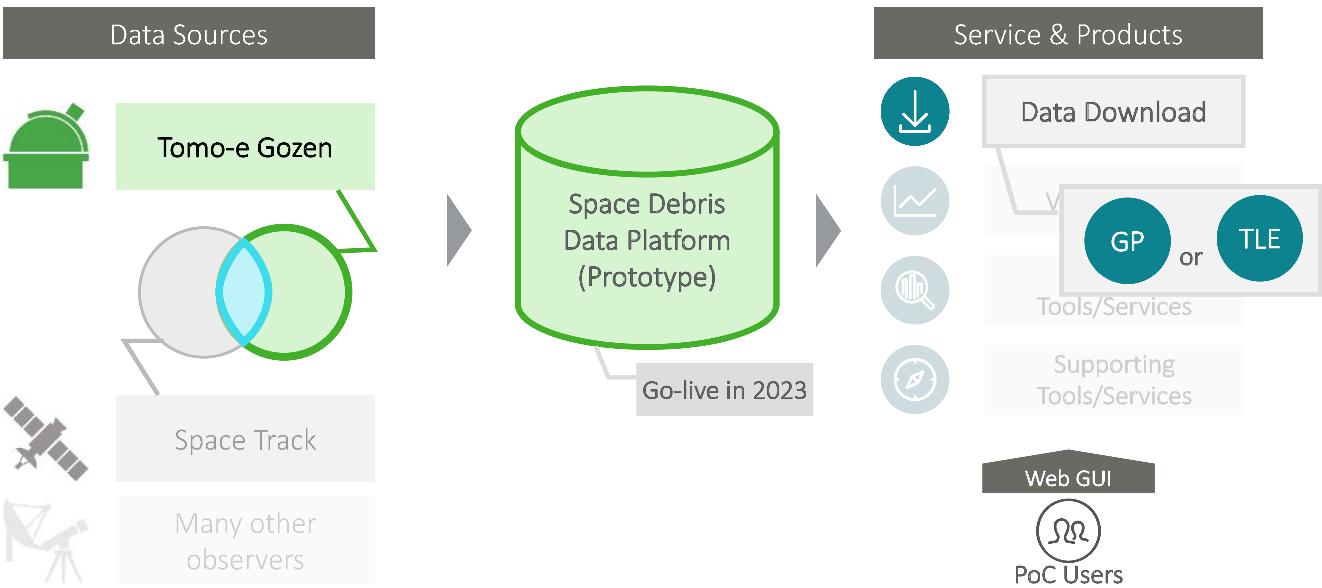
In addition to Tomo-e Gozen, we plan to gather available observational data to make our service and products useful for space business players

Overview of the Space Debris Data Platform



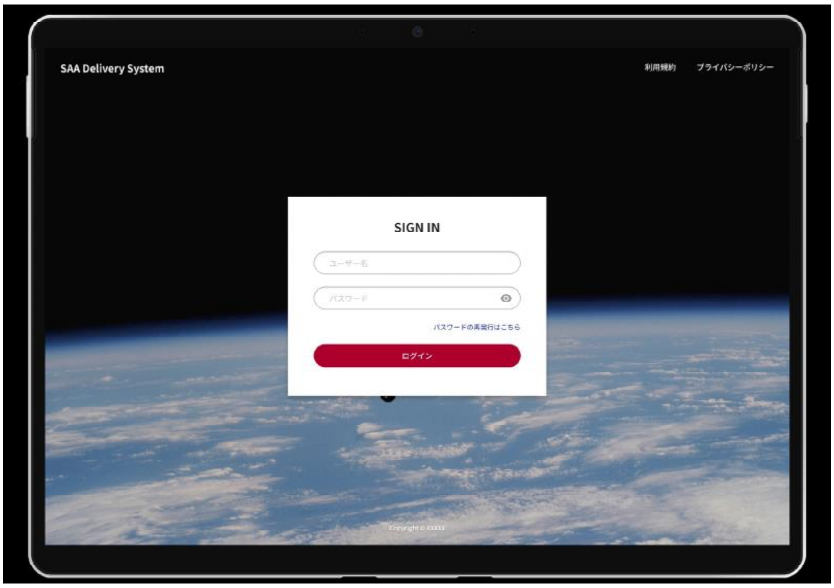
We are developing a prototype of the data platform. Users will be able to download data (GP and/or TLE format) obtained from Tomo-e Gozen's observation

Prototype of the Space Debris Data Platform



Users will be able to access the data on the prototype via web GUI

Prototyping of the Space Debris Data Platform (Demo)



We are planning services related space debris monitoring.
We would like to hear what you need and/or want

Prospective Services to be Provided on the Space Debris Data Platform

Satellite Operators
- Space situation monitoring
- Collision avoidance
- Antenna prediction
- Comprehensive risk services

Launch Servicers
- Proximity analysis including
- Monitoring upper stage of a rocket

Think Tanks
- Reporting debris risks
- Data provision

Insured Satellites
- Risk-based pricing
- Telematics insurance

Educational Institutions
- Space educational program
- Data science education material

Public
- SDGs promotion
- Entertainment app.

Conclusion

We are developing a data platform to provide space debris data obtained as contamination in scientific observations

Conclusion

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- The data and related solutions will be provided on web GUI and API
- A prototype is being developed and going live next year

We would appreciate any questions, comments, requests, or suggestions!

Please Contact Us!

Please contact me for any questions, comments, requests, or suggestions!

Kazuma Mitsuda / 満田 和真

kazuma.mitsuda<at>tohmatsu.co.jp

Deloitte.
デロイト トーマツ

B11

光・赤外大学間連携による Starlink Visorsat の等級評価

Magnitude Estimation of Starlink's Visorsat by the OISTER Collaboration

○堀内 貴史（東京大学），花山 秀和，大石 雅寿（国立天文台），OISER collaboration
○HORIUCHI Takashi (The University of Tokyo), HANAYAMA Hidekazu, OHISHI Masatoshi (NAOJ),
OISER collaboration

SpaceX は高速インターネット通信サービスの充実を目的として 2019 年 5 月に 60 機の Starlink 衛星を低軌道(550km)に打ち上げ，将来的に 12,000 機に達する予定である．一方で，Starlink 衛星は低軌道ゆえに太陽の反射光が明るく見えて，地上観測に多大な影響を残すことが示唆されている．近年，SpaceX は太陽光入射を遮り反射を抑えるため，衛星本体に庇を装着したバイザーサット(Visorsat)を複数開発し 2020 年 6 月に打ち上げた．
我々は紫外から近赤外の領域で Visorsat と庇のない通常のスターリンク衛星の一つ(STARLINK-1113)の等級の比較を行うべく，光・赤外大学間連携(OISTER)による連携観測を実施した．結果として，各波長で Visorsat(7 等程)は 1 等級程度 STARLINK-1113(6 等程)より暗くなり庇の効果を実証することができた．一方で，地上観測への影響は未だに無視できず，更なる反射逓減対策が必要である．

SpaceX launched 60 Starlink satellites into low orbit (550 km) in May 2019 for the purpose of enhancing high-speed Internet communication services, reaching 12,000 satellites in the future. On the other hand, it has been suggested that sunlight reflection from the Starlink satellites strongly shows a significant impact on ground-based observations due to their low orbit. In recent years, SpaceX has developed Visorsat, which are equipped with a sun visor on the main body of the satellite to block the incoming sunlight and suppress the reflection, and its first satellite was launched in June 2020.
We conducted cooperative observations by optical and infrared synergetic telescopes for education and research (OISTER) to compare the magnitudes of Visorsat and one of the ordinary Starlink satellites without the sun visor (STARLINK-1113) in the UV to near-infrared region. As a result, Visorsat (~ 7 mag) is fainter than STARLINK-1113 (~ 6 mag) by about 1 mag at each wavelength region, demonstrating a shading effect of the sun visor. On the other hand, the effect of Visorsat on ground-based observations is still not negligible, and further measurements for dimming of reflections are needed.

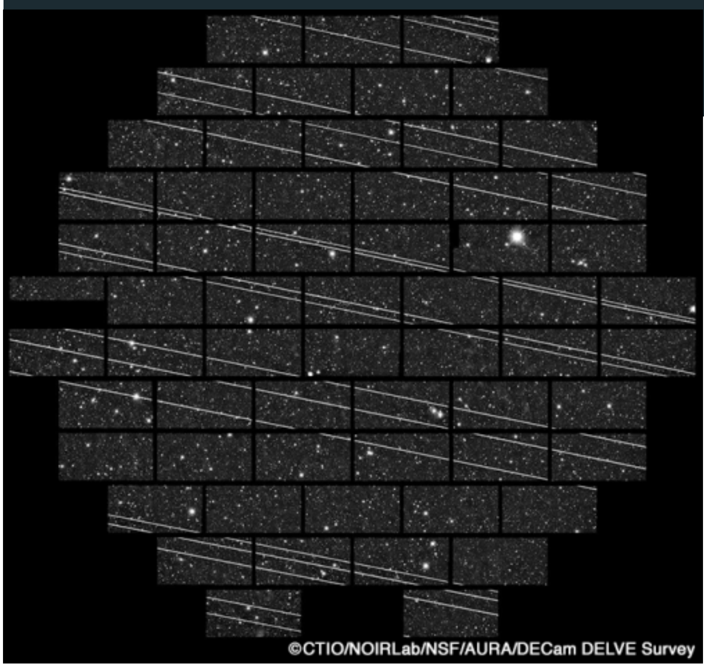
2022/11/28 -30
第10回スペースデブリワークショップ

光・赤外大学間連携による Starlink Visorsat の等級評価

Magnitude estimation of Starlink's Visorsat by the OISTER collaboration

東京大学 天文学教育研究センター
特任研究員
堀内 貴史 / Takashi Horiuchi

Light pollution from the Starlink satellites



☐ SpaceX launched the first 60 Starlink satellites on May 24, 2019 for high-speed internet communications.

☐ However, the mega-constellation including the Starlink satellites pollutes the environment of astronomical observations (orbital height: 550 km).

・IAU expressed the concern on that incident.

☐ SpaceX plans to launch 12,000 satellites until mid 2020s.

Light pollution countermeasures by SpaceX - Darksat and Visorsat -

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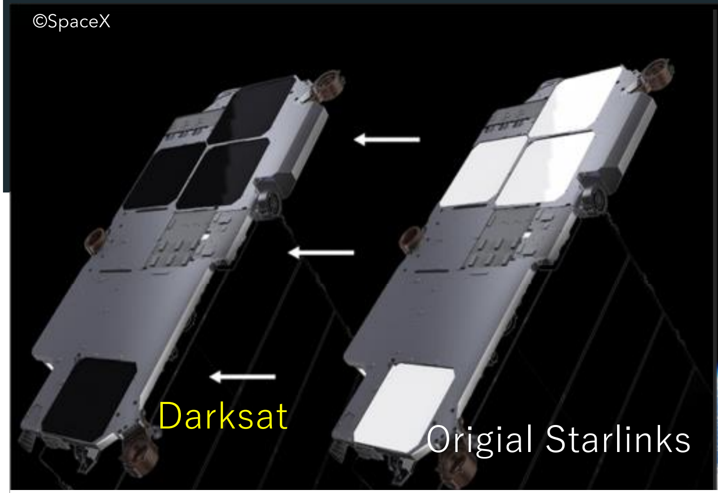

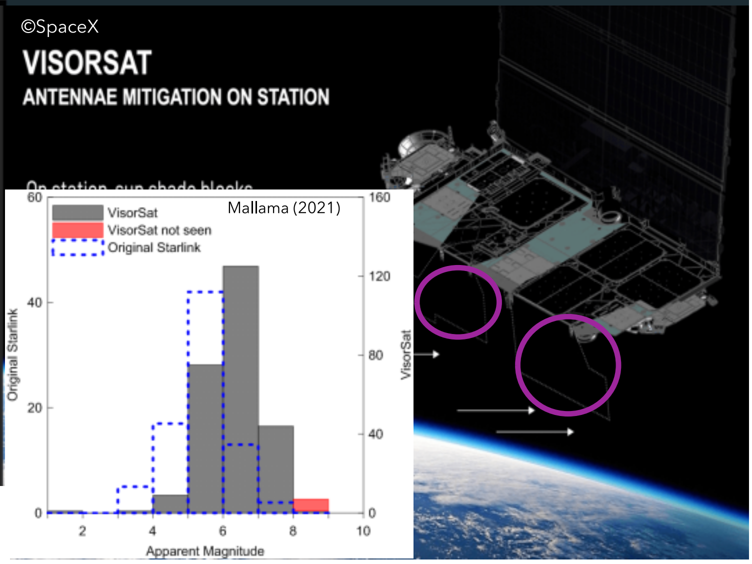

Magnitude at the orbital height of 550 km
(e.g., Horiuchi+2020; Tregloan-Reed+2020)

- Origial Starlink (STARLINK-1113)
  5.33 (g'), 5.60 (Rc), 4.25 (Ic)
- Darksat
  6.10 (g'), 6.00 (Rc), 5.65 (Ic)

Multicolor magnitudes of Visorsat are not well known. ➔➔ Our motivation !

Observation with the OISTER collaboration

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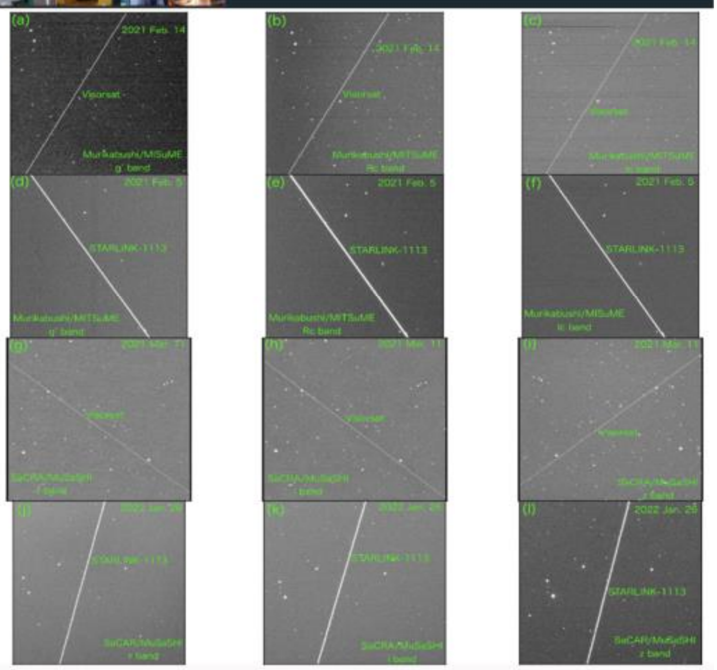
© OISTER



- ☐ Simultaneous multicolor observations with the Japanese OISTER collaboration
  → capture the trail of Visorsat and STARLINK-1113 (original satellite)
- ☐ Telescopes/instruments:
  - Murikabushi and Akeno 50 cm/MITSuME (g, R, I)
  - SaCRA/MuSaSHI (r, i, z)
  - Kanata/HONIR (B, V, H)
  - Nayuta/NIC (J, H, K)
  - Kyoto 40cm (B)
  - Prika/MSI (U)
  - PROMPT6@CTIO (V; other than OISTER)

12 bands

Typical magnitudes of Visorsat

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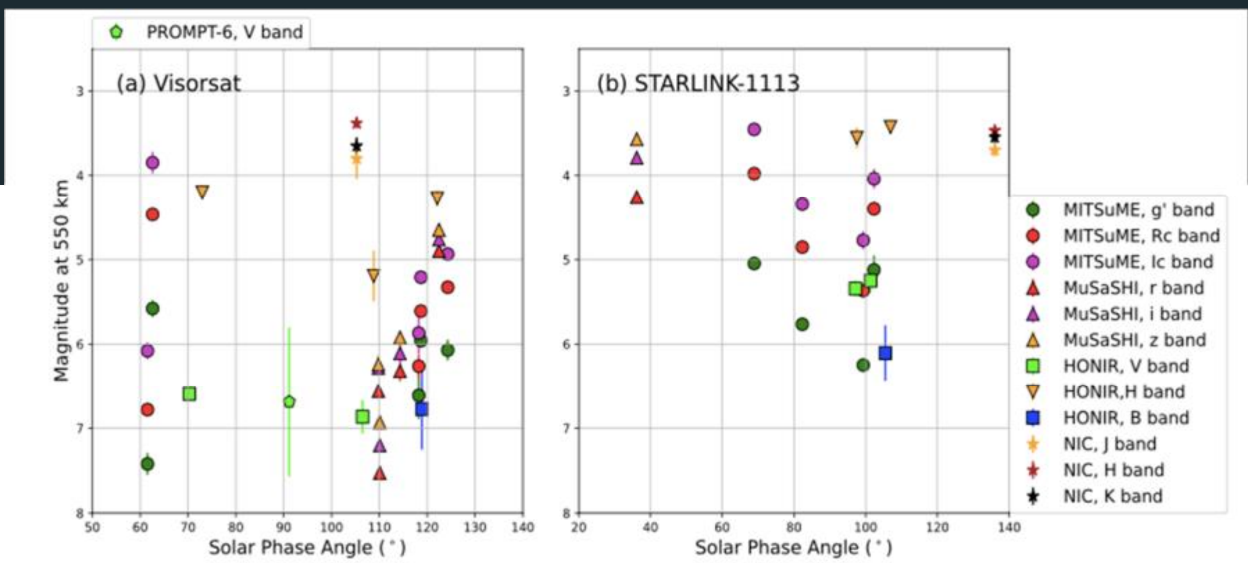
- Magnitudes at a 550 km height.
- U band magnitude was not able to obtain because of the sensitivity of Pirka/MSI (Hokkaido Univ.).
- Visorsat is dimmer than STARLINK-1113 as a trend.
- The longer the observed wavelength, the brighter the satellite magnitudes become.

Band	Visorsat (mag)	STARLINK-1113 (mag)
B	6.77 ± 0.48	6.11 ± 0.33
V	6.61 ± 0.12	5.25 ± 0.13
g‘	6.07 ± 0.12	5.12 ± 0.17
Rc	5.32 ± 0.04	4.40 ± 0.08
Ic	4.94 ± 0.07	4.04 ± 0.12
r	4.90 ± 0.02	4.26 ± 0.03
i	4.76 ± 0.02	3.79 ± 0.03
z	4.65 ± 0.02	3.57 ± 0.02
J	3.80 ± 0.24	3.70 ± 0.08
H	3.38 ± 0.06	3.47 ± 0.05
K	3.65 ± 0.11	3.55 ± 0.07

Phase angle dependence on magnitudes

6/11



☐ The satellite magnitudes are minimized around solar phase angle (Sun-Sat-Observer) of 90° .

☐ The magnitudes of Visorsat are ~ 1 mag dimmer than those of STARLINK-1113.

Blackbody model of the satellite flux

7/11

- ☐ In order to estimate the albedo, a_{mod}, of the starlink satellites, we construct the blackbody model of the satellite (AB) flux.
- ☐ Assuming a_{mod}(STARLINK-1113) ~ a_{mod}(Visorsat), we estimated covering foctor, C_f, of the sun visor on Visorsat (where $U_f = 1 - C_f$).

$$F_{RS} = \pi\left(\frac{R_\odot}{1\,\mathrm{au}}\right)^2 B(\lambda,\, T_\odot)\, a_{mod}\, p(\theta)\, U_f \left(\frac{r_{sat}}{h_T}\right)^2 \frac{\lambda^2}{c}$$

$$F_{REs} = a_E \left(\frac{R_\oplus}{R_\oplus + h_T}\right)^2 \left\{1 - \left(\frac{R_\oplus}{R_\oplus + h_T}\right)^2\right\} \frac{p(\phi)}{p(\theta) U_f} F_{RS}$$

$$F_{TS} = \pi\epsilon \left(\frac{r_{sat}}{h_T}\right)^2 B(\lambda,\, T_{sat}) \frac{\lambda^2}{c}$$

$$F_{TE} = \pi\epsilon \left(\frac{R_\oplus}{R_\oplus + h_T}\right)^2 B(\lambda,\, T_E)\, a_{mod} \left(\frac{r_{sat}}{h_T}\right)^2 \frac{\lambda^2}{c},$$

F_{RS} : sunlight reflection
F_{REs} : earthshine reflection
F_{TS}: thermal radiation of the satellite
F_{TE}: reflection of Earth's thermal radiation

Blackbody fitting to the satellite flux (ex1)

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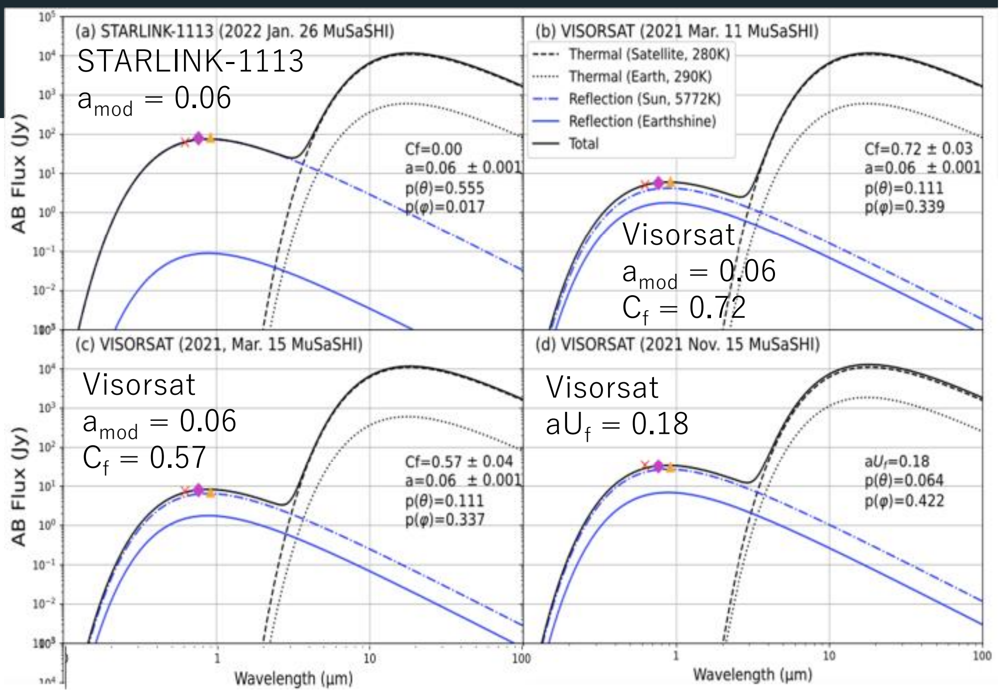
- ☐ Model fitting to r, i, and z band flux obtained with SaCRA/MuSaSHI (Saitama Univ.).
- ☐ Together with the results with other telescopes, the range of the covering factor is $0.18 < C_f < 0.92$.



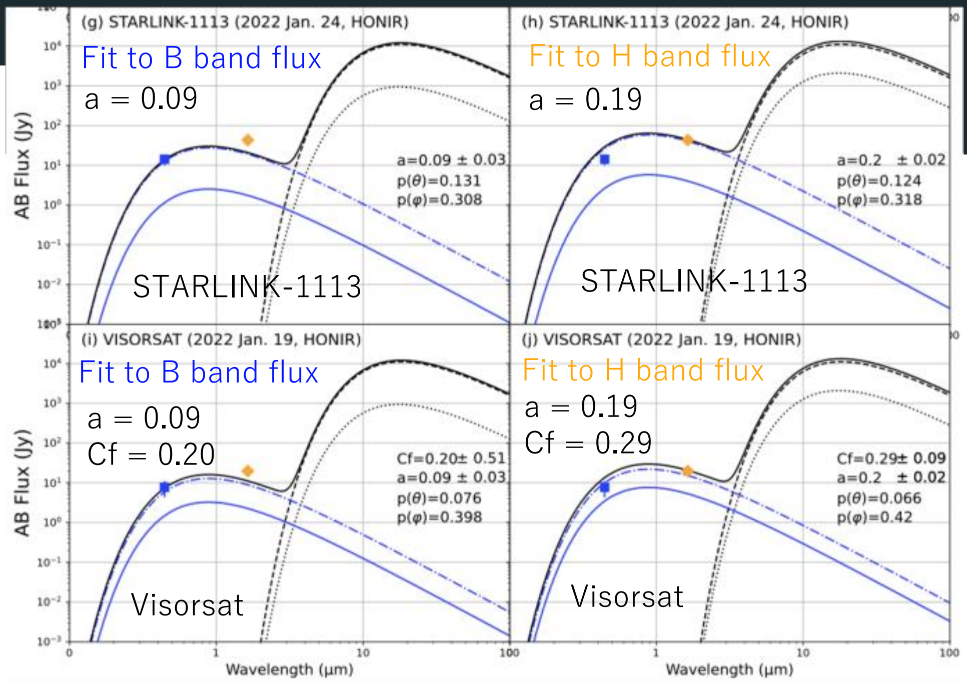
Flux model for B and H bands (ex2)

9/11

☐ B and H bans flux obtained with Kanata/HONIR (Hiroshima Univ.)

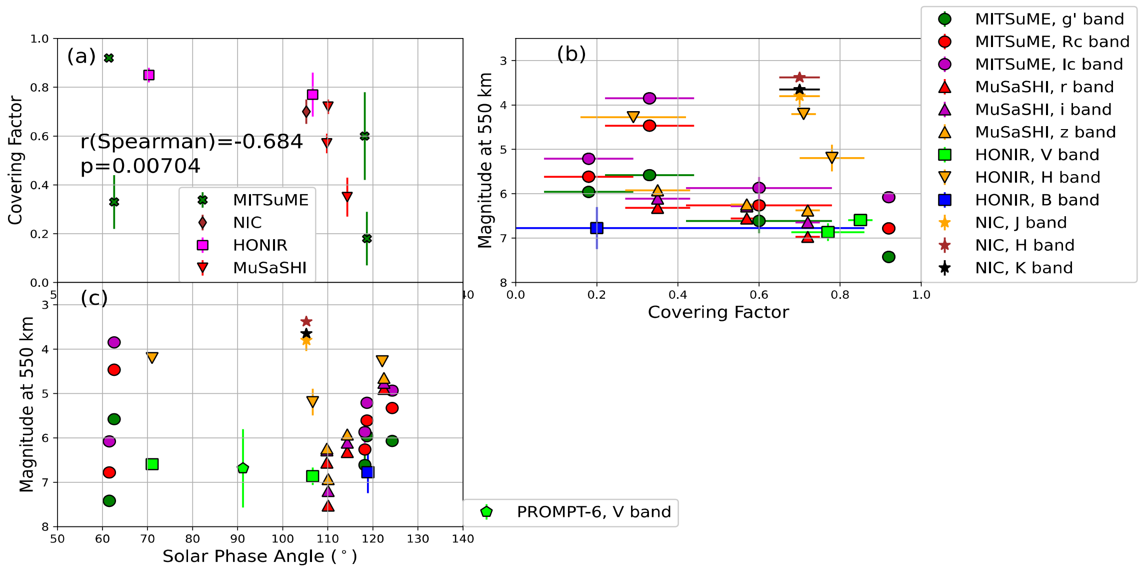
・The albedo of H band is about twice larger than that of B band.

・・The reflectivity of satellite surface materials likely become higher at the longer wavelength.



The relation between covering factor, brightness, and phase angle

10/11



The smaller the covering factor is, the brighter the magnitudes of Visorsat tend to become.

Summary

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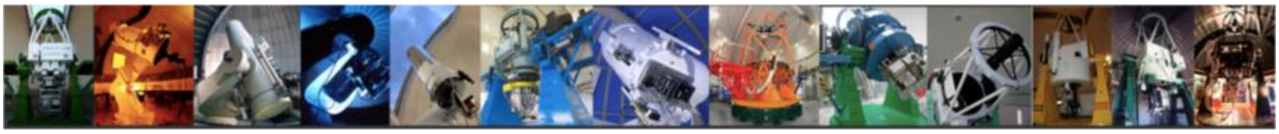
☐ We observed Visorsat and STARLINK-1113 with the OISTER collaboration.

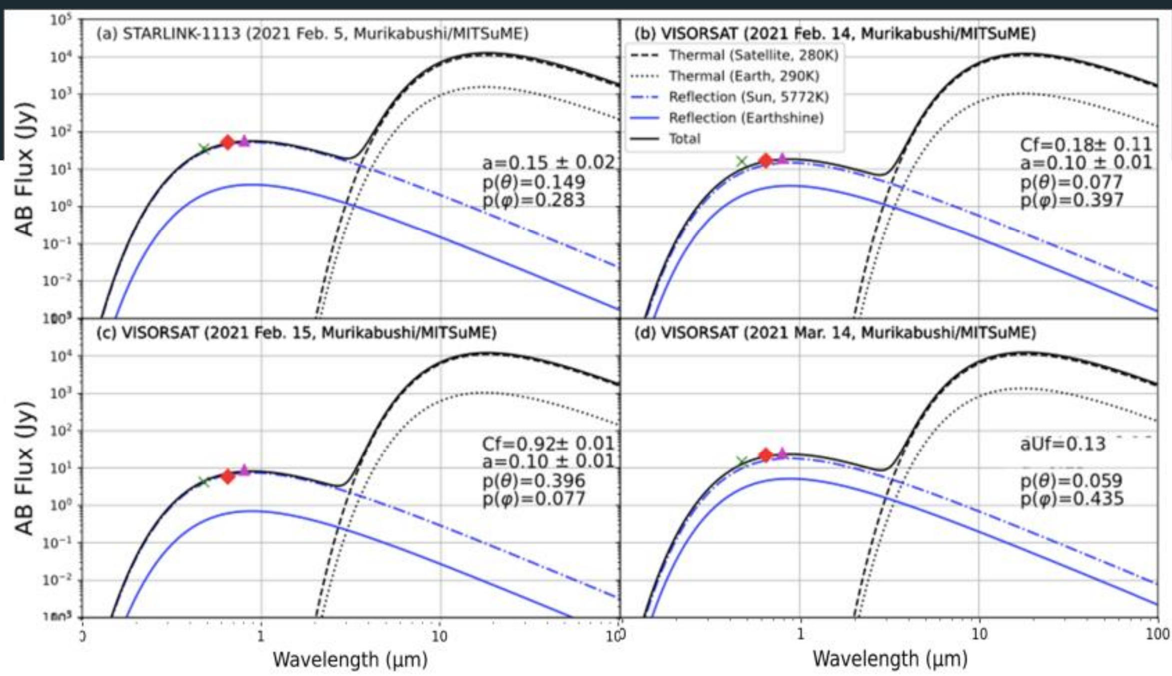
- In most cases, Visorsat is dimmer than STARLINK-1113 as a trend.
- By assuming the blackbody radiation, we estimated a covering factor, Cf, and its range of $0.18 < C_f < 0.92$.
- The reflectivity of satellite surface materials likely become higher at the longer wavelength.

☆ While we showed the shading effect of the sun visor of Visorsat, the observational impact from Visorsat is still profound.

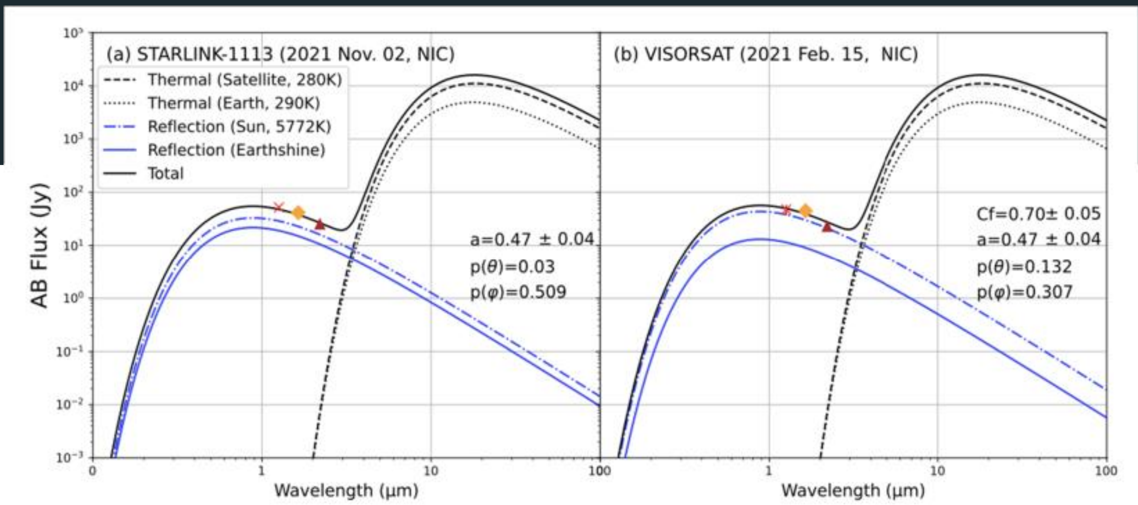


© OISTER

Blackbody fitting to the satellite flux (ex3)

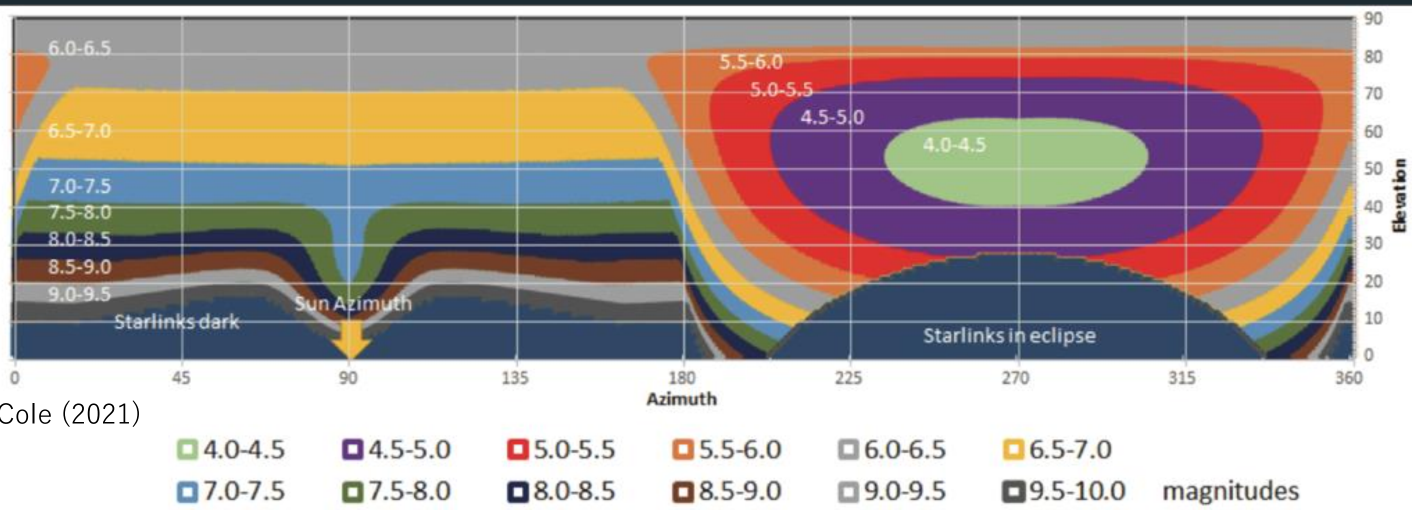


Blackbody fitting to the satellite flux (ex4)



☐ The albedo of near infrared bands (J, H, and K) is somewhat higher than that of optical region.

Az, El dependence of magnitudes



Cole (2021)

Figure 21: The modelled apparent magnitude of the visorsat across the sky using updated best-fit parameters for the June 2021 dataset. This plot is for the pointing mode with the solar-panel at a fixed angle with respect to the local vertical at the spacecraft, in this case 5° towards the Sun-azimuth. The modelled solar azimuth is 90° and depression angle 15°.

Simulation of the impact on astronomical observations with a large telescope

Tyson et al. (2020) simulated the impact from the Starlink satellites on LSST observations

- Using artificial satellite trails at the level corresponding to v0.9 Starlink satellites, they showed the negative impact on CCDs

-- the main trail is ~1000 times brighter than important astronomical signals.

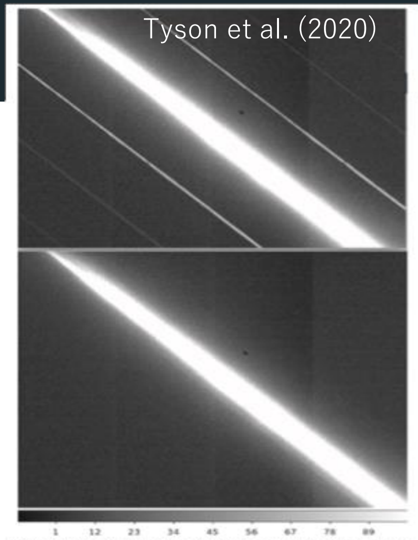


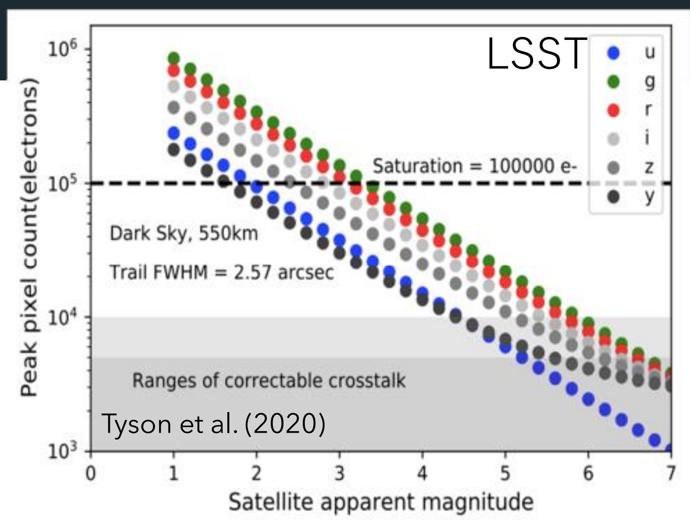
Figure 11. Top: the image that results when an artificial satellite trail at the level corresponding to v0.9 Starlink satellites (bright, but below pixel saturation) is projected onto a e2v CCD in the laboratory. Four of 16 channels of a single raw CCD image are shown, and six crosstalk stripes induced by the main trail are visible. Below: the same image after a preliminary nonlinear crosstalk correction algorithm has been applied (see Section 7.1). While the crosstalk trails are nearly removed, the remaining trail itself is several hundred pixels wide and has a surface brightness ~1000 times that of important astrophysical signals.

Simulation of the impact on astronomical observations with a large telescope

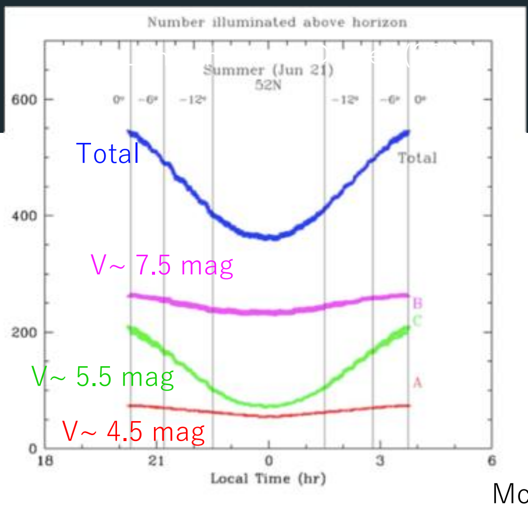
Tyson et al. (2020) simulated the impact from the Starlink satellites on LSST observations

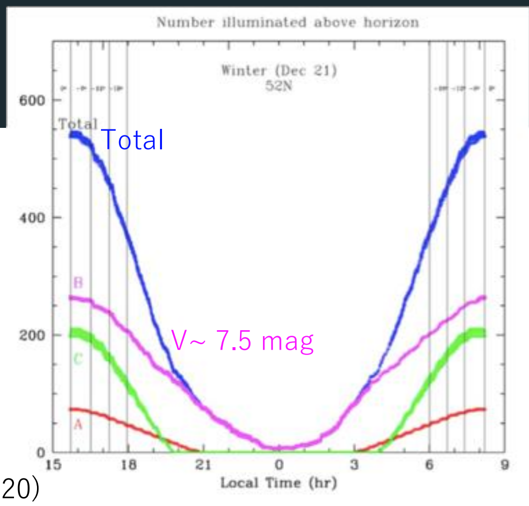
-a satellite magnitude - CCD counts (e-) relation was verified in six passbands: u, g, r, I, z, and y bands

-- the CCD will saturate at ~3.5 and ~1.5 mag in g and y bands, respectively.



Relation between time of day and number of satellites

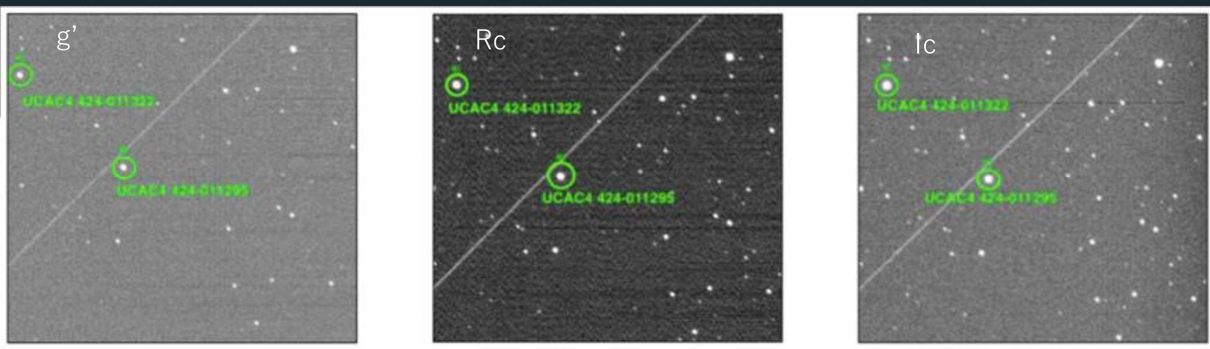




McDowell (2020)

The Starlink satellites can be observed even in the middle of the night.

Simultaneous multicolor observations



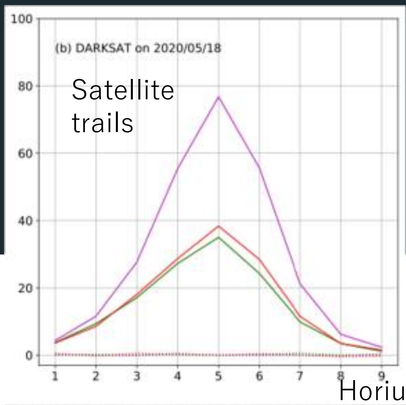
Horiuchi+(2020)

Starlink satellites move too fast to track with telescopes（e.g., ~2000 arcsec s^{-1})

- we pointed the telescope to the calculated position, and waited for the satellite to pass through the field of view.

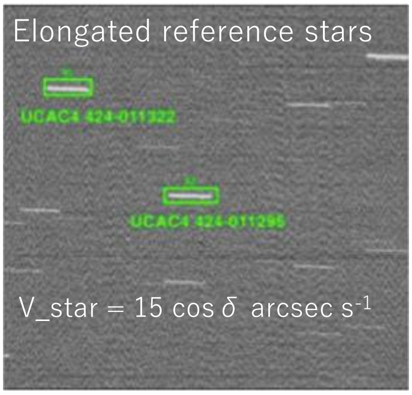
Magnitude estimation

Using “Projection” in DS9, we estimated average cross section counts of satellite trails (f_sat) and “elongated” star images (f_star).



Horiuchi+(2020)

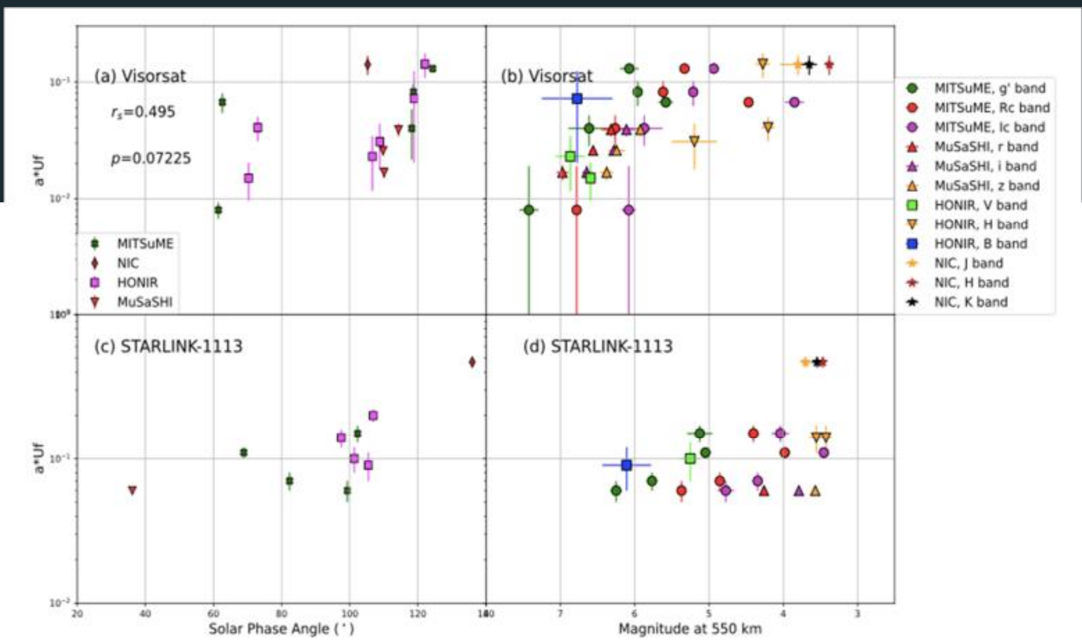
The observed flux is inversely proportional to the satellite velocity, V_sat.



Apparent magnitudes of the satellites, m_{sat}

$$m_{\rm sat} = m_{\rm star} - 2.5\log\left(\frac{V_{\rm sat}}{V_{\rm star}}\frac{f_{\rm sat}}{f_{\rm star}}\right)$$

The relation between covering factor, brightness, and phase angle



The smaller the covering factor is, the brighter the magnitudes of Visorsat tend to become.

B12

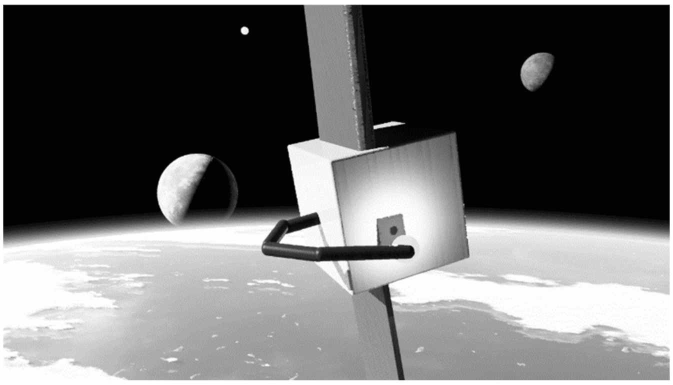
自己位置推定と自律制御を用いた 軌道上微小デブリ衝突痕観測ロボットの開発

Development of In-situ Observation Robot for Micro Space Debris Impact Marks Using Localization and Autonomous Control

○八木宗一郎、中山元晴、平山寛（秋田大学）
○YAGI Soichiro, NAKAYAMA Motoharu, HIRAYAMA Hiroshi (Akita Univ.)

軌道上における微小デブリの存在密度情報にはデータギャップが存在する。回収した宇宙機による解析や観測が比較的困難である SSO や静止軌道において特に顕著である。我々はこれらの軌道上にある宇宙機の観測機器の１つとして、デブリ衝突痕観測システム ODIM を開発している。ODIM は搭載した宇宙機の外観のデブリ衝突痕を自律的に観測することが可能であり、その情報を集約することで微小デブリの存在密度情報の取得を目的としたシステムである。ODIM の観測部は深度カメラと外力を加えても形状維持が可能な構造材料 Morphable Beam(MB)にて構成されている。課題点として、MB 制御はアップリンクによる手動の操作に依存している点が挙げられる。これは MB の柔軟性によって曲げの精度が十分ではないこと、非ホロノミック系であることにより先端位置制御が容易ではことに起因している。本研究ではこれを解決するため､新たな MB を搭載した統合システム MBD-4 と MB の自律制御システムの開発と評価を行った。宇宙機全体の形状データをもとに３次元的に地図情報を作成し、深層学習によって画像処理と自己位置推定技術により，MB 先端位置を割り出すというものである。これにより、ODIM 単体でデブリ衝突痕観測の完全な自動化が見込める。

There is a data gap in the information on the spatial density of micro debris in orbit. This is particularly noticeable in SSO and GEO, where analysis and inspection by recovered spacecraft are relatively difficult. We are developing a debris impact masks observation system, ODIM, as one of the observation instruments for spacecraft in these orbits, which can autonomously observe debris impact marks on the exterior of the onboard spacecraft and obtain information on the existence spatial density of micro debris. The ODIM consists of a depth camera and a morphable beam (MB), a structural material that can maintain its shape even when subjected to external forces. One of the challenges is that the MB control relies on manual operation via uplink. This is because the bending accuracy is not sufficient due to the MB's flexibility, and because it is a nonholonomic system, it is not easy to control the tip position. In this research, in order to solve this problem, we developed and evaluated an integrated system MBD-4 equipped with a new MB and an autonomous control system for the MB. The system creates a three-dimensional map based on the geometry data of the entire spacecraft and determines the current position of the MB tip using image processing on deep learning and localization. This system is expected to fully automate debris impact marks observation with ODIM alone.



Akita University

Development of In-situ Observation Robot for Micro Space Debris Impact Marks using Localization and Autonomous Control

自己位置推定と自律制御を用いた軌道上微小デブリ衝突痕観測ロボットの開発

Soichiro Yagi, Motoharu Nakayama and Hiroshi Hirayama (Akita University)

○八木 宗一郎, 中山 元晴, 平山 寛（秋田大学）

The 10th Space Debris Workshop Nov. 29th, 2022

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1 Introduction

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Model of micro debris

Table1 Debris estimates by size and their characteristics

	Size	Large debris ～100mm	Small debris 100 mm ～ 10 mm	Micro debris 10 mm ～ 1 mm
Estimated number	USSSTRATCOM[1]	20,000	500,000～700,000	100 million
	ESA[2]	36,500	1 million	130 million～
Means of observation		Optical and radar observations from the ground		None
Hazards by collisions[3]		Catastrophic	Structural damage	Partial loss of mission capacity
Approach		Removal Collision avoidance maneuver	None	Protective design of spacecraft

The 1st Problem
Spacecraft risk assessment is difficult due to the lack of established micro debris models.

1) The Cabinet Office Space Development Strategy Promotion Secretariat, Recent changes in space debris, available from < https://www8.cao.go.jp/space/taskforce/debris/dai3/siryou1.pdf >(in Japanese).
2) The European Space Agency, Space debris by the numbers, available from < https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers>. 3) UN. Committee on the Peaceful Uses of Outer Space. Scientific and Technical Subcommittee, Technical Report on Space Debris, 1996.

1 Introduction

4

How to observe micro debris

1. Observation from the ground (Optical / radar)
2. Inspection of retrieved spacecraft
   Space Shuttle / Hubble Space Telescope
3. In-situ detector
   LDEF / The space debris monitor[4]
   Pros : No need for calibration
   Cons : A limit to the area that can be installed on a spacecraft.

Fig.5 The space debris monitor on HTV[4]

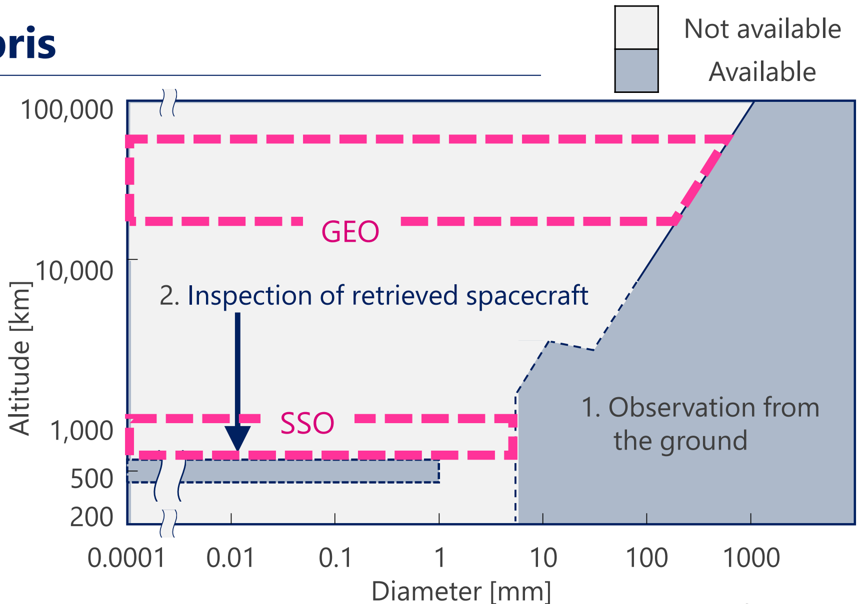


Fig.6 Availability map of information of orbital debris[5) 6)]

The 2nd Problem
A new in-situ observation method is needed to supplement the flux of micro debris

4) Noriko Matsuzaki, Haruhisa Matsumoto, Daiki Nakanishi, Aiko Nagamatsu, Koki Kamiya, Development of JAXA Space Debris Monitor BBM, The 9th Space Debris Workshop, 2021.
5) Yukihito Kitazawa, Kazuo Uematsu, Micro debris Impact Testing and Measurement Technologies, Ishikawajima-Harima Technical Journal, 35-2, 1995, pp. 143-149. 6) J.-C. Liou, Risk from Orbital Debris, RAS Specialist Discussion Meeting on Space Dust and Debris in the Vicinity of the Earth, 2018.

1 Introduction

Observation of micro debris impact marks

Small size・High speed ▶ Difficult to observe directly

↓

Debris impact marks size is up to 10 times larger than debris[7)]

↓

Debris impact marks as in-situ observation target

↓

Size, direction of impact, and time of impact can be estimated

↓

Develop a robot to observe the surface of spacecraft

↓

Mounted on numerous spacecraft

↓

Improve accuracy of micro debris flux information

↓

Enables risk assessment of spacecraft

The entire spacecraft can be viewed as if it is a large micro debris sensor

7) Drolshagen, G. : Hypervelocity Impact Effects on Spacecraft, Proc. Meteoroids 2001 Conf., pp. 533–541, 2001

2 Overview of Observation Robot

Estimated flux in SSO

ORDEM

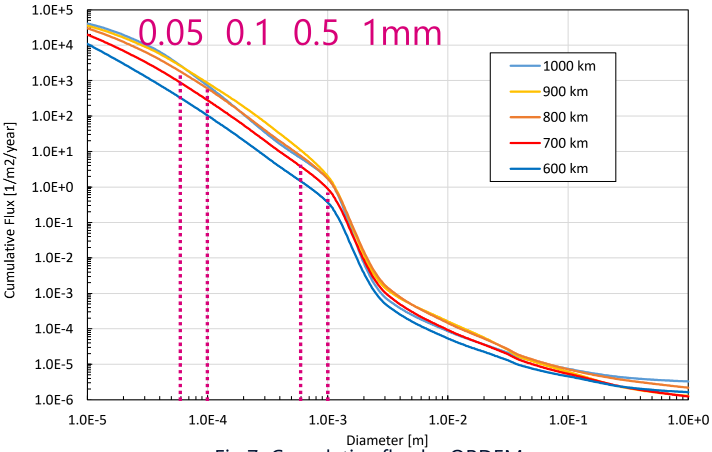


Fig.7 Cumulative flux by ORDEM

MASTER

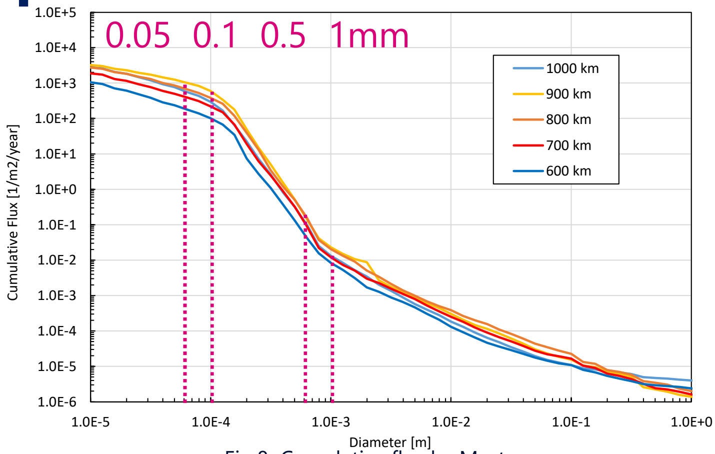


Fig.8 Cumulative flux by Master

Take 4 points as representative points in the zone where the ORDEM and MASTER environmental models diverge significantly and estimate the number of collisions with the spacecraft.

2 Overview of Observation Robot

Number of collisions with spacecraft

$$N_c = F \times A \times T \times N_S$$

N_c: *Number of collisions with spacecraft*
F : *Cumulative Flux* $[1/m^2/year]$
A : *Projected area of spacecraft* $[m^2]$
T : *Time* $[year]$
N_S: *Number of spacecraft*

Fig.9 Overview of GCOM-C ©JAXA

- Installed on 2-ton class satellite as piggy-back payload
  e.g.) GCOM-C SSO 800km
  ▸ Approximate total projected area of the spacecraft A =16 m^2
- Aim for a standard deviation of about 10%, which is superior to ORDEM and MASTER as environmental models.
  ▸ N_c is the target of 100 or more

- $T \times N_S$
  - 0.05 mm ORDEM・MASTER: Shorter than 1 month × 1 spacecraft ▸ LDEF / SDM
  - 0.1 mm ORDEM・MASTER: Shorter than 1 month × 1 spacecraft ▸ LDEF / SDM
  - 0.5 mm ORDEM :1 year × 3 spacecrafts | MASTER :1 year × 14 spacecrafts. ▸ Targets of our research
  - 1 mm ORDEM :1 year × 4 spacecrafts | MASTER :1 year × 256 spacecrafts ▸ Optical / radar

Targets for in-situ observation : 0.5mm ~ 1mm ▸ Selection of Camera

2 Overview of Observation Robot

ODIM : In-situ Observation Robot for Micro Space Debris Impact Marks

Objective

- Micro debris flux information acquired to reduce spacecraft risk
- Proposal for a new robot for in-orbit observation of micro debris impact marks

Design requirements

- Observation target: micro debris in SSO with a particle size of 0.5mm~1.0mm
- Observable range covers the entire surface area of the satellite
- Installed on satellites as piggy-back payload to reduce observation costs
- Compact, lightweight, and power-efficient
  for easy installation on many satellites
- On-board processing
  that minimizes communication
  and does not interfere with the satellite's mission
- Low cost by utilizing consumer components

Table2 Specifications

Size (D×W×H)(Excluding flexible beams)	300 × 355 × 430 mm
Weight	3.69 kg
Power consumption	30 W

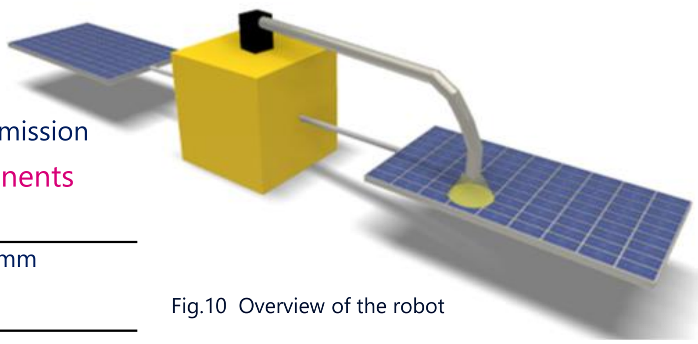
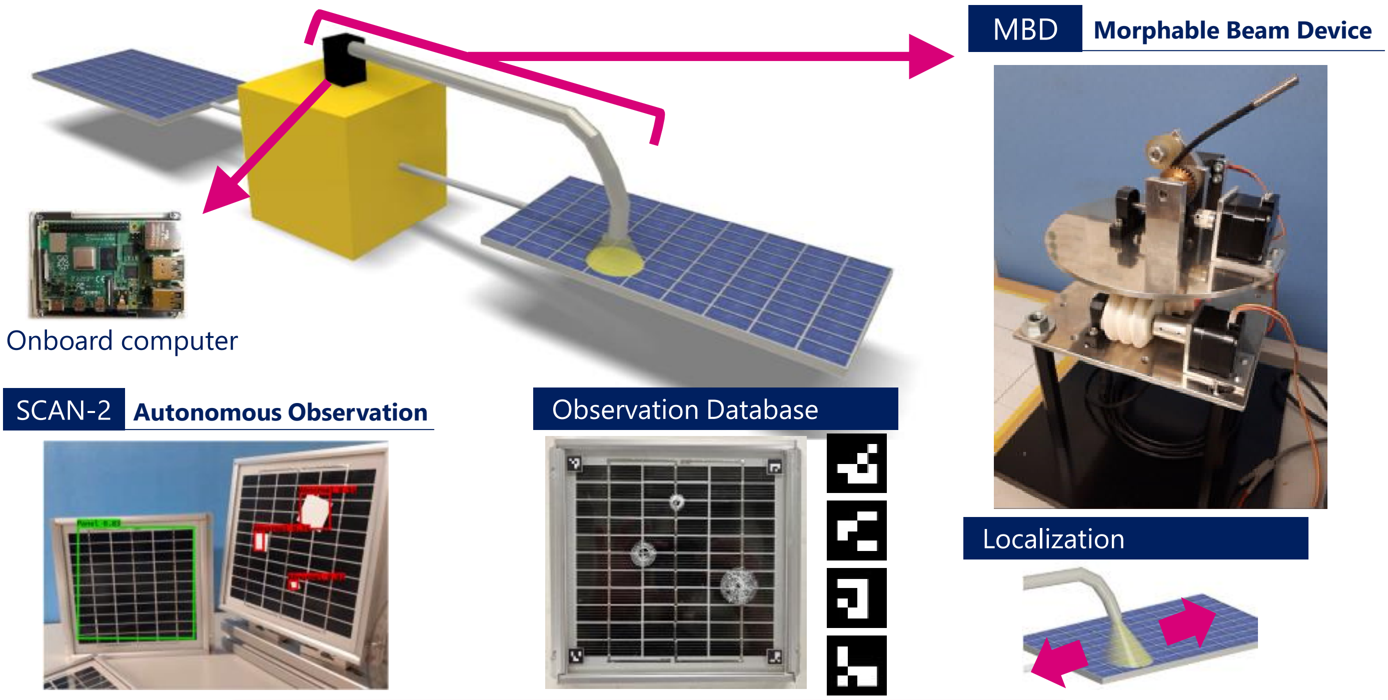


Fig.10 Overview of the robot

2 Overview of Observation Robot

9



Autonomous control is possible by linking four subsystems

3 Autonomous Observation using Deep Learning

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SCAN-2 : Autonomous Observation System

Objective

- Automatic identification of debris impact marks or not for efficient observation

Overview

- We adopted and improved an object detection algorithm YOLOv5 that can simultaneously process object location and classification
- Supervised learning
- Processing is possible with a single board computer
- On-board processing minimizes communication with the ground

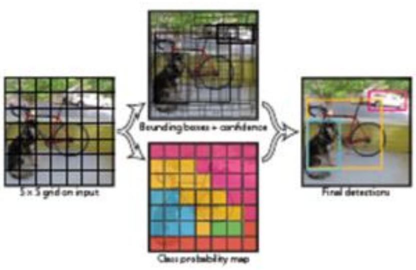

Fig.11 Process flow in YOLO[8)]

8) Redmon, J., and Farhadi, A., YOLOv3, An Incremental Improvement, arXiv:1804.02767, 2018.

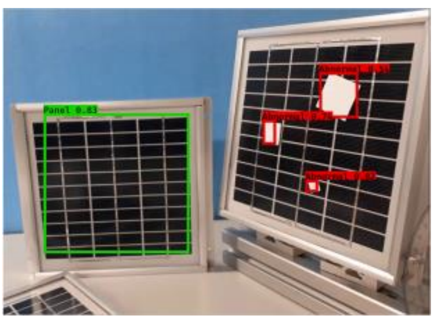

Fig.12 Object detection by SCAN-2

3 Autonomous Observation using Deep Learning

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Unique training data

- Targeting solar arrays, which occupy most of the surface area of satellites
- Insufficient images of solar array damage in space
  - Collected 100 images of damaged solar array on the ground via the web
  - Use data obtained from the spacecraft as new training data to further improve accuracy
- Annotated and trained on each image
  - Implemented in SCAN-2

Fig.13 Some of training data

Normal solar arrays
Damaged solar arrays

Fig.14 Annotation

3 Autonomous Observation using Deep Learning

12

Evaluation experiment of SCAN-2

Objective

- Performance evaluation of SCAN-2
  (Compared with the previous system SCAN)
- Evaluate under what conditions debris impact marks can be detected

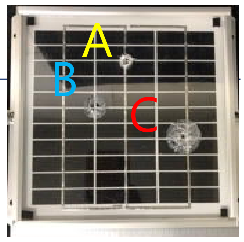


Fig.15 Solar array simulating impact marks

Overview

- Set up an imaging environment that reproduces space
- Prepare a normal solar array and a solar array simulating impact marks

①Measuring confidence score (Varying distances and angles) ▶ Recognition rate

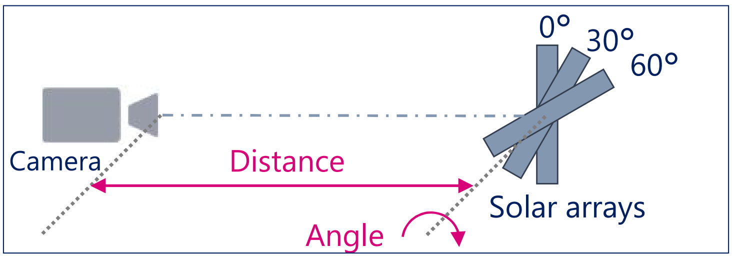


Fig.16 Schematic diagram of the experiment

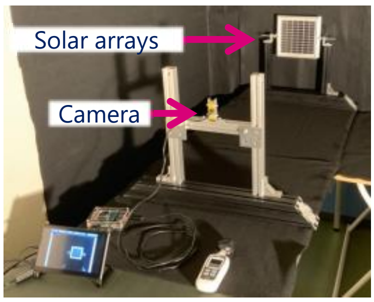


Fig.17 Experimental environment

②Measuring FPS and processing time ▶ Processing speed

3 Autonomous Observation using Deep Learning 13

Evaluation experiment of SCAN-2

- SCAN-2 and SCAN detected solar arrays and impact marks within 500mm and 30°
- No significant difference in recognition rate
- SCAN-2 outperformed SCAN in both FPS and Processing time

Table4 FPS and processing time

	SCAN	SCAN-2
FPS	0.29	0.64
Processing time[s]	19.0	3.0

SCAN-2 can speed up processing while maintaining accuracy.
SCAN-2 is capable of near real-time observation.

3 Autonomous Observation using Deep Learning 14

Overview of Coordinate estimation

- For continuous observation of debris impact marks without omissions
- Flexible beam has a high degree of freedom
  ▸ It is difficult to maintain the distance and angle to the observation target

High-precision coordinate estimation on spacecraft is required

- To reduce cost, coordinate estimation is performed by optical observation without using sensors ▸ Using target markers

Coordinate estimation with an accuracy of a few percent of relative error in any viewing direction

Fig.18 ArUco marker[9)]

Database Example

Table 5 Debris impact marks individual database

Items	Example
ID	1
Time and Date	2022_11_02_071108
Observation No.	1,2,3
Part	Left solar array
Coordinate	[54,67]
Diameter [mm]	5.3

Table 6 Observation database

Items	Example
Start date and time	2022_11_08_070237
End date and time	2022_11_08_080056
How many times	1
Sum of Impact Marks	15

Two databases enable autonomous observation

9) S. Garrido-Jurado, R. Muñoz-Salinas, F.J. Madrid-Cuevas, M.J. Marín-Jiménez : Automatic generation and detection of highly reliable fiducial markers under occlusion, Pattern Recognition, Volume 47, Issue 6, June 2014, pp. 2280-2292, 2014.

4 MBD and Localization for Autonomous Control 15

MBD[9] : Morphable Beam Device

- Morphable Beam is a name for a flexible beam
- The beam can be
  easily reshaped and maintains its shape
  even when the external force is removed
  after reshaping

- MBD-3 is our device that performs
  Three-dimensional control of beam
  - Beam extension
  - Bending
  - Rotation
- Camera mounted on the tip of the beam

Fig.19 Morphable Beam

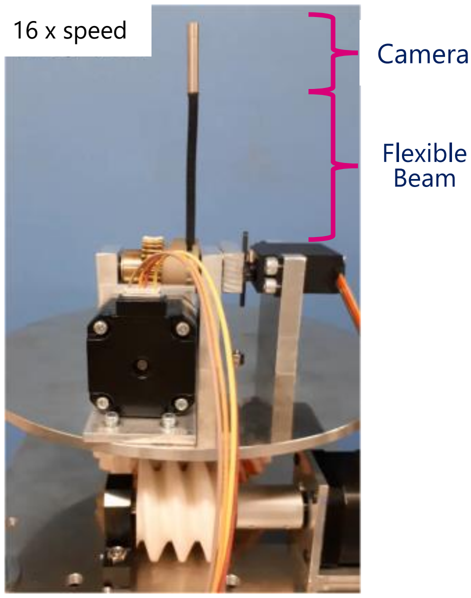


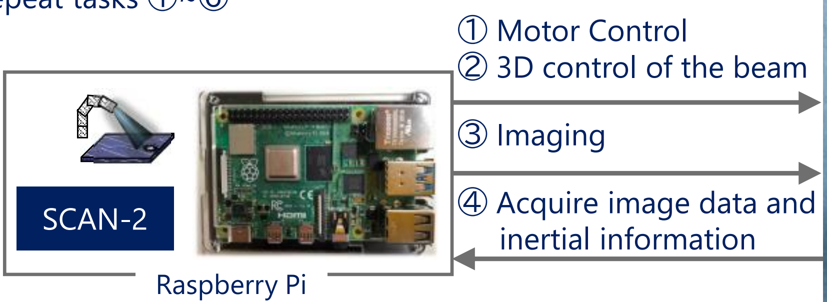
Fig.20 MBD-3 in operation

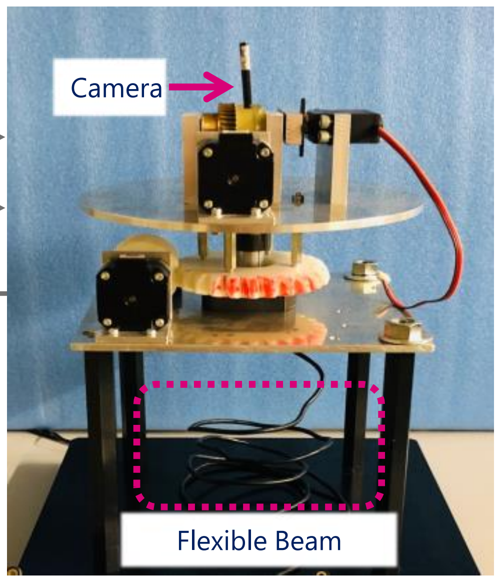
9) Thomas Iljic, Saburo Matunaga, Yohei Tanaka, MORPHABLE BEAM DEVICE AND ITS VISUAL POSITIONING SYSTEM, IFAC Proceedings Volumes, ,Volume 40, Issue 7, 2007, Pages 871-876

4 MBD and Localization for Autonomous Control 16

Configuration of MBD-3 and SCAN-2

Repeat tasks ①~⑥





MBD-3

⑤ Object detection algorithm SCAN-2
to identify debris impact marks
⑥ Refer to the debris impact marks database

Fig.21 Procedure of tasks

4 MBD and Localization for Autonomous Control

How to control of the beam

Problem

- The beam control relies on manual operation via uplink
  - The bending accuracy is not sufficient due to its flexibility
  - A nonholonomic system
  - Not easy to control the tip position
- The subject of imaging is a spacecraft ▶ Looks like a selfie.

Solution

- Localization
  - Estimates the position of the camera section at the tip of the beam relative to a spacecraft
  - Examples of use in autonomous car
- Routing
- RGB-Depth Camera

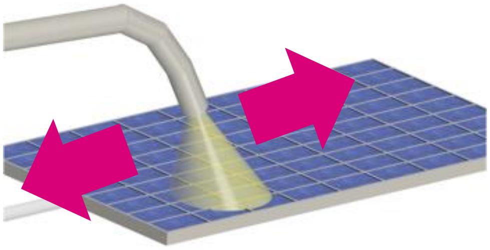


Fig.22 Localization

5 Conclusion and Future Prospects

Conclusion

- Targets for in-situ observation : 0.5mm ~ 1mm
- Proposed a new robot for in-orbit observation of micro debris impact marks
- Design and evaluation experiments of various subsystems
- To automate detection, we developed SCAN-2, which applies object detection
- SCAN-2 succeeded in autonomously observing solar arrays and impact marks
- SCAN-2 is capable of near real-time observation
- A coordinate estimation system and database were built.
  - Possible application to continuous observation of debris with no omissions

Future Prospects

- Develop MBD-4 （Improved MBD-3 with RGB-Depth camera)
- Complete developing localization system
  - 3D control of flexible beams linked to observation
    - Full automation of the entire system

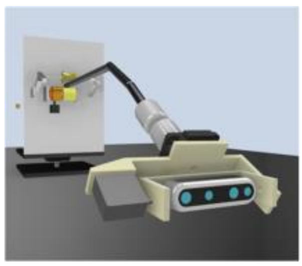


Fig.23 MBD-4 with RGB-Depth camera

B13

SLR反射器（Mt.FUJI）の開発と SLRデータによるPSOを用いた姿勢推定手法の提案

Development of SLR Reflector (Mt.FUJI) and Attitude Motion Estimation Based on Particle Swarm Optimization by SLR Data

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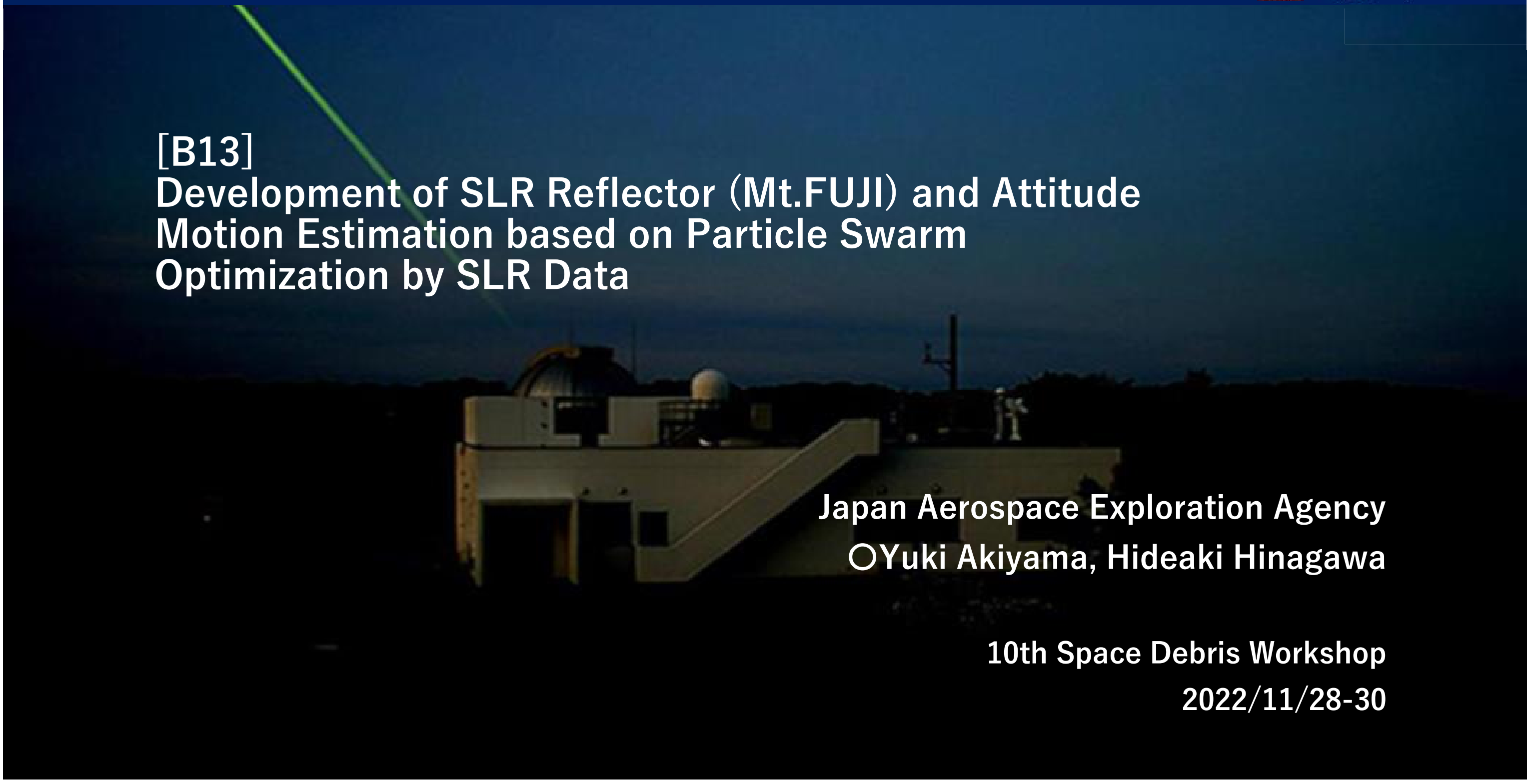
宇宙利用拡大に伴い、デブリ数は増加の一途をたどっている。そのため宇宙状況把握(SSA)の重要性は年々増加している。JAXAはレーダ観測、光学観測に続く第三のデブリ観測手段として衛星レーザ測距(SLR)に着目している。SLRは従来の観測手法に比べ高精度に軌道を決めることができ、さらに観測データから回転運動推定も可能なためである。
SLRを実施するには、通常対象物体にはSLR用の反射器が搭載されている必要がある。しかし、従来の反射器は特注品であり、重く、大きく、高価であったため、反射器が普及しにくい状況であった。そこでJAXAでは、軽く、小さく、安価な汎用的な反射器Mt.FUJIを開発した。Mt.FUJIはHTV-Xにて技術実証される。
一方、従来のSLRによる姿勢運動推定は、せいぜい観測データの波形から回転周期や回転軸を推定する程度であった。そこで筆者らは、遺伝的アルゴリズム(GA)を用いた角速度と姿勢そのものを推定する手法を提案した。しかしGAは解の早期収束が未保証であることや局所探索性能が低いことが欠点としてあった。そこで、これらの欠点を持たない探索手法である粒子群最適化(PSO)を適用した新たな推定手法を提案する。本発表では、Mt.FUJIの紹介とPSOを用いた姿勢運動推定について報告する。

The dawn of space exploration brought a congested and contested space environment with large amounts of space debris in orbit. Therefore, the importance of space situational understanding (SSA) has been increased. Rader and optical observation are conventional approaches to grasp debris' orbital and attitude motion. JAXA is now focusing on satellite laser ranging (SLR) as the third approach because SLR enables us high-accuracy orbit determination and attitude estimation.
If a space object is equipped with an SLR reflector, its visibility from the ground can be ensured even after it becomes debris. However, not many space objects equip with an SLR reflector because conventional SLR reflectors are expensive, heavy, and large. Therefore, JAXA has developed a general-purpose SLR reflector, named Mt.FUJI, with the concept of small size, lightweight, and reasonable price. Mt.FUJI is demonstrated on the HTV-X in orbit.
Although there are many studies about attitude motion estimation by SLR, their estimation is only at least for spin-rate and/or spin-axis. Recently, we have proposed a new attitude motion estimation method based on the genetic algorithm (GA). The method is beneficial to estimate attitude itself, but there are computational drawbacks: no guarantee for early convergence and low performance for local optimization. Therefore, we will newly propose an estimation method by using particle swarm optimization (PSO) instead of GA. In this presentation, we will report the overview of Mt.FUJI and the new estimation method.



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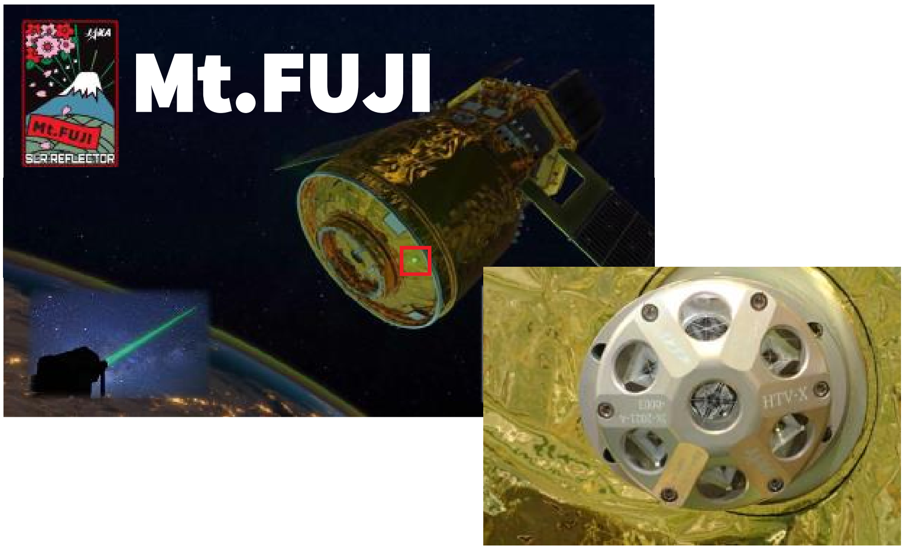
Outline

1. JAXA Developed SLR reflector, Mt.FUJI
2. Motivation of Research
3. Attitude Determination Concept
4. Proposed method
5. Numerical simulation
6. Conclusion

JAXA Developed SLR reflector, Mt.FUJI

- JAXA has developed SLR reflectors as well as SLR equipment.
- The SLR reflector has been successfully developed for general purpose use on low earth orbit satellites and is inexpensive.
- We are planning on-orbit angular velocity estimation experiments on the HTV-X.
- Any object will become SPACE DEBRIS after operation. Higher visibility will help avoid collisions and improve re-entry prediction accuracy.



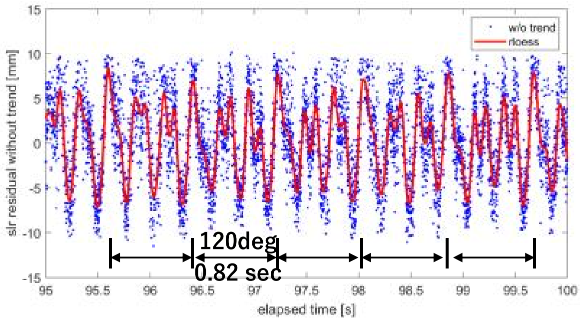
- We are working within JAXA to encourage satellite and launch vehicle projects to mount Mt.FUJI.
- To obtain funds to manufacture several Mt.FUJI, we have asked for donations from the Japanese public. Several people donated money.

Motivation of Research

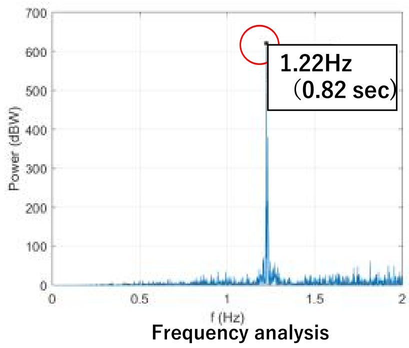
- **Background**
  - As space becomes more crowded, the importance of **ADR (active debris removal)** and **SSA (space situational awareness)** is increasing. In ADR, it is important to grasp the orbit and rotational motion of debris before approaching to the debris.
  - JAXA is focusing on **SLR (satellite laser ranging)** to grasp the orbital and **rotational motion of debris**. SLR can determine orbits with higher accuracy than radar or optical observations and many works stated that SLR can estimate a target attitude motion.
  - Every space objects become space debris after its mission ends. If a space object has SLR reflector, the trackability from the ground would be assured. Such space objects are called as "**Semi-Cooperative**" space debris.
  - Typically, semi-cooperative space debris are bigger than other usual space debris and we believe that they are likely to be chosen as targets of ADR.
  - ESA starts making some frameworks for space debris **attitude** catalog based on the combinations of several techniques (SLR, RADER, optical observations). → Attitude estimation techniques for space debris are becoming increasingly important.

Motivation of Research

- **Motivation**
  - Existing studies were limited to the estimation of rotational period or rotational axis based on the frequency analysis, and **none of them mentioned the estimation of the attitude state (attitude and angular velocity vector) itself.**
  - If attitude state can be estimated from the ground, estimation results can contribute to ADR:
    - Angular velocity is useful for selecting debris that can be removed from the ground
    - Attitude can be used as a priori for the estimation in-orbit by cameras or other sensors
  - Moreover, good attitude information enables us more precise orbit determination
- **Purpose of this research is to construct and verify an attitude estimation technique for semi-cooperative space debris which is better than the existing techniques. For the preliminary study, we focus on SLR data based estimation.**

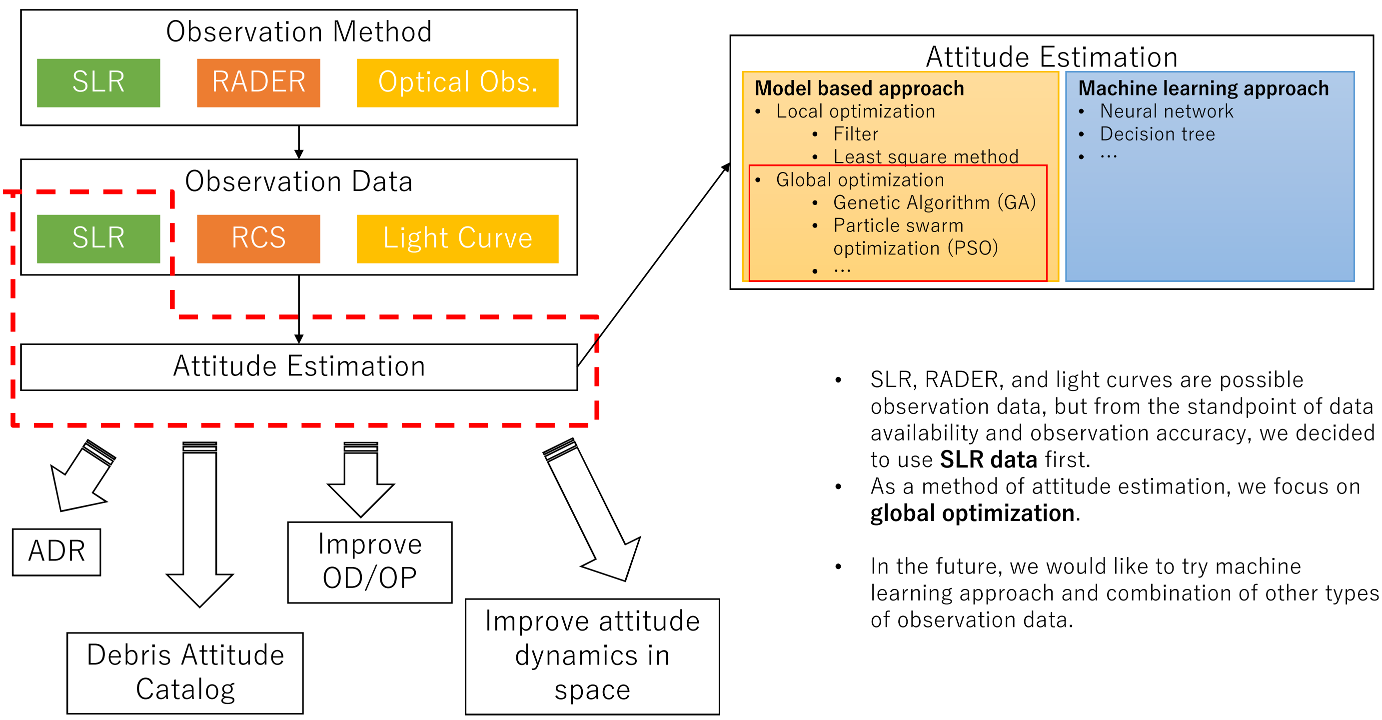


SLR residual



Frequency analysis

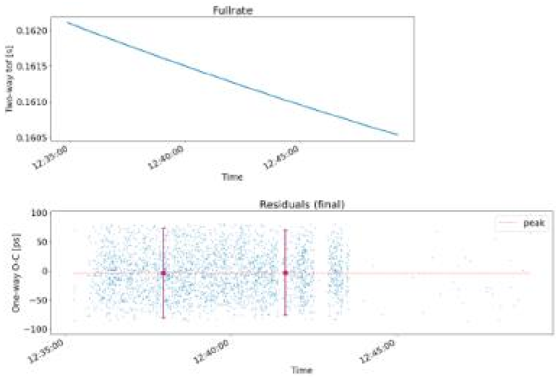
Concept of Attitude Estimation

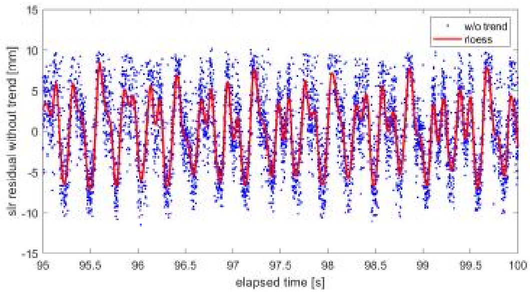


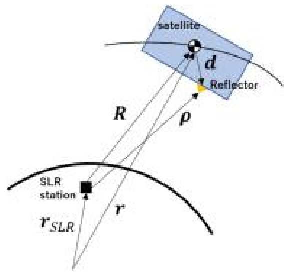
- SLR, RADER, and light curves are possible observation data, but from the standpoint of data availability and observation accuracy, we decided to use **SLR data** first.
- As a method of attitude estimation, we focus on **global optimization**.
- In the future, we would like to try machine learning approach and combination of other types of observation data.

Concept of Attitude Estimation

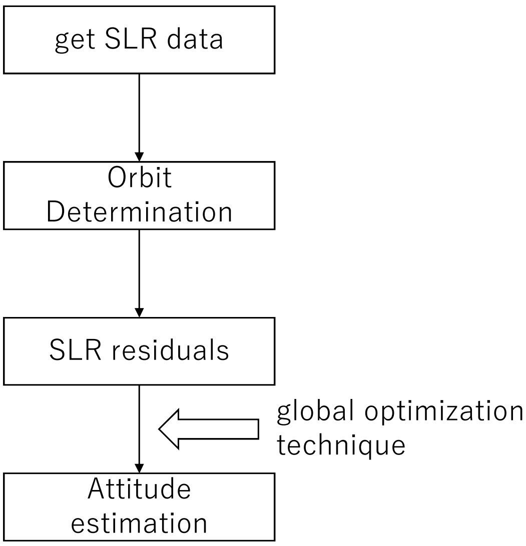
- SLR data is the time history of range between a SLR station and a reflector position.
- Therefore, even if the satellite's center of mass is at the same position, a change in attitude will slightly change the range. →This means SLR data have information of rotational motion.
- From the O-C plot (=SLR residuals), sometimes we can see the rotational motion.
- The basic concept of this research is to estimate attitude state (attitude and angular velocity) by using this SLR residuals.







Concept of Attitude Estimation



- For the preliminary step, we create simplified model and pseudo SLR residuals.
  - Orbit is known
  - No torque perturbation
  - …
- We use the genetic algorithm (GA) and particle swarm optimization (PSO) as the global optimization techniques.

Proposed method: Problem Settings

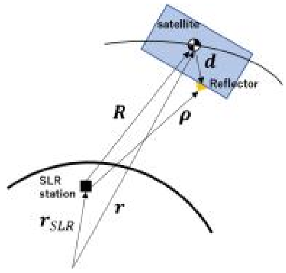
- **Dynamics (only attitude motion, orbit is known)**
  - no noise
  - free rotation

$$\dot{x} = \begin{bmatrix} \dot{q} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\Omega(\omega)q \\ -J^{-1}\omega_{\times}J\omega \end{bmatrix} \quad \Omega(\omega) = \begin{bmatrix} 0 & -\omega^T \\ \omega & \omega_{\times} \end{bmatrix} \in \mathbb{R}^{4\times4}$$

q	quaternion
ω	angular velocity vector
J	inertial tensor
$(\cdot)_{\times}$	skew operator producing the cross-product matrix
y	measurement for estimation model
ρ	vector from SLR station to reflector
R	vector from SLR station to satellite
d	vector from satellite CoG to reflector
r	position vector of satellite CoG
r_{SLR}	position vector of SLR station
v	measurement noise

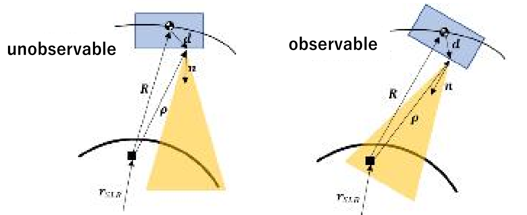
- **Measurement model for estimation**
  - different from SLR measurement model
  - not always obtained due to field of view of reflector

$$y(t) = \begin{cases} \text{null}, & \textit{if unobservable} \\ |\rho(t; q(t_0), \omega(t_0))| - |R(t)| + v(t), & \textit{if observable} \end{cases}$$



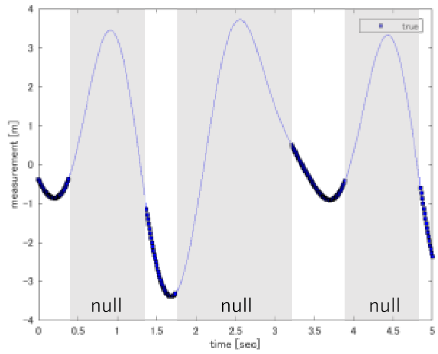
Range between SLR station and reflector, which is possible to calculate by SLR measurement model or convert from SLR measurement data

Range between SLR station and satellite, which is possible to calculate because orbit is known and SLR position can be calculated at any epoch



Due to field of view of reflector, SLR data is not always obtained

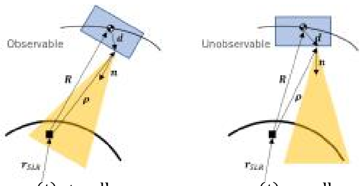
example of measurements



Proposed method: Evaluation function in GA and PSO

Penalize at a time when the error cannot be calculated

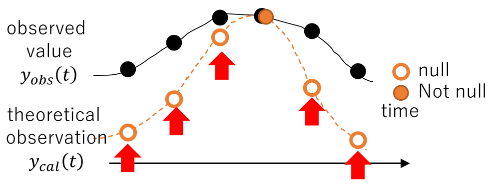
- Errors can NOT be always calculated because sometimes $y_{cal}(t) = null$.



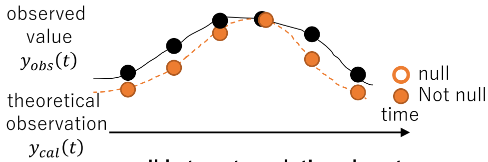
$y(t) \neq \text{null}$ $y(t) = \text{null}$

Patterns of $y_{obs}(t)$ and $y_{cal}(t)$

		$y_{obs}(t)$	
		exist	NOT exist
$y_{cal}(t)$	≠null	pattern 1	pattern 2
	=null	pattern 3	pattern 4



penalties at these points



possible to get a solution close to the true value?

- Evaluate by MSE at a time when error can calculate (only pattern 1).
- Penalize at a time when the error cannot be calculated (pattern 2 and 3).
- In this way, solutions by GA and PSO can be expected to evolve to reduce the penalty.
- We used the penalty term as **the negative values of the logarithms of F-score.**

$$J = \underbrace{\frac{1}{N_{S_1}} \sum_{t \in S_1} \left(y_{obs}(t) - y_{cal}(t; q(t_0), \omega(t_0)) \right)^2}_{\text{MSE term}} \underbrace{- \log \left(\frac{N_{S_1}}{N_{S_1} + \frac{1}{2}(N_{S_2} + N_{S_3})} \right)}_{\text{F-score}}$$

N_{S_i}:the number of times in pattern i.

MSE term
: reduce errors themselves

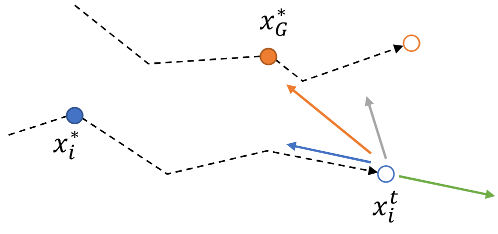
Penalty term : p(F-score)
: reduce the number of times the error cannot be calculated.

- F-score takes values from 0 to 1.
- If the errors can be always calculated when $y_{obs}(t)$ exists, $N_{S_2} = N_{S_3} = 0$ and Fscore $= 1$. Thus, $p(1) = -\log(1) = 0$.
- If the errors can NOT be always calculated, $N_{S_1} = 0$ and Fscore $= 0$. Thus, $p(0) = -\log(0) = \infty$.

Proposed method: Particle Swarm Optimization?

- A swarm intelligence-based optimization algorithm proposed in 1995
- Particles: abstractions of bird and fish positions
- Particles form a flock and search for the optimal position (solution)

- Particle i has below information:
  - position x_i^t, velocity v_i^t
  - best known position of particle i x_i^* and its score $pbest_i$
    - $pbest_i = \min_{\tau=0,1,2,\ldots t} f(x_i^\tau)$
    - $x_i^* = \arg\min_{\tau=0,1,2,\ldots t} f(x_i^\tau)$
  - best known position of the entire swarm x_G^* and its score $gbest$
    - $gbest = \min_i pbest_i$
    - $x_G^* = \arg\min_i f(x_i^*)$
- Positions and velocities are renewed by



$$v_i^{t+1} = \omega^t v_i^t + c_1 R_1^t (x_i^* - x_i^t) + c_2 R_2^t (x_G^* - x_i^t)$$

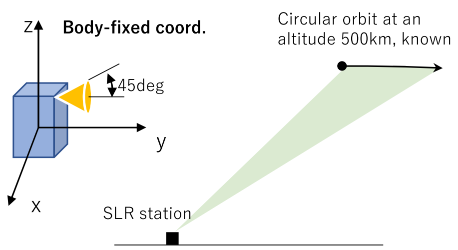
$$x_i^{t+1} = x_i^t + v_i^{t+1}$$

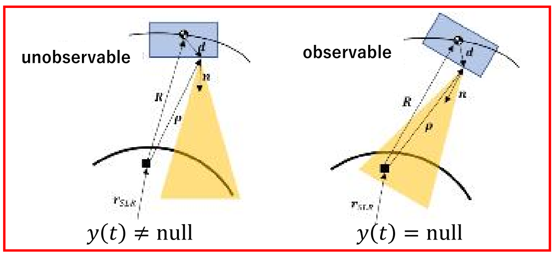
Numerical Simulations

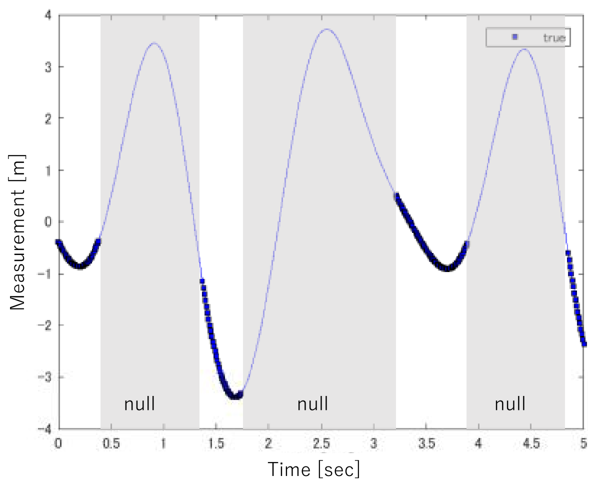
- **Conditions**
  - Orbit
    - type: circular orbit
    - altitude: 500 km
    - orbit is known
  - Attitude
    - free rotation

  - Pseudo SLR Data
    - period: 5 sec
    - sampling interval: 0.01 sec
    - Elevation angle: low (~45 deg)

  - Because obtained solutions are possibly different for each calculation, **the same calculation was performed multiple times** to investigate the distribution of the obtained solutions

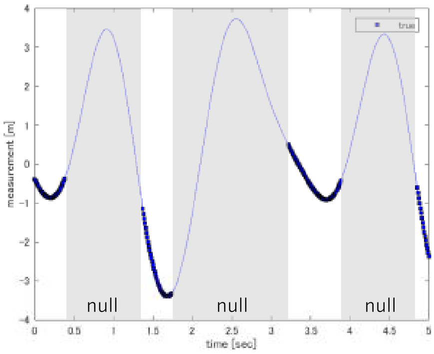






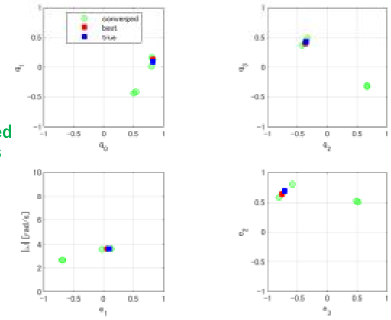
Unobservable areas with no SLR station in the reflector field of view are shown in gray (null).

Numerical Simulations

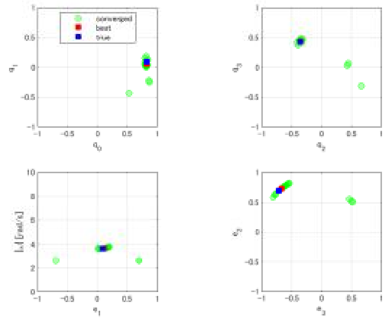


Pseudo-observation data

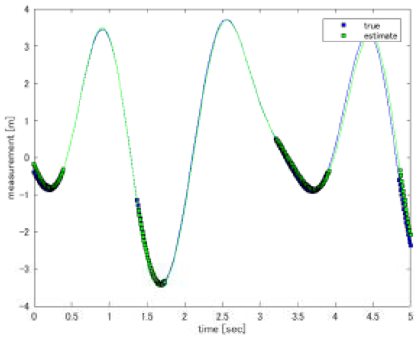
Search **solution** and plot **converged solutions**



Solution space plot (up: GA, bottom: PSO)



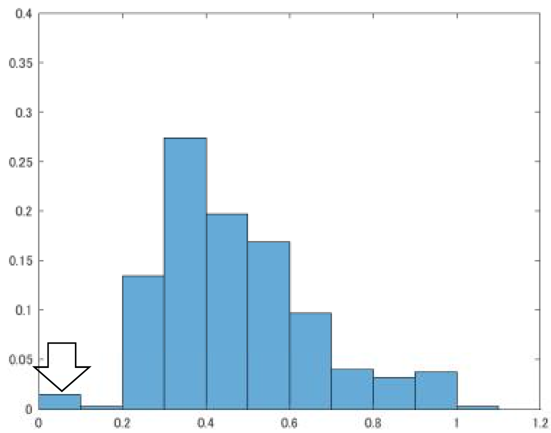
Regenerate theoretical observation using **BEST** solution



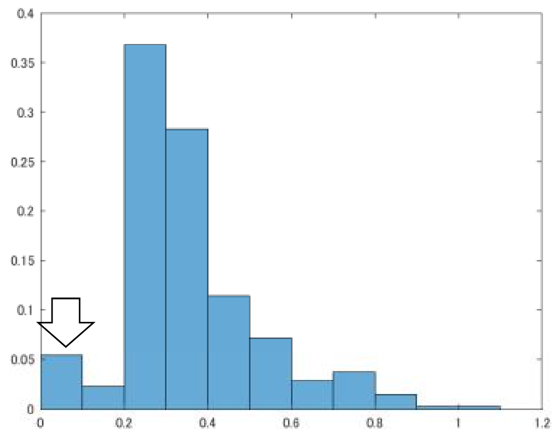
Theoretical observation using **BEST** solution

- **Solutions by GA and PSO** are close to the **true state.**
- **The best solution** is much close to the **true state.**
- The proposed method works well!

Numerical Simulations



Histogram of Evaluation function values(GA)



Histogram of Evaluation function values(PSO)

- **Compared GA and PSO, the ratio of “good solutions” in PSO is greater than in GA.**
- **→In this problem settings, PSO is better than GA?**

Conclusions

- **Summary**
  - Proposed a method for estimating attitude state (attitude and angular velocity vector) using SLR observation data by applying global optimization techniques (GA and PSO).
  - Specifically, the evaluation function is defined as the sum of the mean squared of error (MSE) between the observed data and the theoretical value of the observed quantity, and a penalty term that takes into account the ratio of the time when MSE cannot be calculated.
  - The proposed method can estimate attitude state itself and does not require any prior information about them.
  - PSO seems to be better than GA in the current problem settings.
- **Future works**
  - Creation of a feasible model
  - Verification of the proposed method to the feasible model/real data

B14

H-2A R/B のライトカーブ観測と光学シミュレーション

Light Curve Observation and Simulation of H-2A R/B

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積極的デブリ除去（Active Debris Removal, ADR）は、危険なデブリから宇宙活動の安全を確保し、持続可能な宇宙開発を実現するために有望な方法の 1 つであるが、デブリを捕獲する場合等、事前にターゲットの姿勢や運動が必要になる場合がある。我々は、ADR のターゲット候補の一つである日本の H-2A ロケットの第 2 段のライトカーブを望遠鏡と CMOS センサーで観測し、2 つの手法によるシミュレーションで再現しています。その 1 つである光学シミュレータは、H-2A R/B のスケールモデルを用い、軌道上の天体の姿勢、運動、太陽方向などを考慮して、地上の望遠鏡で観測した光カーブを再現することができます。これまでのシミュレーションは主にこの方法で行っていたが、1 件あたりの時間がかかるため、多くのケースで実験することはできなかった。もう一つは、CG を使ったライトカーブシミュレーションツールで、ライトカーブの全体的な傾向を調べることで、実験時間を大幅に短縮する方法です。本報告では、遠方の 2 地点で同時に観測されたライトカーブを用いて、この CG によるシミュレーションを行った結果を紹介する。

Active Debris Removal (ADR) is one of the most promising methods for ensuring safety and sustainable space activities from danger of debris. In order to carry out an ADR mission, the attitude and motion of the target must be determined precisely in advance. We are observing the light curve of the second stage of the Japanese H-2A rockets, one of the ADR target candidates, using telescopes and CMOS sensors, and reproducing by a two methods simulation. One method, the optical simulator uses a scale model of the H-2A R/B and can reproduce the light curve as observed by a ground-based telescope, considering the attitude, motion, and sun direction of the object in orbit. Previous simulations were mainly performed in this method, but due to the time required per case, it was not possible to experiment in many cases. The other method is a CG-based light curve simulation tool that can significantly reduce experimental time by examining the overall trend of the light curves. In this report, we present the results of this CG-based simulation using light curves observed simultaneously at two distant sites.

Light Curve Observation and Simulation of H-2A R/B

H-2A R/B のライトカーブ観測と 光学シミュレーション

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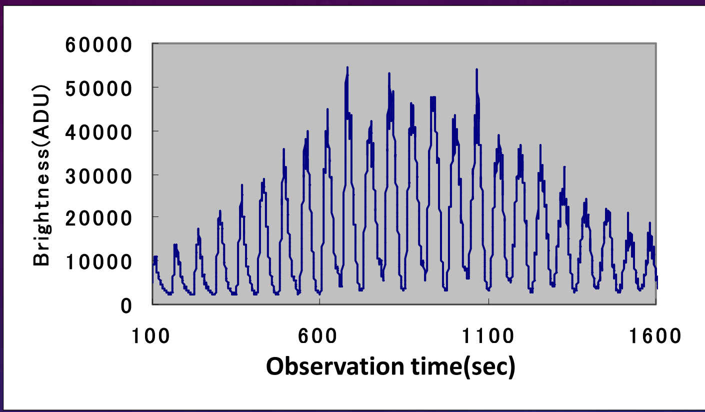
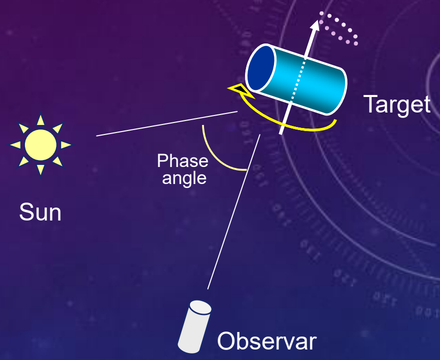
Abstract

Active Debris Removal (ADR) is one of the most promising methods for ensuring safety and sustainable space activities from danger of debris. In order to carry out an ADR mission, the attitude and motion of the target must be determined precisely in advance. We are observing the light curve of the second stage of the Japanese H-2A rockets, one of the ADR target candidates, using telescopes and CMOS sensors, and reproducing by a two methods simulation. One method, the optical simulator uses a scale model of the H-2A R/B and can reproduce the light curve as observed by a ground-based telescope, considering the attitude, motion, and sun direction of the object in orbit. Previous simulations were mainly performed in this method, but due to the time required per case, it was not possible to experiment in many cases. The other method is a CG-based light curve simulation tool that can significantly reduce experimental time by examining the overall trend of the light curves. In this report, we present the results of this CG-based simulation using light curves observed simultaneously at two distant sites.

Light Curve Observation





- Light curve observation is easy and cost effective as compared with the direct imaging with the adaptive optics.
- Technologies to estimate motions and attitudes of targets must be developed.

The optical simulator for simulating light curves was developed.

Two Observatories Chofu and Nyukasa

Mt. Nyukasa Observatry

N 35˚54’05”, E 138˚10’18”
Alt. 1,870m

60cm Telescope

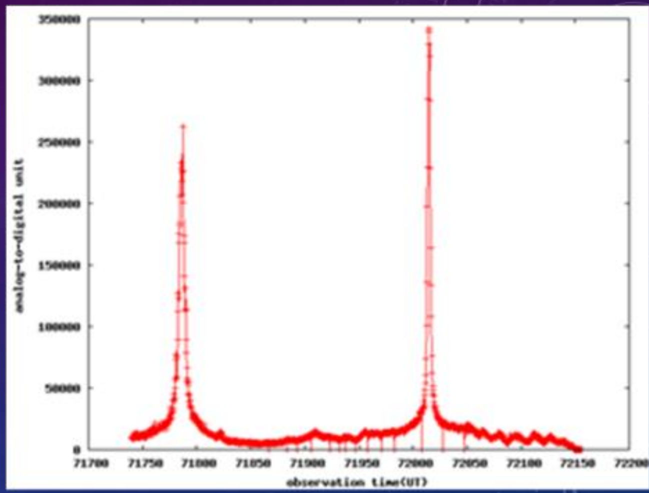
Distance:130km

Tri-Axial alt-azimuth Mount

JAXA Chifu Aerospace Center
N 35°40′42″ E 139°33′24″
Alt. 55m

Light curve observations of H-2A R/Bs

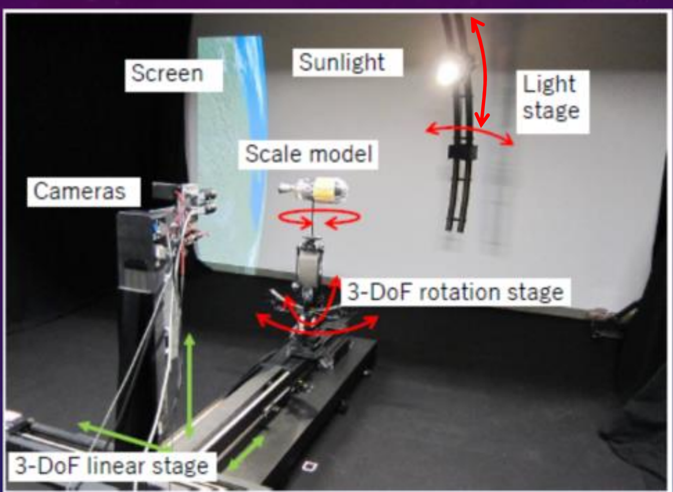
Light curve observations of 4 H-2A R/Bs are being carried out using 60cm telescope

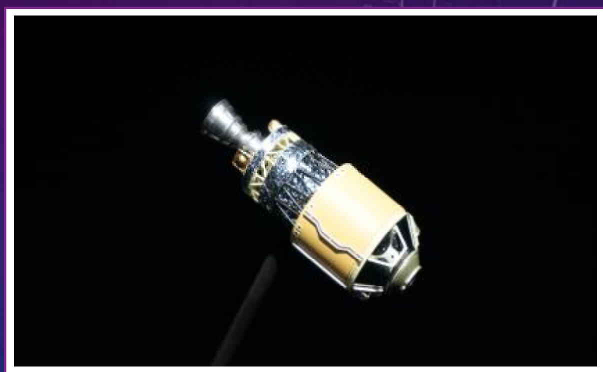


The light curve of 39771 observed on March 19, 2019. Two strong peaks are observable

Light curve simulations were carried out using the optical simulator

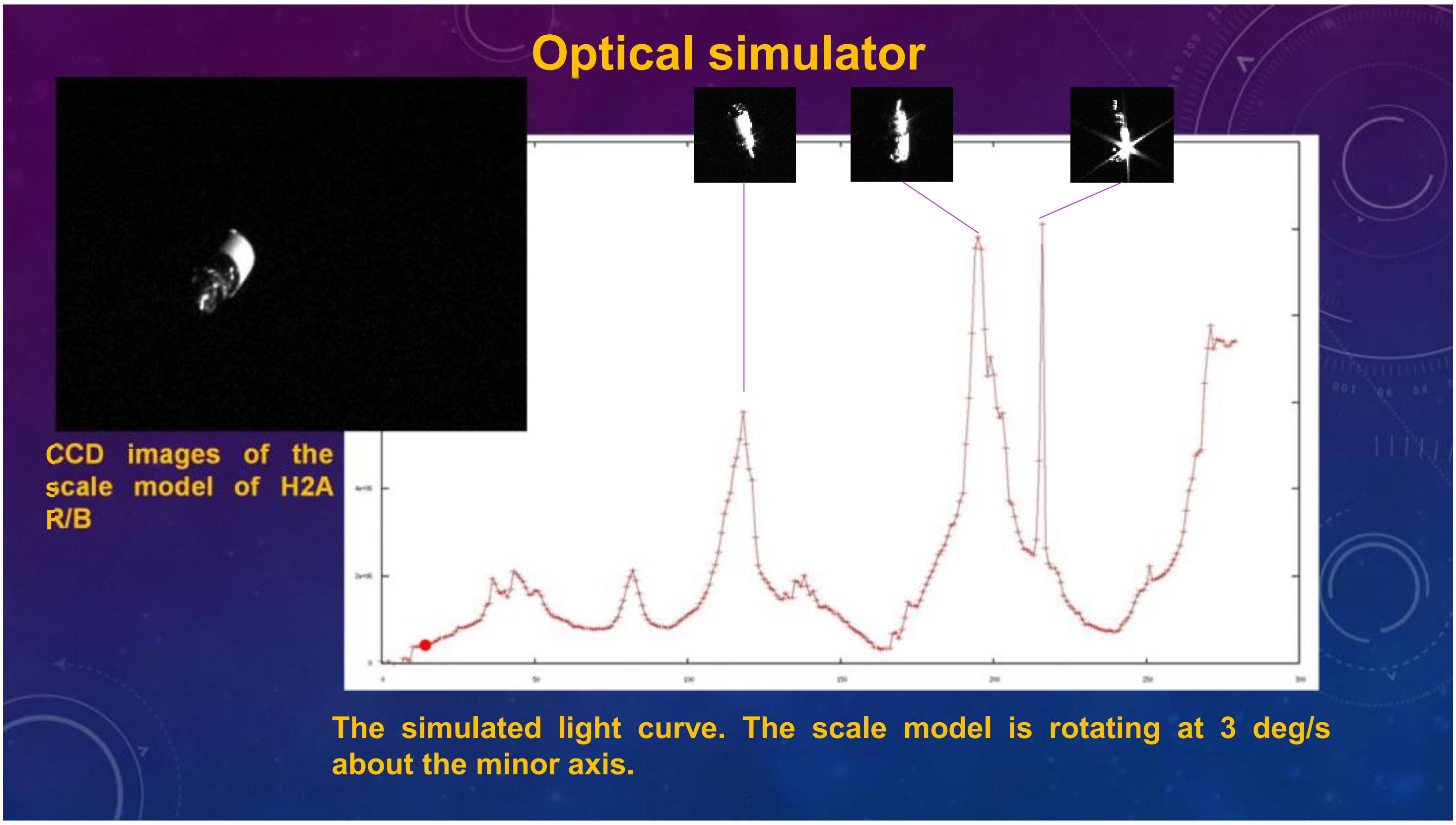
Laboratory optics simulator with scale model

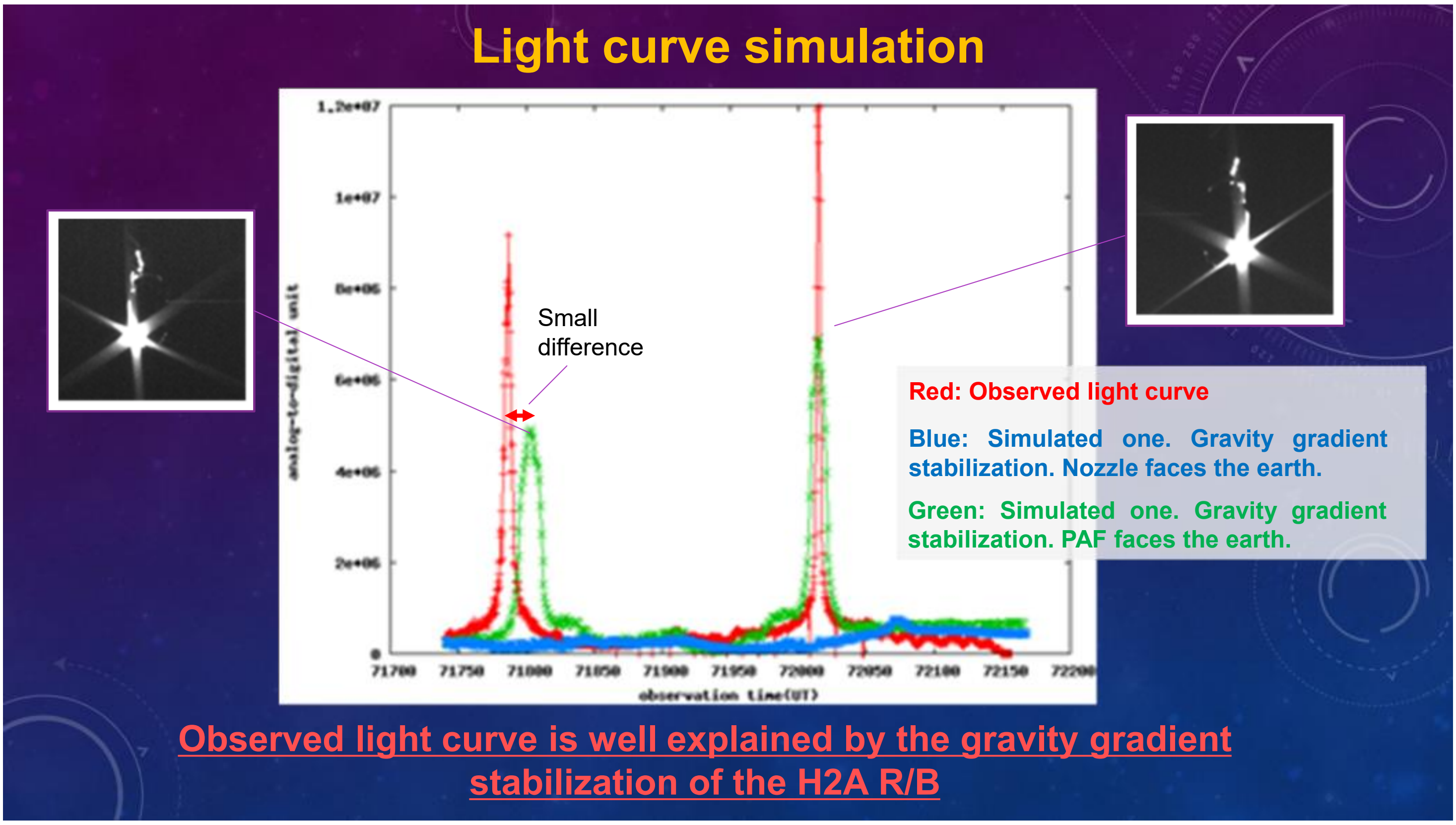




The scale model of H2A R/B

- The optical simulator consists of a 3-DoF (degree of freedom) linear stage, a 3-DoF rotation stage, a light stage, a scale model of the target, and CCD cameras.
- The optical simulator can simulate the orbital environment including lighting condition, attitude and motion of the target.
- Simulated light curve is created analyzing images taken by the CCD camera


Optical simulator
CCD images of the scale model of H2A R/B
The simulated light curve. The scale model is rotating at 3 deg/s about the minor axis.


Light curve simulation
Small difference
Red: Observed light curve
Blue: Simulated one. Gravity gradient stabilization. Nozzle faces the earth.
Green: Simulated one. Gravity gradient stabilization. PAF faces the earth.
analog-to-digital unit
1.2e+07
1e+07
8e+06
6e+06
4e+06
2e+06
0
71700 71750 71800 71850 71900 71950 72000 72050 72100 72150 72200
observation time(UT)
Observed light curve is well explained by the gravity gradient stabilization of the H2A R/B

室内光学シミュレータの弱点
Weakness of laboratory optical simulator

詳細な形状や反射特性の再現が難しい
Difficult to reproduce detailed shapes and reflective characteristics

1つのパターンの実験に時間がかかる
Experiment of one condition takes real time

CG光学シミュレータの利点
Advantages of CG optical simulator

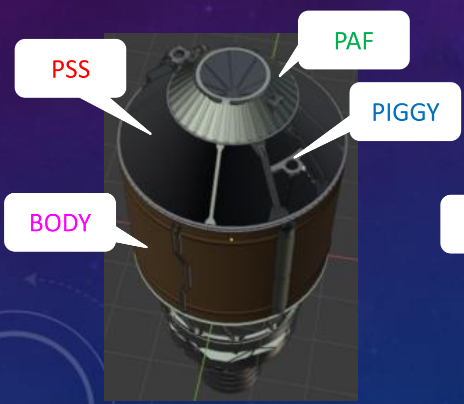
詳細な形状や反射特性を再現できる
Reproduce detailed shapes and reflective characteristics

短時間で数多くの条件を解析することが可能
Numerous conditions can be analyzed in a short time

CG Model(H-2A R/B 38341(21号機))

●反射特性＝Phong reflection modelの使用(鏡面反射のみ)
●簡易形状のCGモデルの使用
- -反射特性を大きく6種類に分類
- -トラス、PIF、PAF上の機器、パネル、配管(一部除く)の削除
- -タンクを除くエンジンマウントリング上の機器削除
- -ノズルスカート以外のエンジン部の機器、配管の削除
- -MLIのしわの除去

Reflective characteristics = Phong reflection model (Mirror reflection only)
CG models of simple shapes
- ・Six major categories of reflective characteristics
- ・Removal of equipment, panels, and piping on trusses, PIFs, and PAFs (except for some)
- ・Removal of equipment on engine mounts and rings (except tanks)
- ・Removal of equipment and piping on engine sections except nozzle skirts
- ・Wrinkle removal on MLI



PAF side

Nozzle side

●反射強度：試験結果に基づいた反射強度
- -ロケット上段表面素材特性評価のBRDF計測結果の最も反射率のピークの高いPSSを1として、各パーツのピークの比率を強度に設定
- -PAF、MLIは計測結果からの比率をそのまま設定
- -PIGGY、NOZZLは、Adapterの計測結果からの比率を仮設定
- -BODY(PIF)は、別途報告された経年劣化(80～90%減)を反映

	解析画像1鏡面反射特性	強度	光沢度	☑ 解析画像2鏡面反射特性	強度	光沢度
R	PSS	1.00000	1000.0	NOZZL	0.26000	400.0
G	PAF	0.11000	100.0	MLI	0.44000	800.0
B	PIGGY	0.26000	200.0	BODY	0.00018	1.0

形状マッチングによる解候補の探索

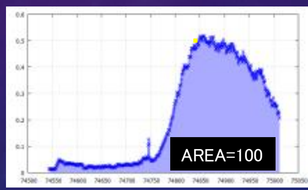
Search for solution candidates by shape matching

●標準化
・サンプリング時刻=1.0[s]
・観測時間帯のライトカーブ面積=100
●評価値(F)
・観測時間での観測値と解析値の差(絶対値)の合計
⇒小さくなるデブリ姿勢の解析条件を解候補

● Standardization
・Sampling Time = 1.0s
・Light curve area during observation time = 100
●Evaluation value (F)
Sum of the difference (absolute value) between observed and analyzed values at the observation time
→The analysis condition for the smaller debris attitude is taken as a solution candidate.

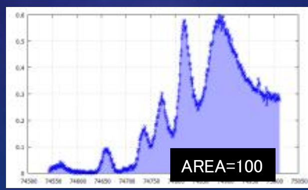
Light curves by observation

Standardization 標準化



after standardization

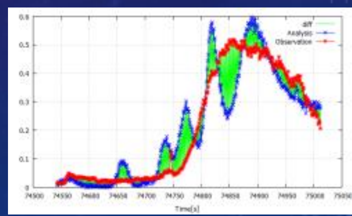
Light curves by analysis



after standardization

$$F=\sum_S^E \| Observation\ val. - Analysis\ val. \|$$
→ min

Evaluation value 評価値



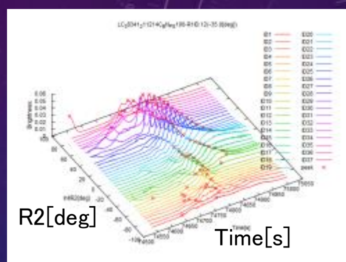
解候補探索のStep

Steps in Solution Candidate Search

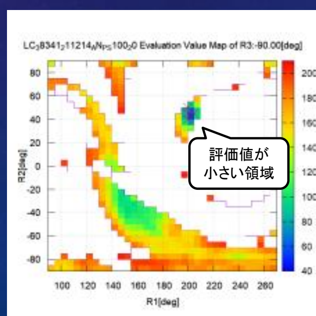
●Step1:
網羅解析:観測開始時のデブリ姿勢角条件を全範囲で粗いステップで変更
−面内姿勢角(R1)(2通り):
・PAF地心方向基準(PAF基準):180[deg]±90[deg] ステップ:5[deg]
・ノズル地心方向基準(ノズル基準) :0[deg] ±90[deg] ステップ:5[deg]
−面外姿勢角(R2): −90[deg]〜90[deg] ステップ:5[deg]
−デブリ円筒軸回り姿勢角(R3):−90[deg]〜90[deg] ステップ:30[deg]
全解析数:9583通り
⇒評価値の小さな解析条件の領域で次ステップの解候補探索範囲を限定。

Exhaustive analysis:
- In-plane attitude angle (R1)
・PAF geocentric direction reference : 180±90 deg. step:5deg.
・Nozzle geocentric direction reference : 0±90 deg. step:5deg.
- Out-of-plane attitude angle:(R2) : -90~+90deg. step:5deg.
- Attitude angle around cylindrical axis (R3) -90~+90deg. step:5deg.
→Limit the range of candidate solution search in the next step in the region of analysis conditions with small evaluation values.

●Step2以降:
−前Stepで限定された解析条件の範囲でより細かいステップの網羅解析
−範囲がある程度限定されたところで、角速度条件を範囲に含めた網羅解析



−Step1 Light Curve Analysis−
In−plane(R2) −90deg〜90deg: Step 5deg



−Step1 Evaluation values map−
横軸:面内角(R1),縦軸:面外角(R2)の評価値をマップ化

解析ケース(2地点、2日)

Analysis Case (2 Sites, 2days)

●**Analysis**

–Case1 :

Chofu : Start time : 2021.12.14 20:42:47(74567s)(UT)　　Observation time : 366s

Nyukasa : Start time : 2021.12.14 20:42:24(74544s)(UT)　　Observation time : 469s

–Case2 : (after 6 days)

Chofu : Start time : 2021.12.20 20:42:17(74537s)(UT)　　Observation time : 365s

Nyukasa : Start time : 2021.12.20 20:41:42(74502s)(UT　　Observation time : 472s

Case1:TLE

```
0 H-2A R/B
1 38341U 12025E   21347.57744250  .00000204  00000-0  31373-4 0  9997
2 38341  98.5193 185.3194 0054097 284.5746  74.9470 14.84345241518076
```

Case2:TLE

```
0 H-2A R/B
1 38341U 12025E   21354.52068479  .00000830  00000-0  10402-3 0  9996
2 38341  98.5188 192.7341 0054042 261.7872  97.7209 14.84354256519185
```




at Nyukasa　　at Chofu　　at Nyukasa　　at Chofu

Case 1　　Case 2

Step1 解析結果例

Example of Analysis Result

●評価値ランキングTOP20(評価値の昇順) Top 20 evaluation value ranking

・PAF基準：ほぼ同じ領域(R1:200[deg]、R2:40[deg]付近に上位ランクの解析条件が存在

・ノズル基準：ノズル地心方向(R1=R2=0.0[deg])に近い解析条件がランキング上位を占める

・PAF criteria: Top ranked analysis conditions exist near approximately the same area (R1:200deg R2:40deg)

・Nozzle criteria: conditions close to nozzle geocentric direction (R1=R2=0.0deg)

–Case1–

PAF基準

Rank	Total	調布	入笠	R1[deg]	R2[deg]	R3[deg]
1	41.469	22.831	18.639	205	45	0
2	42.167	21.164	21.003	205	45	30
3	43.205	20.873	22.332	200	45	30
4	45.370	19.214	26.156	200	45	90
5	45.616	20.124	25.492	200	45	−90
6	46.503	24.006	22.497	205	45	−90
7	46.957	21.547	25.410	205	45	90
8	47.483	28.490	18.993	200	50	−60
9	48.074	23.405	24.669	200	45	−60
10	48.856	35.833	13.023	200	40	90
11	48.999	33.229	15.771	200	50	−90
12	49.144	27.667	21.477	200	50	30
13	49.186	21.165	28.021	200	45	0
14	49.900	23.652	26.248	205	45	−60
15	50.375	37.612	12.763	200	40	−90
16	50.392	33.728	16.664	200	40	60
17	50.504	33.253	17.251	205	40	−60
18	51.134	26.168	24.967	200	40	−60
19	51.533	38.521	13.012	200	40	0
20	53.165	32.040	21.125	200	50	90

Nozzle基準

Rank	Total	調布	入笠	R1[deg]	R2[deg]	R3[deg]
1	39.276	19.650	19.626	−5	−5	90
2	39.704	21.244	18.460	−5	0	0
3	41.921	26.748	15.173	0	0	90
4	42.616	21.603	21.014	−5	0	−60
5	43.080	20.859	22.220	−5	0	−90
6	43.208	21.995	21.213	−5	0	90
7	44.118	23.701	20.417	−5	0	30
8	46.348	21.761	24.586	−10	−5	−60
9	46.930	21.646	25.284	−5	0	−30
10	47.014	27.308	19.706	0	0	−30
11	47.306	23.951	23.356	0	5	0
12	47.518	23.440	24.078	−5	−5	−90
13	48.201	25.857	22.344	−5	0	60
14	49.253	25.396	23.857	0	0	60
15	49.342	21.072	28.271	−5	−5	60
16	49.353	23.594	25.759	−20	−20	0
17	49.356	27.523	21.832	0	5	−60
18	49.389	26.139	23.250	−5	5	−30
19	50.351	23.409	26.942	−10	−5	−90
20	50.375	27.414	22.962	0	5	60

–Case2–

PAF基準

Rank	Total	調布	入笠	R1[deg]	R2[deg]	R3[deg]
1	32.572	15.554	17.018	200	45	−60
2	34.222	18.807	15.415	205	45	0
3	35.013	15.015	19.998	200	45	30
4	36.669	18.559	18.110	205	45	30
5	36.937	16.867	20.069	205	45	−60
6	43.506	12.959	30.547	200	45	−90
7	43.903	25.870	18.033	200	40	60
8	44.105	19.846	24.259	205	45	−90
9	44.268	17.166	27.102	205	45	90
10	45.078	21.030	24.049	200	40	−60
11	45.155	13.411	31.744	200	45	90
12	47.713	30.027	17.686	205	40	−60
13	48.000	28.458	19.542	200	40	30
14	48.201	28.490	19.711	200	40	90
15	49.297	31.641	17.656	200	40	−90
16	50.980	20.575	30.404	200	45	0
17	51.083	18.418	32.664	200	45	60
18	52.303	32.479	19.824	200	50	−90
19	52.930	21.341	31.589	200	45	−30
20	54.228	31.307	22.921	200	50	90

Nozzle基準

Rank	Total	調布	入笠	R1[deg]	R2[deg]	R3[deg]
1	38.425	17.604	20.821	−5	0	−30
2	40.110	18.689	21.421	−5	0	90
3	40.962	20.047	20.915	−5	−5	90
4	41.076	19.031	22.045	−5	0	−90
5	41.509	19.513	21.997	−5	0	−60
6	42.985	21.331	21.655	−45	−30	30
7	43.317	23.861	19.456	−20	−10	0
8	43.554	20.766	22.788	−5	−5	−30
9	43.641	23.348	20.293	−45	−30	−30
10	44.071	20.475	23.596	−20	−15	0
11	44.440	22.993	21.447	−5	0	60
12	46.213	24.611	21.603	−10	−10	90
13	46.423	24.104	22.319	0	0	60
14	47.195	19.839	27.356	−45	−30	−60
15	47.699	29.139	18.560	−40	−15	−60
16	47.798	31.346	16.451	−45	−35	30
17	48.003	23.132	24.871	−5	−5	−90
18	48.365	28.563	19.802	−40	−15	30
19	48.912	27.774	21.138	−40	−10	30
20	49.052	25.166	23.886	−20	−10	60

Step1 解析結果／評価例

Step 1 Example of Analysis Result

●Case1とCase2の評価値マップ比較(反射パターンB)
–異なる日(6日後)で、ほぼ同じマップのパターン
⇒デブリの姿勢変化が小さい、
あるいは、周期的運動で偶然に姿勢が一致？

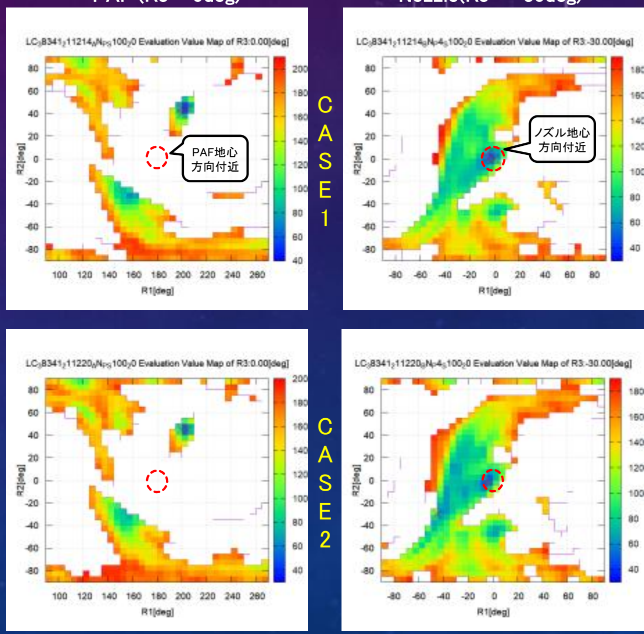
Comparison of evaluation value maps of Case1 and Case2 (reflection pattern B)
- Different days (6 days later), almost the same map pattern
→Debris attitude change is small, Coincidence of Posture in Periodic Motion?

–デブリが重力傾斜安定で姿勢変動が小さい
⇒評価値が小さい領域となるノズル地心方向付近で重力傾斜安定の可能性が高
- Debris is stable due to gravity tilt and attitude fluctuation is small
→The possibility of gravity tilt stability is high near the nozzle geocenter direction, where the evaluation value is small

–Step2以降
⇒ノズル地心方向近傍での探索を実施
→Search near nozzle geocentric direction

–Step1 Evaluation value maps –

–PAF (R3 = 0deg)– –Nozzle(R3 = –30deg)–



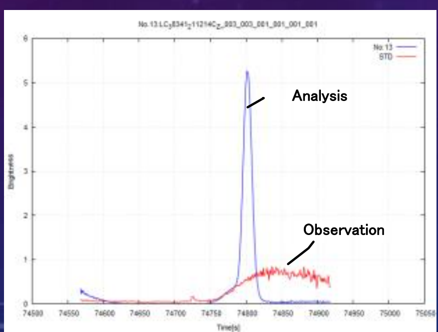
Step1 解析結果／評価例

Step 1 Example of Analysis Result

●PAF地心方向の重力傾斜安定でのライトカーブ解析結果(解析例：CASE1の調布観測)
–PSSの鏡面反射特性が支配的なライトカーブとなる
→本観測結果でのデブリのPAF地心方向での重力傾斜安定の可能性は極めて低い

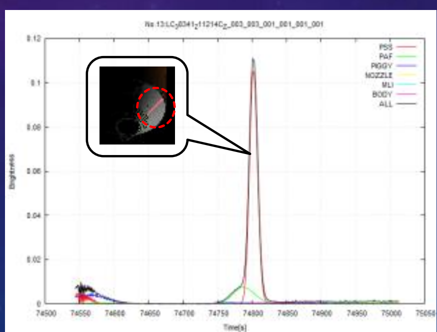
Light curve analysis results with gravity tilt stability in the PAF geocentric direction
- Specular reflection characteristics of PSS dominates the light curve
→The possibility of gravity tilt stability of debris in the direction of the PAF geocenter in this observation is extremely low

–標準化ライトカーブの比較–



Comparison of standardized light curves

–解析ライトカーブの成分プロット–
(赤がPSSの鏡面反射成分)



Component plots of analytical light curves
(Red is specular reflection component of PSS)

–解析ライトカーブのCG動画(40倍)–
(赤がPSSの鏡面反射成分)

CG animation of analytical light curve (40x)
(Red is specular reflection component of PSS)

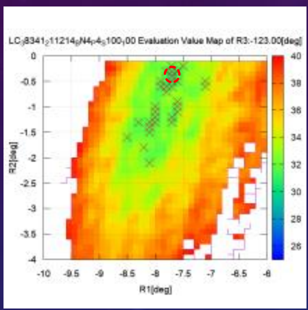
最終ステップ　（Step3）解析結果

Final step (step 3) Result of Analysis

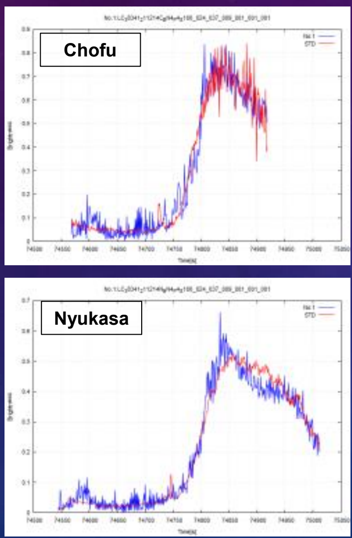
●Case1評価値ランクNo.1のライトカーブ解析結果((R1,R2,R3)=(−7.7, −0.4, −123.0)deg])

−LOX TANKのMLIの鏡面反射特性が支配的

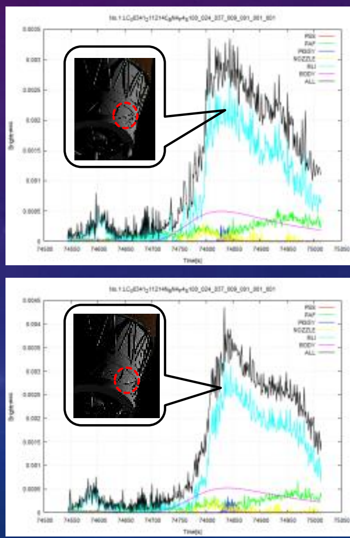
Analyzed light curve for Case 1 with evaluation value rank No. 1　- Dominated specular reflection characteristics of LOX TANK MLI



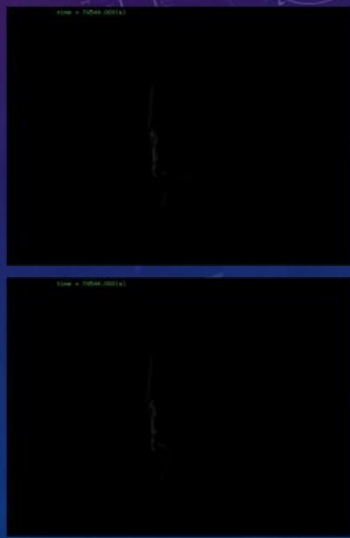
Evaluated value map including No.1 analysis condition



Comparison of standardized light curves (Red: observation, Blue: analysis)



Component plots of analyzed light curves Light blue is specular reflection component of MLI



CG animation of analytical light curves (40x)

最終ステップ（Step3）解析結果

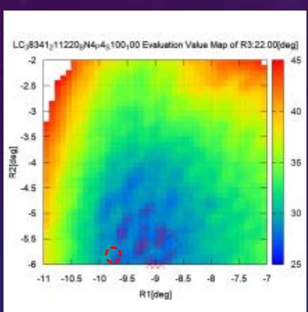
Final step (step 3) Result of Analysis

Case 2 Analysis result of light curve with evaluation value rank No. 1

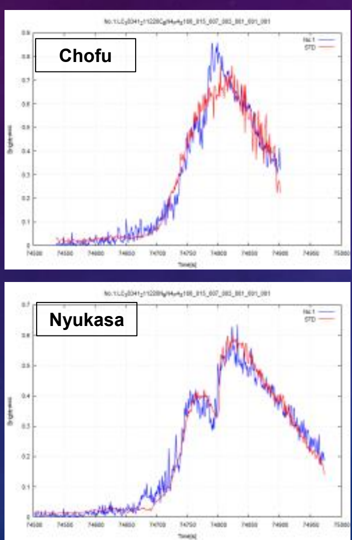
●Case2評価値ランクNo.1のライトカーブ解析結果((R1,R2,R3)=(−9.6, −5.4, 22.0)[deg])

－LOX TANKのMLIの鏡面反射特性が支配的。エンジンマウントトラスの干渉でピークが2つ。

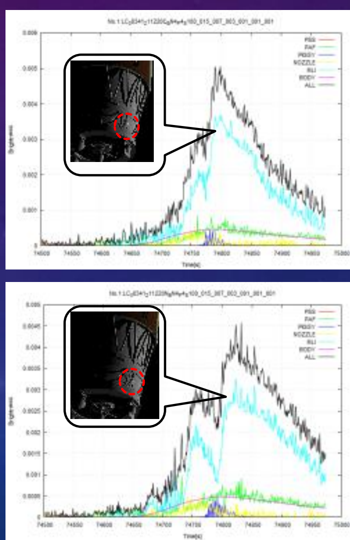
Dominant specular reflection characteristics of MLI in LOX TANK　Two peaks occurred caused by interference with engine mount trusses



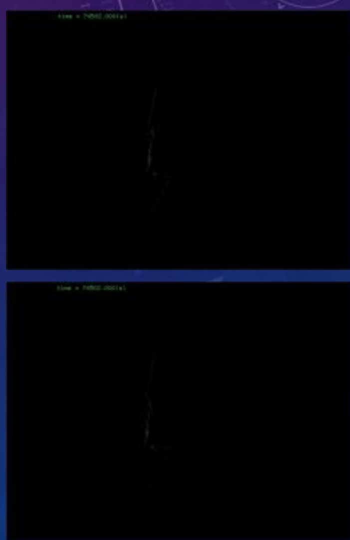
Evaluated value map including No.1 analysis condition



Comparison of standardized light curves (Red: observation, Blue: analysis)



Component plots of analyzed light curves Light blue is specular reflection component of MLI



CG animation of analytical light curves (40x)

Conclusions

●CG光学シミュレータのライトカーブ解析によるデブリの姿勢推定方法を提案
　−形状マッチング、複数地点観測、複数日観測の実施
　−解析例
●今後の方針
　−解析数（観測数)を増やして、解析手法の改善／確立
　−スケールモデル(模型)による解析結果の検証

●Proposed method of debris attitude estimation by light curve analysis of CG optical simulator
-Shape matching, multiple sites, several days of observation, etc.
-Presents an example of analysis
● Future plans
-Increase the number of analyses (number of observations) and improve/establish analysis methods
-Verification of analysis results using scale models (models)

B15

静止衛星のライトカーブと数値シミュレーション

Observations and Numerical Simulations of Light Curves for GEO Satellites

○藤原智子、奥村真一郎、西山広太（日本スペースガード協会）
○FUJIWARA Tomoko, OKUMURA Shin-ichiro, NISHIYAMA Kota (Japan Spaceguard Association)

未知のスペースデブリの形状や構造材料、その運動状態を知るためには、まず既知の人工衛星を対象とした観測を実施し、物体の物理的特性が観測結果にどのように反映されるか理解することが重要である。測光観測で得られるライトカーブには、衛星の形状や運動状態が反映される。
我々は運用中の静止衛星であるQZS-3（NORAD ID: 42917）とHIMAWARI-8/9（40267/41836）を対象に、JAXA美星スペースガードセンター0.5m望遠鏡を使った連続測光観測を行い、ライトカーブを取得した。次に衛星の光度が光源である太陽の入射角にどのように依存するか調べるため、機体のコンフィギュレーションや光学的特性の情報を用いて数値シミュレーションを行った。本講演では、各衛星の光度変化がどのように生じるか、ライトカーブと数値シミュレーションの結果を報告する。

The basic study of optical observations for active satellites in geostationary Earth orbit (GEO) is quite useful to construct some methods to understand characteristics of unresolved space debris. Since spacecrafts can be visible by reflecting sunlight, the brightness of satellites simply depends on the position of the Sun, their own dimensions and reflectivity properties. Photometric light curves obtained by continuous observations should represent in more detail appearance characteristics associated with the configuration.
In order to obtain and to analyse light curves for active GEO satellites QZS-3 (NORAD ID: 42917) and HIMAWARI-8/9 (40267/41836), we made photometric observations using the 0.5-m telescope at JAXA Bisei Spaceguard Center (BSGC). Simultaneously, for the interpretation of observational results, we performed numerical simulations based on the physical configuration and its optical properties. In this paper, we show results of photometric observations and numerical simulations for each satellite, and discuss their different characteristics.

10th Space Debris Workshop (28-30 Nov, 2022)

Observations and numerical simulations of light curves for GEO Satellites

静止衛星のライトカーブと数値シミュレーション

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Contents

1.Introduction

Aims:

Interpretation of light curves for active satellites in geostationary Earth orbit (GEO) in order to construct some methods to understand observational results of unresolved space debris

Methods:

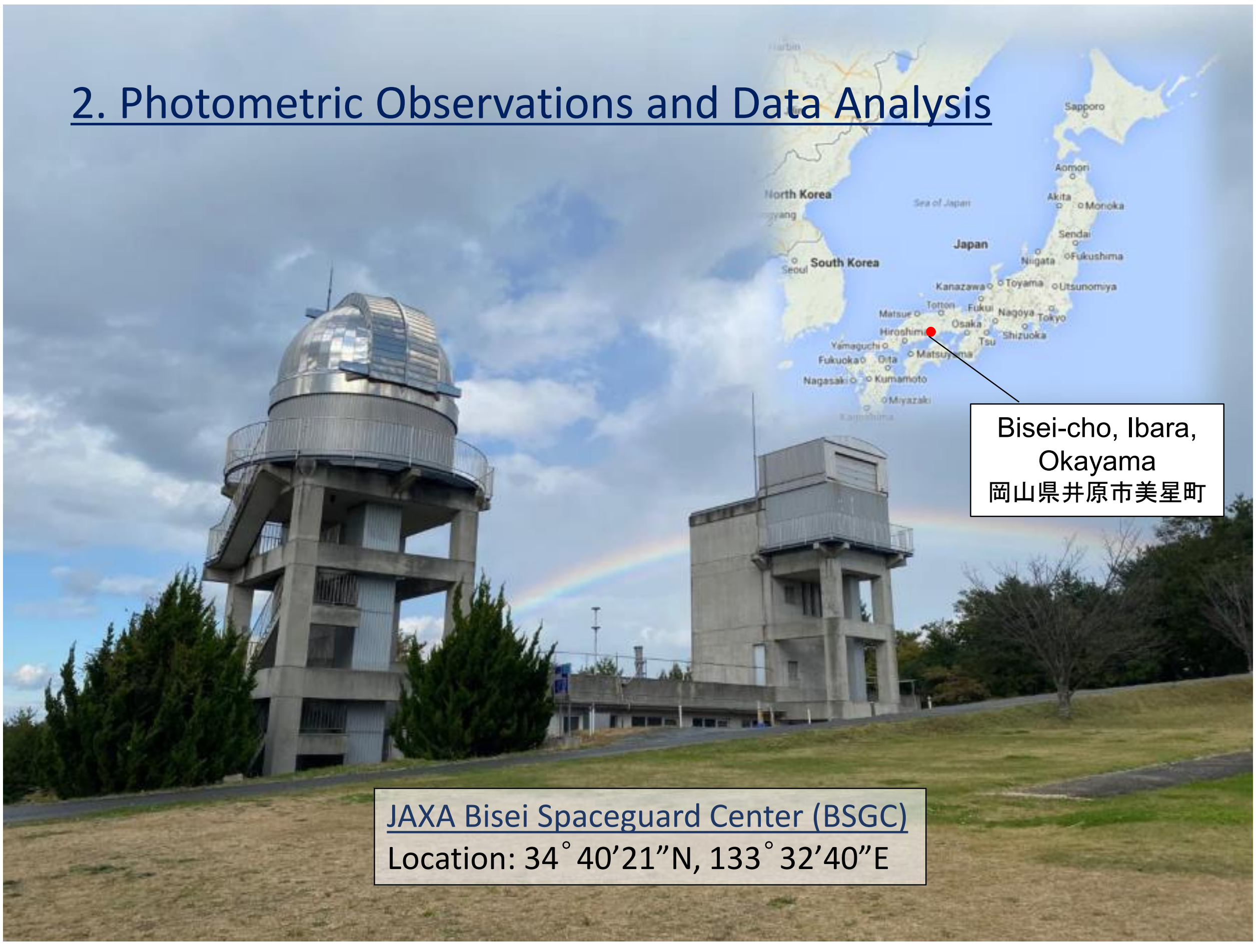
- Photometric Observation
  in order to obtain light curves that represent appearance characteristics associated with the configuration
- Numerical Simulation
  in order to construct a model based on the physical configuration and its optical properties for the interpretation of observational results

Target Objects

Quasi-Zenith Satellite

SAT NAME	QZS-3 (MICHIBIKI-3)	HIMAWARI-8	HIMAWARI-9
			
Int'l Designator (COSPAR ID)	2017-048A	2014-060A	2016-064A
NORAD ID	42917	40267	41836
Launch	2017-08-19	2014-10-07	2016-11-02
Orbit	GEO (127°E)	GEO (140.65°E)	GEO (140.75°E)
Operator	Cabinet Office (JPN)	Japan Meteorological Agency (JPN)	
Mission Type	Navigation	Weather	
Manufacturer & Bus	Mitsubishi Electric DS2000		

2. Photometric Observations and Data Analysis



Instrument Specifications

Telescope	0.5-m Reflector
Focal Ratio Optical Configuration Mounting	F/2.0 Cassegrain Equatorial, Open fork
CCD Camera	Apogee Alta U42 (partly SBIG ST-10)
Chip Array Size (pixels) Pixel Size (μm) Pixel Scale	EV2 CCD42-40z 2048 x 2048 13.5 x 13.5 2.93”/pix
Others	•Filter: Wi (5880-9380Å) •Field of View(R.A.x decl): 100’ x 100’ •Limiting magnitude: 17 (2 min exposure)

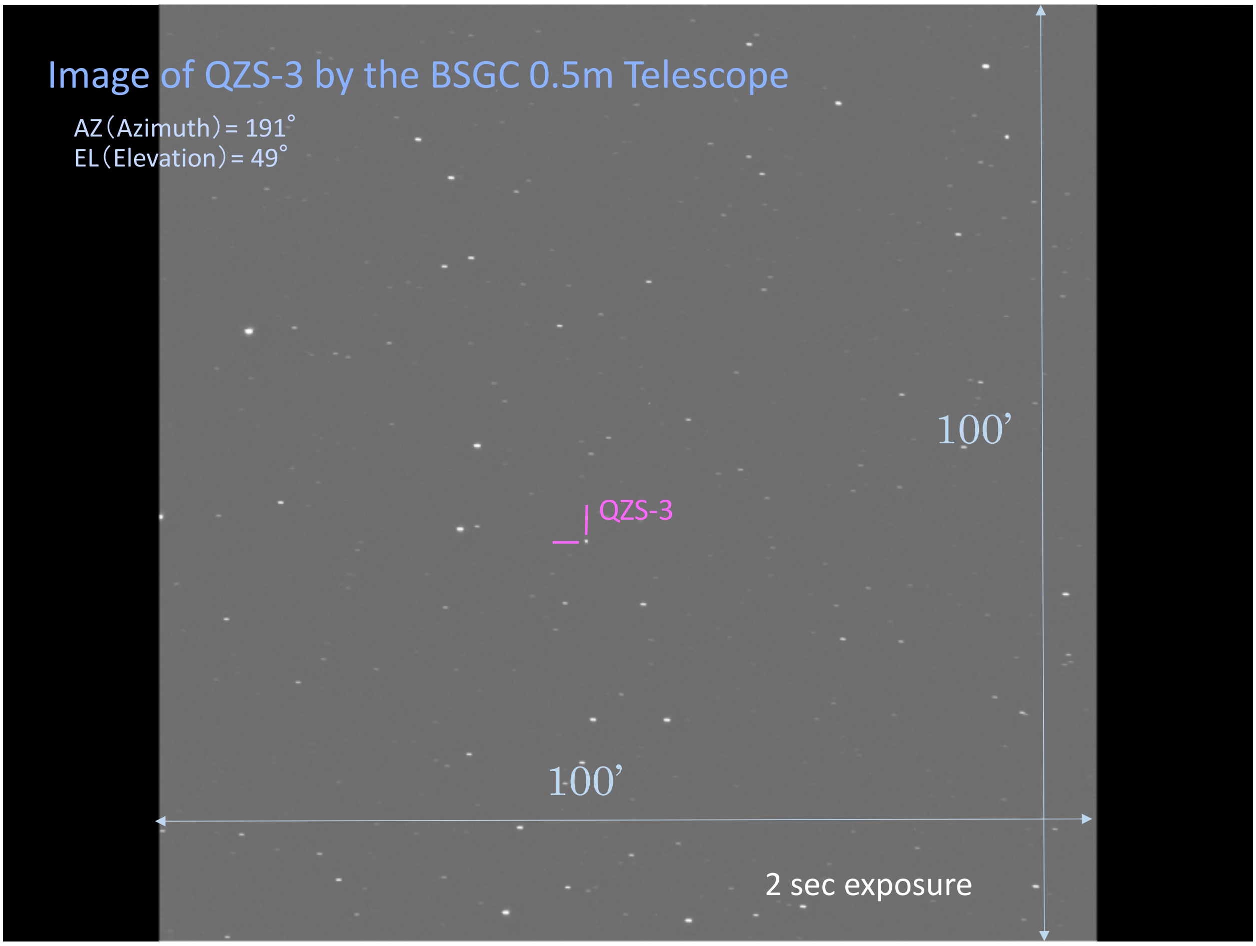


Image of QZS-3 by the BSGC 0.5m Telescope
AZ（Azimuth）= 191°
EL（Elevation）= 49°
100’
QZS-3
100’
2 sec exposure

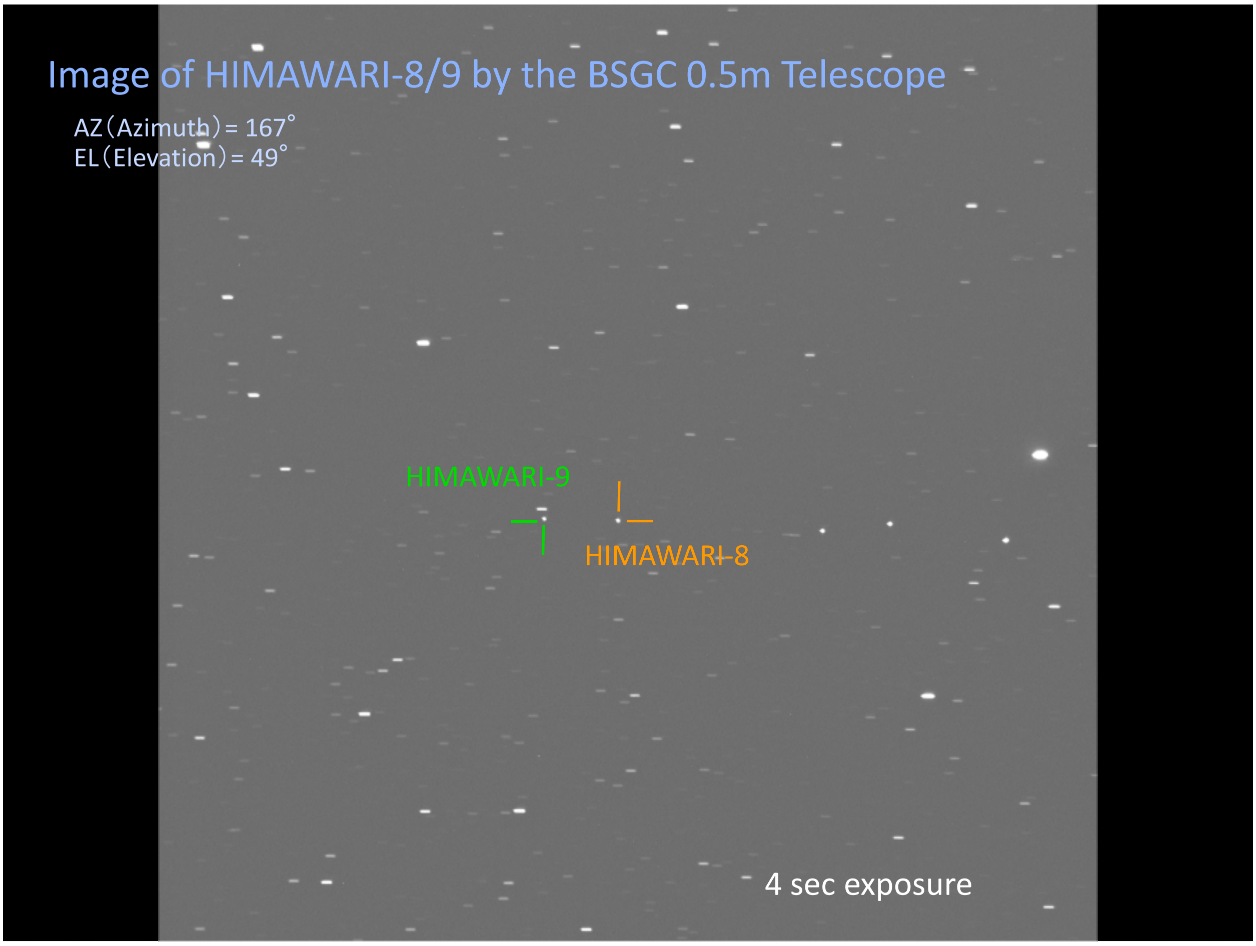
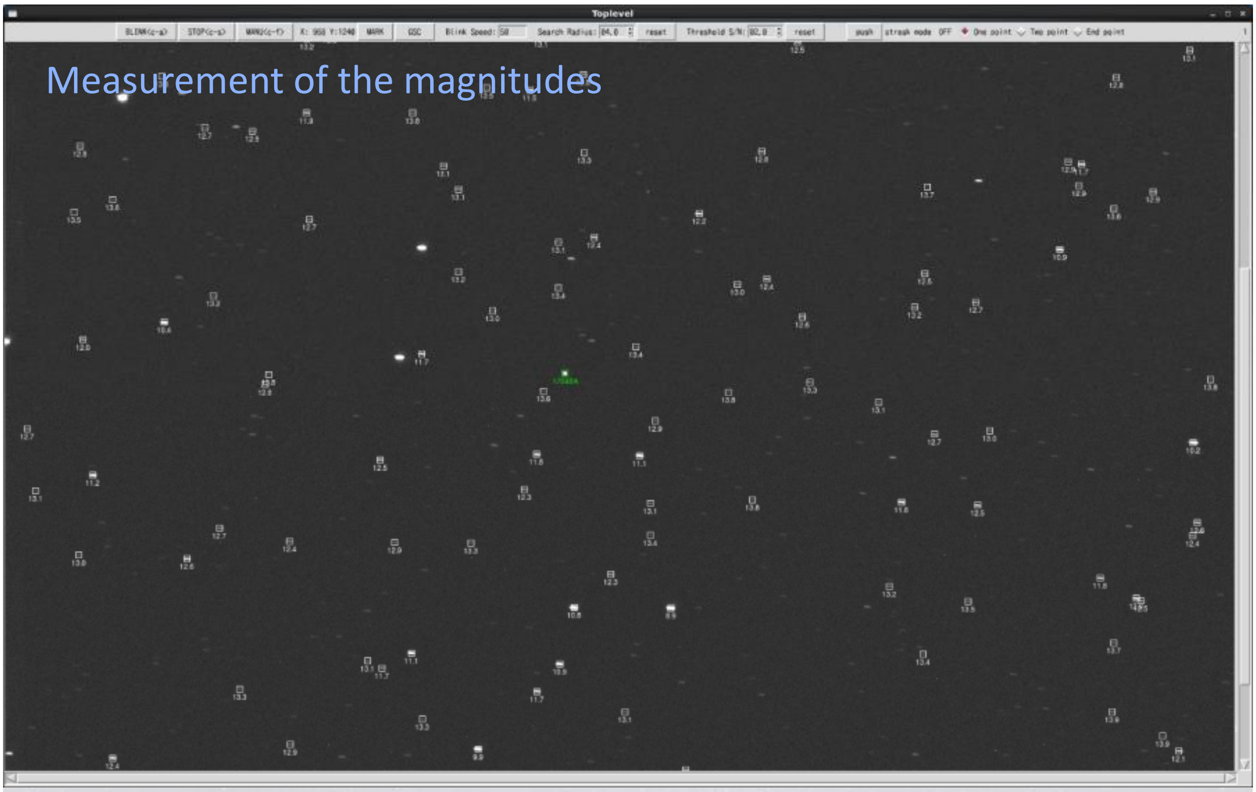


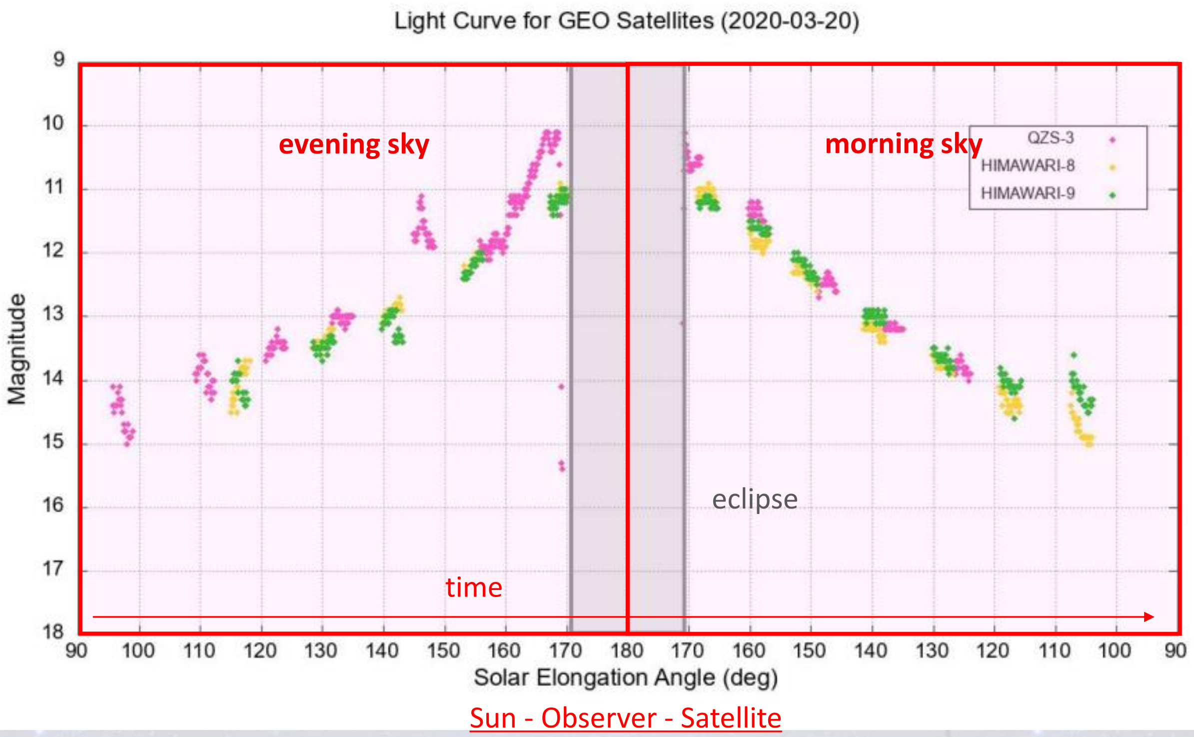
Image of HIMAWARI-8/9 by the BSGC 0.5m Telescope
AZ（Azimuth）= 167°
EL（Elevation）= 49°
HIMAWARI-9
HIMAWARI-8
4 sec exposure

Measurement of the magnitudes

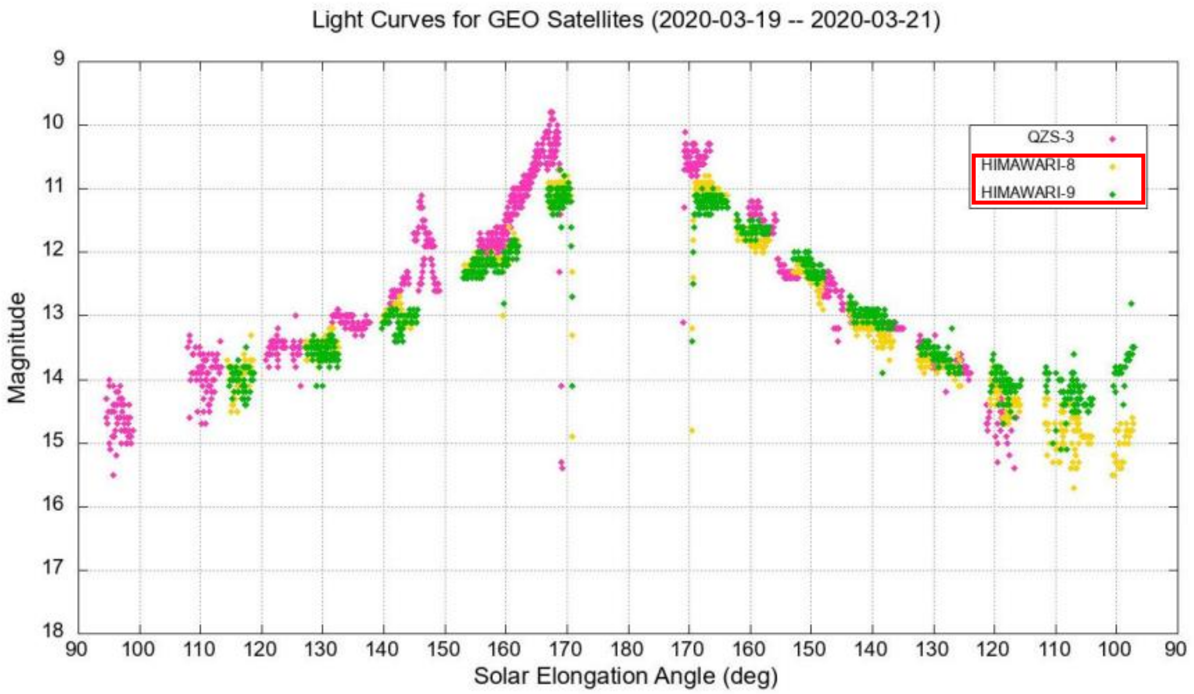


Measuring brightness of satellites in comparison to the magnitude for stars of known brightness in the same field (Reference Catalogues: USNO-2.0 or GSC (Guide Star Catalog))
As each image catches different stars, estimated magnitudes contain errors of ±0.3.

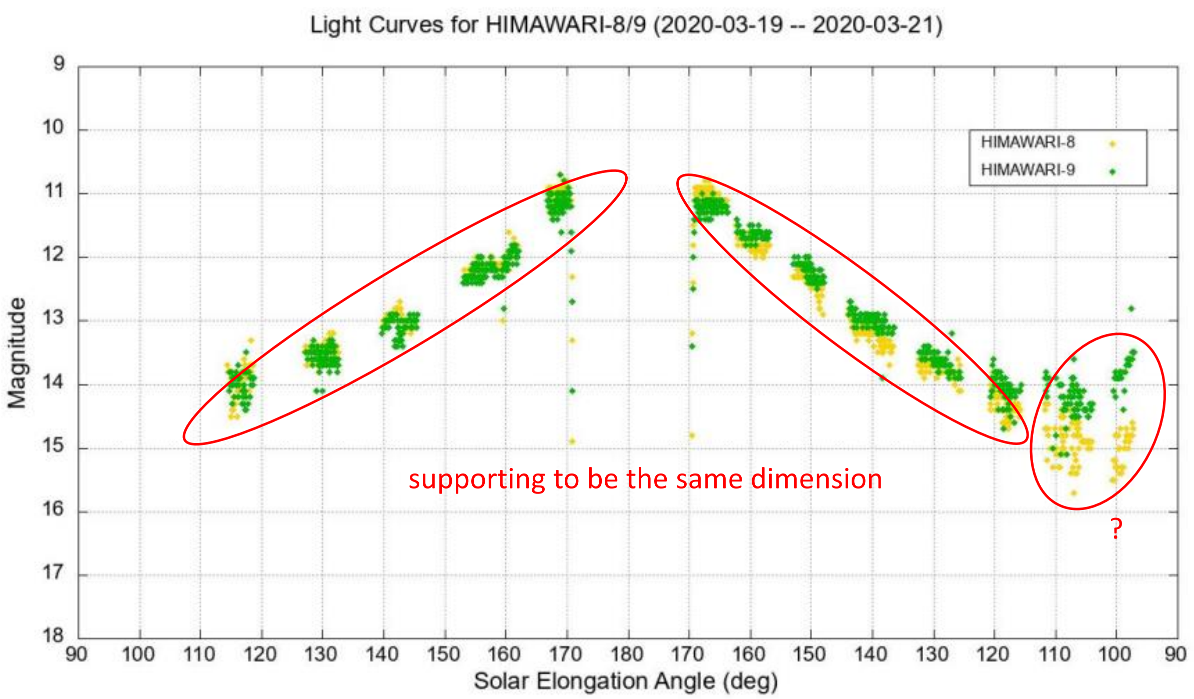
Light Curves for GEO Satellites during the Vernal Equinox (2020-03-20)



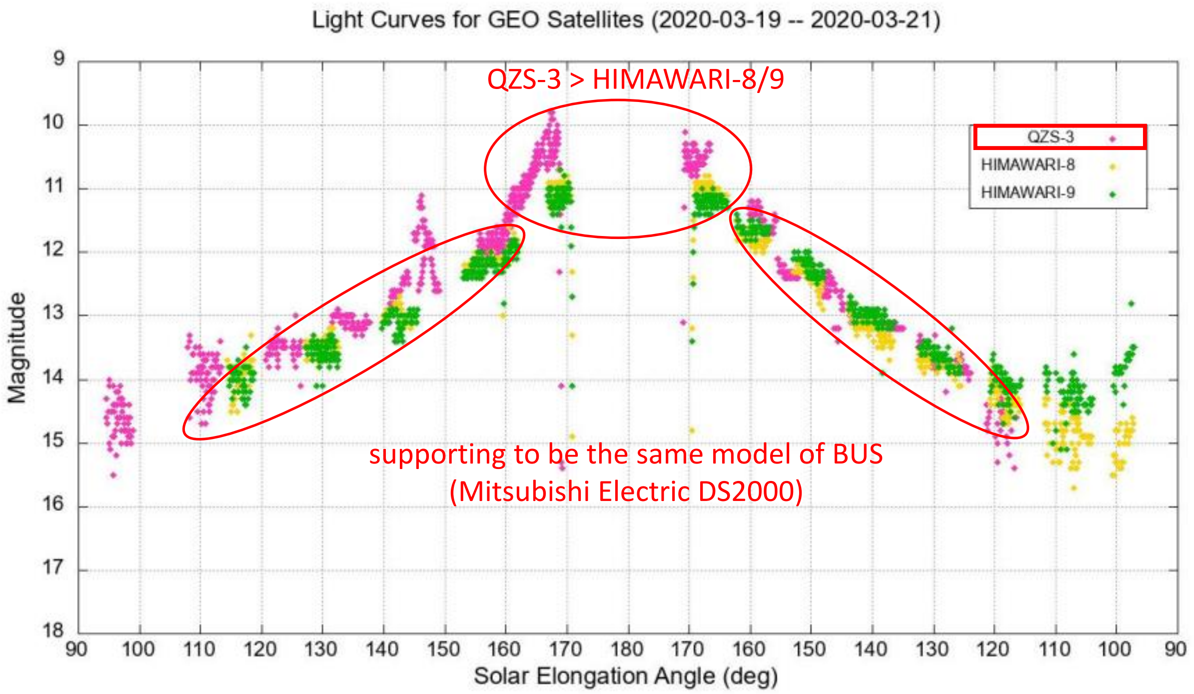
Light Curves for GEO Satellites during the Vernal Equinox (2020-03-19-- 2020-03-22)



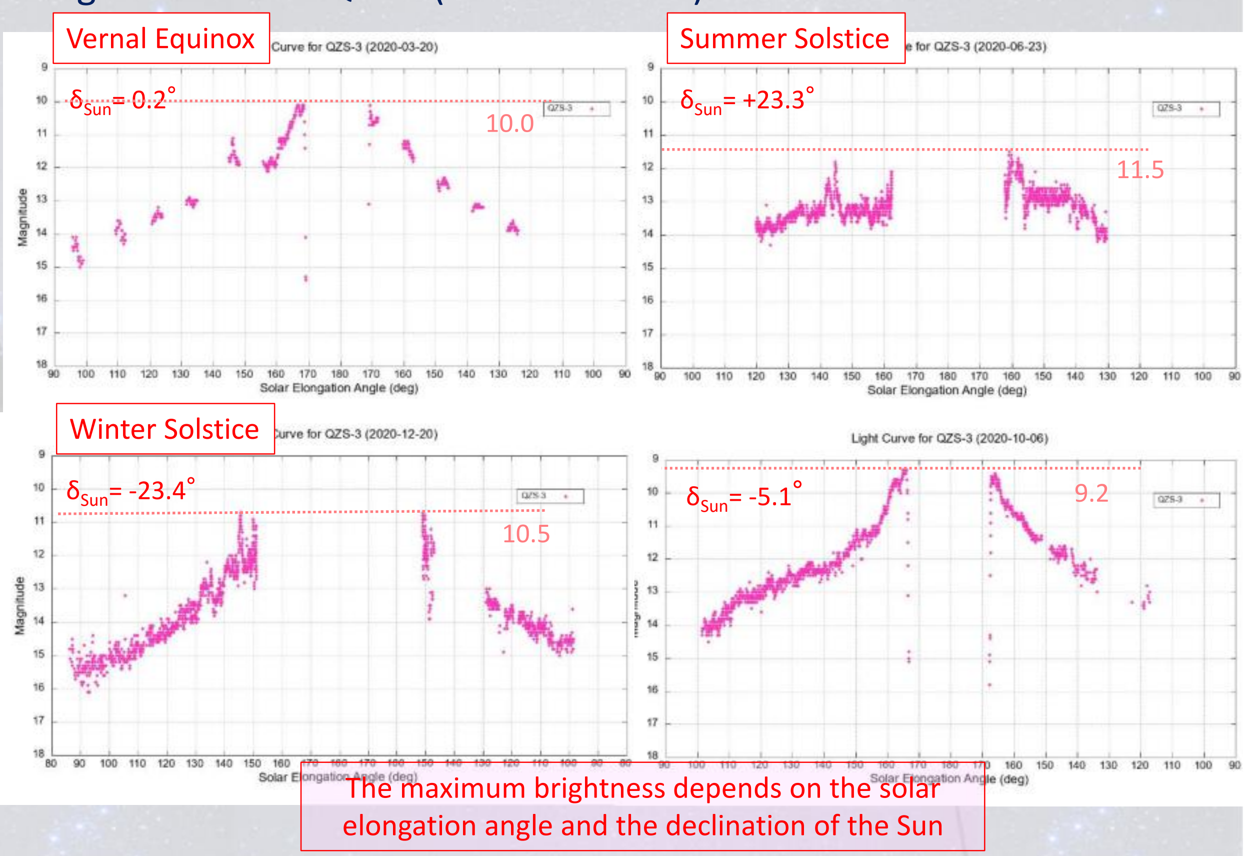
HIMAWARI-8 vs HIMAWARI-9 (2020-03-19~22)

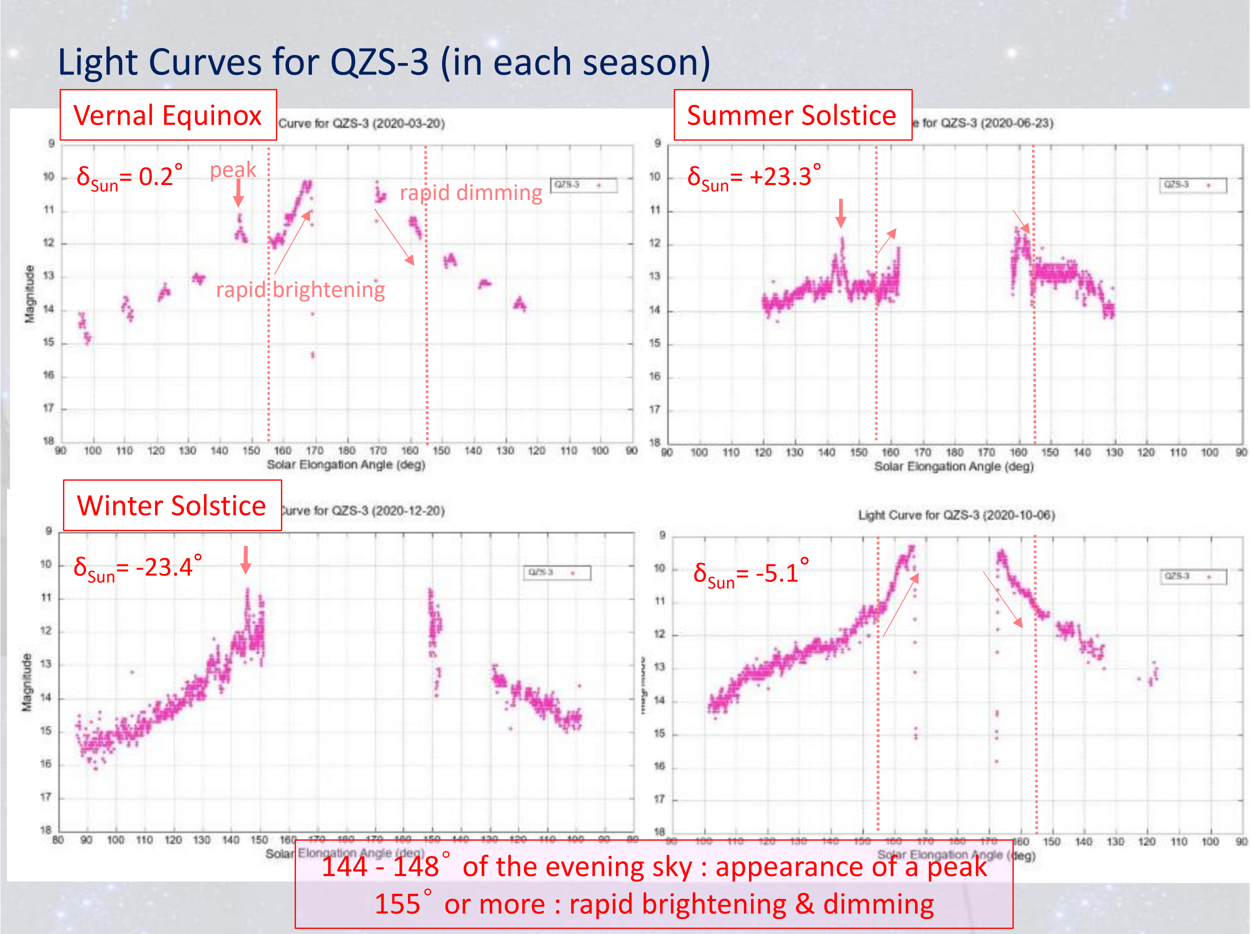


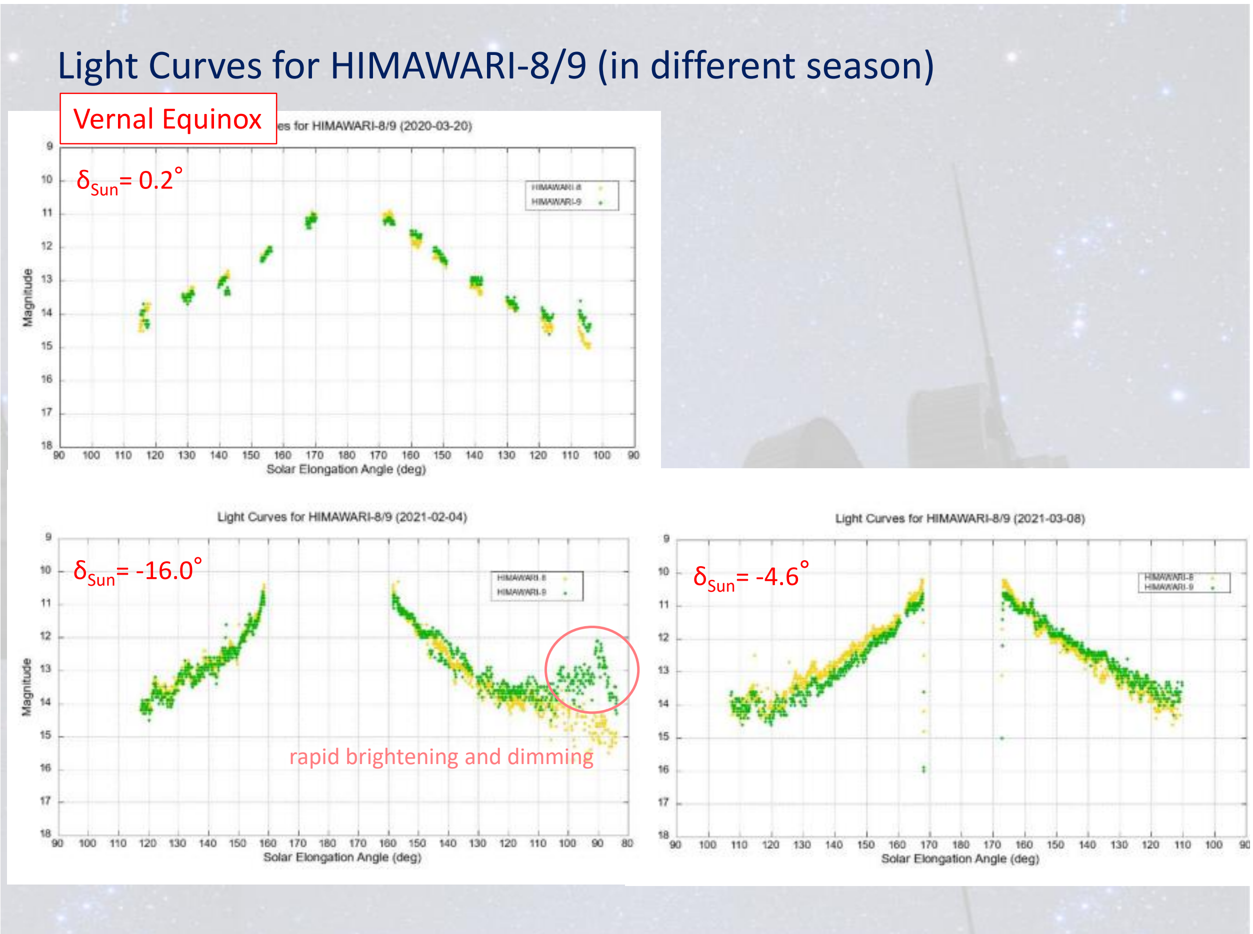
QZS-3 vs HIMAWARI-8/9 (2020-03-19~22)



Light Curves for QZS-3 (in each season)

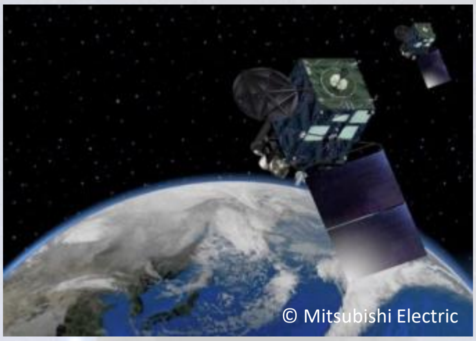



Light Curves for QZS-3 (in each season)
Vernal Equinox
Curve for QZS-3 (2020-03-20)
δSun= 0.2°
peak
rapid dimming
rapid brightening
Summer Solstice
e for QZS-3 (2020-06-23)
δSun= +23.3°
Winter Solstice
Curve for QZS-3 (2020-12-20)
δSun= -23.4°
Light Curve for QZS-3 (2020-10-06)
δSun= -5.1°
Magnitude
Solar Elongation Angle (deg)
144 - 148° of the evening sky : appearance of a peak
155° or more : rapid brightening & dimming


Light Curves for HIMAWARI-8/9 (in different season)
Vernal Equinox
es for HIMAWARI-8/9 (2020-03-20)
δSun= 0.2°
HIMAWARI-8
HIMAWARI-9
Light Curves for HIMAWARI-8/9 (2021-02-04)
δSun= -16.0°
rapid brightening and dimming
Light Curves for HIMAWARI-8/9 (2021-03-08)
δSun= -4.6°
Magnitude
Solar Elongation Angle (deg)

3. Numerical Simulation

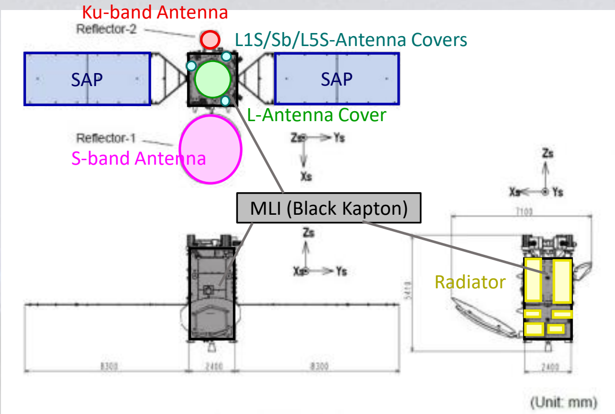
QZS-3

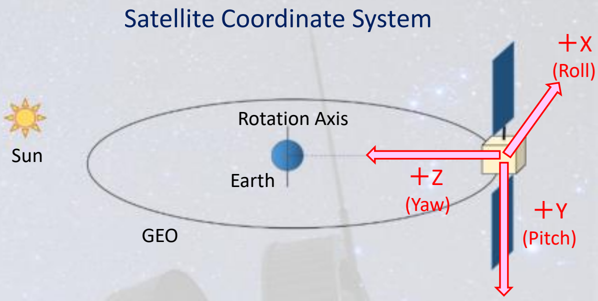


HIMAWARI-8/9

Light curve simulations for each satellite based on
- physical configuration
- optical properties

Geometry and Materials of QZS-3



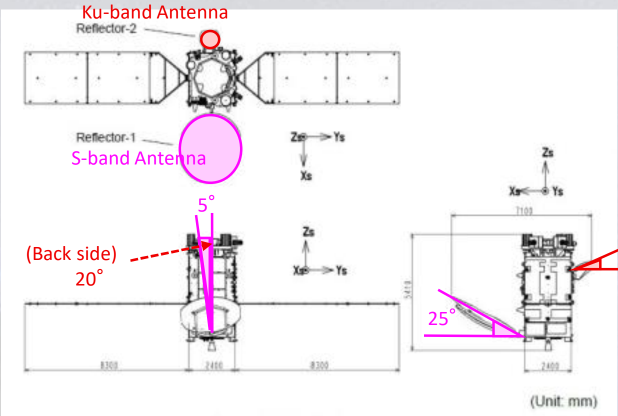


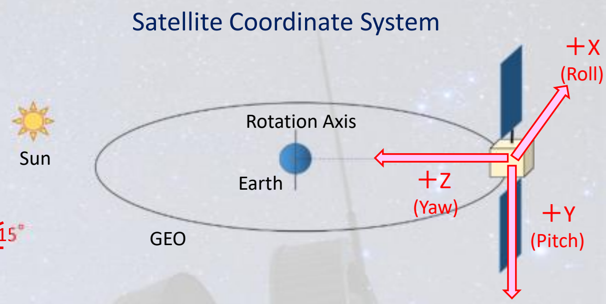
SAP: Solar Array Panel
MLI: Multi-layer Insulation

Location	Material	Area [m²]	Absorption	Specular	Diffuse
+ X	MLI	10.1	0.926	0.035	0.039
	S-band Antenna (Front)	9.1	0.619	0.005	0.046
- X	MLI	10.1	0.926	0.035	0.039
	Ku-band Antenna (Front)	0.8	0.617	0.023	0.360
+ Y	MLI	5.0	0.926	0.035	0.039
	Radiator	5.1	0.026	0.954	0.020
	SAP	14.9	0.923	0.068	0.009
- Y	MLI	4.8	0.926	0.035	0.039
	Radiator	5.3	0.026	0.954	0.020
	SAP	14.9	0.923	0.068	0.009
+ Z	MLI	3.0	0.926	0.035	0.039
	L-ANT Cover	2.1	0.485	0.459	0.056
	L1S/Sb/L5S-ANT Covers	0.4	0.553	0.100	0.347

ref: Cabinet Office, *QZS-3 Satellite Information*, 2021.

Geometry and Materials of QZS-3





SAP: Solar Array Panel
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Location	Material	Area [m²]	Absorption	Specular	Diffuse
+ X	MLI	10.1	0.926	0.035	0.039
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ref: Cabinet Office, *QZS-3 Satellite Information*, 2021.

Conditions for a Light Curve Simulation

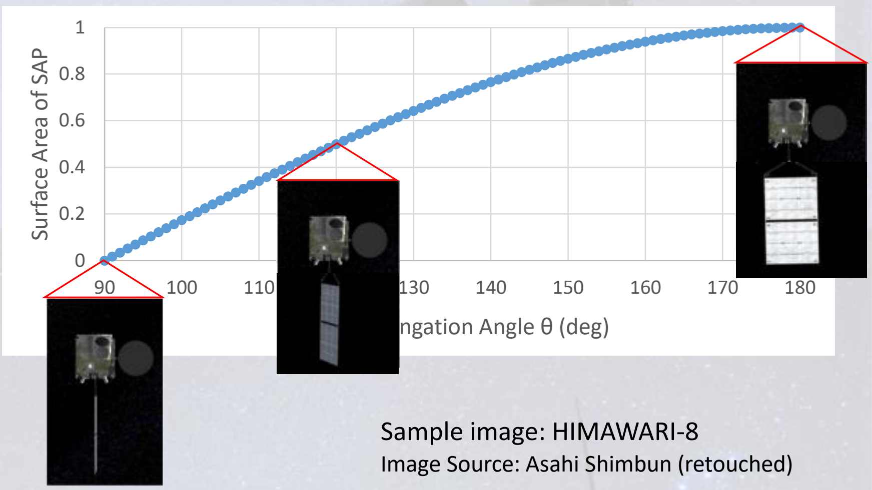
- The shape of antennas

  →assumed planar antennas
- Variations in absorption rates due to long-term deterioration

  →ignored
- Surface areas of each material

  SAP ∝ cos (180° – θ) (θ: Solar Elongation Angle)

  The others = const.



Sample image: HIMAWARI-8
Image Source: Asahi Shimbun (retouched)

Geometry and Materials of QZS-3

				Reflectance	
Location	Material	Area [m^2]	Absorption	Specular	Diffuse
+ X	MLI	10.1	0.926	0.035	0.039
	S-band Antenna (Front)	9.1	0.619	0.005	0.046
- X	MLI	10.1	0.926	0.035	0.039
	Ku-band Antenna (Front)	0.8	0.617	0.023	0.360
+ Y	MLI	5.0	0.926	0.035	0.039
	Radiator	5.1	0.026	0.954	0.020
	SAP	14.9	0.923	0.068	0.009
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	SAP	14.9	0.923	0.068	0.009
+ Z	MLI	3.0	0.926	0.035	0.039
	L-ANT Cover	2.1	0.485	0.459	0.056
	L1S/Sb/L5S-ANT Covers	0.4	0.553	0.100	0.347

Estimation of the Reflection Intensity

(1) Specular Reflection (Regular Reflection)

- reflected from smooth surfaces like mirrors
- causes light rays to reflect at the same angle as they hit the surface

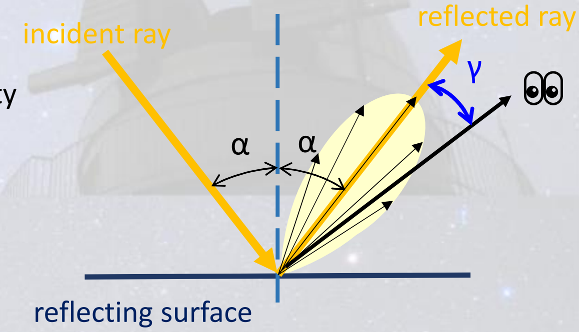
$I_s = I_i K_s \cos^n \gamma$ (Phong reflection model)

I_i : intensity of incident ray

K_s : specular reflectance

n : coefficient depending on the reflectivity of the surface (specular exponent)

γ : angle between the direction of reflection and the direction of the viewpoint



Estimation of the Reflection Intensity

(2) Diffuse Reflection

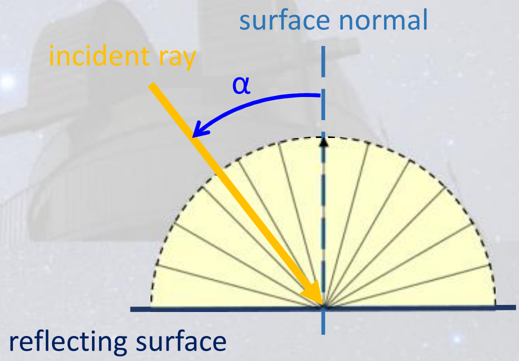
- produced by rough surfaces
- scatters light rays in different directions

$I_d = I_i K_d \cos\alpha$ (Lambert's cosine law)

I_i : intensity of incident ray

K_d : diffuse reflectance

α : angle of incidence（between the normal）



4. Results and Discussion

Light Curve Simulations for Each Material of QZS-3

Location：BSGC (34°40'21"N, 133°32'40"E)

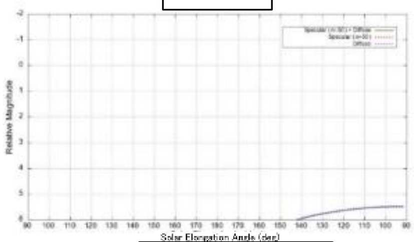
Epoch：Vernal Equinox (δ_{Sun}= 0.0°, Intensity of Solar Radiation I =1.38 kW/m²)

Total Reflection
Specular Reflection (n =50)
Diffuse Reflection

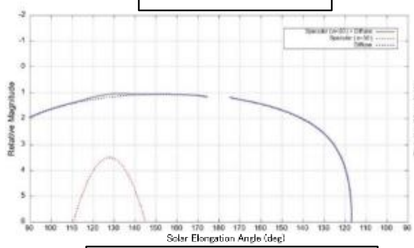
Reflections by the following materials could be hardly detected .

- -X: MLI
- +Y: MLI
- +Y: Radiator
- -Y: MLI
- -Y: Radiator

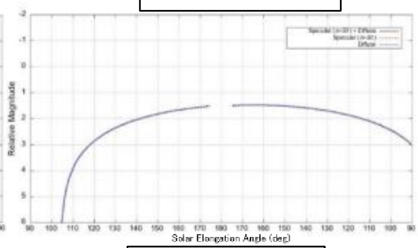
+X: MLI



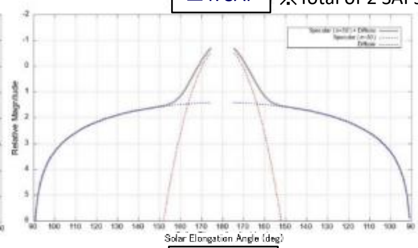
+X: S-band Antenna



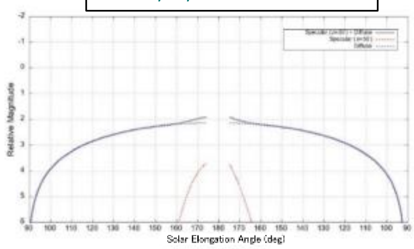
-X: Ku-band Antenna



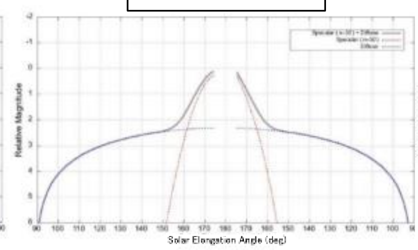
±Y: SAP　※Total of 2 SAPs



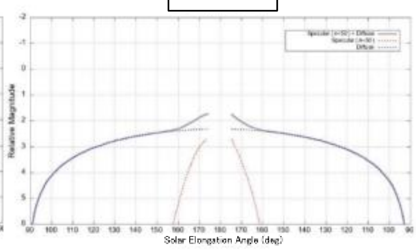
+Z: L1S/Sb/L5S-Antenna Covers



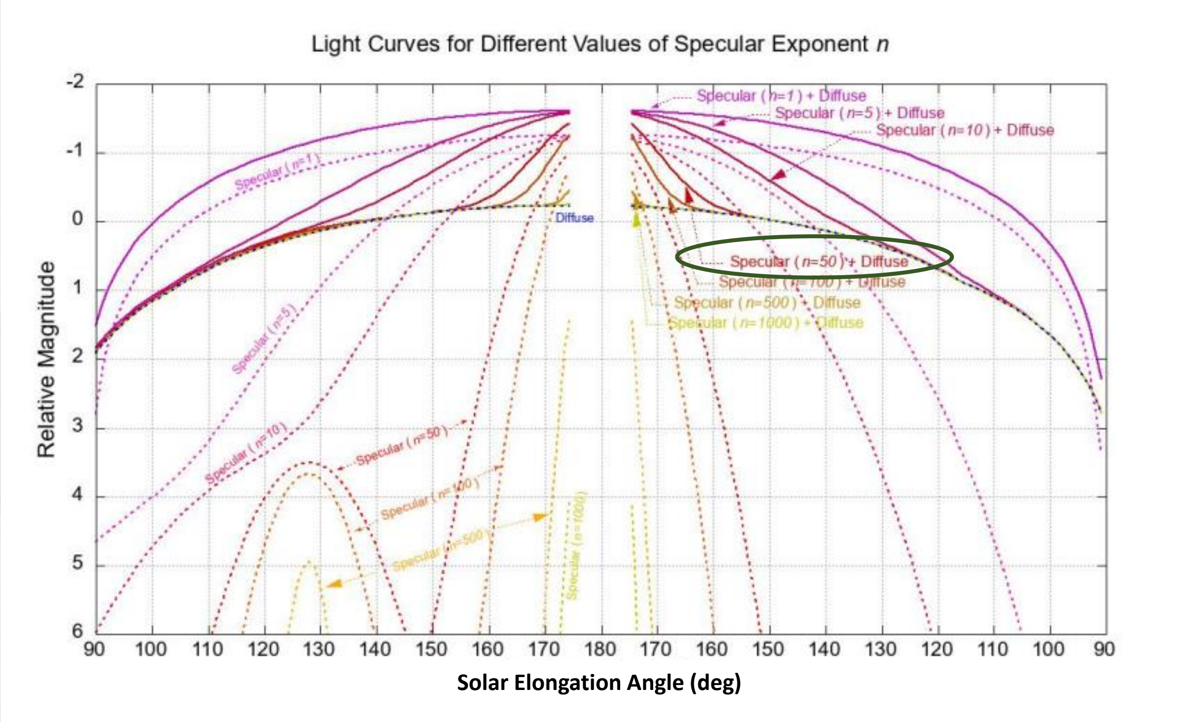
+Z: L-Antenna Cover



+Z: MLI



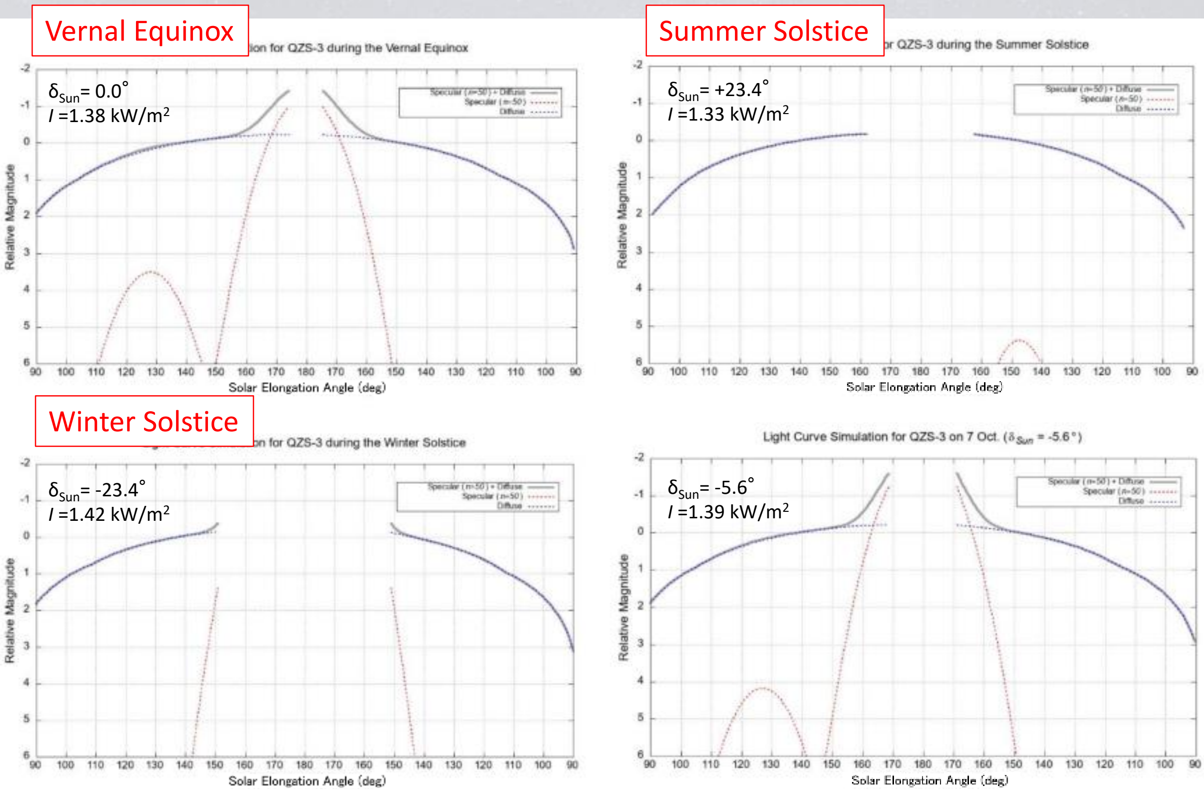
Shape of the Specular Reflection for Different Values of *n*



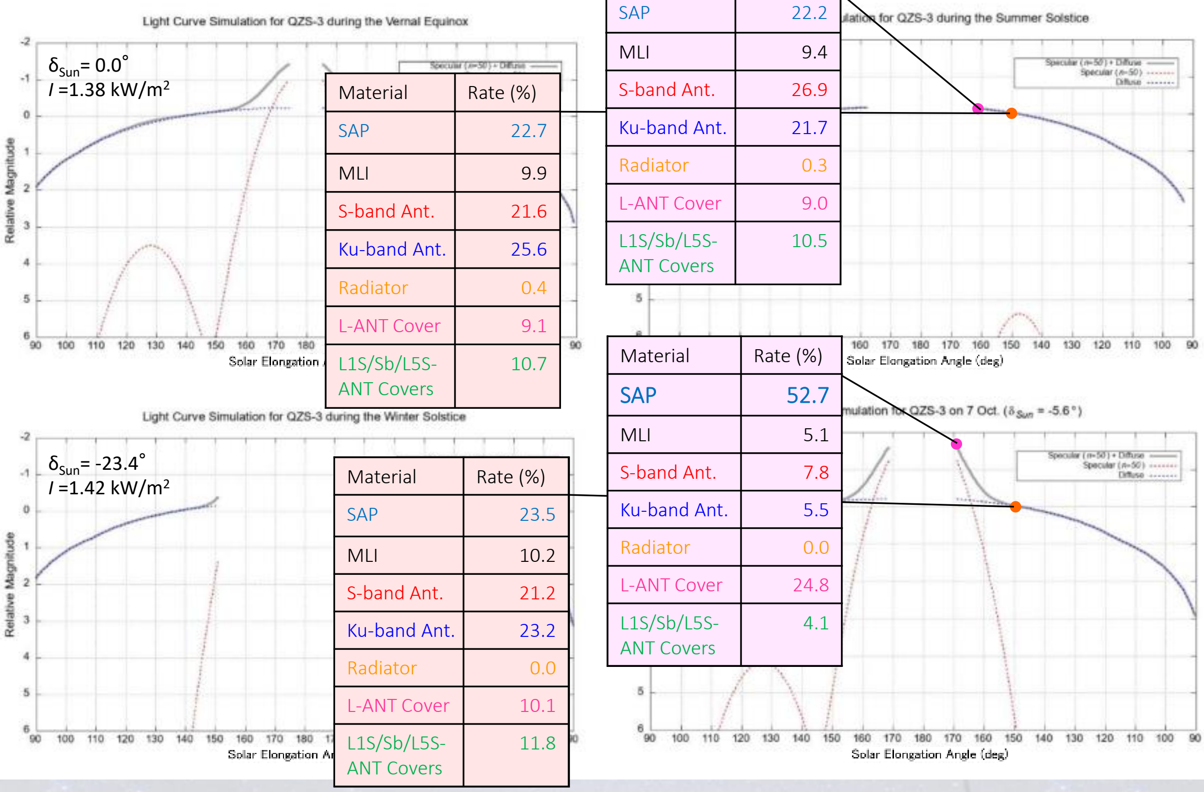
※ in case of n > 5000, the specular reflection component becomes negligibly small

Light Curve Simulations for QZS-3 (in each season)

Total Reflection
Specular Reflection (*n* =50)
Diffuse Reflection



Occupancy of Reflection Intensity



Material	Rate (%)
SAP	22.7
MLI	9.9
S-band Ant.	21.6
Ku-band Ant.	25.6
Radiator	0.4
L-ANT Cover	9.1
L1S/Sb/L5S-ANT Covers	10.7

Material	Rate (%)
SAP	22.2
MLI	9.4
S-band Ant.	26.9
Ku-band Ant.	21.7
Radiator	0.3
L-ANT Cover	9.0
L1S/Sb/L5S-ANT Covers	10.5

Material	Rate (%)
SAP	23.5
MLI	10.2
S-band Ant.	21.2
Ku-band Ant.	23.2
Radiator	0.0
L-ANT Cover	10.1
L1S/Sb/L5S-ANT Covers	11.8

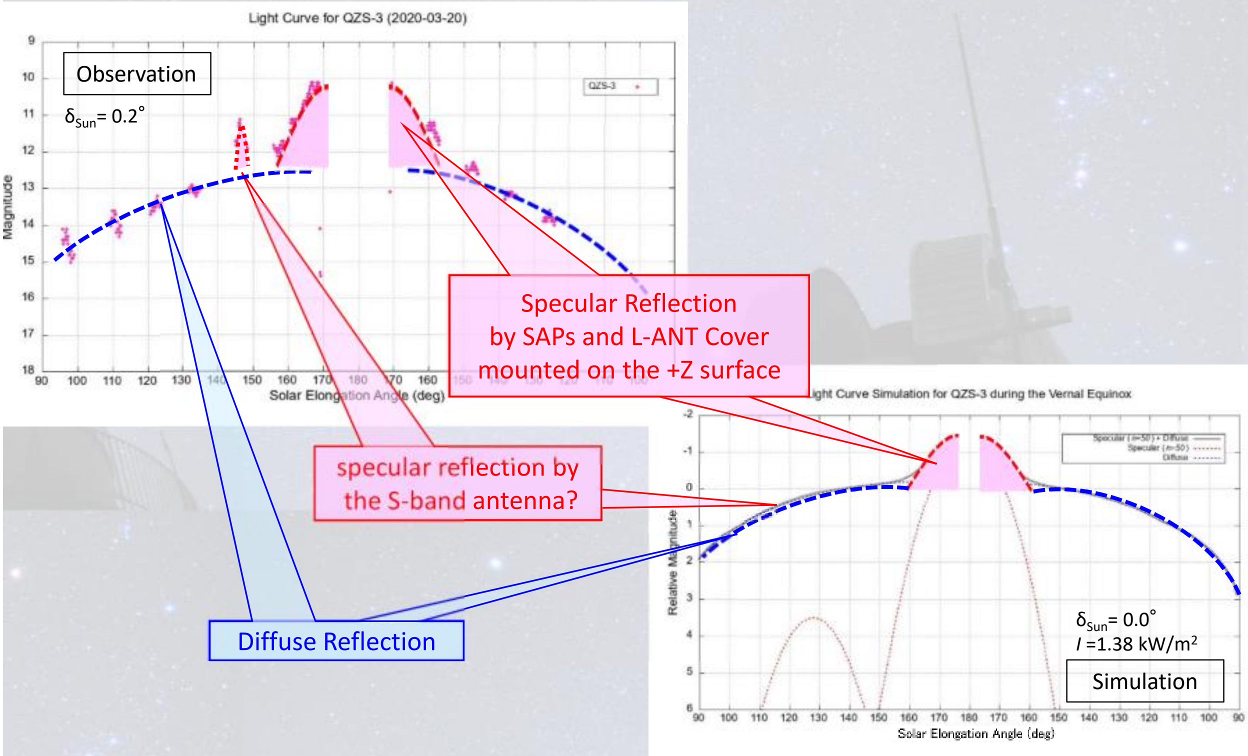
Material	Rate (%)
SAP	52.7
MLI	5.1
S-band Ant.	7.8
Ku-band Ant.	5.5
Radiator	0.0
L-ANT Cover	24.8
L1S/Sb/L5S-ANT Covers	4.1

Occupancy of Reflection Intensity by Materials (for QZS-3)

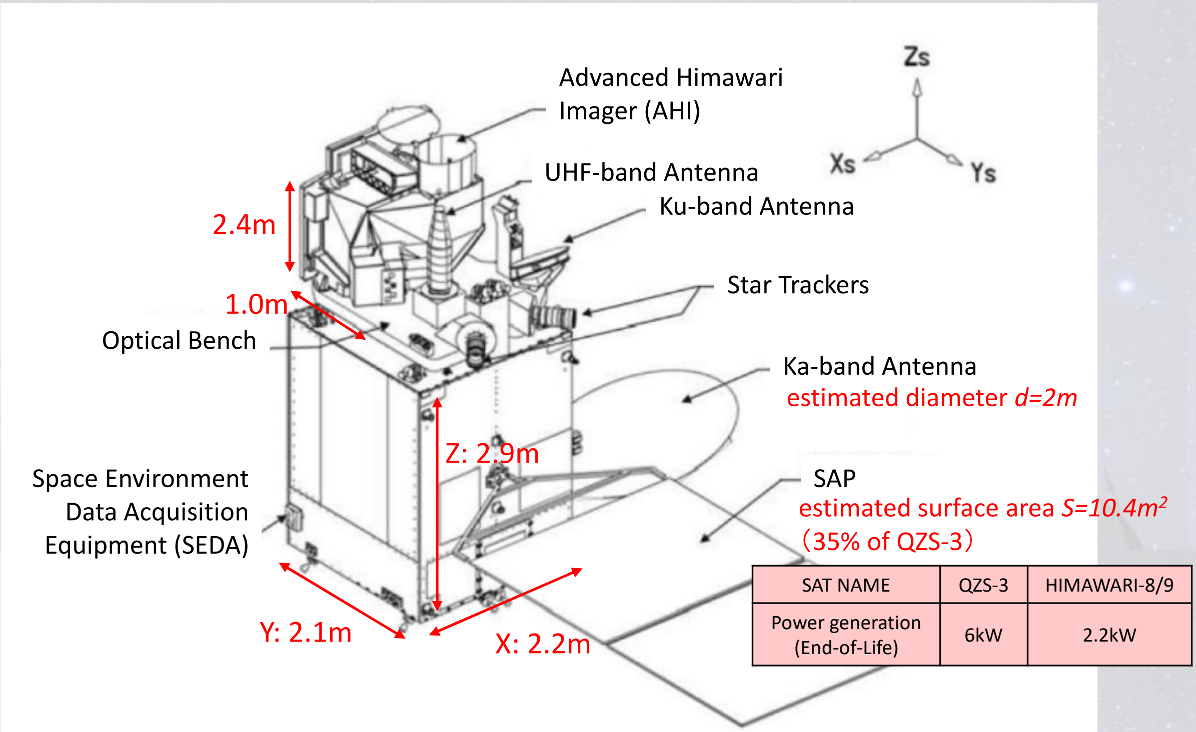
Unit: %

	Vernal Equinox (δ_{Sun}= 0.0°)							Summer Solstice (δ_{Sun}= +23.4°)						
SolarElongationAngle (deg) / Material	89	120	150	Max 174	150	120	91	91	120	150	Max 162	150	120	93
SAP	0.0	18.3	20.8	49.8	23.0	25.5	6.2	0.0	18.5	21.2	22.2	22.7	24.2	3.6
MLI	0.0	8.2	9.1	5.5	10.2	11.9	0.0	4.3	8.6	9.1	9.4	9.9	11.6	11.0
Reflector-1 (S-band)	100.0	45.9	33.6	9.4	21.1	5.0	0.0	93.3	41.6	31.3	26.9	21.6	6.7	0.0
Reflector-2 (Ku-band)	0.0	9.6	16.4	6.7	24.1	33.9	93.8	0.0	14.0	19.1	21.7	25.6	36.1	81.9
Radiator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.6	0.4	0.3	0.4	0.7	3.5
L-ANT Cover	0.0	8.3	9.3	24.0	10.0	10.9	0.0	0.0	7.7	8.6	9.0	9.1	9.4	0.0
L1S/Sb/L5S-ANT Covers	0.0	9.7	10.8	4.6	11.7	12.8	0.0	0.0	9.0	10.2	10.5	10.7	11.2	0.0
	Winter Solstice (δ_{Sun}= -23.4°)							δ_{Sun}= -5.6°						
SolarElongationAngle (deg) / Material	87	120	150	Max 151	150	120	89	89	120	150	Max 169	150	120	90
SAP	0.0	22.3	29.3	32.3	30.4	28.7	12.8	0.0	19.0	21.4	52.7	23.5	26.0	6.4
MLI	0.0	9.1	8.8	8.5	9.0	12.1	17.2	0.0	8.5	9.2	5.1	10.2	12.0	9.4
Reflector-1 (S-band)	100.0	41.3	24.6	21.9	22.3	8.6	0.0	100.0	44.9	32.9	7.8	21.2	5.6	0.0
Reflector-2 (Ku-band)	0.0	7.2	14.0	13.8	16.0	26.0	70.0	0.0	9.0	15.9	5.5	23.2	32.3	84.2
Radiator	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L-ANT Cover	0.0	9.2	13.3	13.9	12.0	11.3	0.0	0.0	8.5	9.6	24.8	10.1	11.0	0.0
L1S/Sb/L5S-ANT Covers	0.0	10.8	10.0	9.5	10.4	13.3	0.0	0.0	10.1	10.9	4.1	11.8	13.0	0.0

Observational Results vs Simulations for QZS-3



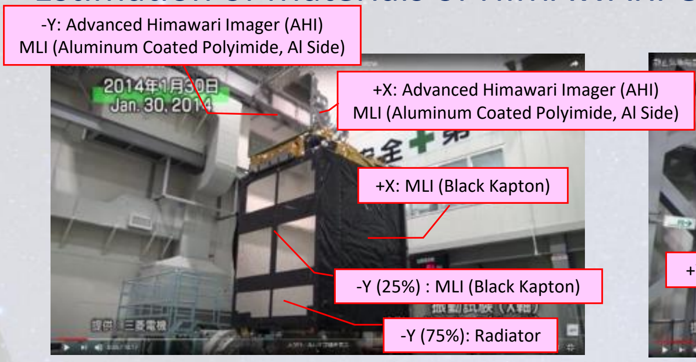
Configuration of HIMAWARI-8/9



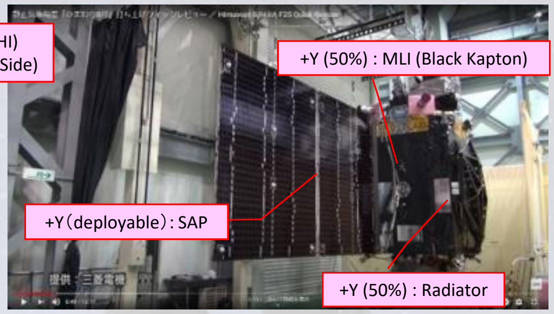
SAT NAME	QZS-3	HIMAWARI-8/9
Power generation (End-of-Life)	6kW	2.2kW

ref:
- 観測部気象衛星課,「静止気象衛星ひまわり8 号・9号の概要」, 測候時報, 第 85 巻, 2018.
- 高原修ほか,「高精度気象観測システムの実現に向けたひまわり8, 9号の衛星システム設計」, 三菱電機技報, Vol.88, No.2, pp. 21-24, 2014.
- 関根功治ほか,「静止衛星標準バス"DS2000"の開発と今後の指針」, 三菱電機技報, Vol.90, No.2, pp. 19-22, 2016.

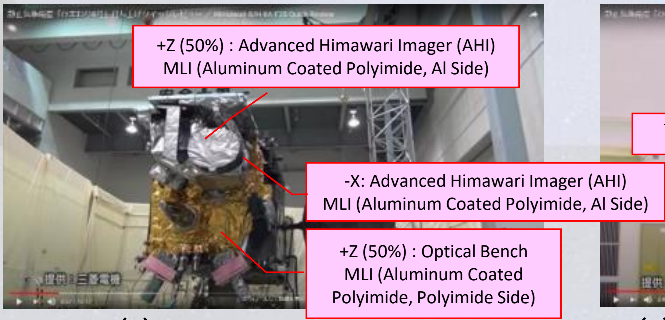
Estimation of Materials of HIMAWARI-8/9



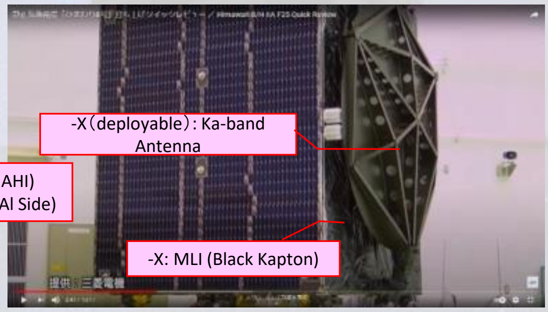
（1）-Y（left）& +X（right）



（2）+Y & SAP



（3）+Z & Ka-band Antenna



（4）-X（right）viewed from the +Y direction

ref: 静止気象衛星「ひまわり8号」打ち上げクイックレビュー (https://www.youtube.com/watch?v=PYyF7rx8bi0).

Estimation of Optical Properties of MLI

MLI (silver)
→Aluminum Coated Polyimide, Al Side

MLI (gold)
→Aluminum Coated Polyimide, Polyimide Side

Sheldahl
A Flex Company

PRODUCT BULLETIN

Aluminum
Polyimide

Aluminum Coated (One Side) Polyimide

Sheldahl® polyimide films that are aluminized on one side can be used as either first or second surface mirrors and are often used in multi-layer insulation (MLI) blankets when a wide temperature range is desired. When used as a first surface mirror these products provide low emittance and low solar absorptance. When used as a second surface mirror these products provide moderate absorptance and moderate emittance values, and the polyimide film gives them an amber or gold color.

This product may be ordered with 0.3, 0.5, 1, 2, 3, or 5 mil thick polyimide that conforms to the requirements of ASTM D-5213. The aluminum coating is nominally 1000 Å thick, and the most common width is 48 inches (1.22 m).

PRODUCT CHARACTERISTICS

assumed 90% for the specular reflection & 10% for the diffuse reflection

Parameter (independent of film thickness)	Specified Value
First surface solar absorptance (α)	≦0.14
First surface hemispherical emittance (ε_H)	≦0.035
First surface normal emittance (ε_N)	≦0.035
Typical first surface α/ε	4 - 5
Aluminum surface resistivity	≦1 Ω/square
Intermittent temperature range	-250° C to 400° C (-420° F to 750° F)
Continuous temperature range	-250° C to 290° C (-420° F to 550° F)

Reflectance = 0.86

Standard Item Number	Thickness mil (µm)	Second Surface Mirror Properties			Typical Weight (g/m²)	Perforation Item Number
		α	εN	εH		
146455	0.3 (8)	≦0.35	≧0.40	≧0.40	11	160478
146454	0.5 (12.5)	≦0.36	≧0.50	≧0.52	19	177735
146446	1.0 (25)	≦0.39	≧0.62	≧0.64	36	160013
146448	2.0 (51)	≦0.44	≧0.71	≧0.71	71	159946
146450	3.0 (76)	≦0.46	≧0.77	≧0.77	109	160824
146452	5.0 (127)	≦0.49	≧0.81	≧0.81	181	174402

～0.42　Reflectance = 0.58

assumed 50% for the specular reflectance & 50% for the diffuse reflectance

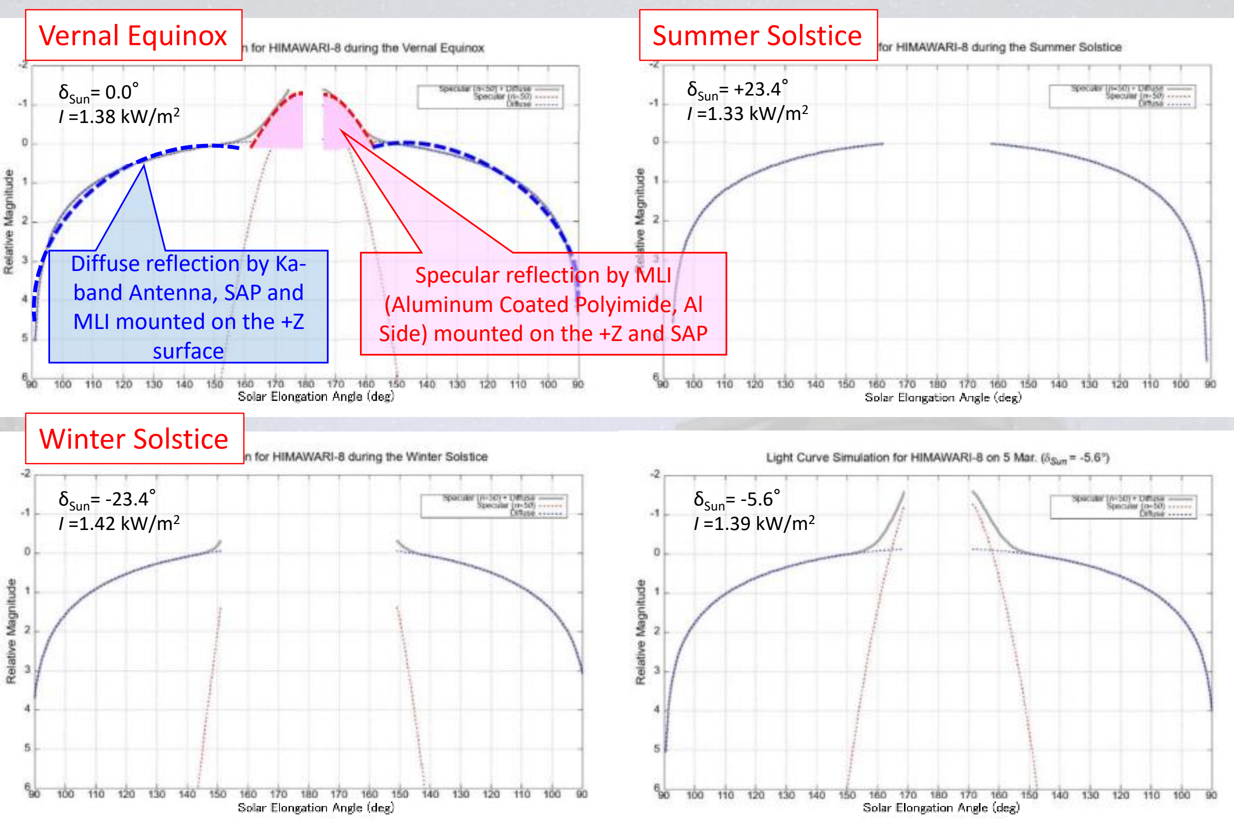
ref:
- 静止気象衛星「ひまわり8号」打ち上げクイックレビュー (https://www.youtube.com/watch?v=PYyF7rx8bi0).
- Sheldahl , *The Red Book*, Rev. E, 2020.

Estimation of Materials and Optical Properties of HIMAWARI-8/9

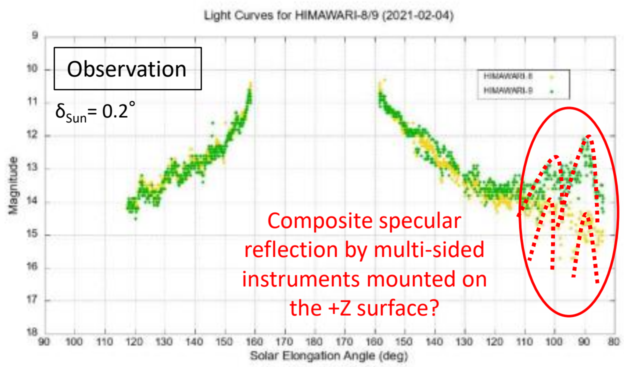
Location	Material	Area [m^2]	Absorption	Specular	Diffuse
+ X	MLI (Black Kapton)	6.1	0.926	0.035	0.039
	MLI (Aluminum Coated Polyimide, Al Side)	2.4	0.14*1	0.77*2	0.09*2
- X	MLI (Black Kapton)	6.1	0.926	0.035	0.039
	Ka-band Antenna	3.1	0.619	0.005	0.046
	MLI (Aluminum Coated Polyimide, Al Side)	2.4	0.14*1	0.77*2	0.09*2
+ Y	MLI (Black Kapton)	3.2	0.926	0.035	0.039
	Radiator	3.2	0.026	0.954	0.020
	SAP	10.4	0.923	0.068	0.009
- Y	MLI (Black Kapton)	1.6	0.926	0.035	0.039
	Radiator	4.8	0.026	0.954	0.020
	MLI (Aluminum Coated Polyimide, Al Side)	5.3	0.14*1	0.77*2	0.09*2
+ Z	MLI (Aluminum Coated Polyimide, Al Side)	2.3	0.14*1	0.77*2	0.09*2
	MLI (Aluminum Coated Polyimide, Polyimide Side)	2.3	0.42*1	0.29*2	0.29*2

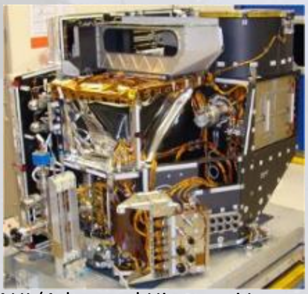
*1 mean value in a Sheldahl catalogue
*2: estimated value

Light Curve Simulations for HIMAWARI-8

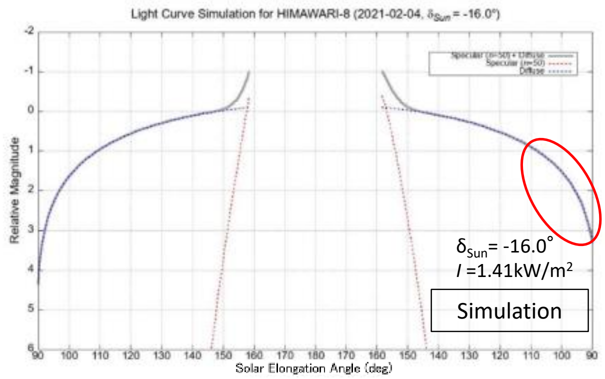


Observational Results vs Simulations for HIMAWARI-8/9





AHI (Advanced Himawari Imager)



ref: https://www.data.jma.go.jp/mscweb/en/himawari89/space_segment/spsg_ahi.html.

5. Conclusions

1. The brightness of GEO satellites varies with the solar Elongation angle and with the declination of the Sun
   - (brighter) large solar elongation angle ⇔ small solar elongation angle (dimmer)
   - (brighter) δ_{Sun}=-5.6 ⇔ summer solstice: δ_{Sun}=+23.4 (dimmer)
2. Each transient brightening event (detected as a peak on the light curve) is caused by the specular reflection from materials on the satellite.

★Acknowledgements★

We are grateful to the following people / institutions:

・Dr. Takayuki Saitoh (Kobe U.) for advices of a simulation model construction

・Flight Dynamics Team of JAXA and Japan Space Forum for providing opportunities of photometric observations

B16

ロケット上段モニタ装置と飛行中ロケットの衝突回避
Launch Vehicle Upper Stage Monitor and Collision Avoidance for Ascending Rocket

〇高木 友士、小早川 豊範、竹中 健一朗、木村 友久（三菱重工業株式会社）
〇TAKAKI Yuji, KOBAYAKAWA Toyonori, TAKENAKA Kenichiro, KIMURA Tomohisa
(Mitsubishi Heavy Industries, Ltd.)

スペースデブリの数は現在増加の一途をたどっており、将来の宇宙活動において国際的な課題となっている。スペースデブリの数はデブリ同士の衝突によってさらに増加しており、本課題が解決されない場合、飛行中のロケットがデブリに衝突する確率も増大することが懸念される。MHI は打上げ輸送サービス事業者として、スペースデブリ問題を重要な課題であると認識しており、H-IIB ロケット上段の制御再突入等、デブリ低減のための取り組みを実施してきた。本講演では、ロケット上段モニタリング装置（M-Pack）開発や、飛行中ロケットのデブリ衝突回避による打上げ輸送サービス信頼性向上等の MHI の近年の取り組みについて紹介する。

Space debris have been increasing and recognized as international issue for future space activities. Space debris also increase due to collision between different debris. If this issue is left as it is, the risk of collision between ascending rockets and space debris will increase.
MHI, as a launch service provider and as a player in space activities, recognizes the importance of space debris issue. MHI has been taking actions against space debris issue, such as the controlled reentry of upper stage of the H-IIB rocket. This paper shows MHI's recent activities such as M-Pack(Monitoring Package for launch vehicle upper stage) and collision avoidance strategies for ascending rocket to ensure reliable and frequent launch services.

B16
ロケット上段モニタ装置と飛行中ロケットの衝突回避

第10回スペースデブリワークショップ

〇高木 友士、小早川豊範、竹中 健一朗、木村 友久 (三菱重工業)
2022 11/29

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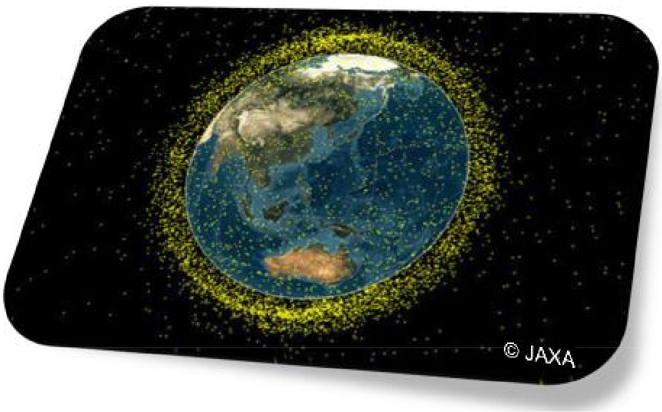
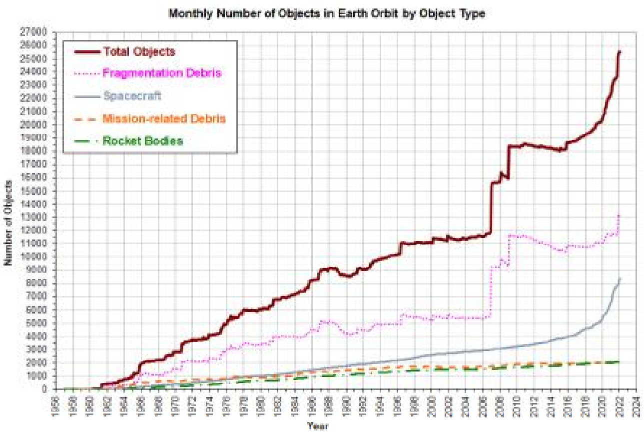
1. 打上げ輸送サービス事業者としてのスペースデブリの脅威
2. ロケットのスペースデブリ回避に関するケーススタディ※
3. ロケット上段機体モニタ装置の検討※
4. おわりに



※本報告の一部は、環境省「令和３年度GOSAT シリーズのスペースデブリ化防止対策実現可能性検討業務」における業務成果に基づくものである。

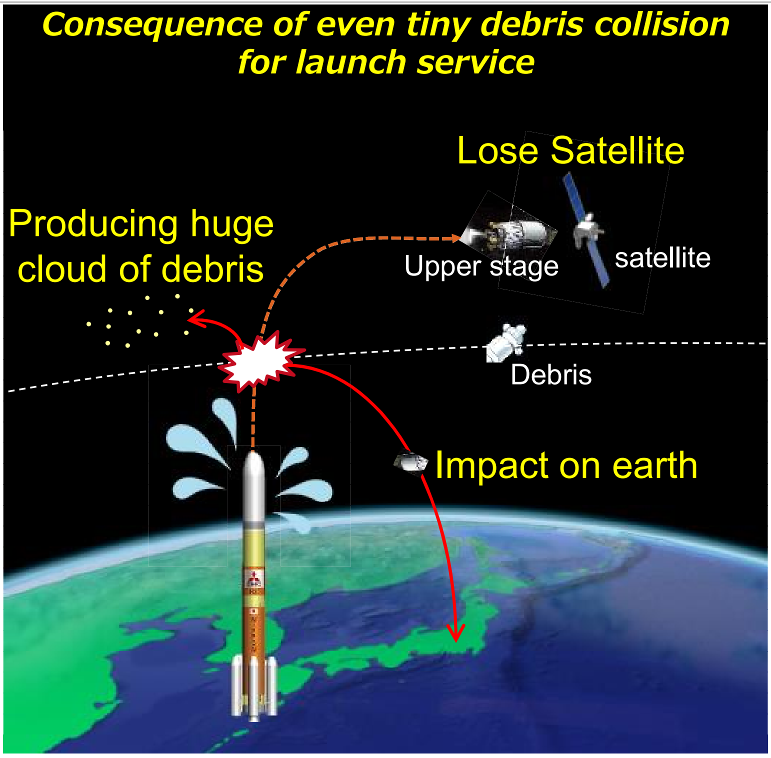
1.打上げ輸送サービス事業者としてのスペースデブリの脅威

MITSUBISHI HEAVY INDUSTRIES



(https://orbitaldebris.jsc.nasa.gov/modeling/legend.html)

- Number of debris is increasing!
- Estimated Number of non-trackable debris is said to be above 10 million!



1.打上げ輸送サービス事業者としてのスペースデブリの脅威

MITSUBISHI HEAVY INDUSTRIES

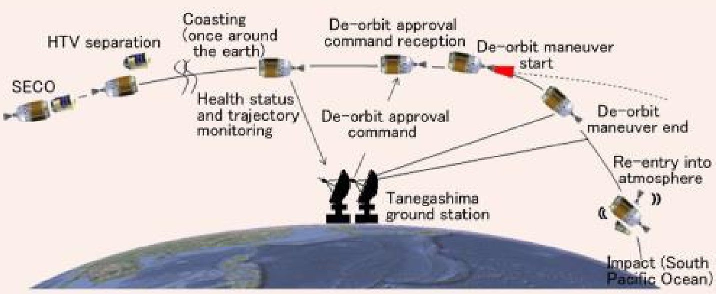
これまでのMHIの取り組み事例

無害化処置

✓ ミッション終了後の推進薬排出

制御再突入 (H-IIB)

(*全ミッション成功!!*)



今後取り組むべき方向性

デブリ低減

✓ ADR

✓ 微小デブリへの対応

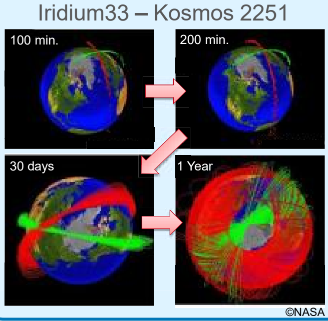
衝突防止

✓ ロケットとデブリの衝突回避

✓ デブリ同士の衝突回避

First collision accident (2009)

Iridium33 – Kosmos 2251



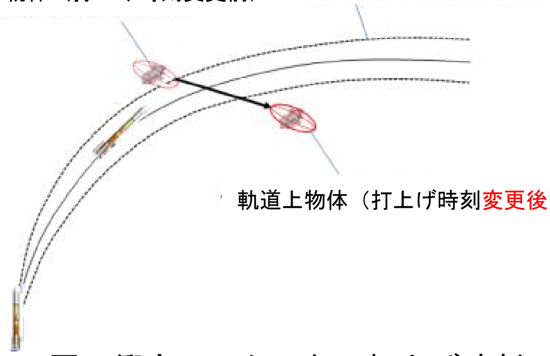
Collision produces huge cloud of non-trackable debris

2.ロケットのスペースデブリ回避に関するケーススタディ

MITSUBISHI HEAVY INDUSTRIES

ロケットと軌道上物体との衝突リスク

- 昨今の軌道上物体数の増加により打上げ時ロケットとの衝突リスクが増加する可能性がある
- 現行の打上げ運用では、ロケット飛行経路を固定して衝突リスクのない打上げ時刻を選定している



図：衝突リスクのない打上げ時刻の選定

4/

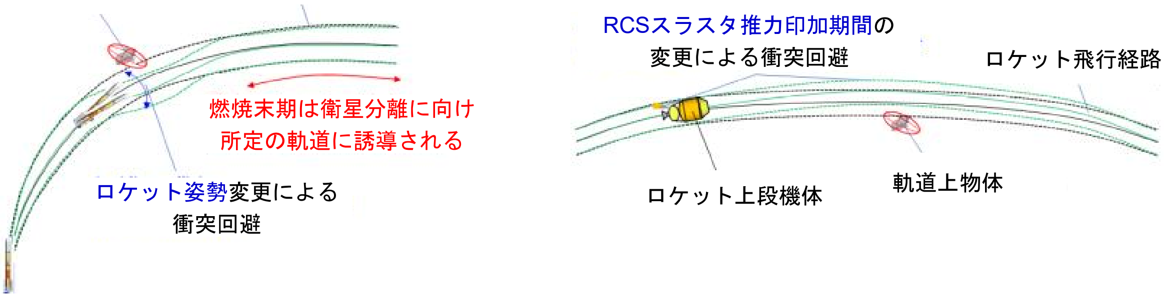
2.ロケットのスペースデブリ回避に関するケーススタディ

MITSUBISHI HEAVY INDUSTRIES

ロケット飛行経路修正による衝突回避

- ロケット側の飛行経路修正による衝突回避検討を実施
- 動力飛行中はロケット姿勢、慣性飛行中はRCSスラスタ推力印加期間を修正パラメタとする

*）RCS：Reaction Control System



図：ロケット飛行経路修正による衝突回避策
（左：動力飛行中、右：慣性飛行中）

5/

2.ロケットのスペースデブリ回避に関するケーススタディ

MITSUBISHI HEAVY INDUSTRIES

ロケット飛行経路修正による衝突回避効果

- 各打上げ日時に対して衝突リスクを評価し
  提案手法による衝突回避効果を確認
- 衝突リスクを20%程度低減可能な見通しを得た

【主要前提条件】
- 衝突確率閾値：10^{-6}
- 軌道上物体数：
  既存物体：1108個
  大型コンステ衛星：4583個(予測値)
- ロケット飛行経路：SSOミッション
- 評価期間：約7000秒(1周回)

表：衝突リスク評価（ロケット飛行経路修正なし）

Day 1		Day 2		Day 3		Day 4		Day 5	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	Go	Go	Go	NoGo	Go	Go	NoGo	Go
Day 6		Day 7		Day 8		Day 9		Day 10	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	NoGo	Go	NoGo	NoGo	Go	Go	NoGo	NoGo
Day 11		Day 12		Day 13		Day 14		Day 15	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	NoGo	NoGo	NoGo	Go	Go	Go	Go	Go	NoGo
Day 16		Day 17		Day 18		Day 19		Day 20	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	Go	NoGo	Go	Go	NoGo	NoGo	Go	Go
Day 21		Day 22		Day 23		Day 24		Day 25	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
NoGo	Go	Go	Go	Go	NoGo	NoGo	NoGo	Go	Go
Day 26		Day 27		Day 28		Day 29		Day 30	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	Go	Go	NoGo	Go	Go	Go	Go	Go

注）NoGoは衝突確率が10^{-6}以上となる打上げ日時を表す

表：衝突リスク評価（ロケット飛行経路修正あり）

Day 1		Day 2		Day 3		Day 4		Day 5	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	Go	Go	Go	NoGo	Go	Go	Go	Go
Day 6		Day 7		Day 8		Day 9		Day 10	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	NoGo	Go	NoGo	Go	Go	Go	NoGo	Go
Day 11		Day 12		Day 13		Day 14		Day 15	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	NoGo	NoGo	Go	Go	Go	Go	Go	NoGo
Day 16		Day 17		Day 18		Day 19		Day 20	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	Go	Go	Go	Go	Go	Go	Go	Go
Day 21		Day 22		Day 23		Day 24		Day 25	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	Go	Go	Go	Go	Go	Go	Go	Go
Day 26		Day 27		Day 28		Day 29		Day 30	
2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.	2 a.m.	2 p.m.
Go	Go	Go	Go	Go	Go	Go	Go	Go	Go

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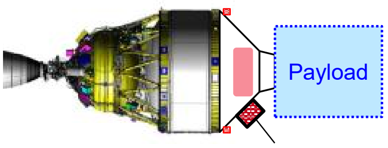
3.ロケット上段機体モニタ装置の検討

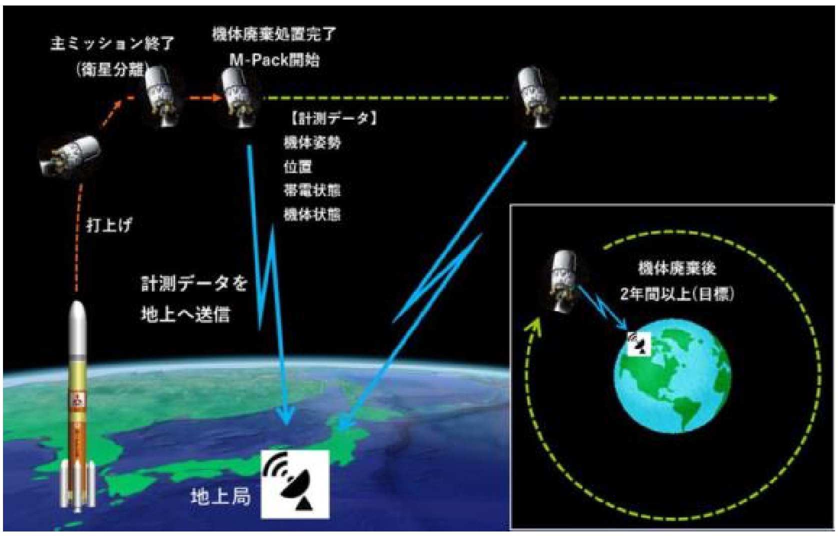
MITSUBISHI HEAVY INDUSTRIES

ロケット上段モニタ装置（M-Pack*）



M-Packとは・・・
ミッション終了後のロケット上段
（デブリ）の長期挙動を直接監視

- ✔デブリ研究へ貢献
- ✔デブリ対策技術開発へ貢献
- ✔ADR計画検討へ活用　他



【運用構想案】
計測対象：ロケット2段機体
運用期間：ロケット廃棄処置完了後
　　　　　から2年以上(目標)
計測データ：機体姿勢(回転)，位置，
　　　　　　帯電状態，機体状態　他
計測頻度：90分(地球1周回相当)
　　　　　あたり1回以上(目標)

*)Monitoring motion Package for second stage rocket

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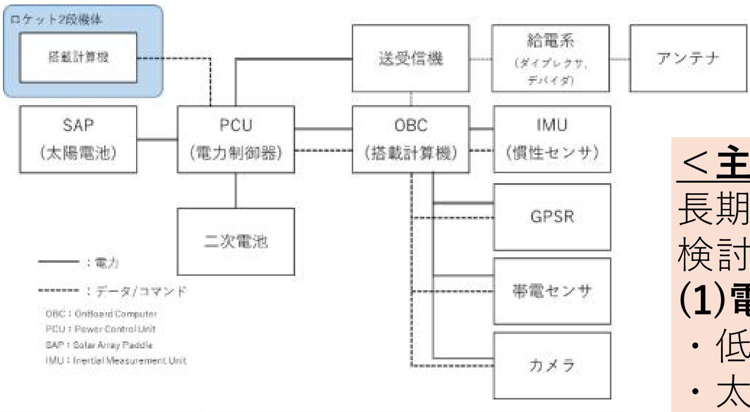
3.ロケット上段機体モニタ装置の検討

M-Packブロック図

・ロケットシステムとは分離独立したシステム
・電力供給/データ計測/制御・データ処理/通信の各機能



機能	概要
電力供給機能	電力供給制御、二次電池充電
データ計測機能	機体状態センサ計測
制御・データ処理機能	計画管理、時刻管理、機器電源ON/OFF制御
通信機能	データ送信、コマンド受信

＜主要課題＞
長期間＆機体姿勢不定のため、以下の対策検討が今後必要。
(1)電力リソース確保
・低消費モード運用
・太陽電池(SAP)面積確保と複数位相へのSAP搭載
(2)地上とのリンク確保
・複数位相へのアンテナ搭載

3.ロケット上段機体モニタ装置の検討

M-Pack発展性

搭載センサや装置を変更・追加することで発展可能性有り。

(1)ADRとの連携
ADR事前計画立案へ活用。
"準"協力物体＝接近・キャプチャ運用でのリスク低減.

(2)PMDデバイスとの連携
デバイスの確実な作動と軌道降下状況の直接モニタ可能。

(3)軌道上実証テストベッド(右図)
ロケット2段を軌道上実証テストベッドとして活用。
宇宙空間での技術実証機会の提供。

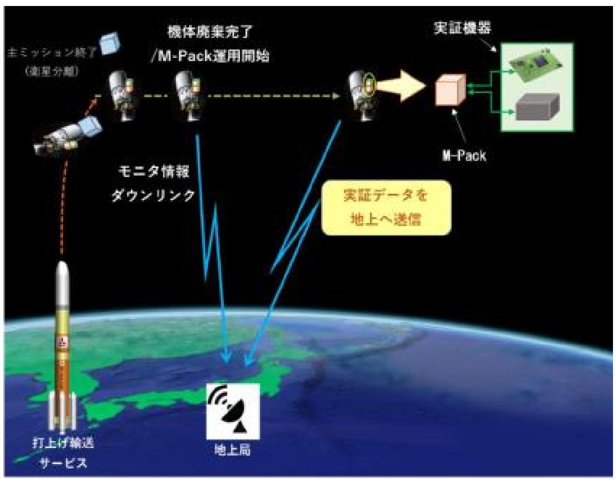
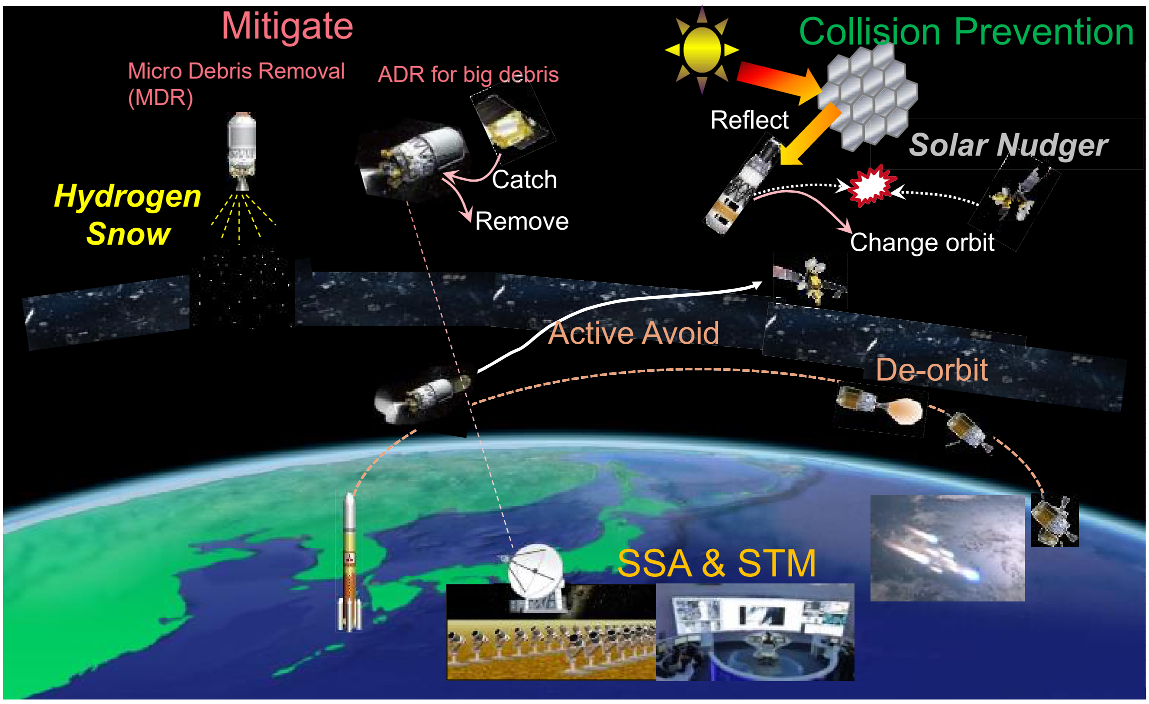


図　M-Pack発展性－軌道上実証テストベッド

4. おわりに

MITSUBISHI HEAVY INDUSTRIES

MHI will do all-out effort for sustainable space activities!



B17

ISO 国際標準化機構における大規模衛星コンステレーションに関する規格化の状況

Status of Standardization for Large Constellation of Spacecraft in ISO

○加藤 明（加藤技術士事務所）
○KATO Akira (Kato Professional Engineer’s Office)

大規模衛星コンステレーション（衛星群）は軌道環境に与える影響が非常に大きいことから、日米共同で国際標準化機構(ISO)に対し、「大規模衛星コンステレーションに関する技術仕様」を提案しており、それが近く制定される。その概要を紹介する。大規模コンステレーションは既に 1,000 機程度の衛星が運用されている軌道域に更に数万の衛星を配置するものである。コンステレーション内部の衝突及び他の衛星との衝突を防ぐためには、確実な衝突回避、不具合の発生防止、運用終了後の処分などの点で従来以上の厳しい管理を要求せざるを得ない。例えば運用寿命 5 年の衛星を廃棄する場合、軌道寿命 25 年の軌道に廃棄すると運用機数の 5 倍近くの廃棄衛星が軌道に残存してしまう。廃棄後の軌道寿命は更に厳しく制限すべきである。今回作成する「技術仕様」は早急に「規格」に昇格させて今後のコンステレーションプログラムに反映されることを願うものである。

Since large-scale spacecraft constellations have great impacts on the orbital environment, Japan and the United States jointly proposed "Technical Specifications for Large-scale Spacecraft Constellations" to the International Organization for Standardization (ISO), and it will be published soon. An overview is presented here. Large-scale constellations place tens of thousands of spacecrafts in congested orbital regions where about 1,000 spacecrafts are already in operation. In order to prevent collisions within the constellation and with other spacecrafts, stricter control than before is required in terms of avoiding collisions during operation, preventing malfunctions, and disposing of spacecrafts after operation. For example, if constellation spacecrafts with design life of 5 years would be disposed to the orbit where the orbital life is 25 years, it would be result in that nearly five times of the number of constellation spacecrafts would remain in orbit. The requirement of the orbital life after disposal should be more stringent. We hope that this "technical specifications" will be developed to "standards" as soon as possible and reflected in future constellation programs.

B17
“Status of standardization for large constellation of spacecraft in ISO”
ISO国際標準化機構における大規模衛星コンステレーションに関する規格化の状況

The 10th Space Debris Workshop
Administration Bldg. No.1
Chofu Aerospace Center
Research and Development Directorate
Japan Aerospace Exploration Agency
Nov. 29, 2022

Akira Kato （Kato Professional Engineer’s Office）

第10回スペースデブリワークショップ
宇宙航空研究開発機構
研究開発部門
調布航空宇宙センター 事務棟1号館講堂
2022年11月29日

加藤 明（加藤技術士事務所）

1

Outline

- Since the “large constellations of spacecraft (S/C)”(defined tentatively that consists of a hundred or more S/C) would pose great impacts on the orbital environment, Japan and the United States jointly proposed "Technical Specifications (TS) for Large constellations of S/C" to the International Organization for Standardization (ISO), and it will be published within several month. The outline of the TS will be presented here.
- Several large constellation programs are being planned and have been already deployed nearly 5,000 S/C in orbit. Traditionally, about 1,000 S/C have been operated in the useful orbital regions. Now, additional tens of thousand of S/C is about to be deployed into the region.
- In order to minimize the impact on the orbital environment posed by the constellations, dues to the collisions within the constellation, collision with other constellations or other S/C, and other fragmentation events caused by those S/C, stricter control than before is required in terms of avoiding collisions during operation, preventing malfunctions, and proper disposing of S/C after decommission. For example, if constellation S/C with design life of 5 years would be disposed to the orbit where the orbital life is defined as 25 years, it would be result in that nearly five times of the number of constellation S/C would remain in orbit. Stricter rule shall be applied.
- The ISO document developed here is "Technical Specification" not "Standard" in the ISO document system. We will continue to make efforts to promote it to a “Standard" as far as possible so that it can be reflected in the newly planed and designed constellation programs.

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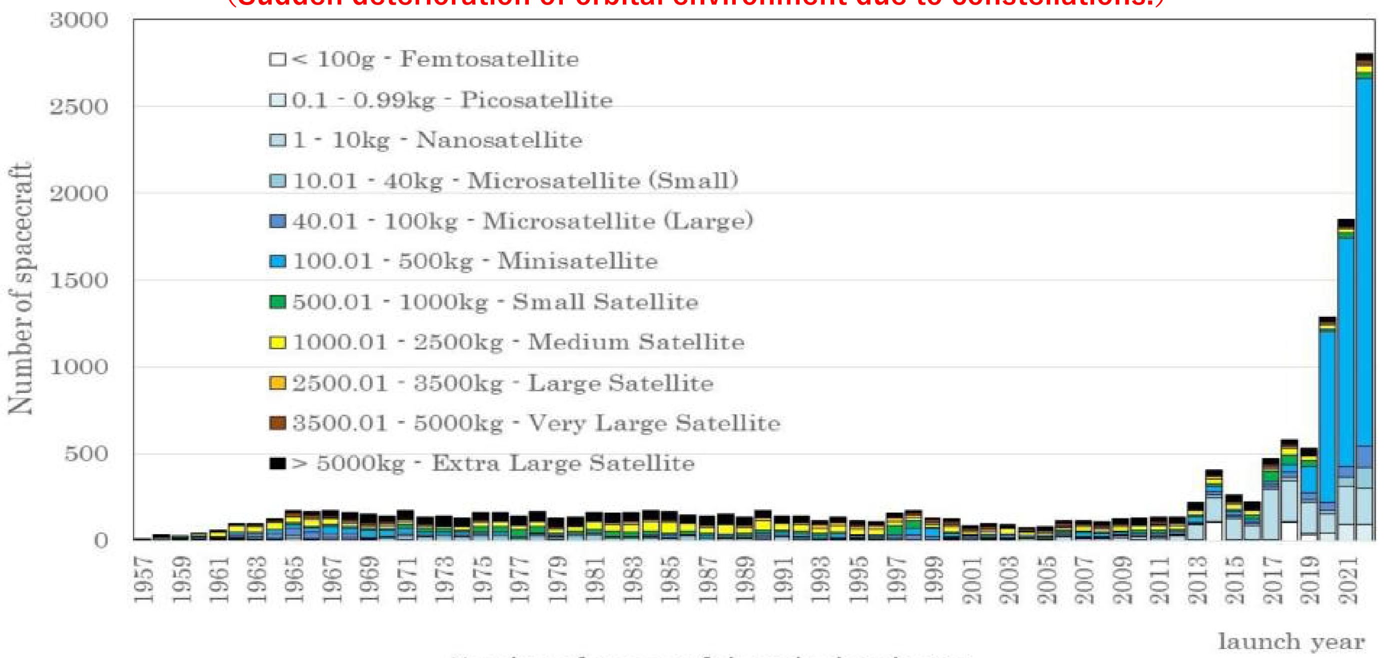
Contents

1. Identification of the status of the large constellation programs

1.1 Numbers of S/C that have launched or planned in history

(Sudden deterioration of orbital environment due to constellations.)



Number of spacecraft launched each year
(launched by the end of August 2022 and planned after Setember 2022, excluding sub-orbital S/C)

1.2 Attention to the numbers of S/C of large constellations [from 2011 to 2025]

（Deterioration has just initiated, will continue further.）

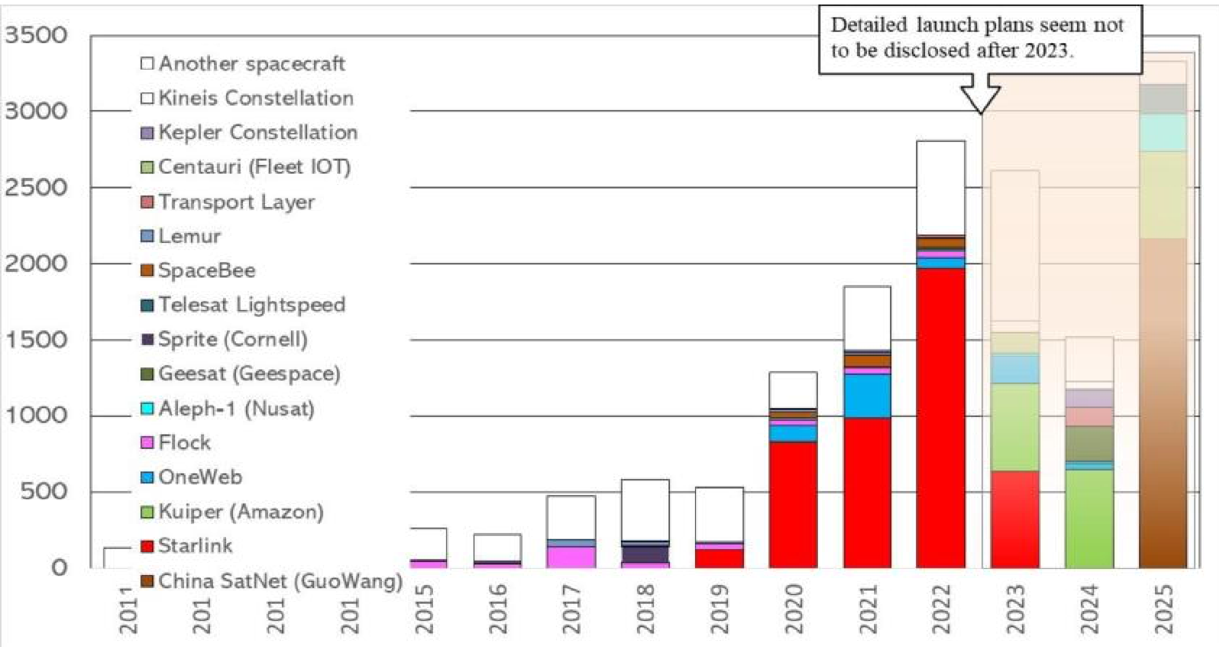


Fig.- Launch history and future launch of LEO Large constellations and other stand-alone spacecraft @ 2022/10/31

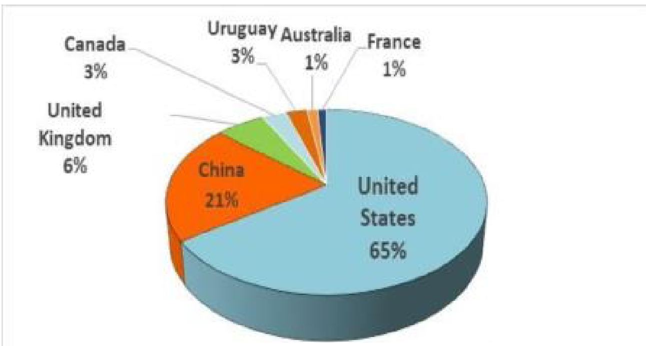
[Future spacecraft are limited to that are endorsed by Order of spacecraft, Letter of Intent(LOI), Memorandum of Understanding(MOU) or Announcement,]

1.3 List of large constellation programs (consisting of more than 100 S/C)

Several constellation programs are being under deployment or planned. Table-1 shows constellation programs constituted of more than 100 S/C (deployed in orbit from 2011 to 2025) *[Future S/C are limited to that are endorsed by Order of S/C, Letter of Intent(LOI), Memorandum of Understanding(MOU) or Announcement,]*

Table-1 Number of LEO S/C of large constellations (Data source: *Seradata Space Trak 3)* @2022.10.31)

Name of constellation	Number of S/C	Mass (kg)	Nationality
Starlink	4547	290	United States
China SatNet (GuoWang)	2165	500	China
Aleph-1 (Nusat)	300	37.5, 41	Uruguay
Centauri (Fleet IOT)	141	10	Australia
Flock	519	5	United States
Geesat (Geespace)	242	120	China
Kepler Constellation	138	12	Canada
Kineis Constellation	125	25	France
Kuiper (Amazon)	1804	100.01 - 500kg	United States
Lemur	157	4.6	United States
OneWeb	684	147.4	United Kingdom
SpaceBee	172	0.45, 0.6	United States
Sprite (Cornell)	209	0.01	United States
Telesat Lightspeed	198	700	Canada
Transport Layer	146	200	United States



Ownership percentage by country

1.2 Attention to the numbers of S/C of large constellations [from 2011 to 2030]
(Deterioration has just initiated, will continue further.)

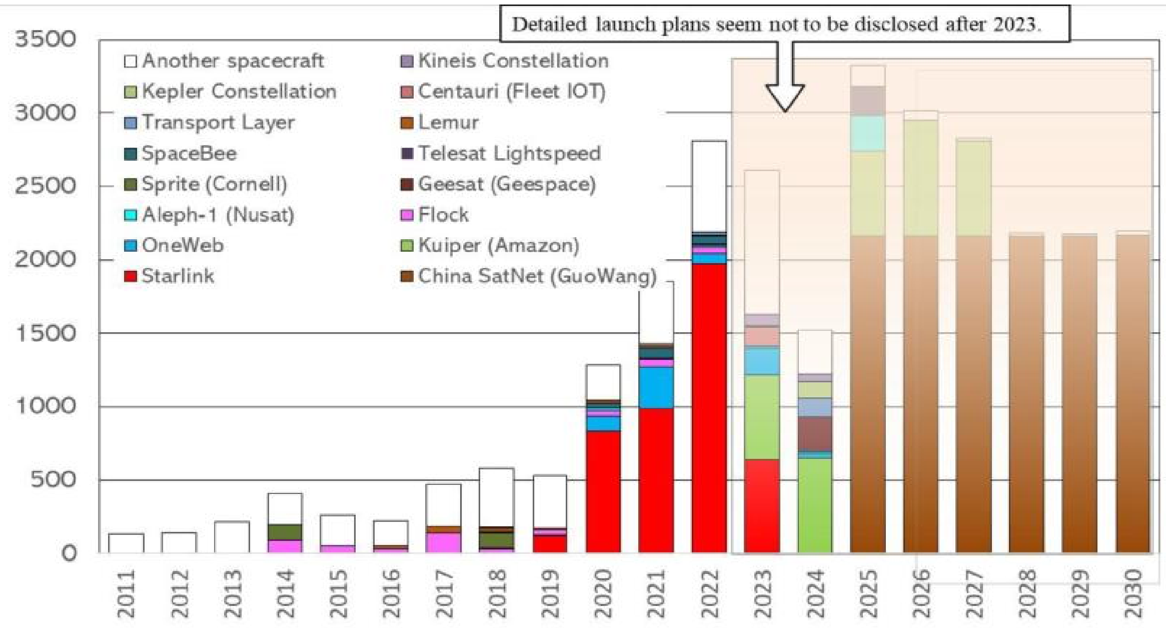


Fig.- Launch history and future launch of LEO Large constellations and other stand-alone spacecraft @ 2022/10/31

[Future spacecraft are limited to that are endorsed by Order of spacecraft, Letter of Intent(LOI), Memorandum of Understanding(MOU) or Announcement,]

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Several constellation programs are being under deployment or planned. Table-1 shows constellation programs constituted of more than 100 S/C (deployed in orbit from 2011 to 2030) *[Future S/C are limited to that are endorsed by Order of S/C, Letter of Intent(LOI), Memorandum of Understanding(MOU) or Announcement,]*

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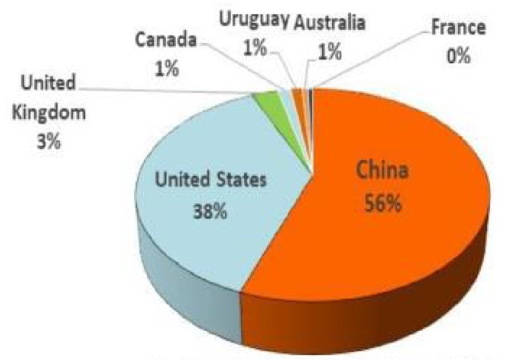
China SatNet (GuoWang)	12992	500	China
Starlink	4547	290	United States
Kuiper (Amazon)	3236	100 - 500kg	United States
OneWeb	684	147.4	United Kingdom
Flock	519	5	United States
Aleph-1 (Nusat)	300	37.5, 41	Uruguay
Geesat (Geespace)	242	120	China
Sprite (Cornell)	209	0.01	United States
Telesat Lightspeed	198	700	Canada
SpaceBee	172	0.45, 0.6	United States
Lemur	157	4.6	United States
Transport Layer	146	200	United States
Centauri (Fleet IOT)	141	10	Australia
Kepler Constellation	138	12	Canada
Kineis Constellation	125	25	France

Probably, too low estimation



Ownership percentage by country

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2. Concept of this "Technical Specifications for the Large Constellations

1. Risk identification

- Sudden increase of number of spacecraft is far beyond the condition that current guidelines and stabdard are based on.
- The suspected number of the rate of explosions, or the rate of successful disposal is unknown in the large constellations.
- The chain reaction of fragmentation among the elements of constellations of same altitude is worried.
- Once the fragmentation would occur, the effect would not be limited to the operation radial band but expand to a few thousands' kilometers in altitude.
- The total Ec per a constellation may surpass the threshold (< 0.0001) based on the traditional space activities.

2. Basic concept

Feasible, practical and effective measures (**actually taken by some owners of constellation programs**) should be recommended to the future constellation owners. This TS should be published as soon as possible. Further improvements are possible in the next version. Major aims are;

- Select the operating orbital region to be less risky for collision.
- Avoid the collision within the constellations.
- Avoid the collision with the other constellations
- Conduct the proper V&V procedure to assure the best quality. And avoid that the failed spacecraft would be staying in the operating region of its constellation.
- Controlling the total Ec, and asses the total Ec of all the member spacecraft of a constellation

Respect several studies in UN, IADC, ISO, FCC, etc. And learn from the study compiled by SSC that was endorsed by major world space players.

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3. Learn from the measures already adapted or planned by constellation owners

Actions for;	Oneweb	Starlink (SpaceX)	Kuiper (Amazon)
Contingency for the serious failure	Launched into a 475 km orbit, test & checkout, and raise to 1200 km.		Conduct system checks below the ISS then raising to their target orbit.
Collision avoidance with operating S/C, or other constellations	① Operating in the low-density region, 1200 m. ② 125-kilometer separation zone between constellations	① Probability of collision < 0.001 ② Take separate altitude >125 km from other constellations	40 kilometers above a SpaceX's Starlink constellation
①Assurance of fine disposal measures. ②Contingency for the malfunction of disposal function ③Avoiding electromagnetic interference	① Lifetime < 5 years in disposal orbit ② Deorbit reliability > 0.9 ③ Designed for removal enable uncooperative capture.	① Lifetime < 5 years ② Various measures to avoid RF interference	① In case the loss of contact beyond a "pre-determined wait period," automatically decommission, **deorbit in 5 - 7 years** ② The decommissioning process involves orbit lowering, depleting batteries, emptying fuel lines and tanks, and ensuring charging circuits are "permanently switched off or fused" ③ Disposed within a year by propulsion, ④ use an "unpressurized non-explosive propellant storage" for a chemically inert fuel.
Controlling the total Ec of the elements of a constellation	Design for demise (materials)		

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4. Learn from : Space Safety Coalition's Best Practices for the Sustainability of Space Operations

Endorsed by major space industry stakeholders in 2019

The Space Safety Coalition (SSC, SpaceSafety.org) is an *ad hoc* coalition of companies and other space relate organizations , that actively promotes responsible space safety through the adoption of relevant international standards and practices, and the development of more effective space safety guidelines, etc.

The SSC publishes a "Best Practices for the Sustainability of Space Operations" document to address gaps in current space governance and promote better spacecraft design, operations and disposal practices aligned with long term space operations sustainability. This document is a living set of best practices assembled and "owned" by the coalition of like-minded space organizations which have endorsed it.

In the section 3 of above document, focusing on **constellation designers and operators, and putting priority on space safety, it provide best practices for designing architectures and operations concepts for individual spacecraft, constellations and/or fleets of spacecraft. (As shown in the next page.)**

Space Safety Coalition's **Best Practices for the Sustainability of Space Operations**

Date: 16 September 2019

3. Mission and constellation designers and spacecraft operators should make space safety a priority when designing architectures and operations concepts for individual spacecraft, constellations and/or fleets of spacecraft.

a. Constellation architectures should include a safety-by-design approach:

- **i. Adequate radial separation between large constellations** should be maintained to assure a margin of safety under both nominal and anomalous operational conditions.
- ii. Constellation designers should limit the need for **active control to mitigate collision risk between their own spacecraft.**
- iii. Constellation designers should favor constellation designs which increase the time available to detect a failed spacecraft within their constellation and avoid colliding with it.

b. Precautions should be taken to safeguard the environment from dead-on-arrival (DOA) deployments, particularly when launching spacecraft based on a new design*. Such precautions should include one or more of the following:

- i. Rigorous **ground-based environmental acceptance testing based upon established acceptance test standards and procedures** to include [24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41].
- **ii. Qualification-level testing of all proto-flight spacecraft**, until all critical systems (including those required for maintain spacecraft control and perform active collision avoidance) have been demonstrated on-orbit.
- iii. Launch into and **initial operation in orbits that comply with a natural orbit lifetime of less than 25 years**;
- iv. Launch into and initial operation in orbits at seldom-used altitude (see definition of "seldom-used altitude").

Space Safety Coalition's **Best Practices for the Sustainability of Space Operations**
Date: 16 September 2019

4. Spacecraft designers and operators should design spacecraft that meet the following best practices:

a. Spacecraft should strive for a disposal process providing a **probability of successful disposal of 95%.**
b. Specific criteria for initiating the disposal of a spacecraft should be developed, included in a disposal plan, evaluated during the mission and, if met, consequent actions should be executed.
c. Spacecraft with apogee altitude above 400 km should be **capable of performing timely and effective collision avoidance maneuvers** to reduce the probability of collision per conjunction to less than 0.0001.
d. Spacecraft disposed of through atmospheric re-entry should reduce the casualty risk to less than 1:10,000 per spacecraft and additionally should evaluate casualty risk on a system-wide, annual basis.
e. Spacecraft should have means to improve the reliability of **passivation functions, even after loss of command or loss of contact.** Enabling this capability should be at the discretion of the spacecraft operator, i.e., later in mission life, or once the deorbit phase has been initiated.
f. Spacecraft should be considered to include **technologies and features that facilitate capture and deorbit in the event that the spacecraft becomes derelict.**
g. In order to facilitate for future servicing and/or removal by an in-orbit service provider, the information on their spacecraft's inertia tensors, array positioning and other associated spacecraft characteristics should be maintained..
h. Spacecraft should be designed to be reliably trackable from the ground using passive tracking means (e.g., radar, optical and passive RF). Spacecraft with limited observability should include features that enhance visibility (e.g., laser retro-reflectors and/or radar-cross-section enhancements).
i. Spacecraft should be considered using methods (e.g., encryption) in spacecraft command and control to maintain positive control of, and **avoid unauthorized access** to, space asset flight command functions.

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Space Safety Coalition's **Best Practices for the Sustainability of Space Operations**
Date: 16 September 2019

5. Space operations concepts that enhance sustainability of the space environment should be adopted.

a. Spacecraft in orbits with apogee altitude above 400 km **should conduct active collision avoidance** to reduce the probability of collision per conjunction to less than 0.0001, until the spacecraft fails or has been passivated.
b. **Collision avoidance maneuvers should be coordinated** with the other spacecraft operator(s).
c. The condition of a spacecraft should be **monitored periodically during its operation** to detect and mitigate any anomalies that could either lead to an accidental break-up or prevent successful disposal.
d. In case of mission extension, the capability of a spacecraft to perform successful disposal should be reassessed considering the status of the spacecraft at the beginning of the mission extension.
e. A spacecraft operating in the GEO protected region with a periodic presence should be disposed of in such a way that long-term perturbation forces do not cause it to enter the GEO protected region within 100 years.
f. The timing of post mission spacecraft passivation should be based on a tradeoff between the risk of debris generation due to self-break-up versus that due to collision with orbital debris over the passive deorbit period:
   i. GEO spacecraft should be moved into a GEO disposal orbit and should be passivated as soon as practical.
   ii. LEO spacecraft with long passive deorbit durations (greater than 5 years) should be passivated after its active deorbit maneuvers. LEO spacecraft should be placed so as maximizes average cross-sectional area.
   iii. Spacecraft with **short passive deorbit durations** (i.e., less than 5 years) should be passivated as late as practical so they may **continue to perform collision avoidance maneuvers**. It will reduce the risk of collision.
   iv. Hazardous fluids that are expected to survive reentry should be vented prior to reentry.
g. LEO spacecraft should be disposed of by means of atmospheric re-entry.
h. Spacecraft that use chemical or electric propulsion should strive **to complete the deorbit phase within 5 years.**
i. Passively deorbited spacecraft should strive to deorbit as soon as possible after the end of the life.
j. Spacecraft should strive to maintain current and 48h-predicted positional knowledge of their assets to within 500 m (two-sigma). This accuracy pertains to predicted ephemerides provided under Best Practice 1.(a) above.

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[Reference] Statement of IADC @2017

Selected measures specific to large constellation programs

Actions for;	IADC Statement
Contingency for the serious failure	① *spacecraft should be considered* ***for injection into a low altitude region****, such that in case of failures or explosion, the environmental impact on other space objects (including human spaceflight) is minimised. Spacecraft should* ***then move to their operational altitude*** *only after a complete and successful functional check-out.* ② ***Test functionality*** *of individual spacecraft at low altitude orbital regimes with low space debris density and short orbital lifetimes* ***before raising it to its intended operational orbit***
Collision avoidance - TCBM - visibility	① ***Radial separations at intersections between orbital planes*** *of a constellation have shown to provide positive environmental effects if significant enough to avoid* ***inter-plane conjunctions*** ② *It is recommended* ***to provide information on planned trajectories prior to performing orbit transfer manoeuvres*** *(e.g. during deployment to the operational orbit and disposal)* ③ ***Manoeuvre plans should be communicated*** *to the relevant actors in a timely manner* ④ *It is recommended to* ***enhance trackability by adding onboard active and/or passive components***
Avoiding interference among other constellations	*It is recommended to consider* ***sufficient radial separation between all parts of the constellation and with respect to other large constellations*** *and crowded orbits in order to minimise the potential collision risk.*
Contingency for the malfunction of disposal function	① *It is recommended to consider* ***higher probability of success of the Post*** *Mission Disposal for large constellations.* ② ***Monitor*** *on a regular basis the availability of the* ***post mission disposal function*** *and initiate disposal actions as soon as post mission disposal reliability drops to a critical level, even if design lifetime is not reached*

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5. Contents of this TS

General
(1. Scope, 2. Normative reference, 3. Terms and definitions, 4. abbreviated terms)

5.1 Mission design
- 5.1.1 Orbit selection to minimize collision risk *(Radial separation)*
- 5.1.2 Intra-constellation collision avoidance
- 5.1.3 Space debris mitigation
- 5.1.4 Selection of launch service providers
- 5.1.5 Assessment on the long-term evolution of environment

5.2 Spacecraft design
- 5.2.1 Reliability design
- 5.2.2 Design to support collision avoidance
- 5.2.3 Space debris mitigation design
- 5.2.4 Design to support successful disposal *($P_{disposal}$ > 0.95)*
- 5.2.5 Safe re-entry
- 5.2.6 Radio frequency interference mitigation
- 5.2.7 Minimization of disruptive visual brightness *(Naked eye observation)*

5.3 Qualification and testing
- 5.3.1 V&V based upon established standards and procedures *(Full test)*
- 5.3.2 Check-out before to injecting into the planned orbit *(C/O in low orbit)*

5.4 Operations and collision avoidance
- 5.4.1 Quality and Reliability control during operation *(Check $P_{disp.\ /\ statisticaly}$)*
- 5.4.2 Conjunction assessment and collision avoidance
- 5.4.3 Radio frequency interference mitigating operation
- 5.4.4 Minimization of disruptive visual brightness

5.5 Disposal of spacecraft
- 5.5.1 Post-mission disposal *(Orbital lifetime < 5 years)*
- 5.5.2 Criteria for initiating disposal
- 5.5.3 Determination of Mission Extension or Termination
- 5.5.4 Disposal upon decommissioning *(Continue CAM)*
- 5.5.5 Spacecraft passivation *(Passivation as late as possible)*
- 5.5.6 Active debris removal in operations

6. Intention of major requirements

6.1 Requirement of radial separation from other large constellations

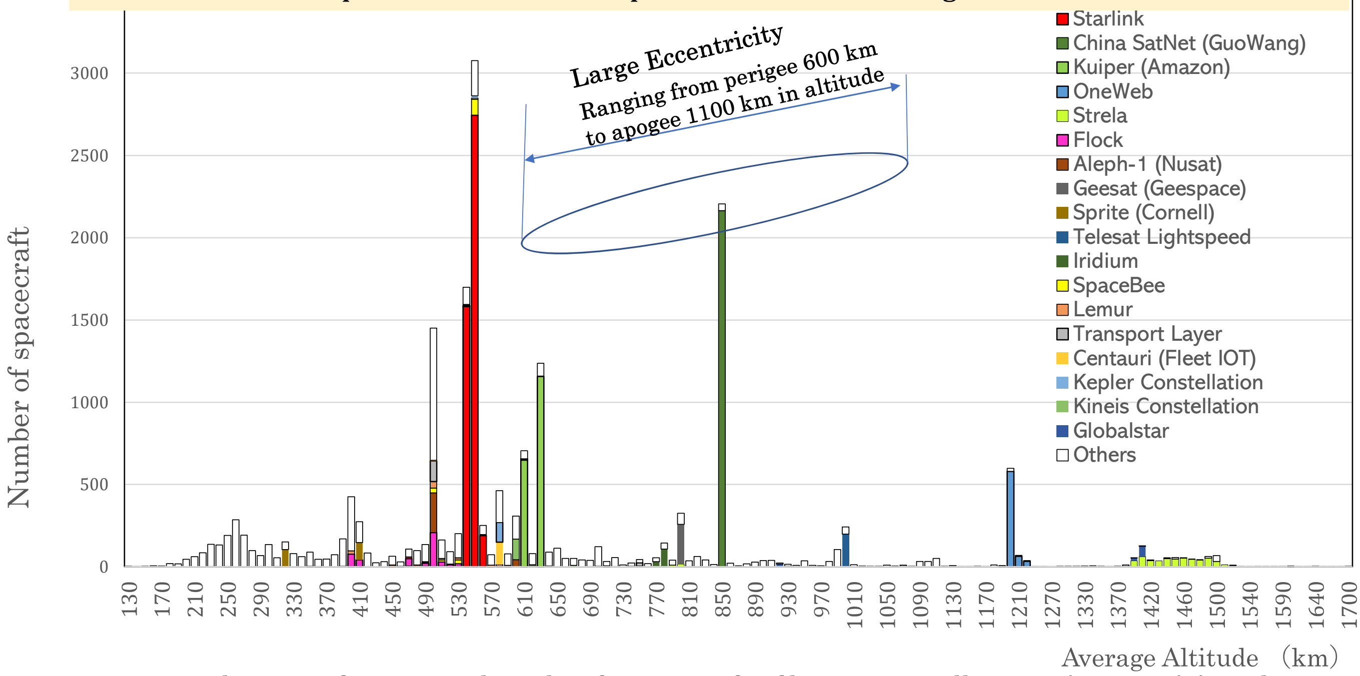

Fig. Distribution of average altitude of spacecraft of large constellations (>100 S/C) and other spacecraft (Launched from 1997 to 2025 as planned)

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6. Intention of major requirements

6.2 Requirement of orbital lifetime after disposal to be 5 years

Orbital lifetime is required to be shorter than 5 years (or shorter than design life).
When the design life of spacecraft of a large constellation is 5 years, and the allowable orbital lifetime is same to the design life, maximum number of spacecraft in orbit would be limited to the two times of planned number of operational spacecraft. While if current 25-year-rule would be applied, the number of S/C accumulated in orbit would be 6 times of planned number of operational spacecraft.

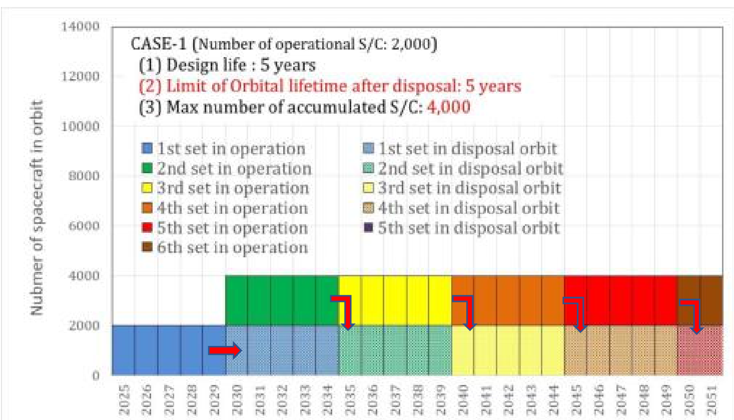

Fig.- Max number of S/C when orbital lifetime after disposal is limited to the design life

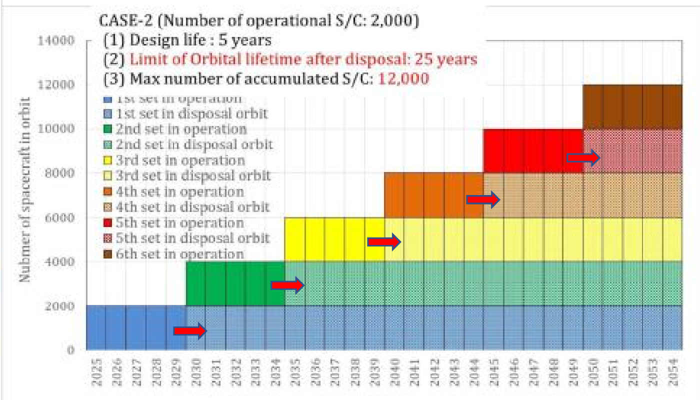

Fig.- Max number of S/C when orbital lifetime after disposal is longer than the design life

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6. Intention of major requirements

6.3 Full V&V test shall be done.

We may tend to think that the failure rate of spacecraft in constellations would be smaller than that of ordinal spacecraft because of mass production of same systems. However as shown in the chart below. Rate of retirement due to failure is not necessarily low. Full specifications for V&V shall be applied. Workmanship errors, defects of parts and materials, etc. must be rejected in validation test.

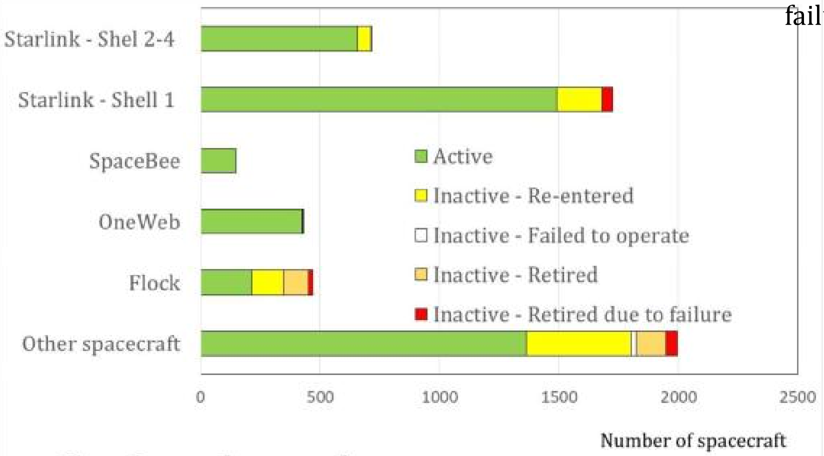


Fig. - Status of spacecraft launched from January 2011 to April 2022
(data from Seradatabase Space trak 3 @ 2022/5/1)

Table Percentage of "retired spacecraft due to failure" to "number of spacecraft launched after 2011"

	Percentage of "retired spacecraft due to failure"
Starlink - Shell 1	2.6%
Starlink - Shell 2-4	0.1%
SpaceBee	0.0%
OneWeb	0.2%
Flock	4.2%
Another spacecraft	2.4%

@2022/05/01

19

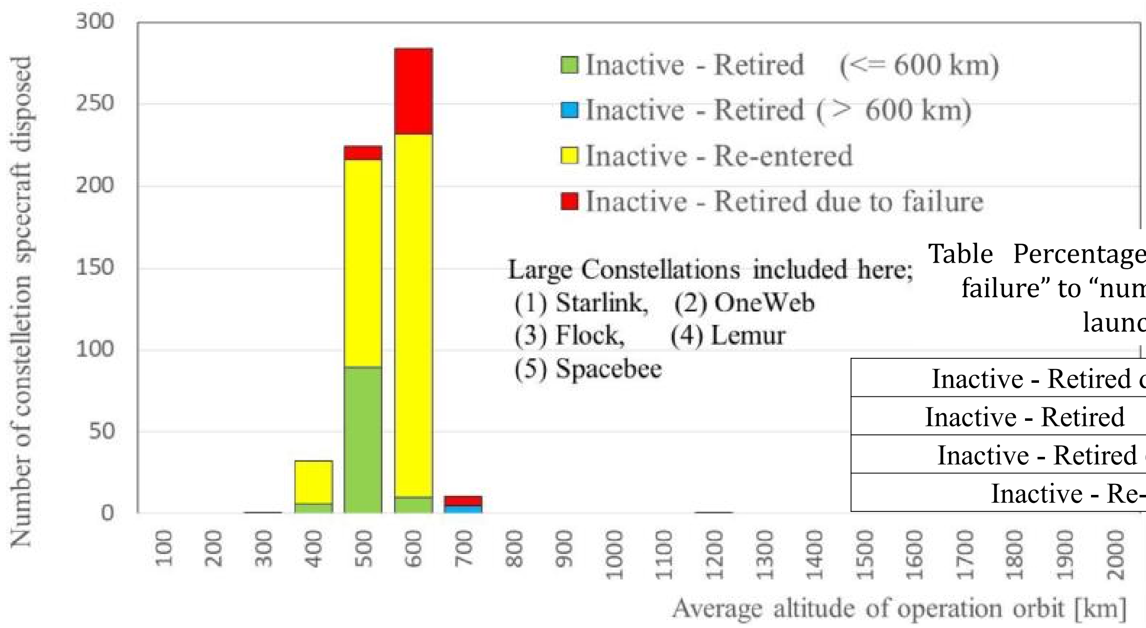


Fig.- Status of inactive spacecraft of large constellations along the average altitud
(For the S/C launched after Jan. 2011 and terminate missions before Dec. 2022)

Table Percentage of "retired spacecraft due to failure" to "number of mission ended S/C launched after 2011"

Inactive - Retired due to failure	11.9%
Inactive - Retired (<= 600 km)	19.0%
Inactive - Retired (> 600 km)	0.9%
Inactive - Re-entered	68.2%

@2022/05/01

Rate of Incompliance to the 25-year rule is 2.0 % (Stay > 600 km after EOL)

20

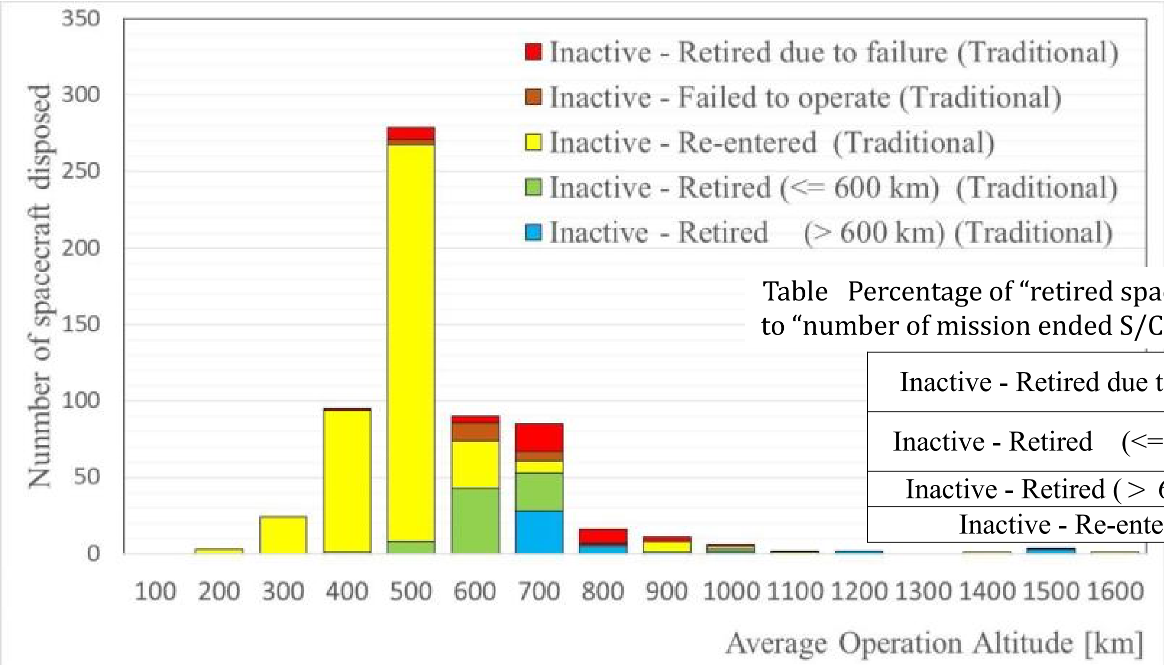


Table Percentage of "retired spacecraft due to failure" to "number of mission ended S/C launched after 2011"

Inactive - Retired due to failure	8%
Inactive - Retired (<= 600 km)	13%
Inactive - Retired (> 600 km)	7%
Inactive - Re-entered	72%

@2022/05/01

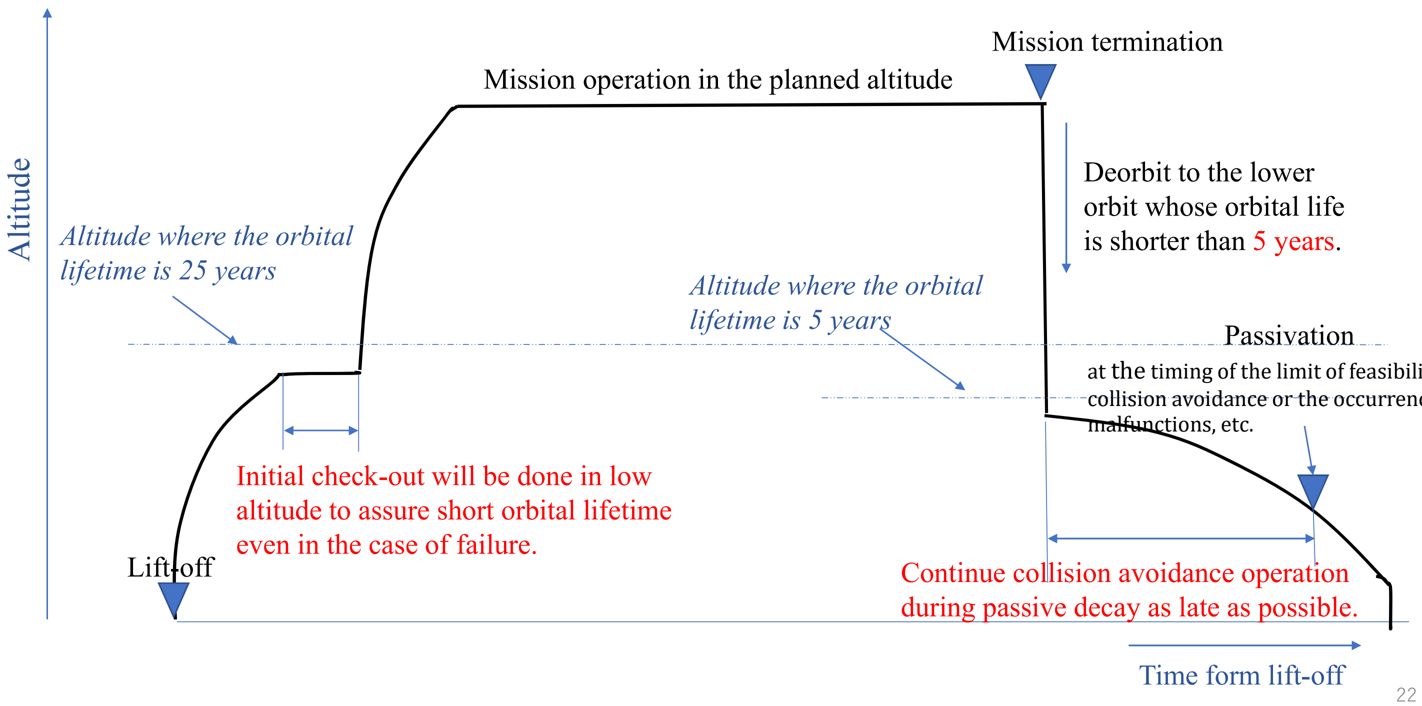
Fig.- Status of inactive S/C excluding that of large constellations along the average altitud (For the S/C launched after Jan. 2011 and terminate missions before Dec. 2022)

Rate of Incompliance to the 25-year rule is 12.1 % (Stay > 600 km after EOL)

21

6. Intention of major requirements

6.3 Initial check-out in low orbit region, and keeping collision avoidance operation during passive decay



22

7. Conclusion

(1) As shown in the previous charts, several constellation programs have initiated, and large number S/C (at least 30 thousands of S/C at the end of CY2030) will be placed into the useful orbital region. Such activities poses great risk to the traditional space users. The orbital environment, which should be a common property of mankind, is now being occupied by a small number of IT companies and developed countries. Their activities seem to be justified by the convenient phrase "freedom of space activity should be guaranteed".

(2) This project was proposed in FY2019, and will be registered within FY2022, earlier than the initial schedule. But since ISO documents are not international law, their effectiveness is very limited. At the very least, we should upgrade from TS to a formal standard within three years. We would like to continue our efforts to improve its effectiveness even a little.

(3) The author thinks that, to support readers of this TS and future STD version, a Technical Report can be proposed to help to understand the requirements in this TS and their justifications, and the procedure to comply with them.

B18

H-2A 断熱材の軌道上剥離・飛散について

Orbital Fragmentation of Insulator from H-2A Launch Vehicles

○加藤 明（加藤技術士事務所）
○KATO Akira (Kato Professional Engineer's Office)

世界の衛星調達市場及びロケット打上げサービス市場において、環境に配慮した機種を選択するよう格付けを行うシステムが適用されつつある。その中で、我が国の H-2A ロケットは軌道上破砕を複数回発生させているものとして低い評価を受けつつある。世界のロケットの中には残留推進剤の爆発などにより多数の破片を発生させているロケットがあるが、H-2A に関しては残留推進剤による爆発は起こしたことが無いにもかかわらず低い評価となっている。その原因は第二段機体の極低温推進剤タンクを覆っている断熱材の剥離であると考える。同様の現象は米国の DELTA-4 でも発生しているとみられる。ここではその根拠を剥離破片の軌道データから示す。世界市場に向けて H-2A 及び次期 H-3 ロケットの打上げサービスの基本的販売促進戦略の一環としてこの問題の原因を公表し、改善に真剣に取り組み、世界に発信することが必要と考える。

In the world satellite procurement market and rocket launch service market, a rating system is being applied to select environmentally friendly models. Among them, Japan's H-2A launch vehicle is given a low rank because of causing multiple orbital break-ups. Among the launch vehicles in the world, there are vehicles that generate many fragments due to explosions of residual propellants, etc., but the H-2A is ranked low even though it has never caused an explosion due to residual propellants. I believe that the cause of the H-2A's fragmentation is peeling of the insulators covering the cryogenic propellant tanks of the second stage. A similar phenomenon appears to have occurred at DELTA-4 in the United States. Here, the technical ground for this insight is shown from the orbital data of the peeled fragments. As part of the basic sales promotion strategy for the H-2A and next-generation H-3 launch services for the global market, we believe it is necessary to disclose the cause of this problem, make serious efforts to improve it, and disseminate it to the world.

B18
“Orbital fragmentation of insulator from H-2A launch vehicles”
H-2A断熱材の軌道上剥離・飛散について

The 10th Space Debris Workshop
Administration Bldg. No.1
Chofu Aerospace Center
Research and Development Directorate
Japan Aerospace Exploration Agency
Nov. 29, 2022
Akira Kato（Kato Professional Engineer’s Office）

第10回スペースデブリワークショップ
宇宙航空研究開発機構
研究開発部門
調布航空宇宙センター 事務棟1号館講堂
2022年11月29日
加藤 明（加藤技術士事務所）

1

Outline

- In the world satellite procurement market and rocket launch service market, a rating system is being applied to select the environmentally friendly models. Among them, Japan's H-2A launch vehicle is given a low-ranking position because it has caused multiple orbital break-up events.
- Among the launch vehicles in the world, there are other vehicles that generate many fragments due to explosions of residual propellants, etc., but the H-2A is ranked low even though it has never caused an explosion due to residual propellants.
- The cause of the H-2A's fragmentation is due to peeling off the insulators covering the cryogenic propellant tanks of the second stage. A similar phenomenon seems to be occurred in the DELTA-4 of the United States. Here, the technical ground for this insight is shown in this paper, based on the orbital data of the 2nd stage and fragments, surveillance of design, manufacturing and operation record.
- As a part of the basic “sales strategy” of the launch service to the global market, it is necessary to disclose the cause of this phenomena to the world and make efforts to improve it.

Ref. This report includes the part of JAXA’s report GEF-06003 produced in 2007 which cleared the suspected causes of this phenomena at first time in the history of H2A.

2

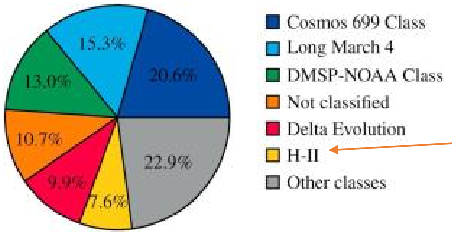
Contents

1. Evaluation of H2A in "Space Sustainability Rating" (SSR)

The World Economic Forum (WEF) has selected a consortium of companies, universities and agencies to develop a system to rate the sustainability of space systems, one that its backers hope will encourage good behavior in space. WEF announced on 2019 May 6th that a team from the European Space Agency, together with one led by the Massachusetts Institute of Technology (MIT) Media Lab, will work on development of a "Space Sustainability Rating". It is a metric that will define how well an individual space system follows guidelines to ensure the long-term sustainability of space.

In such study, bad evaluation is given to the Japanese launch vehicle H2A. It is induced from the phenomena that the many fragments of thermal insulator peeled from the cryogenic propellant tanks.
Due to the low density, such fragments will soon decay. And the mechanical damage when they would impact to the spacecraft can't be ignored but not so serious than the case of metallic fragments according to the concept of the "energy-to-mass ratio (EMR)" which is parameter to identify the threshold of impact energy to the mass of spacecraft, that would cause the catastrophic break-up.

I hope that JAXA will not underestimate the high level of interest in the "long-term sustainability of space activities" in the world, and that JAXA should share the information on this issue with the rest of the world, show its attitude to make efforts to improve it, and improve its ranking in the global launch service market.



Assessment on H-II

Fig. 1 Most common object classes involved in fragmentation events

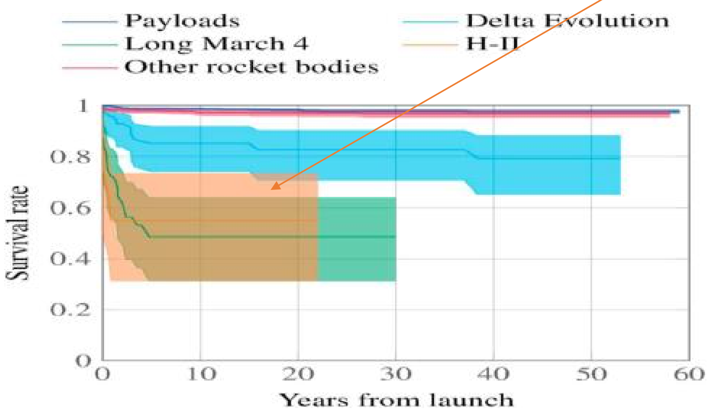


Fig. 2 Kaplan-Meier estimator for rocket bodies and payload objects, considering different launcher families. The shaded area indicates the 0.95 confidence interval.

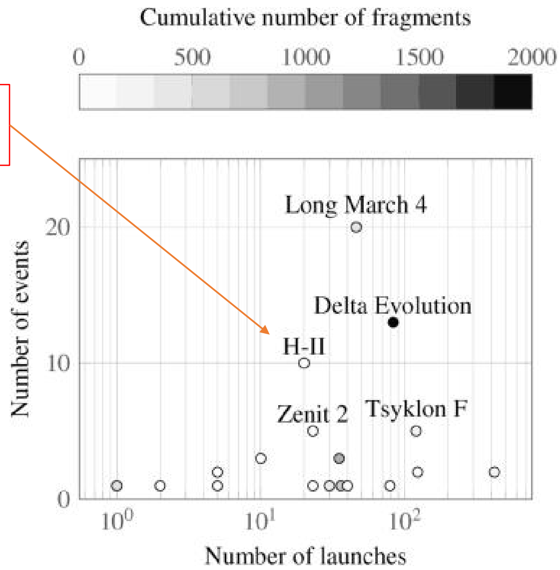


Fig. 3 Number of launches and fragmentation events for different launcher families.

5

Several charts presented to evaluate the hazards posed by H-II

Ref. "Environment capacity as an early mission design driver", written by Francesca Letiziaa,*, Stijn Lemmensb, Holger Kragb Acta Astronautica 173 (2020) 320–332

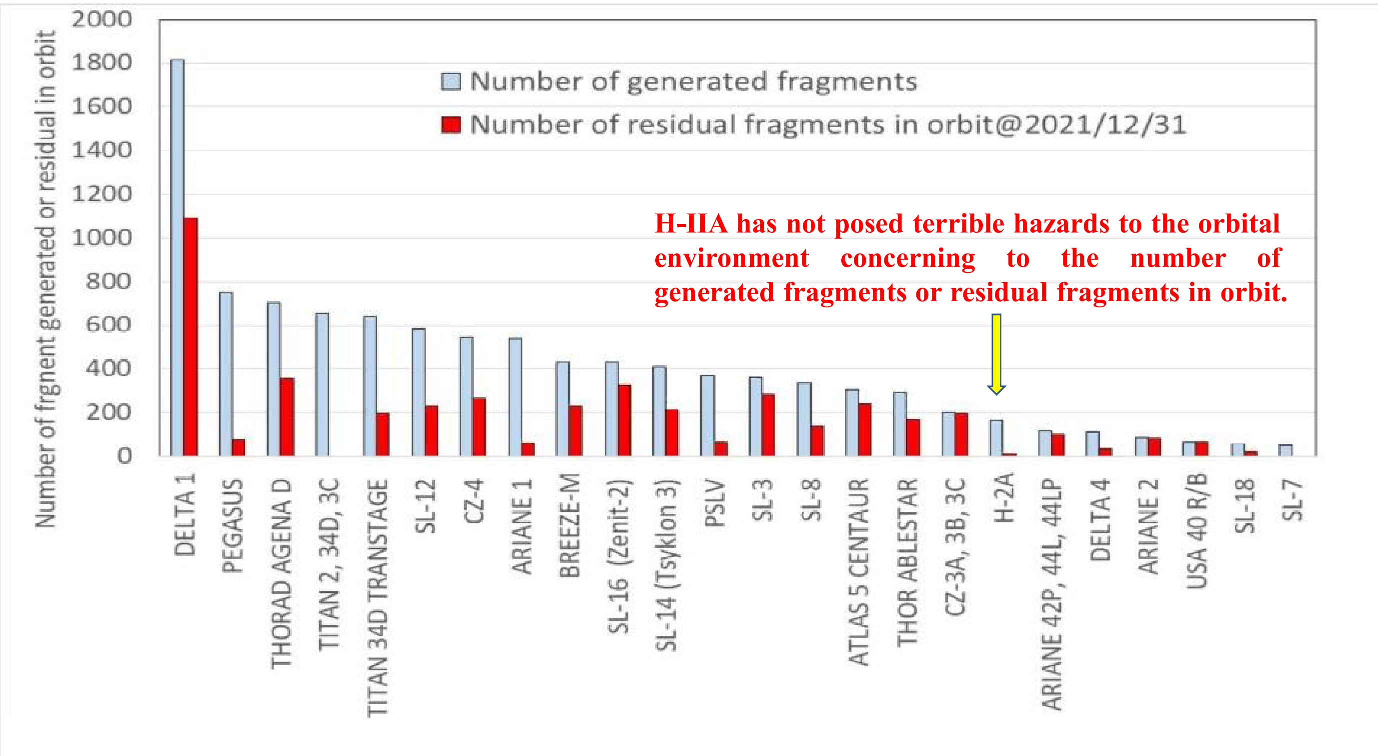


Fig.-4 Number of debris generated from the launch vehicles and number of debris still in orbit

6

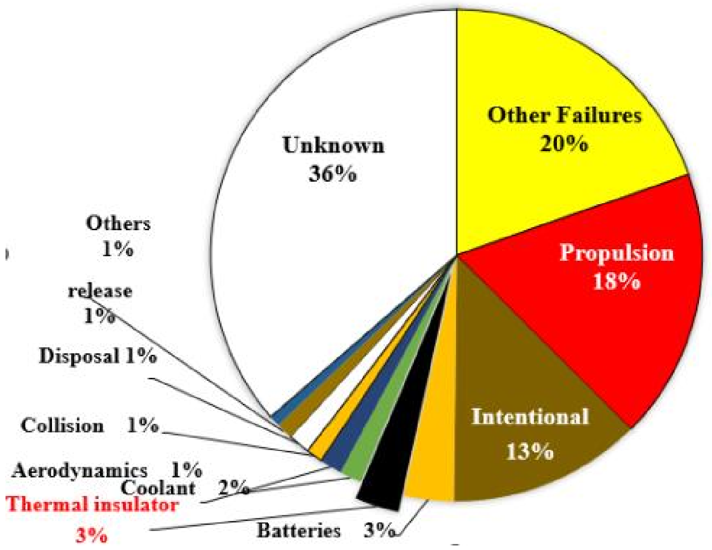


Fig.-5 Distribution of number of break-up events per causes

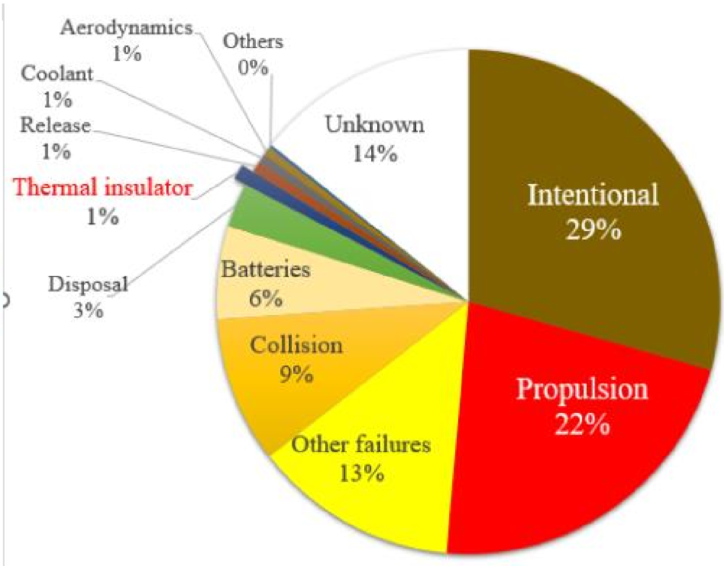


Fig.-6 Distribution of number of generated fragments per causes of break-ups

[Data source: Space-Trak 3 2022/2/5]

Thermal insulator is not a significant matter among the many break-up events in terms of both number of events and number of fragments.

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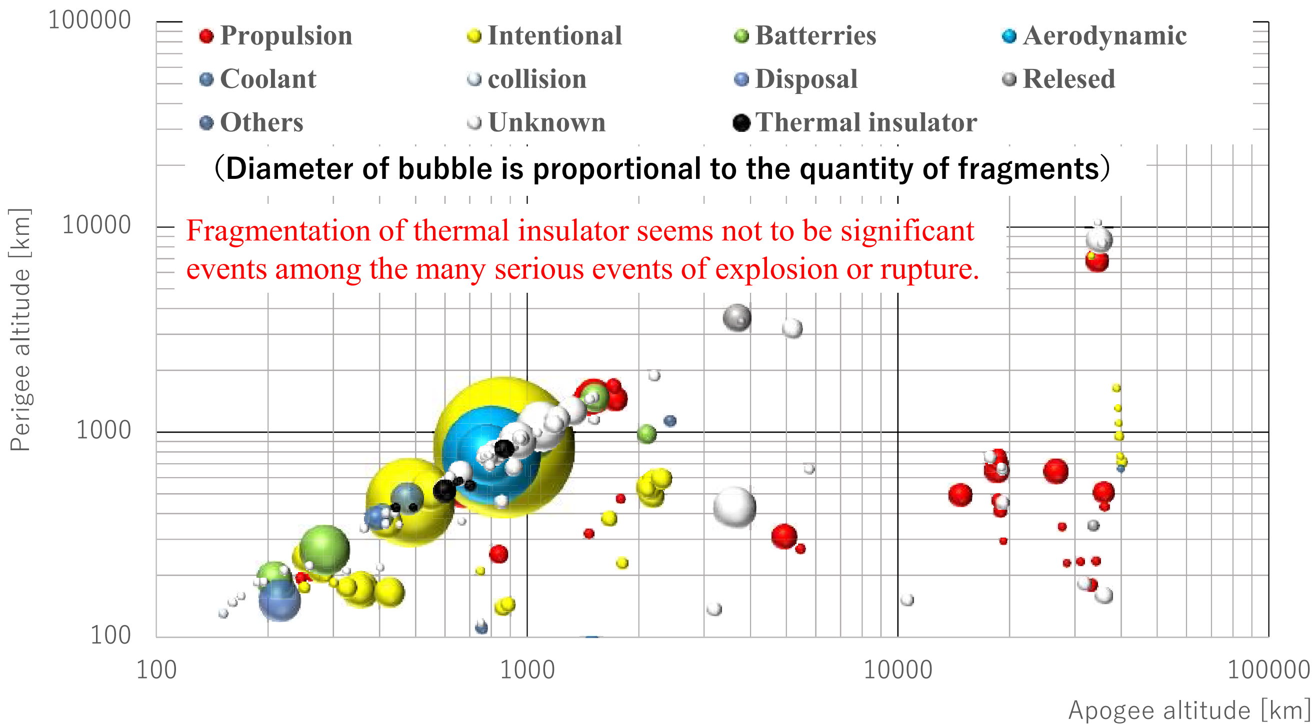

Fig.-7 Various break-up events in the history presented with their causes, altitude and image of amount of fragments
(Only the events that generated more than 10 fragments) (Data source: JSpOC Space track @ 2022/01/05)

8

2. Experience of the first fragmentation of the thermal insulators from H2A

1. Outline

In the 8th flight mission of H2A launched on 24th January 2006 to inject ALOS into LEO, the 2nd stage generated orbital debris in August 2006. All the debris were decayed within 118 days.

As the result of survey and analysis, although there was not enough information to verify that, the most probable cause was found to be that a tiny orbital object might impact on the cryogenic propellant tanks of the 2nd stage and peeled the thermal insulator (PIF: Polyisocyanurate Foam) coated there.

2. Phenomena

The 2nd stage of H-2A ALOS mission generated orbital debris. Based on the Space Surveillance Data (SNN), NASA reported to JAXA that 4 objects were generated on August 8th and 17objects were on August 27th, which means that 15 – 34 days after the generation, 21 objects were registered as cataloged objects in CSpOC/Space track/SSR. Delta velocity caused by the fragmentation event seemed to be very low.

Ref. Summary of technical report on Generation of orbital debris from the 2nd stage of H-2A in 8th flight mission, 12, December 2006, by A.Kato in Secretary of the Space Debris Mitigation Promoting Committee Institute of Aerospace Technology / JAXA

3. Survey and analysis

3.1 Items for survey and analysis were;

(1) estimation of break-up energy from;

a) the change of orbital characteristics of the 2nd stage after fragmentation, and observed image obtained by the on-ground observation facility, and

b) the orbital characteristics of generated objects,

(2) review the first flight items, confirming the potential causes of fragmentation with FTA, and the condition of the 2nd stage known from the telemetry data,

(3) estimation of the physical characteristic (density) of debris,

(4) estimation of the probability of impact with debris, and

3.2 Result of survey

(1) Estimation of break-up energy

A) As far as known from the orbital characteristics of the 2nd stage obtained from the TLE data, there was no evidence that any impact energy or break-up energy would affect on the orbital characteristics of the 2nd stage.

B) As far as known from the image data acquired by the FGAN RADAR (in Germany) didn't show any indication of the catastrophic break-up.

C) As far as known from the orbital characteristics of the fragments, with considering the number of generated fragments and their distribution mode, the possibility of explosion was denied.

Ref. Knowledge from the ground observation data

The image data acquired by the FGAN didn’t show any indications of explosion or rupture which caused the catastrophic break-up.

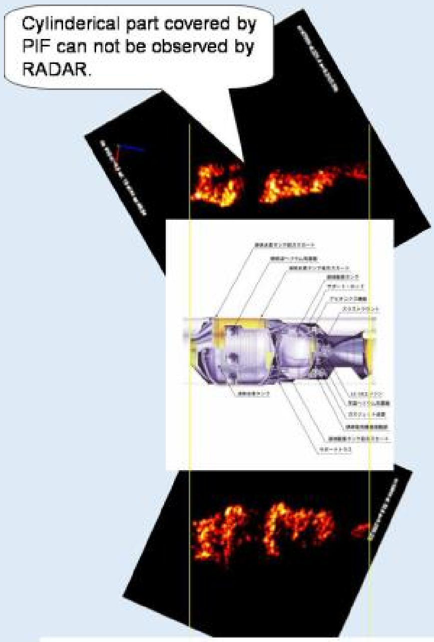

Fig.-8 Image of 2nd Stage obtained by FGAN RADAR

Ref. the orbital characteristics of fragments

The following chart shows the distribution of objects in the orbit 34 days after the event. The chart shows the apogee and perigee of ALOS, rocket body, and fragments. The diameter of bubble is drawn proportional to the size of the actual object, except the bubbles of ALOS and rocket body are 100 times smaller than the bubbles of fragments. It looks that the all the fragments are existing within about 100 km of delta altitude from the rocket body, and being decayed. There were no indication that large break-up energy have imposed o the fragments.

In Fig.-9, the size is expressed as the Radar Cross Section (RSC) under the assumption of an ideally conducting metallic object (Scattering coefficient = 1).
In this chart, the fragments are not metallic objects so that the size is just for reference.

According to the other analysis, the change of orbital characteristics suspected to be caused by break-up or collision energy of the rocket body was not identified.

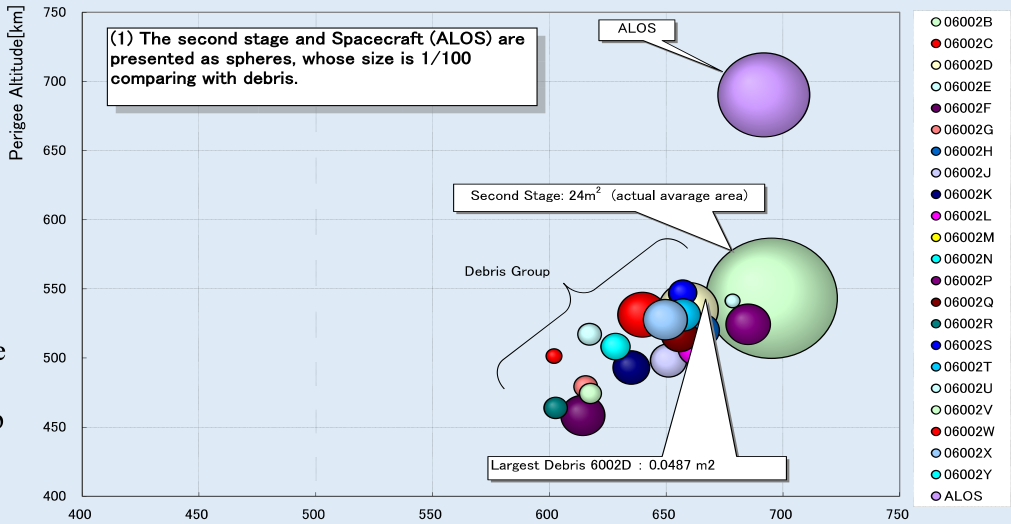

Fig.-9 .1 Altitude and Size of Rocket Boby and Debris

(3) Estimation of the orbital characteristics of the fragments

- Fig. -10 shows the history of semi-major axis of debris. ［Remarks: orbital characteristics of fragments were determined 15 – 34 days after generation.]

- NASA reported that the fragments were generated twice (August 8th and 27th) . Some fragments have two points that both relative distance and velocity with parent body are zero on August 8th and 27th. Then it was supposed that some fragments generated on August 8th again approached to the parent body on 27th, or impacted on the body on 27th and generated fragments secondary.
- In any case, fragments seem to be released without additional velocity.

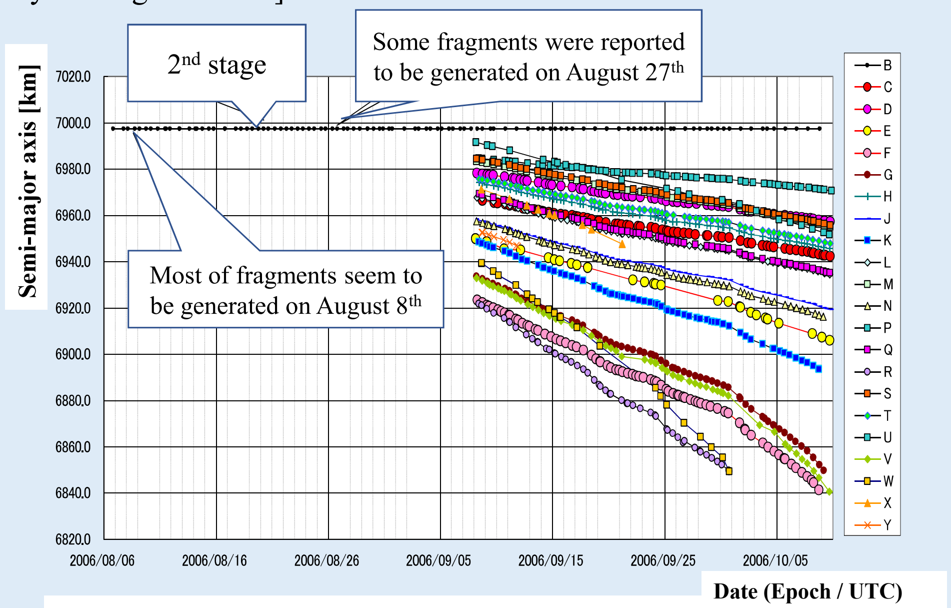

Fig.-10 History of semi-major axis of 2nd stage and fragments

Remark: NASA reported that the fragments were generated twice. But, for example, fragment (2006-002L), identified to be generated on August 27th, approached to the 2nd stage also on August 8th . Fig.-11 chart shows the relative distance between the 2nd stage and fragment 2006-6002L on August 8th.

This phenomena might insinuate that some fragments generated on August 8th again approached to the 2nd stage, or even impacted to it on August 27th to generate another secondary fragments.

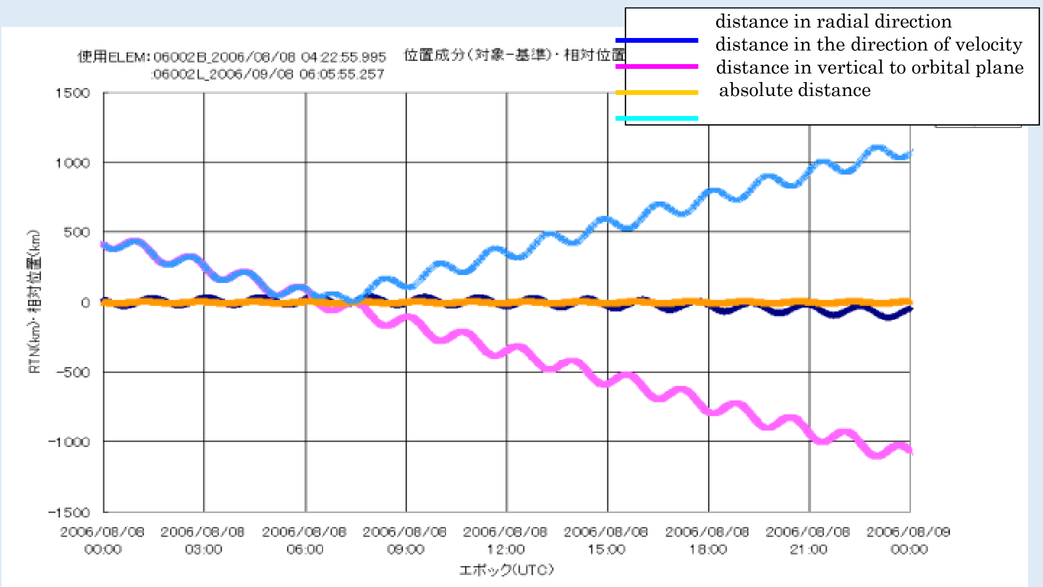

Fig.-11 Distance between 2nd stage and fragment (2006-002L) which is reported to be generated on August 27th

(2) First flight items, and physical condition of the 2nd stage known by telemetry data

- The design changes, which were applied to the second stage of ALOS mission for the first time, are reviewed, and confirmed non of them seem to cause fragmentation.
- From the result of Fault Tree Analysis, it was confirmed that there were no potential causes of fragmentation except debris impact.
- The Space Debris Mitigation Standard (JMR-003) was applied to the H-2A so that the preventive design and practices for on-orbital break-ups were naturally conducted.
- It was impossible to verify actually the completion of passivation due to the geographical limit that could keep the telemetry signal. However, it could be proven to some extent that all conditions in the vehicle were healthy until the time limit of communication black-out, and that means passivation would be conducted properly.

(3) Estimation of the physical characteristic (density) of debris

A) All the fragments were re-entered within 118 days, which indicated that its density was very small or drag coefficient was very large.

B) Fig.-12 shows orbital lifetime of 4 materials (plates whose area is 55 cm^2 made of stainless, aluminum, CFRP and PIF) which might be released from the 2nd stage.

A block made of PIF will fallen shorter than 2 months, and other plates will not decay so soon.

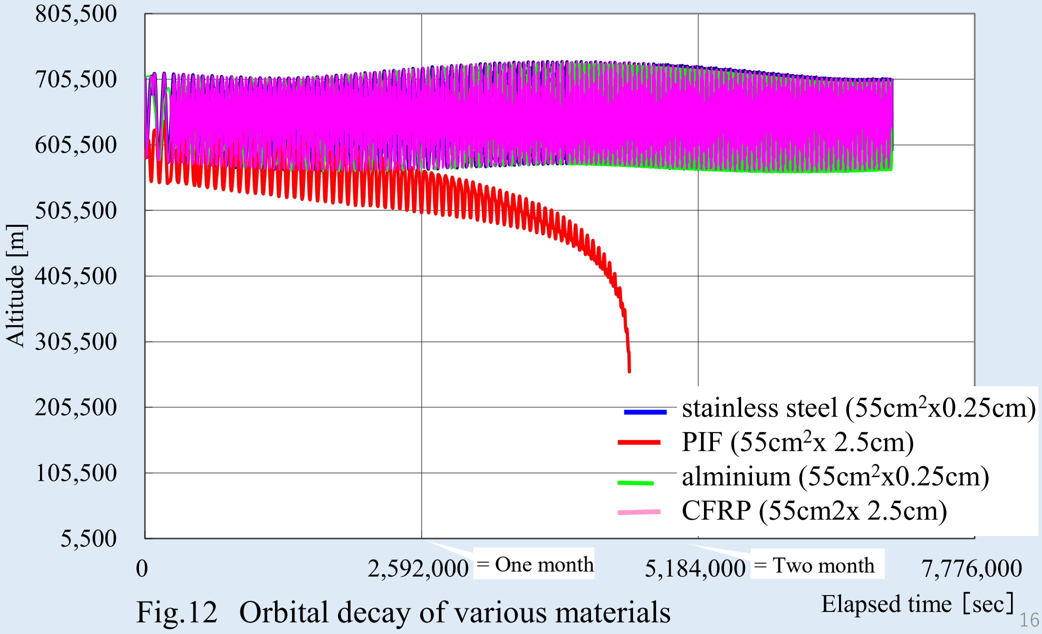

Fig.12 Orbital decay of various materials

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C) Fig.-13 shows the orbital lifetime of each debris that actually observed and result of analysis for PIF (RSC= 55 and 400 cm^2). This chart shows good agreement between phenomena and result of analysis if they are PIF. Then, most of them seem to be PIF or other materials whose density is smaller than PIF.

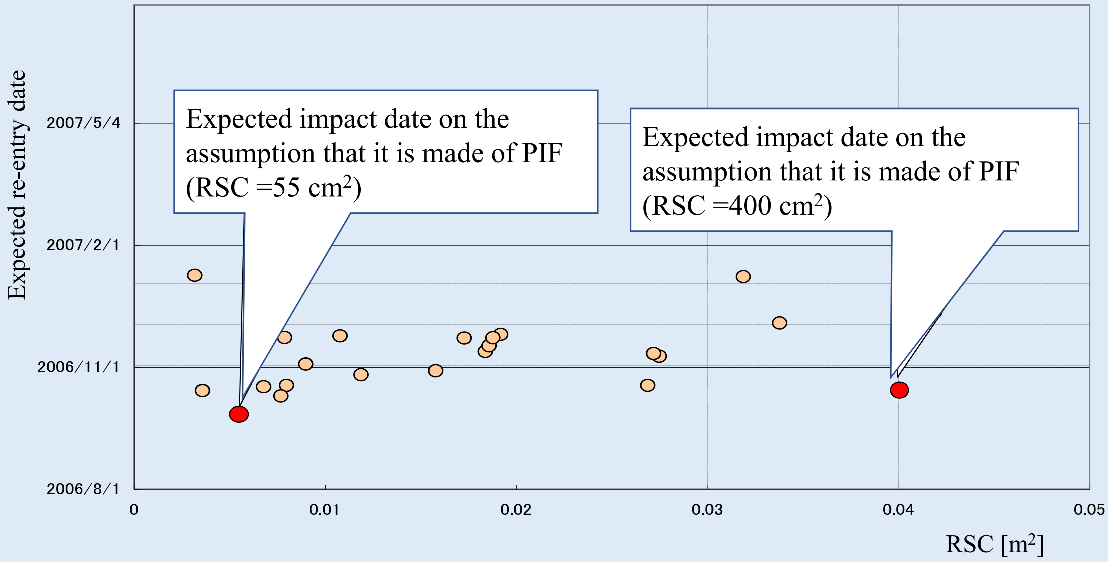


Fig.-13 RSC (Radar Cross Section) and Orbital lifetime fragments

(4) Estimation of the probability of impact with objects

- The task team for “the incident of separation of PIF on STS-114” points out several causes which possibly invite the separation of PIF from the propellant tank. However, those causes such as “difference of temperature between inside and outside of tank-wall”, and ”vibration, aerodynamics force, and heating effects” are available only for powered flight, and not applicable to this case which occurred 6 months after the proper mission termination.
- The most probable cause is debris impact. Fig.-14 shows annual collision probability of debris with the 2nd stage (area: 23 m^2), according to the MASTER2005. The 10 cm debris will cause a catastrophic break-ups, with the probability 10^{-4} [event/year]. The debris of 1 cm may penetrate the tank wall but not cause fragmentation nor large disturbance of the orbital characteristics, at the probability of 10^{-3} or larger.

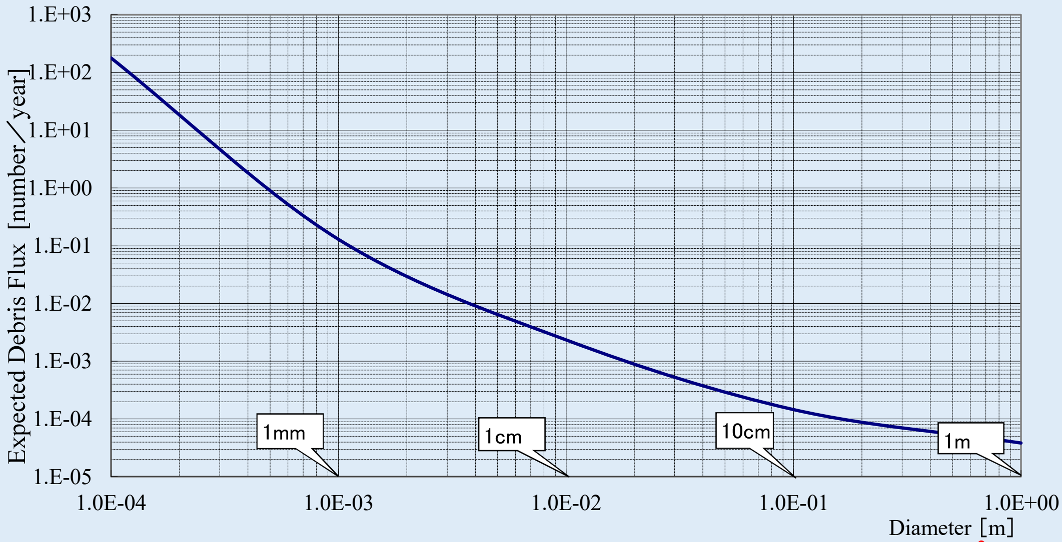


Fig-14 Expected Number of Debris Impact on the 2nd stage (Area: 23 m^2)

Ref. Effect of debris impact

The annual probability of debris impact on the 2nd stage is in order of 10^{-1} [event/area of R/B/year] for 1 mm-class size. When it impacts on the propellant of 2nd stage at the hyper-velocity over 10 km/sec, it would penetrate the tank wall and also generate ejecta and fragments of PIF blocks.

[Ref.] Phenomena of debris impact

In general, if metallic debris would impact on aluminum element, it would increase temperature which melt and vaporize aluminum material and make large crater. If the debris is larger than 10 – 15 percent of wall thickness, it makes penetrative hole and cracks, and also generate ejecta and fragments of PIF to the back side. Also, the generated fragments inside will make damage the tank. Even the size of 0.2 mm is enough to penetrate the wall and make damage inside the tank, and may affect to push PIF outside.

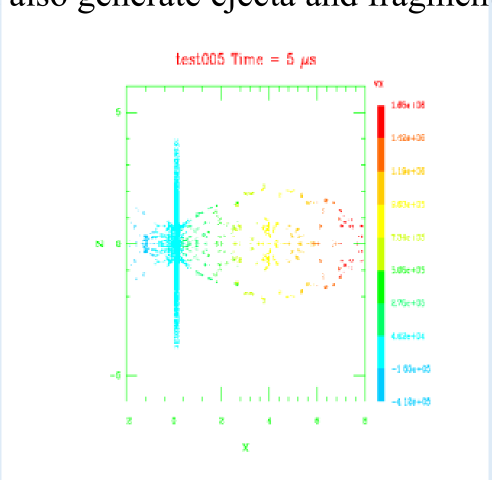
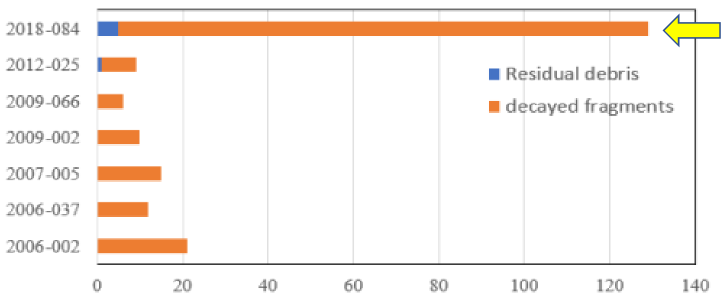
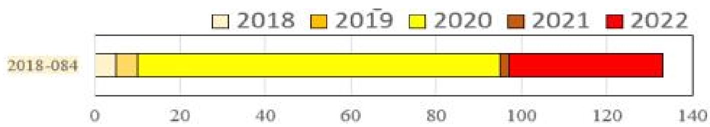


Fig.15 Example of hyper-velocity impact simulation
[Aluminum sphere 5 mm dia., impact vel. V = 5 km/sec, Alminum wall with thickness 2mm]
[Ref. : IADC Protection Mnual]

3. Other similar events that thermal insulator would generate fragments





Timing of generation of fragments

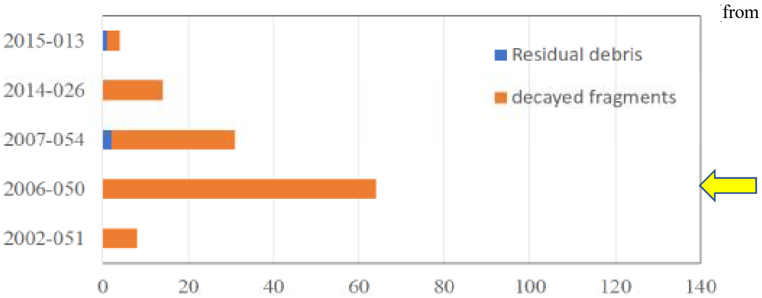
Some vehicles may keep generating fragments during in orbit.

Fig.-16 Numbers of fragments (suspected to be thermal insulator) from H-2A

from CSpOC SSR 2022/11/23]

Example of wrong information

The Universe. Space. Tech > Astronomy news, astrophysics and space science reported "Fairing of a Japanese rocket collapsed in orbit" on 18.07.2022 reported with a phrase as "such incidents are usually associated with the explosion of the remaining fuel vapor in the tanks?" or it is quite possible that the chain of destruction is connected with the design features of the fairing itself. In this case, we can see a repetition of such events with fragments left over from other launches of the HII-A rocket?



DELTA 4 vehicles, being applied same insulator, are suffering from same situation.

Fig.-17 Numbers of fragments (suspected to be thermal insulator) from DELTA 4

[from CSpOC SSR 2022/11/23]

4. Risk assessment

The risk assessment of the impact of PIF fragments on the active spacecraft will include the assessment of the probability of impact and the severity (expected damage to the spacecraft).

a) The most of fragments generated in the useful orbital region are soon decayed, so the assessment of the probability of impact must include the aspect of orbital lifetime of debris. However, the total number itself may reach to more than a hundred as actual event showed. Also, the event may be repeated in the same body. The design of thermal insulator should not be left as is, and shall not be followed by the next generation, the H3 vehicle.

a) The expected damage to the active spacecraft due to impact of low-density material has never been confirmed yet. It would also depend on the size of fragments. So far, nobody can tell the optimistic evaluation.

Without waiting for the fine risk assessment. Design improvement for thermal insulation should be conducted.

5. Conclusion

A) Phenomena learned from experience in the H2A/8th flight mission

- Based on the behavior of the 2nd stage in orbit, observation data from ground radar site, and distribution mode of fragments, there was no evidence to show the explosion (or rupture) generated metallic fragments.
- Judging from the healthy condition just before the black-out of the telemetry link, the propellants and other fluids seem to be vented properly.
- The cause of the debris generation was that small pieces of debris collided with the second stage, scattering fragments of the insulator (PIF) surrounding the cryogenic propellant tank.
- Such defects should not be repeated in the future launch service, even if a risk assessment is not completed.

B) Statement to the rest of the world

- It is unacceptable to repeat such defects. However, given their low-density properties that soften impact damage and reduce orbital lifetime, they are clearly not as dangerous as metallic fragments. This point can be announced to the world to gain better status in “space sustainability assessments”.

C) Improvement

- Even if it would be the short-term influence, the design improvement is urgently necessary to preserve orbital environment, safety assurance for active spacecraft, security not to disturb the strategic space service, and acquire better competitive status in the world launch service providing activities. It is also the obligation to the taxpayer in Japan.

B19

宇宙の持続可能性をめぐる最近の政策動向について
Introduction of the Recent Policy Trend on Space Sustainability

○岩本 彩（アストロスケール）
○IWAMOTO Aya (Astroscale Japan Inc.)

特に低軌道を中心に宇宙物体の急増による軌道の混雑化が進む中、各国や民間企業による宇宙の持続可能性（Space Sustaiability)の取組みが進展している。この講演では、米国や英国を始めとした最新の宇宙の持続可能性に関する政策動向、民間企業の取組を紹介した上で、宇宙の持続可能性確保のためのガバナンスのあり方について考察を行う。

The orbital traffic has increasingly congested due to the exponential increase of space objects including space debris. Against background this change of orbital environment, some states and private companies has taking initiative on developing new policy to ensure space sustainability. This presentation introduces some of new trend on policies around space sustainability as well as efforts by commercial actors. It also proposes what further needs to be done in terms of global governance for space sustainability.


Astroscale
宇宙の持続可能性をめぐる最近の政策動向について
Introduction of the recent policy trend on space sustainability
第10回スペースデブリワークショップ
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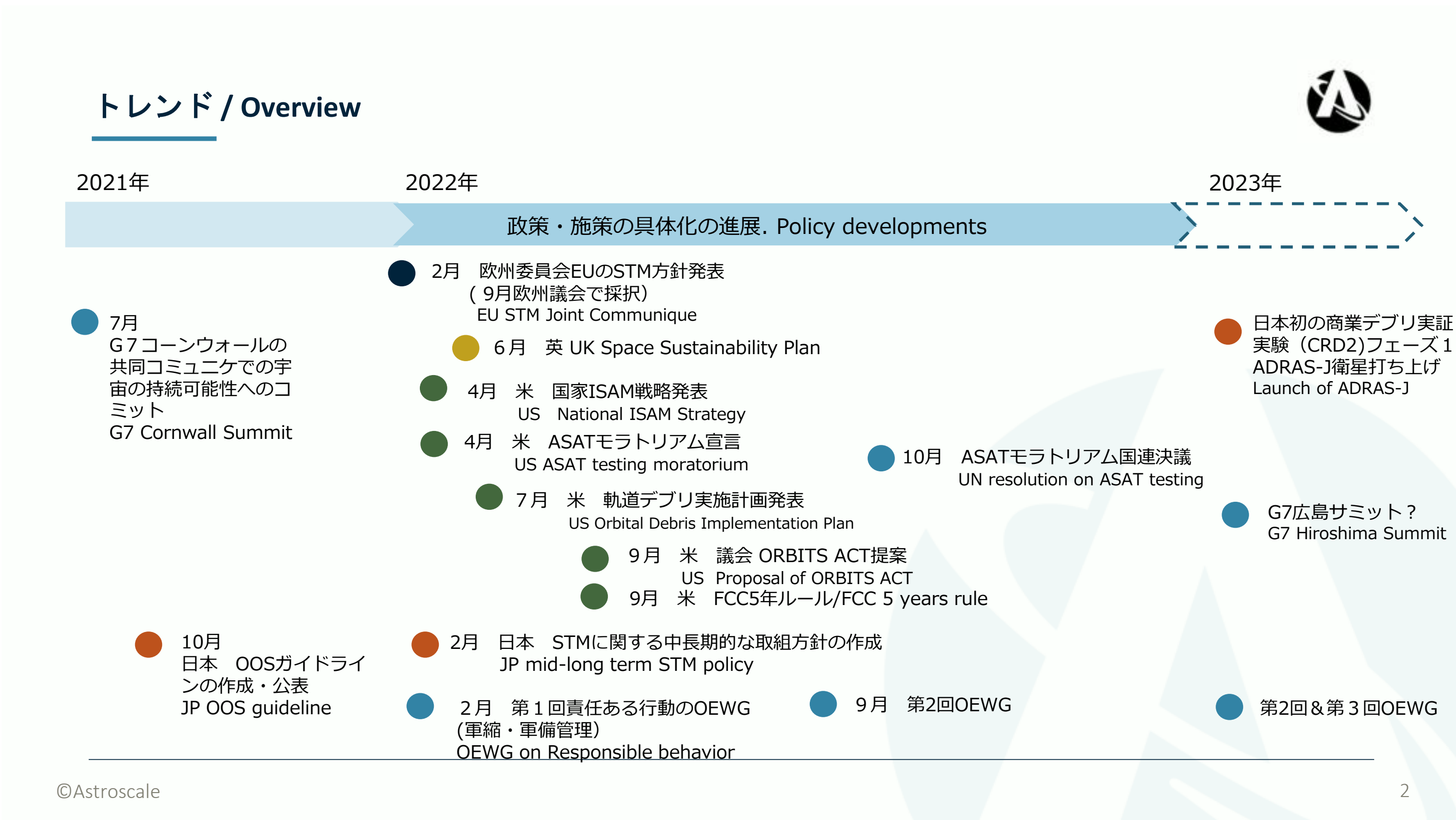
株式会社アストロスケール Astroscale Japan
Director, Japan Space Policy
岩本彩 Aya IWAMOTO


トレンド / Overview
2021年
2022年
2023年
政策・施策の具体化の進展. Policy developments
2月 欧州委員会EUのSTM方針発表
(9月欧州議会で採択)
EU STM Joint Communique
7月
G７コーンウォールの共同コミュニケでの宇宙の持続可能性へのコミット
G7 Cornwall Summit
6月 英 UK Space Sustainability Plan
4月 米 国家ISAM戦略発表
US National ISAM Strategy
4月 米 ASATモラトリアム宣言
US ASAT testing moratorium
7月 米 軌道デブリ実施計画発表
US Orbital Debris Implementation Plan
9月 米 議会 ORBITS ACT提案
US Proposal of ORBITS ACT
9月 米 FCC5年ルール/FCC 5 years rule
10月 ASATモラトリアム国連決議
UN resolution on ASAT testing
日本初の商業デブリ実証実験（CRD2)フェーズ１ ADRAS-J衛星打ち上げ
Launch of ADRAS-J
G7広島サミット？
G7 Hiroshima Summit
10月
日本 OOSガイドラインの作成・公表
JP OOS guideline
2月 日本 STMに関する中長期的な取組方針の作成
JP mid-long term STM policy
２月 第１回責任ある行動のOEWG
(軍縮・軍備管理)
OEWG on Responsible behavior
９月 第2回OEWG
第2回＆第３回OEWG
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G7首脳会合（コーンウォール、2021年6月11日～13日）　G7 Cornwall summit

G７カービスベイ首脳コミュニケ
～より良い回復のためのグローバルな行動に向けた我々の共通のアジェンダ～

３５．これらの優先事項のほかに、我々は、将来的な先端領域に関するその他の協力分野が適切なものであるかどうかの再評価を行う。**我々は、現在と未来の人類の熱意を支えるべく、安全で持続可能な宇宙利用にコミットする。**我々は、宇宙交通の管理と調整のため の協調的アプローチの必要性に則して、持続可能な宇宙活動に関する共通の基準、ベスト・プラクティス及びガイドラインを作成することの重要性を認識する。我々は、次世代のために宇宙環境を保全すべく、国連宇宙空間平和利用委員会、国際標準化機構、国際宇宙機関間スペースデブリ調整委員会といったグループを通じ、全ての国が協働することを求める。

35. Beyond these priorities, we will review whether other areas of collaboration with respect to future frontiers are appropriate. We are committed to the safe and sustainable use of space to support humanity's ambition now and in the future. We recognise the importance of developing common standards, best practices and guidelines related to sustainable space operations alongside the need for a collaborative approach for space traffic management and coordination. We call on all nations to work together, through groups like the United Nations Committee on the Peaceful Uses of Outer Space, the International Organization for Standardization and the Inter-Agency Space Debris Coordination Committee, to preserve the space environment for future generations.

出典：外務省ウェブサイトhttps://www.mofa.go.jp/mofaj/files/100200083.pdf
写真含む

出典：英宇宙庁ウェブサイト（https://www.gov.uk/government/news/g7-nations-commit-to-the-safe-and-sustainable-use-of-spacee）

 3

UK/EU　宇宙の持続可能性が重要課題、政策・施策の具体化の進展（2022年～）

The Plan for Space Sustainability

英国が、特に規制を活用し持続可能な宇宙利用を促す上でリーダーシップを取ることにコミット。

1. グローバルな規制のスタンダードとなるような規制枠組みに向けたレビューの実施
2. 宇宙の持続可能性についての国際的な取組みの実施
3. 宇宙活動が宇宙の持続可能性に与える影響を図るための「指標（metrics）」の作成
4. 追加的な500万£のADR計画のための支援

～2022年6月　英科学・研究・イノベーション大臣

https://www.gov.uk/government/news/government-announces-package-of-new-measures-to-drive-space-sustainability

esa
European Space Agency

「2030年までに、 **Zero Debris**を目指す」
「運用終了後直ちに価値のある地球軌道から全ての欧州の衛星を一貫し、確実に(consistently and reliably)除去する」
「野心的な目的を掲げ、欧州が前例となることで、新たなゼロ・デブリ・プラットフォームを作り、他のアクターの行動をも促す」
～欧州宇宙機関アッシュバッハー長官

https://www.esa.int/ESA_Multimedia/Videos/2022/06/ESA_DG_Josef

（参考）宇宙活動と地球のESG
Statement for a Responsible Space Sector
(2022年11月)
- ESAと欧州の主要な宇宙企業による５つの原則

ESA - "Statement for a Responsible Space Sector" Initiative

宇宙交通管理（Space Traffic Management）に関する欧州としての共通のスタンスの作成

JOINT COMMUNICATION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL An EU Approach for Space Traffic Management An EU contribution addressing a global challenge

～欧州胃委員会（2022年２月策定
欧州議会（2022年10月採択）

 4

US/米国：InnovationSpace Economy、所管する組織の明確化、国際的な規範

White House

Office of Science, Technology & Policy

- **ISAM国家戦略**（ISAM (In-Space Servicing, Assembly and Manufacturing) National Strategy)）（2022年4月）
- **軌道デブリ実施計画**（The Orbital Debris Implementation Plan）(2022年7月）
  - 44の具体的なアクションの特定と主管庁の特定
  - ３つの柱
    - Debris Mitigation
    - Tracking and Characterization of Debris
    - Remediation of Debris

国家宇宙会議（National Space Council）

- 国際的なルールと規範の促進表明（第２回国家宇宙会議(2022年9月9日））
  - 先端的な宇宙活動（軌道上での衛星の修理、燃料補給など）に関するルール・規範の作成
  - 自主的な地上発射型ミサイルによる衛星破壊実験停止に係る国連総会第一委員会（10月）決議提出の表明
- 既存の規制でカバーされない革新的な宇宙活動についての業界ヒアリングの実施

米国上院

The Orbital Sustainability Act of 2022（the "ORBITS Act"）（2022年9月）

- 超党派の法案として上院に提出。まだ委員会には付託されていない。
- 法案の主な内容
  - 法案成立から90日以内の「the greatest immediate risk（喫緊のリスクをもたらす）」デブリの特定、リスト作成と公表（将来のアップデート含む）。**リストには、他国のデブリも含まれる**。
  - NASAによるRemediation*実証プログラムの開始。2023年度から2027年度にわたり1.5億ドルの予算付け。NASAをサービス調達者として指定。
  - 国際協力の推進：上記リストに含まれる外国由来のデブリについての協力・共同の可能性に関し、二国間・多数国間の協議を通じて促進。

*Remediationの定義：デブリ除去以外に、デオービットの促進、転用、その他のデブリ除去を含むとされている。

5

FCC：5年ルールの経緯と概要 New Five Years Rule

経緯 Background

- 2004年 FCCデブリ低減ガイドライン作成
- 2018年のSPD-3（大統領令第３号）、軌道環境の変化を踏まえ、**同年11月より見直し開始**
- 2020年４月　改訂版のR&O公表（2021年10月より効力発生
- 一部の論点については、継続協議（Further Notice of Proposed Rulemaking (FNPRM)）
- **継続協議となっていた論点のうち、今般25年ルールの見直し部分について新たな決定が発出**。

今回のFCC決定の内容/ outline of the new rule

- 2022年９月、LEO上で運用する衛星について、運用終了から大気圏突入までの期間を５年に短縮
  - すでに運用中の衛星については適用されない
  - 2022年9月29日からの祖父条項（猶予期間）
  - 米国市場にアクセスする外国企業の衛星にも適用
  - 大学等の研究用のミッションについては、適用除外も検討可能。

(参考)
継続協議となっている事項
- 偶発的な破砕の確率、複数の衛星システムの衝突確率、マヌーバビリティの要求、損害リスク、免責、パフォーマンス・ボンド（保証金）
- FCCは、宇宙空間でのサービス、組立及び製造（ISAM)に関するミッションを促進するための政策見直しのための意見募集の公告発出（2022年8月）しており、本件はNew Spaceに対応するための一連の規制見直しの第一弾との位置付け。

6

日本/Japan

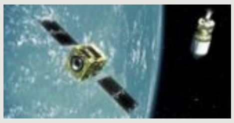
- **宇宙交通管理に関する関係府省等タスクフォース（旧デブリタスクフォース）と軌道利用のルール作りに関する中長期的な取組方針の策定 （2022年３月）**
  Release of the mid and long term policy on the rules of the use of orbit (March, 2022)
- **軌道上サービスを実施する人工衛星の管理に係る許可に関するガイドライン（2121年10月）**
  The guidelines for mission licensing for the on-orbit servicing (Oct, 2021)

JAXA CRD2 （商業デブリ除去実証）

Mission:
日本のロケットデブリを対象に、世界初の低コストデブリ除去サービスの技術実証
The world first low cost space debris removal demonstration

Phase I:
- 日本のロケット上段（非協力なクライアント）に対するランデブー、近傍制御、映像の取得。
- 2023年に打ち上げ予定（Rocket Lab社、NZからの打ち上げ）

Phase II：
- ロケット上段（非協力なクライアント）へのランデブー、近傍制御、映像の取得、大型デブリの除去
- 商業デブリ除去実証フェーズ II フロントローディング技術検討の企画競争（弊社と川崎重工業株式会社が落札）




民間企業の宇宙活動における持続可能性の意識の高まり

民間各社 Space Industry

Space Sustainabilityに対するレポートの発行開始
Space Sustainability Report

https://oneweb.net/about-us/responsible-spac
https://www.inmarsat.com/en/insights/corporate/2022/space-sustainability.htmle

Paris Peace Forum（パリ平和フォーラム）“Net Zero Space” Initiative

ネットゼロ・スペース・イニシアティブ
- 2030年までに全ての人類の利益のための宇宙空間の持続可能な利用を達成することを求める。
  ”By launching the “Net Zero Space” initiative, we are calling for a global commitment to achieving sustainable use of outer space for the benefit of all humankind by 2030. ”
- 2021年から、以下の方法を通じて地球軌道環境の汚染を抑制し、減じるための緊急の行動を奨励する
  - 危険なデブリの発生の回避
  - 危険な既存のデブリの除去
- Endorsee 民間企業、宇宙機関、団体など（１年間で11の組織から50を超える組織に拡大（24か国）
- 2022年には２つのWhite paperを作成
  - Fostering Better and More Interoperable Norms: Recommendations For Enhanced Regulations and Public Policy with Regard to Space Debris
  - Developing Reference Modelling to Assess Risks of Collision in Orbit

https://parispeaceforum.org/en/initiatives/net-zero-space/

宇宙の安全保障の分野でも

DOD's Tenet/5つの信条

2021年6月
- 宇宙空間の軍事的な活動についての責任ある行動として公表
- 宇宙空間の規範に言及したのは初めて
- そのうちの一つに**「長期的なデブリの創出の制限」**あり

The Defense Department released an updated policy document that recognizes space "as a priority domain of national military power" and formally adopts rules for safe operations in space.

- Operate in, from, to and through space with due regard to others and in a professional manner
- limit the generation of long-lived debris
- avoid the creation of harmful interference
- maintain safe separation and safe trajectory
- communicate and make notifications to enhance the safety and stability of the domain

https://media.defense.gov/2021/Jul/23/2002809598/-1/-1/0/TENETS-OF-RESPONSIBLE-BEHAVIOR-IN-SPACE.PDF

CSpO Vision 2031

- 2022年２月公表
- 宇宙 計画・作戦の強化を目的とした連合宇宙作戦統合（CSpO）
- 豪、加、仏、独、NZ、英及び米（Australia, Canada, France, Germany, New Zealand, the United Kingdom, and the United States）
- Guiding Principleの一つに**「責任のある及び持続可能な宇宙利用」**が含まれる。
  - Responsible and Sustainable Use of Space: The world is reliant on space-based systems – activities in space have consequences across the spectrum of human activity. CSpO Participants pursue activities that endeavour to minimise the creation of long-lived space debris and contribute to the enduring sustainability of the outer space environment.

https://www.gov.uk/government/publications/combined-space-operations-vision-2031/combined-space-operations-vision-2031

ASAT 実験モラトリアム宣言と国連決議　ASAT testing moratorium

米国のユニラテラルな宣言と他国の賛同

- 2022年４月、米国は、破壊的な直接上昇型ミサイルによる衛星破壊（ASAT)実験を実施しないことにコミットすることを宣言し、これを国際的な責任ある行動の規範とする意図を表明

  Vice President Kamala Harris announced that the United States commits not to conduct destructive, direct-ascent anti-satellite (ASAT) missile testing, and that the United States seeks to establish this as a new international norm for responsible behavior in space.

- これまでに、カナダ（5月）、NZ（6月）、日・独（9月）、英、韓国及び豪州、スイス（10月）が同様のコミットを宣言

- 日本（2022年9月）

  「日本政府は、宇宙空間における責任ある行動の規範の形成に向けた国際場裏での議論を積極的に推進していく考えから、今般、破壊的な直接上昇型ミサイルによる衛星破壊実験を実施しない旨を決定しました。」（外務省HP)

国連総会第１委員会決議 (UN Resolution)

- 「破壊的な直接上昇型ミサイルによる衛星破壊（ASAT)実験（Destructive direct-ascent anti-satellite missile testing）」決議（A/C.1/77/L.62)
- 第77回国連総会第１委員会へ、米国が提出（日本、ブラジルなど９か国が共同提案国）。
- 第１委員会では、154か国の賛成、８か国反対、10か国の棄権。12月に国連総会で投票・採択の予定。

- 決議の主な内容
  - 全ての国に対し、破壊的な直接上昇型ミサイルによる衛星破壊（ASAT)実験を行わないよう求める

    Calls upon all States to commit not to conduct destructive direct-ascent anti-satellite missile tests
  - かかるコミットメントは、宇宙空間の軍備競争を防ぐための更なる措置の策定にも貢献するものであると同時に、宇宙空間の環境に損害をもたらすことを防ぐことを目的とする初期、かつ、喫緊の措置であることを考慮する
    - Considers such a commitment to be an urgent, initial measure aimed at preventing damage to the outer space environment, while also contributing to the development of further measures for the prevention of an arms race in outer space

Astroscale

まとめ Summary

まとめ　Summary

- 宇宙の持続可能利用が必要という認識が、具体的な政治的なアクション、政策となってきている。
  - 科学的・技術的なコンセンサスから政治的なアクション、具体的な政策につながりつつある。
  - 原則や目標に留まらない。宇宙デブリを含め、責任を持って所管する組織やアクションの特定など、具体的な実施に繋がる政策も登場。
  - 宇宙の持続利用を実現する上での「政策」「規制」役割の重要性。

- 科学的・技術的な軌道環境への配慮のみならず、軌道の利用によりもたらされる経済的な側面（宇宙経済の促進）、地上の経済活動、開発、地球環境への影響などへの考慮も後押し。民間企業の自主的な取組。

- 軍事的な宇宙利用においても、持続可能な宇宙利用が規範となりつつある。

- 今後の課題・期待
  - コンセンサスからアクションに繋げる必要性。具体性を持った政策・規制が期待される
  - 軌道環境の容量（carrying capacity)や個別ミッションの環境に与える評価などの指標についての技術的な議論と政治・外交的な議論の双方が必要。
  - 包括的な国際的な調整は将来的には必要。各国レベルのでの措置→国際的な規範？

Summary

- The recognition on the need for space sustainability has been translated into political actions and actual policies.
  - From the scientific and technical consensus to political actions.
  - Not just principles and aims. Some policies identify responsible organizations and specific actions including on space debris.
  - The increasing awareness of the role of policy and regulation for space sustainability

- Not just scientific and technical consideration for space environment. Consideration on the need for promoting space economy, economic activities and development on earth and earth environment are taking into considered and pushing this trend. Role of commercial space.

- Space Sustainability is an important norm in space security field.

- Future agendas
  - From consensus and principles to action. Need further policies that specifies actions.
  - Need technical discussions including threshold-based models or metrics as orbital environmental capacity, assessment of each mission as well as political and diplomatic discussion in order to move space governance discussion forward.
  - Comprehensive coordination at the global level in the future are necessary. Unilateral and pluri-lateral approach to broader global framework?

B20

STM をめぐる米欧関係と日本への示唆

U.S.-European Relations Regarding STM and Implications for Japan

○岩城 陽大（JAXA 経営企画部推進課）
○IWAKI Akihiro (Management Division, Strategic Planning and Management Department, JAXA)

本発表では，米国 STM 政策に関する米国内の近時の状況と EU の反応を取り上げる．とりわけ安全保障上も既に米国と SSA 分野の協力を深めている EU 諸国がいかなる理由で米国の STM システムからの独立を志向しているかを検証し，米国と EU の双方が STM の国際規範形成を産業上の優位性をめぐる競争の一環とも捉え，これをリードする意思を示していることを指摘した上で，日本への政策的な示唆を検討する．

This paper addresses the recent developments in the U.S. on a civil regime for STM and the European response to the initiative. In particular, it will examine the reasons why EU countries, which have already deepened their security cooperation with the U.S. in the field of SSA, are seeking to become independent from the U.S. STM system. It points out that both the U.S. and the EU view the formation of international norms for STM as part of the global competition for industrial advantage and have indicated their willingness to take the lead in this area, and then examines the policy implications for Japan.

B20. U.S.-European Relations Regarding STM and Implications for Japan

10th Space Debris Workshop
29TH November 2022

Akihiro Iwaki (JAXA)
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1

Background: Space is becoming more crowded due to security and civilian activities.

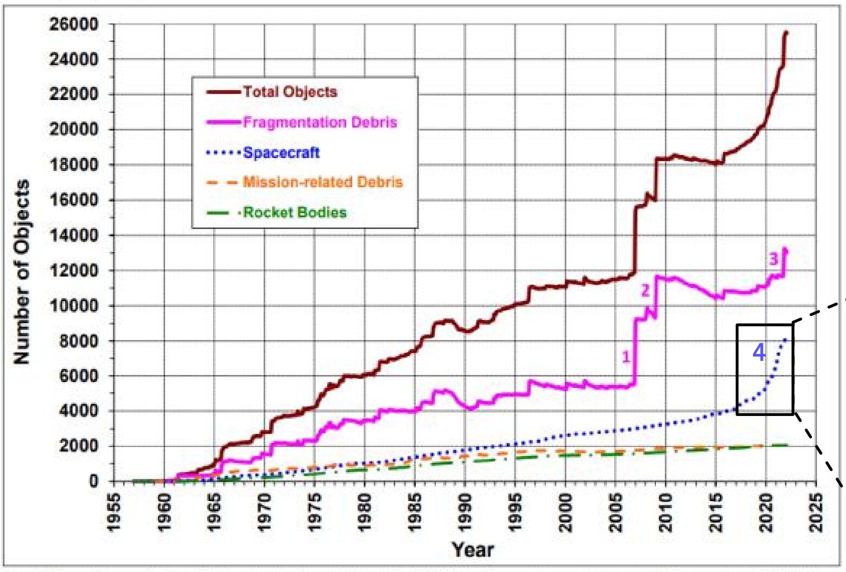
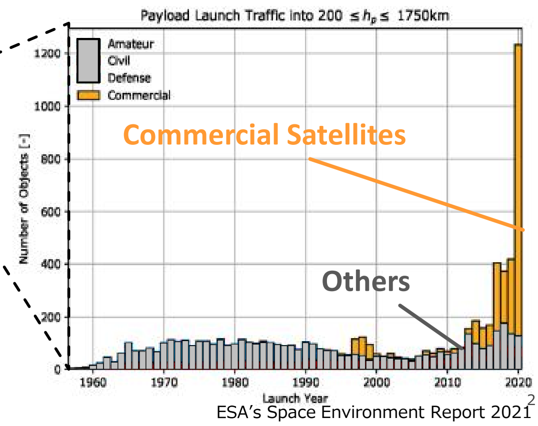


Figure 4. Historical increase of the cataloged objects based on data available on 1 March 2022. The three upward jumps in fragmentation debris correspond to (1) the ASAT test conducted by China in 2007, (2) the accidental collision between Iridium 33 and Cosmos 2251 in 2009, and (3) the ASAT test conducted by the Russian Federation in November 2021. More Cosmos 1408 fragments are expected to the added to the catalog in the coming weeks and months.

https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv26i1.pdf

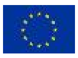
1. Chinese Anti-Satellite Test（2007）
2. The Collision of Iridium 33 and Cosmos 2251 (2009)
3. Russian Anti-Satellite Test(2021)
4. Large constellations (2018~)

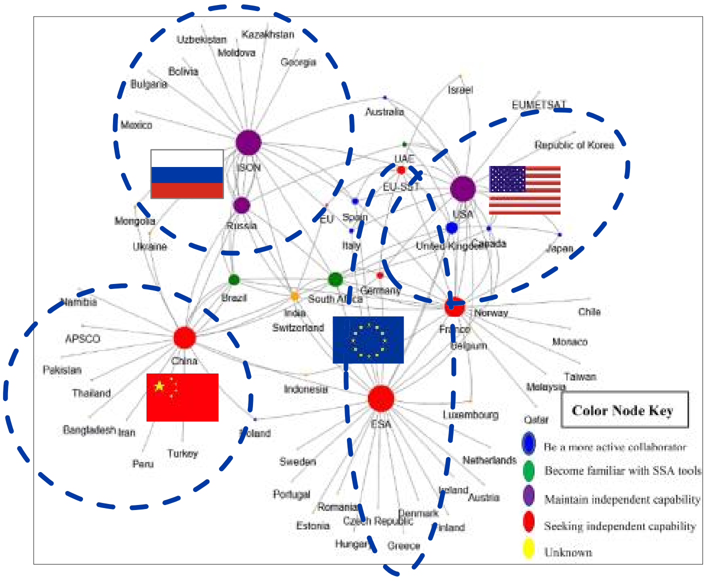


ESA's Space Environment Report 2021

2

Background: The global SSA system is divided into four poles; US, Russia, China, and Europe.

US 	• The world's largest space surveillance network (SSN), more than 30 optical telescopes and radars and six satellites. • SSA data sharing agreements with over 100 countries and companies worldwide.
Russia 	• The second most advanced SSA capability. Utilizing infrastructure developed during the Cold War for missile warning and other purposes, the capability has been reactivated through modernization since the early 2000s. • Nearly 100 optical sensors to 40 stations in 16 countries through ISON.
China 	• An advanced network of optical telescopes and radars. On-orbit satellites to collect information on other countries' satellites from 2010 onward. • Through APSCO, 15cm telescopes in Peru, Iran, and Pakistan; 50cm class telescopes are scheduled to be installed in all eight member countries.
EU 	• More than 50 sensors managed by EU SST, which is operated by France, Germany, Italy, Poland, Portugal, Romania, and Spain.



Partnerships on Space Activities, particularly for SSA

（Source）Global Counterspace Capabilities, Secure World Foundation, 2022; Lal et al. "Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM)", The Institute for Defense Analyses, 2018

Europe and the U.S. have a cooperative relationship including space security.

✓ **All EU SST member states have signed SSA data sharing agreements with the U.S.**

✓ **The EU SST's current conjunction messages are using data shared from the U.S.**

✓ **France and Germany have concluded an agreement to exchange classified SSA data as well. Both countries also participate in multilateral wargames with Japan, such as Schriever Wargame, hosted by the U.S. Space Force.**

Question

What are the motivations for EU toward an independent SSA system?

- **Developments in the U.S.**
- **Developments in Europe**
- **U.S. and European Developments in STM norms formation**
- **Political Implications for Japan**

US: Continued progress toward establishing a civilian STM system

Although Congress has not yet approved the transfer of authority, the SPD-3 policy remains in place and efforts are underway to establish a civilian STM system.

Administrations

Space Policy Directive (SPD)-3 by the Trump Administration
The Department of Commerce will make space safety data and services available to the public, while the Department of Defense maintains the authoritative catalogue of space objects.

United States Space Priorities Framework by the Biden Administration
The United States will bolster space situational awareness sharing and space traffic coordination.

Feb. OADR Prototype released
RFI for Commercial SSA data
Jul. RFP for Commercial SSA data
Sep. MOA between DoD and DoC

2018 2019 2020 2021 2022

https://www.space.commerce.gov/president-signs-space-traffic-management-policy/

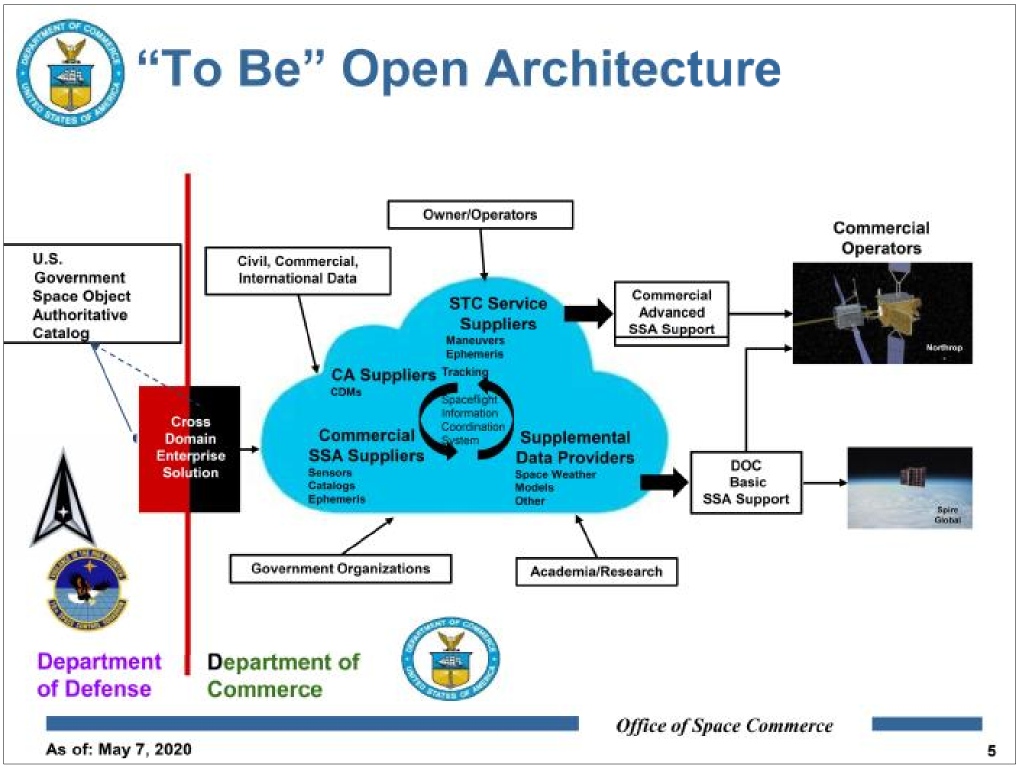
Congress

Consolidated Appropriations Act
funding for the Office of Space Commerce

Approved the STM pilot program for OADR

May. the House Committee hearing titled, **"Space Situational Awareness: Guiding the Transition to a Civil Capability."**

➡ No conclusion has yet been reached on the appropriate sharing of roles between commercial services and government.



7

US : Commercial SSA market is expanding and there are many new entrants

How to evaluate and utilize the various capabilities related to SSA and STM of private operators is one of the issues in the U.S. Congress

COMSPOC	Developed the first commercial off the shelf (COTS) SSA enterprise system. Verified by the U.S. military in its JMS initiative, COMSPOC's SSA Software Suite provides HiDeph ephemerides using comprehensive, sensor-agnostic data fusion and advanced analytics.
L3 Harris Technologies	Owns and operates the Global Optical Network (GON) of electro-optical telescopes from seven observatories around the world.
ExoAnalytic Solutions	Operates the ExoAnalytic Global Telescope Network, the largest commercial observation network of 275 telescopes in 25 observatories tracking all objects larger than 10 cm in GEO.
LeoLabs	Operates 4 radars and is building a network of 20+ radars to detect and track objects as small as 2 centimeters.
Privateer	Founded by Apple co-founder Steve Wozniak and others. The first technology demonstration 3U cubesat Pono1 is scheduled for launch at the end of 2022.
SCOUT	Launch with SSA payload in July 2021. 6U original satellite OVER-Sat to be launched in 2Q 2023. 100+ satellites planned by 2026.

8

US : The private sector is taking the lead in setting standards and guidelines related to STM.

Practices developed by private forums are reflected in the government regulations and international standards.

Space Safety Coalition (SSC)	• Best Practices for the Sustainability of Space Operations	Aims to promote space safety and sustainability through the promotion of industry best practices. Provides recommendations and technical standards. Endorsed by industry members.
CONFERS	• Guiding Principles for Commercial RPO and OOS • Recommended Design and Operational Practices • On-Orbit Satellite Servicing Mission Phases	An industry-led consortium based on initial DARPA funding. Publishes government and industry best practices as technical and operational standards for OOS and RPO.
ASCEND	• Satellite Orbital Safety Best Practices	Produced by SpaceX, OneWeb, and Iridium with the AIAA, which discusses and documents best practices for low Earth orbit (LEO) operations.

National regulations **International Standards**

Ex) **SSC Best practices**
5. h. **Operators of spacecraft that use chemical or electric propulsion to deorbit should strive to complete the deorbit phase within 5 years of end-of-mission**
⇒ **FCC adopts 5-year rule for LEO deorbit**

ISO Developing	• RPO and OOS • Launch Collision Avoidance (LCOLA)

➡ "Coordination and Management of Space Traffic" was rejected by European industry and ESA. Demanded that new standards be developed from scratch with all stakeholders.

9

EU : Building European STM structure to ensure strategic autonomy and industrial leadership

Strong recognition of the importance of U.S.-European cooperation, but also cautious about U.S. construction of a civilian STM system as part of the America First policy.

European Space Policy Institute : **Towards a European Approach to Space Traffic Management(2020)**	• ***"U.S. plans to encourage U.S. commercial leadership in STM solutions"*** • ***"The promotion of such U.S.-led standards as a basis for the establishment of common global best practices could also extend their influence to other markets."*** • ***"Europe must play an active role in the development of STM standards and best practices"***
ASD-EUROSPACE*: **Position Paper : Space Traffic Management (STM)** **An Opportunity to Seize for the European Space Sector** **EUROSPACE Manifesto for a European Global Answer on STM, (2021)** *Eurospace is the trade association of the European Space Industry. Eurospace member companies today represent 90% of the total turnover of the European Space Industry.	• ***"(s)ome countries (i.e., the US) have already paved the way for a national STM regulation that will eventually have an impact on European actors and jeopardise European sovereignty as an overarching objective of the EU for space"*** • ***"The reforms undertaken by the US administration could indeed potentially have a very significant impact on:*** **(1) The sustainability of the European model of autonomous access to space and its use:** ①Because of the inherent dependency to the US, especially in light of a possible introduction of stringent requirements only reachable through the use of data exclusively available from the US ②Because of the need to comply with a set of guidelines and best practices defined by and **(2) The competitiveness of the European space manufacturing industry:** ① The European satellite manufacturers' competitiveness on exports markets could be threatene ② Disadvantage to launch operators due to lack of launch window and collision avoidance certifications from the U.S. authorities. ③ SSA data sharing agreements with the US could potentially be subject to the fees. ④ SSA/STM service development provided by the DoC is dominated by U.S. companies. ⑤ Major industrial initiatives for STM are always led by the U.S. ⑥ STM-related standardization in ISO is based on U.S. proposals without a unified European stance

10

EU: An EU Approach for Space Traffic Management - An EU contribution addressing a global challenge

European Commission laid out the EU STM approach would build on the following four avenues developed in parallel.

1 Assessing the STM requirements and impacts for the EU	**Establish a consultation mechanism with all stakeholders in the EU** to understand the requirements for STM in Europe and the impact of STM progress; **compile military and civilian needs for an EU STM approach by early 2023**, and maintain a regular dialogue for related developments thereafter.
2 Enhancing EU operational capabilities to support STM	**EU SST** is positioned **as the operational foundation of the EU STM**. Develop to **the capability to observe all space objects larger than 10 cm to ensure European autonomy**. Develop satellite-based space-deployed sensors, high-performance ground-based radar and telescope systems, and observation facilities outside the European continent. **By the end of 2024, the EU SST will have its own space object catalog**, part of which will be made available to EU industry for the development of high value-added information. **Maximize the use of the European ecosystem, including new space created through the establishment of the EU SST, and contribute funds** to promote related private sector technological development and innovation. ⇒April 2022: the EU Industry and Start-up Forum (EISF) on STM was launched.
3 Fostering STM regulatory aspects	**Establish a regulatory coordination forum within the EU by the end of 2023** to take advantage of the industrial benefits of the development of STM standards and related standards; **develop new European and international standards** in cooperation with EU SST participating countries, EU industry, ESA, etc., and promote the standards and guidelines selected therein at the EU level ⇒This is also taken up in the EU-wide standardization strategy "Strategy for securing international leadership in standardization".
4 Promoting the EU STM approach globally	In the future, it would be **ideal to establish a global STM system under the framework of the United Nations**. The various initiatives described in 1-3 above are preconditions for a global STM system. Promote **"privileged dialogue" with the U.S.** and dialogues other countries.

11

The U.S. and European Developments in the Formation of STM Norms

Both the U.S. and Europe are strongly recognizing the benefits to the space industry of STM norm and have indicated their willingness to lead the international norm setting

	US	EU
STM system	**The Department of Commerce will make space safety data and services available to the public**, while the Department of Defense maintains the authoritative catalogue of space objects	**EU SST** is positioned **as the operational foundation of the EU STM**. Develop to **the capability to observe all space objects larger than 10 cm to ensure European autonomy**
Private Sector Partnership	**Collaboration with the private sector through ODAR**	**Building an SSA ecosystem that includes SMEs**
Norm Setting	Reflecting rules considered by private forums in government regulations and international standards **⇒Led by private forums**	Willingness to take the lead internationally by solidifying standards and guidelines within the EU region. **⇒Formation of a regional forum of industry and government**

12

Policy Implications for Japan

The private sector can play a significant role in shaping international norms for STM by creating industry standards and best practices and providing input to the government.

Utilize private sector capacity in establishing STM structure	In the Japanese Basic Plan on Space Policy, the importance of private sector utilization in SSA is clearly stated, and concrete efforts have already been made. In addition to utilizing existing capabilities, **it is also essential to create and foster an industrial ecosystem, including a domestic new space for SSA and STM, based on active investment similar to that in the U.S. and Europe**.
Ensuring "Strategic Autonomy" is the Subject of Building an independent STM System in Europe	As space congestion becomes more and more serious in the future, SSA/STM capability will be of vital importance for the continuity of space activities in general, including rocket launches, satellite operations, and on-orbit services. Therefore, **it is necessary to examine what kind of SSA/STM capabilities Japan should maintain in the future, from the perspective of possessing independent space activity capabilities as stipulated in the Basic Space Act.**
Responding to the formation of different STM systems between the U.S. and Europe	Basically, it is assumed that necessary services can be provided by the U.S. STM and private services using it. On the other hand, depending on the usage and needs of the services, situations where the EU system and EU private services are utilized are also expected. **From the perspective of ensuring user convenience and avoiding international confusion, it is important to ensure interoperability and complementarity between the two systems.**
The viewpoint that sees the formation of international STM norms common to the U.S. and Europe as the basis of industrial competitiveness.	Japan has also established a “Policy for Med- and Long-Term Initiatives Concerning Rule-Making for Orbit Use” It stated that Japan will proactively work on rule-making for track use ahead of other countries. At the same time**, it is necessary to immediately follow up appropriately on the creation of international standards at ISO, where important developments are already underway.** **From the perspective of linking international norms on STM to ensuring Japan's industrial competitiveness, the private sector can play a significant role through the formation of industry standards and best practices and providing input to the government.**

Thank you for your attention.

B21

新たな宇宙活動のルール作りに関する軌道上サービスガイドラインの含意

Implications on Japanese Guidelines on a License to Operate a Spacecraft Performing On-Orbit Servicing

○菊地耕一（JAXA 総務部）
○KIKUCHI Koichi (JAXA General Affairs Department)

2021 年 11 月、日本において「軌道上サービスを実施する人工衛星の管理に係る許可に関するガイドライン」が制定・公表された。同ガイドラインは、宇宙活動法の下で実施する能動的デブリ除去（ADR）を含む軌道上サービスミッションに対し、安全性と透明性を確保するための法的、技術的、組織的な要求を定めている。2020 年 12 月、「スペースデブリに関する関係府省等タスクフォース」の下にサブワーキンググループが設置され、軌道上サービスのルールの検討が開始された。2021 年 5 月、サブワーキンググループはタスクフォースの大臣級会合で、報告書とルールを提出し、同ルールがガイドラインに反映された。政府が迅速に軌道上サービスのルールを作成した背景には、実際に軌道上サービス事業を計画している民間企業の存在がある。本発表は、ガイドラインの概要を説明するとともに、新たな宇宙活動のルール作りに関するガイドラインの含意を探るものである。

In November 2021, the Guidelines of a License to Control a Spacecraft Performing On-Orbit Servicing were established and published in Japan. The Guidelines provide legal, technical, and organizational requirements to ensure safe and transparent on-orbit servicing missions including active debris removal (ADR) carried out under the Space Activities Act. In December 2020, the sub-working group established under the Inter-Agency Task Force on Space Debris started the study of the rules for the on-orbit servicing missions. In May 2021, the sub-working group delivered the report and the rules which were to be reflected in the Guidelines at the Ministers' Meeting of the Task Force. The presence of the space companies in Japan which are engaged in the on-orbit servicing including ADR motivated the government to formulate the appropriate rules for their business in the timely manner. In this presentation, I will explain the overview of the Guidelines and explore the implications on the rule making for the emerging space activities.

IMPLICATIONS ON JAPANESE GUIDELINES ON A LICENSE TO OPERATE A SPACECRAFT PERFORMING ON-ORBIT SERVICING

KOICHI KIKUCHI
JAPAN AEROSPACE EXPLORATION AGENCY (JAXA)
KEIO UNIVERSITY SPACE LAW CENTER
THE UNIVERSITY OF TOKYO GRADUATE SCHOOL OF PUBLIC POLICY (GRASPP)
THE UNIVERSITY OF TOKYO INSTITUTE FOR FUTURE INITIATIVES (IFI)

CHRONOLOGY

- In November 2020, the Government of Japan's Inter-Agency Task Force on Space Debris decided to start studying the rules and regulations for on-orbit servicing (OOS) missions.
- In December 2020, the Sub-Working Group on On-Orbit Servicing was established and started its study.
- In May 2021, the Sub-Working Group delivered the report with the Rules for On-Orbit Servicing.
- In November 2021, based on the Rules, the Guidelines on a License to Operate a Spacecraft Performing On-Orbit Servicing (OOS Guidelines) were established and published.


(Tentative translation/For reference purpose only)

Guidelines on a License to Operate a Spacecraft
Performing On-Orbit Servicing

National Space Policy Secretariat
Cabinet Office, Japan

10 November 2021

1

OOS Guidelines
(Source: Cabinet Office, Japan)

BACKGROUND

- The Astroscale is carrying out the Commercial Removal of Debris Demonstration (CRD2) program as a partner of JAXA.
- In JFY2020, the Asctroscale is planning to launch their spacecraft to carry out rendezvous and proximity operations to take the images of the other space object as technology demonstration mission for the active debris removal (ADR).

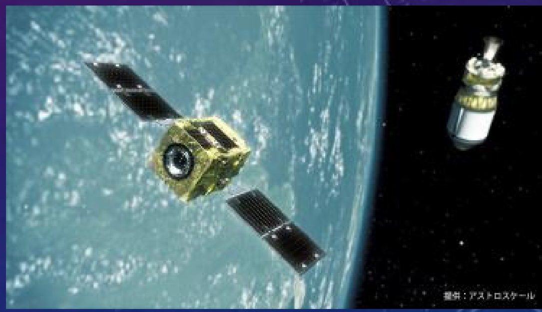


Image of CRD2 Phase 1
(Source: Astroscale)

SPACE ACTIVITIES ACT

- Act on Launching of Spacecraft, etc. and Control of Spacecraft (Space Activities Act)
- Order for Enforcement of Act on Launching of Spacecraft, etc. and Control of Spacecraft (Cabinet Order)
- Regulation for Enforcement of the Act on Launching of Spacecraft, etc. and Control of Spacecraft (Cabinet Office Order)
- Review Standards and Standard Period of Time for Process Relating to Procedures under the Act on Launching of Spacecraft, etc. and Control of Spacecraft
- Guidelines for laws and regulations

Legal Framework of Space Activities in Japan

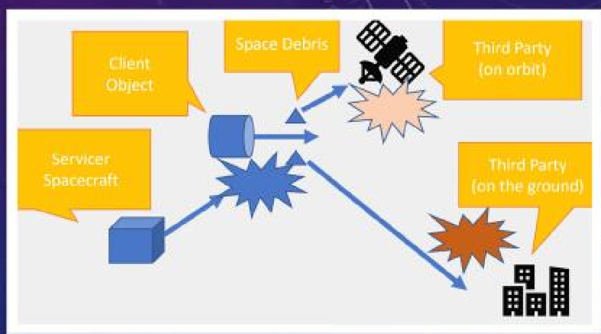
INTERNATIONAL FRAMEWORK

- Basic international legal framework
  - State Party to OST is responsible for its national space program.
  - Launching State(s) is(are) liable for damage to the third State caused by the space object launched.
  - State of registry obtains jurisdiction and right of control over the space object registered.
  - State of registry is equal to or included in the launching State(s).
- LTS Guidelines
  - Section A.3, A.5, B.1, B.4, B.8, B.10

UNCOPUOS
(Source: Ministry of Foreign Affairs of Japan)

CASE STUDY

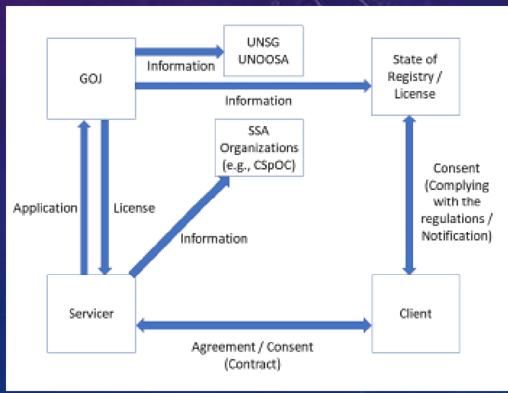
- Technical Aspects
  - The servicer should know the architecture of the client object to ensure safe operation throughout the mission.
- Legal Aspects
  - The stakeholders should understand the responsibility and liability to both of servicer spacecraft and client space object.
- International Relations
  - The rules should ensure safe and transparent OOS missions, and should be open.



Possible Scenarios

OVERVIEW OF THE RULES

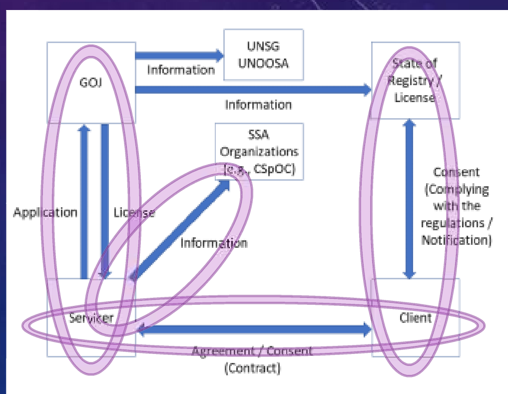
- The OOS mission should be conducted on the agreement between the servicer and the client or the consent from the client.
- The registration of the client object should be done.
- The client should comply with the rules of the State which registered or licensed the client object or notify the mission to that State.
- The servicer should provide the Space Situational Awareness (SSA) organization with the operation plan and other information.
- The servicer provide potentially affected entities in the case of malfunction or accident with the information necessary.



Framework of OOS

LEGAL REQUIREMENTS

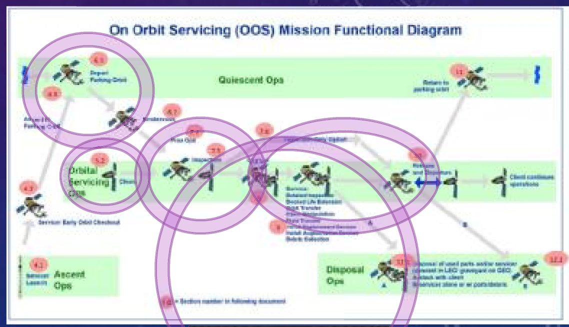
- Prevention of infringement of rights related to the client object
  - Confirmation of title to the client object
  - Respect for regulations of the state of registry/license
- Prevention of ex post facto interference caused by the client object
- Information disclosures for ensured transparency
  - Notification and reporting of the operation
  - Providing information in emergencies



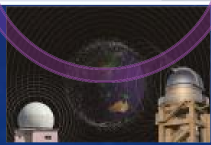
Framework of OOS

TECHNICAL REQUIREMENTS

- Study of the architecture of and other information on the client object for assurance
- Architecture of the servicer spacecraft
  - Recognizing the on-orbit state of the client object
  - Space situational awareness of the area where rendezvous and other operations are executed
  - Basic principle for approaching trajectories
  - Conditions of not taking a passively safe trajectory
  - Ensuring of stable operation during capture and docking
  - Employment of Go/No-go testing at appropriate timings in operations
- Identification of failure modes and risk mitigation
- Safety measures for specific missions (beaming and the release of objects)
- Architecture and an operations and management plan for securing the servicer spacecraft control



Mission Profiles of OOS (Source: CONFERS)



Space Situational Awareness (Source: JAXA)

ORGANIZATIONAL REQUIREMENT

- Appropriate structure for the operation
- Point of contact for inquiries from related organizations

HTV Mission Control Room (Source: JAXA)

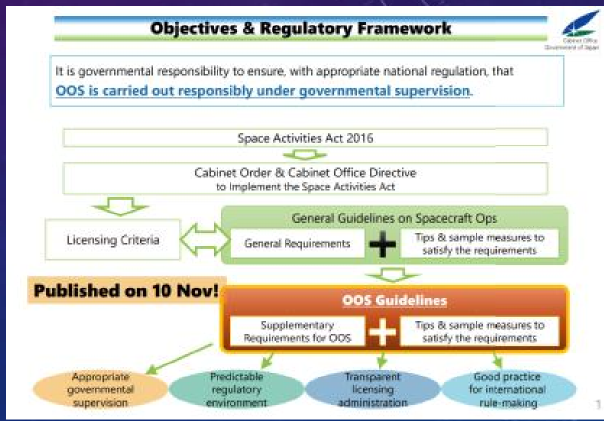
CONCLUSIONS AND NEXT STEPS

Conclusions

- The OOS missions are beneficial only when the safe and transparent operations are ensured.
- The Rules address the risks and employ safety and transparency as the principles.
- The principles of safety and transparency can be the norms for the sustainable space activities.

Next Steps

- The Government of Japan is expected to establish the national operational framework based on the Guidelines.
- Japanese space companies are expected to demonstrate the effectiveness and rationality of the Guidelines.



Objectives of OOS Guidelines
(Source: Cabinet Office, Japan)

THANK YOU FOR YOUR ATTENTION!

Related Websites

- Cabinet Office, the Government of Japan
  https://www8.cao.go.jp/space/english/stm/index.html
- Space Law Center, Keio University
  http://space-law.keio.ac.jp/ (in Japanese)
- Institute for Future Initiatives, The University of Tokyo
  https://ifi.u-tokyo.ac.jp/projects/space-and-cyber-risk-governance/ (in Japanese)
  https://spacepolicyandlaw.com (under construction)

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B22

宇宙活動における国家の責任ある行動の法的根拠と展開
Legal Rationale & Development of “Responsible Behavior” of States in Space Activities

○竹内悠（JAXA 研究開発部門）
○TAKEUCHI Yu (JAXA Research and Development Directorate)

持続可能な宇宙活動の実施に関心が集まるにつれて、責任ある行動（responsible behavior）が国家に求められる場面が増えている。この言説は政治的な文脈で用いられることも多いが、法的含意を持っていることもあるため、本稿では、責任ある行動の要求が国際法上のどのような法的根拠に基づいており、どのような法的効果を持つかを論じる。これにより、どのような水準での宇宙活動であれば、責任ある行動の範疇と認識されるのかの明確化を試みる。

As interest in the implementation of sustainable space activities grows, responsible behavior is increasingly required of states. Since this discourse is often used in a political context, but also has legal implications, this paper discusses on what legal basis and with what legal effect the demand for responsible behavior is based under international law. By doing so, it will attempt to clarify at what level space activities can be recognized as a category of responsible behavior.

10th Biannual Space Debris Workshop @ JAXA Chofu Aerospace Center
29 November 2022

B22
Legal Rationale & Development of "Responsible Behavior" of States in Space Activities
宇宙活動における国家の責任ある行動の法的根拠と展開

TAKEUCHI YU
竹内悠
(JAXA/KEIO SPACE LAW CENTER)

1."Responsible behavior" ?

2

United Nations A/AC.105/1262

General Assembly

Distr.: General
6 December 2021
English
Original: Chinese

Committee on the Peaceful Uses of Outer Space

Information furnished in conformity with the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies

Note verbale dated 3 December 2021 from the Permanent Mission of China to the United Nations (Vienna) addressed to the Secretary-General

The Permanent Mission of China to the United Nations (Vienna) presents its compliments to the Secretary-General of the United Nations and has the honour to refer to article V of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies[1] (the Outer Space Treaty), which provides that "States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary-General of the United Nations of any phenomena they discover in outer space, including the Moon and other celestial bodies, which could constitute a danger to the life or health of astronauts ". In accordance with the above-mentioned article, China hereby informs the Secretary-General of the following phenomena which constituted dangers to the life or health of astronauts aboard the China Space Station.

The China Manned Space Programme completed five launch missions in 2021, with the successful launching into orbit of the Tianhe core module of the China Space Station, the Tianzhou-II and Tianzhou-III cargo spacecraft and the Shenzhou-XII and Shenzhou-XIII crewed spacecraft. The China Space Station has travelled stably in a near-circular orbit at an altitude of around 390 km on an orbital inclination of about

ARTICLE V

States Parties to the Treaty shall regard astronauts as envoys of mankind in outer space and shall render to them all possible assistance in the event of accident, distress, or emergency landing on the territory of another State Party or on the high seas. When astronauts make such a landing, they shall be safely and promptly returned to the State of registry of their space vehicle.

In carrying on activities in outer space and on celestial bodies, the astronauts of one State Party shall render all possible assistance to the astronauts of other States Parties.

States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary-General of the United Nations of any phenomena they discover in outer space, including the moon and other celestial bodies, which could constitute a danger to the life or health of astronauts.

3

Space Station performed an evasive manoeuvre again on the same day to avoid a potential collision between the two spacecraft.

In view of the foregoing, China wishes to request the Secretary-General of the United Nations to circulate the above-mentioned information to all States parties to the Outer Space Treaty and bring to their attention that, in accordance with article VI of the Treaty, "States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty."

REUTERS World Business Legal Markets Breakingviews Technology Investigations More

China's foreign ministry spokesperson Zhao Lijian attends a news conference in Beijing, China November 16, 2021. REUTERS/Carlos Garcia Rawlins

BEIJING, Dec 28 (Reuters) - The Chinese foreign ministry said on Tuesday that the United States ignored obligations under outer space treaties, exposing astronauts to danger.

China urges the United States to act responsibly, Zhao Lijian, spokesperson at the foreign ministry, said at a regular press conference.

(Source) "China urges U.S. to act responsibly in space", *Reuters*, Dec. 28, 2021.

4

May 9, 2021
RELEASE 21-060

NASA Administrator Statement on Chinese Rocket Debris

NASA Administrator Sen. Bill Nelson released the following statement Saturday regarding debris from the Chinese Long March 5B rocket:

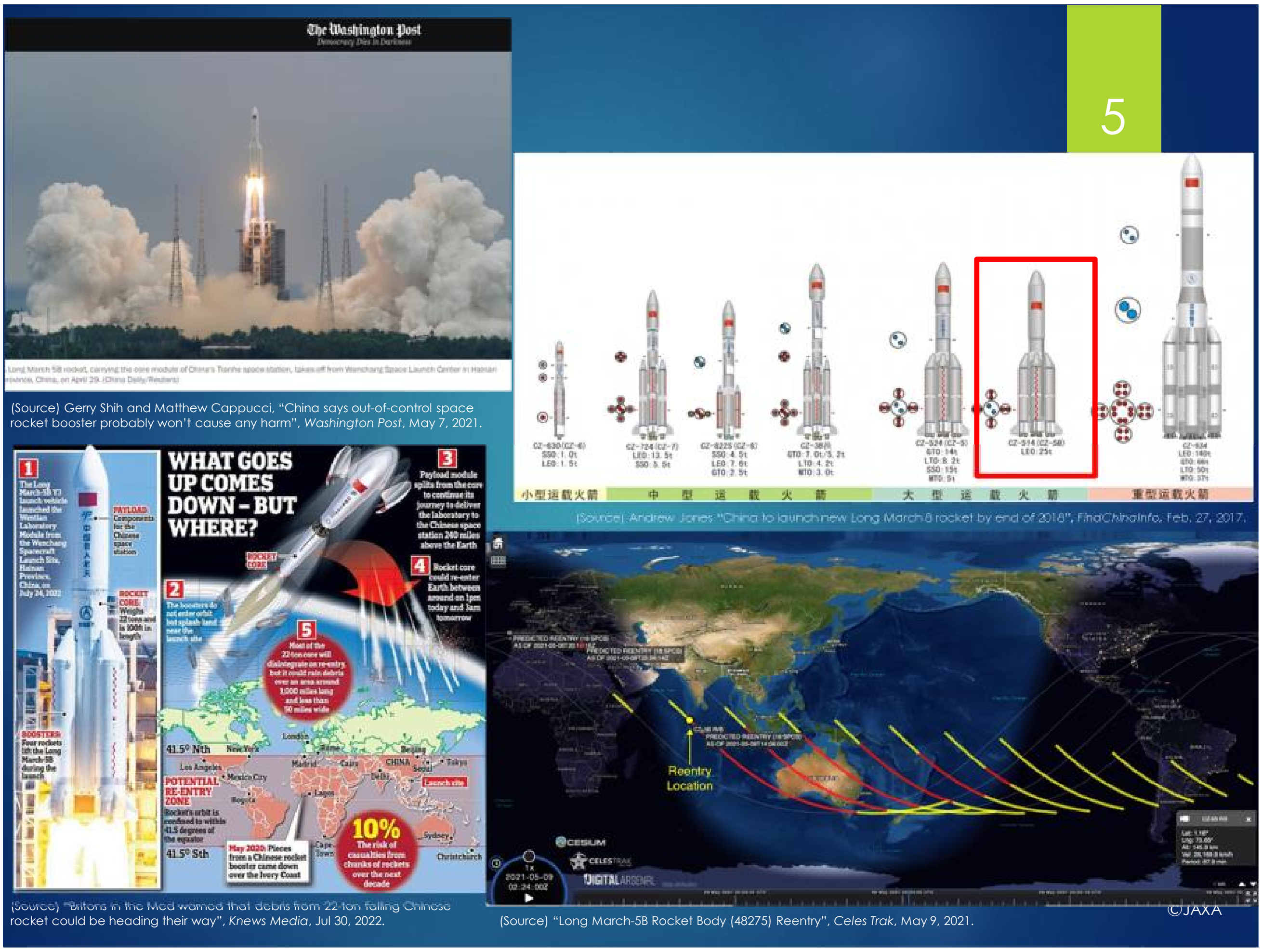
"Spacefaring nations must minimize the risks to people and property on Earth of re-entries of space objects and maximize transparency regarding those operations.

"It is clear that China is failing to meet responsible standards regarding their space debris.

"It is critical that China and all spacefaring nations and commercial entities act responsibly and transparently in space to ensure the safety, stability, security, and long-term sustainability of outer space activities."

For more information on NASA and agency activities, visit:

(Source) NASA Press release, "NASA Administrator Statement on Chinese Rocket Debris", May 9, 2021.



NASA Administrator Statement on Chinese Space Debris

NEWS PROVIDED BY
NASA →
Jul 30, 2022, 14:25 ET

SHARE THIS ARTICLE

WASHINGTON, July 30, 2022 /PRNewswire/ -- NASA Administrator Bill Nelson released this statement Saturday regarding debris from the Chinese Long March 5B rocket:

"The People's Republic of China (PRC) did not share specific trajectory information as their Long March 5B rocket fell back to Earth.

"All spacefaring nations should follow established best practices and do their part to share this type of information in advance to allow reliable predictions of potential debris impact risk, especially for heavy-lift vehicles, like the Long March 5B, which carry a significant risk of loss of life and property. Doing so is critical to the responsible use of space and to ensure the safety of people here on Earth."

For more information on NASA and agency activities, visit:
https://www.nasa.gov

(Source) NASA Press release, "NASA Administrator Statement on Chinese Space Debris", Jul. 30, 2022.

7

SPACENEWS

U.S. declares ban on anti-satellite missile tests, calls for other nations to join

by Sandra Erwin — April 18, 2022

Vice President Kamala Harris speaks April 18, 2022, at Vandenberg Space Force Base, California. Credit: @SLDelta30

VP Harris: A commitment to not destroy satellites in orbit should become a 'new international norm for responsible behavior in space'

WASHINGTON – Vice President Kamala Harris announced April 18 that the United States will ban direct-ascent anti-satellite (ASAT) missile tests that create orbital debris.

(Source) Sandra Erwin, "U.S. declares ban on anti-satellite missile tests, calls for other nations to join", *SpaceNews*, Apr. 18, 2022.

2. Legal Rationale of "Responsible behavior"

8

OUTER SPACE TREATY

ARTICLE VI

States Parties to the Treaty shall bear **international responsibility** for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or **by non-governmental entities**, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty. When activities are carried on in outer space, including the moon and other celestial bodies, by an international organization, responsibility for compliance with this Treaty shall be borne both by the international organization and by the States Parties to the Treaty participating in such organization.

[international responsibility]

- Requirements: international **wrongful act** of a State
- Effects: restitution（原状回復）, compensation（金銭賠償） and satisfaction（満足）.

(UNILC draft text of "Responsibility of States for Internationally Wrongful Acts", 2001.)

[International Wrongful Act]

There is an internationally wrongful act of a State when conduct consisting of an action or omission … **constitutes a breach of an international obligation of the State.**

An international obligation to be breached…

9

OUTER SPACE TREATY

ARTICLE IX

In the exploration and use of outer space, including the Moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with **due regard (妥当な考慮)** to the corresponding interests of all other States Parties to the Treaty. (…)

[Due regard]

- Chagos Marine Protected Area Arbitration (Mauritius v United Kingdom), Arbitration, 2015.
- *In exercising its rights and performing its duties under this Convention in the exclusive economic zone, the coastal State shall have* ***due regard*** *to the rights and duties of other States and shall act in a manner compatible with the provisions of this Convention.* (UN Convention on the Law of the Sea, Art.56(2))
  - *“(T)o have such regard for the rights of Mauritius as is called for by the circumstances and by the nature of those rights”* ***≠ “universal rule of conduct”/”uniform obligation” for “due regard”.***
- Whaling in the Antarctic (Australia v Japan: New Zealand intervening), ICJ, 2014.
- *States party has an obligation to give “****due regard****” to non legally binding Commission recommendations calling for assessment of the feasibility of non-lethal scientific research methods.*

- “**Due regard tests impose only procedural requirements on States**, though it may be admitted that in some circumstances assessing compliance could involve an element of judgement on substantive matters.” (Foster 2020.)

3. Legal Development of ”Responsible behavior”

10

“Responsible behavior” = due regard = procedural requirements test

- Established procedural requirements:
  - Outer Space Treaty Article VI

    …The activities of non-governmental entities in outer space, including the moon and other celestial bodies, **shall require authorization and continuing supervision** by the appropriate State Party to the Treaty. …
  - UNCOPUOS “Recommendations on national legislation relevant to the peaceful exploration and use of outer space” (A/C.4/68/L.2), 2013.

Scope for Activities	Scope of Applicants	Regulatory Framework
- Launch. - Return from space. - Operation of launch and re-entry site. - Operation and control on orbit.	- Territory under jurisdiction and/or control of the State. - Activities carried out by State’s citizens (including legal persons).	Clearly established in the national regulatory framework, with conditions and procedures for granting, modifying, suspending, and revoking the authorization.

- Elements on substantive matters:
  - UNCOPUOS “Space Debris Mitigation Guidelines” (A/RES/62/217), 2007.
  - UNCOPUOS “Guidelines for the Long-term Sustainability of Outer Space Activities” (A/AC.105/2018/CRP.20), 2018.

“Responsible behavior” =

- Establishing national systems for authorization and continuing supervision including the “elements of substantive matters”.
- Require further elaboration for security aspects.

11

Thank you

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C01

微小デブリ観測衛星を用いた破砕起源の推定

Origin Identification of Breakup Event from In-situ Debris Measurements

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TANAHASHI Mahiro, YOSHIMURA Yasuhiro (Kyushu Univ.), FUJITA Koki (Nippon Bunri Univ.),
〇HANADA Toshiya (Kyushu Univ.)

この論文では、その場デブリ計測から、破砕した物体の軌道要素をいくつか（具体的には、特定の時間における角運動量の方向とその時間変化）推定する新しいアプローチを簡単に紹介する。従前の研究では、検出された破片がその場デブリ計測衛星と地心位置ベクトルを共有するという事実から導き出された拘束方程式に非線形最小二乗フィッティングを適用した。新しいアプローチでは、検出時の地心赤緯の履歴に非線形最小二乗フィッティングを適用する。また，従前の研究では、すべての破片は破砕した物体とその場デブリ計測衛星の２つの軌道面の交線上で検出されるという理想的な条件下で検証されている。ただし、この研究では、接近解析を用いてより現実的なその場デブリ計測データを利用して検証する。

This paper briefly introduces a new approach to estimating some orbital parameters of on-orbit satellite fragmentations (precisely, the direction of angular momentum at a specific time and its time change) from in-situ debris measurements. Previous studies have applied a nonlinear least-squares fitting to a constraint equation derived from the fact that a piece of debris detected shares the geocentric position vector with an in-situ debris measurement satellite. However, the new approach applies a nonlinear least-squares fitting to the history of geocentric declination at the detection time. The previous studies have been verified under ideal conditions where all detections are assumed to be at the intersection of the two orbital planes of a broken-up object and an in-situ debris measurement satellite. However, this study verifies using more realistic measurements from a close approach analysis.

Kyushu University 2011 100th Anniversary

The 10th JAXA Space Debris Workshop

Origin Identification of Breakup Event from In-situ Debris Measurements

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November 30, 2022

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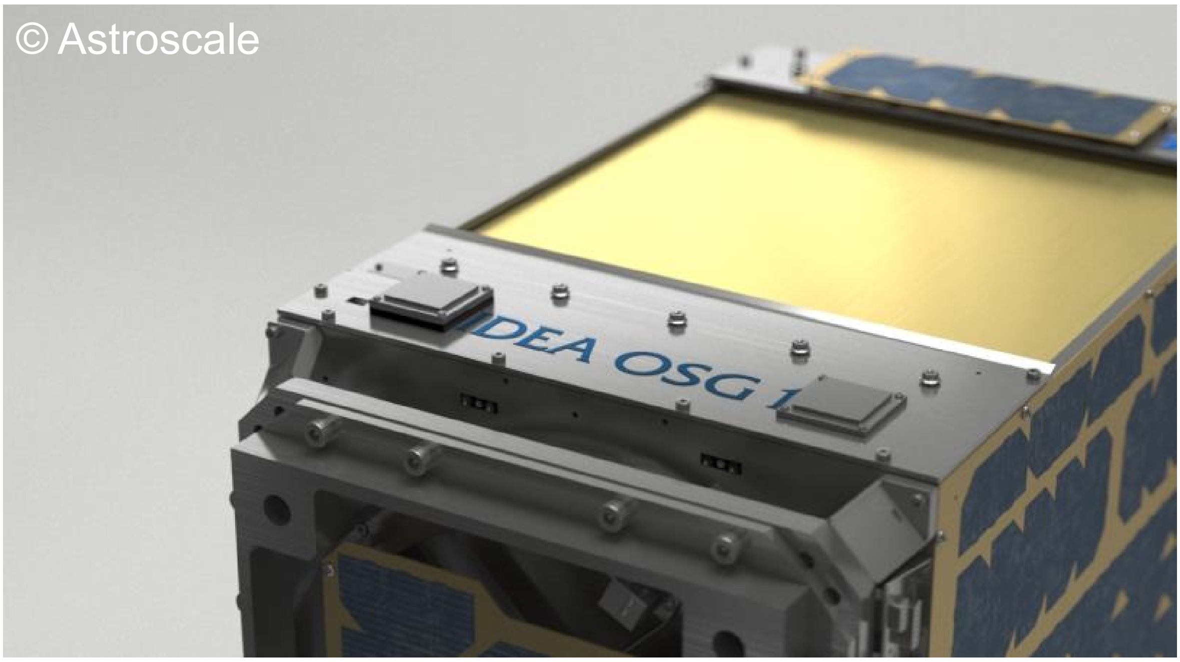
IDEA the Project for In-situ Debris Environmental Awareness



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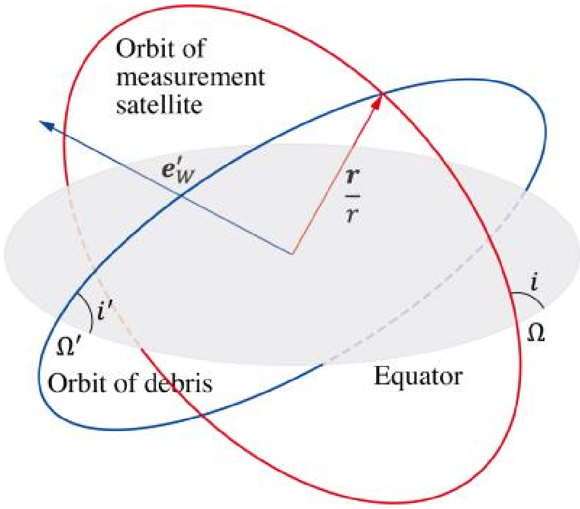
Constraint on Orbital Plane

A constraint on the orbital plane, where a measurement satellite detects a piece of debris, may be given by

$$\boldsymbol{e}'_W \cdot \boldsymbol{r} = 0$$

where

$$\boldsymbol{e}'_W = \begin{pmatrix} \sin\Omega' \sin i' \\ -\cos\Omega' \sin i' \\ \cos i' \end{pmatrix}$$



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Orbital Parameters to Estimate

Inclination: i'

RAAN at $t = t_0$: Ω'_0

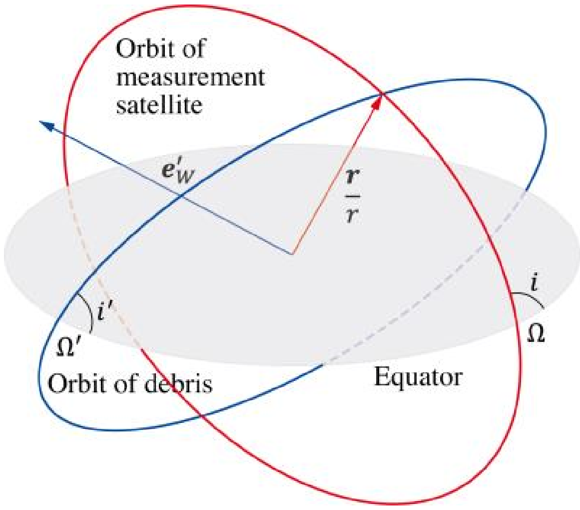
Rate of change in RAAN: $\dot{\Omega}'$

Note

$$\Omega'(t) = \Omega'_0 + \dot{\Omega}'(t - t_0)$$

and

$$\dot{\Omega}' \propto -\cos i'$$



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Orbital Parameters at the Time of Breakup

Objects	Measurement satellite	Broken-up object
Semi-major axis [km]	7176.138	7234.34
Eccentricity [–]	0.0001	0.0012112
Inclination [deg]	98. 567	50.6433
RAAN [deg]	267.7799	1.6779
Argument of perigee [deg]	357.6699	285.4809
Mean anomaly [deg]	258.5027	219.8224

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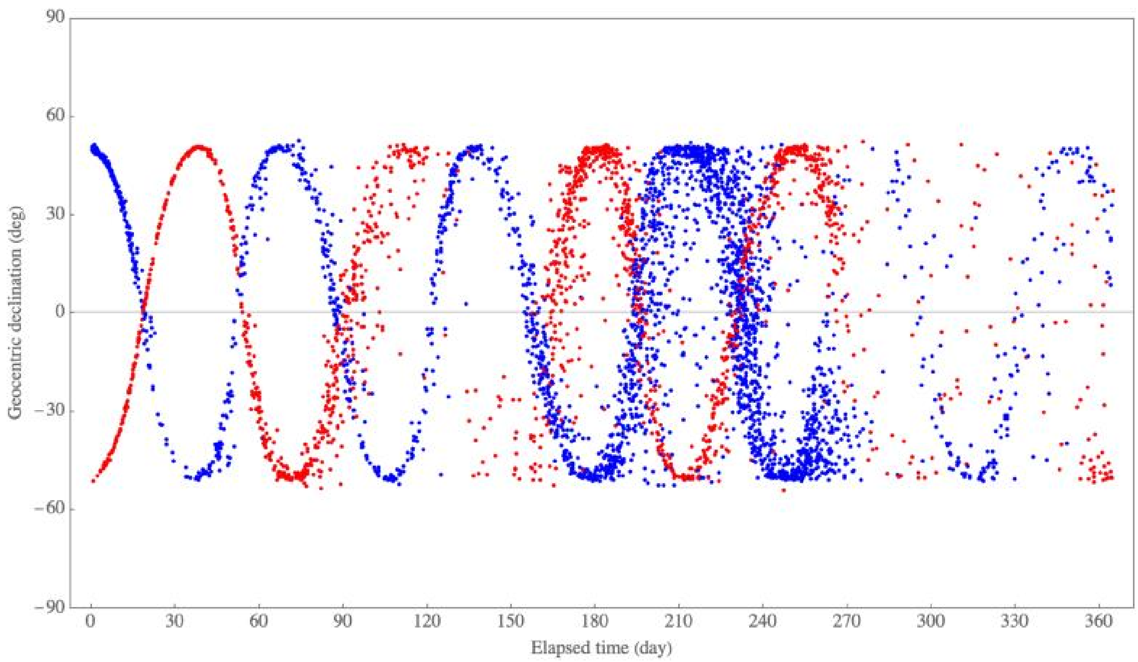
Geocentric Declination at the Time of Detection



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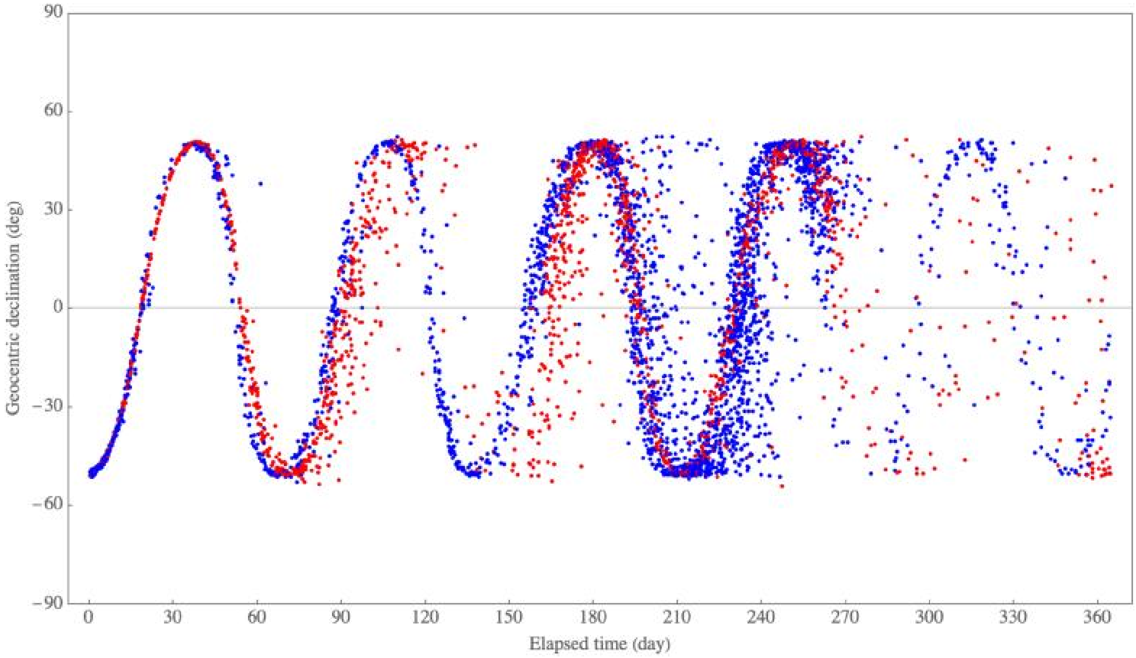
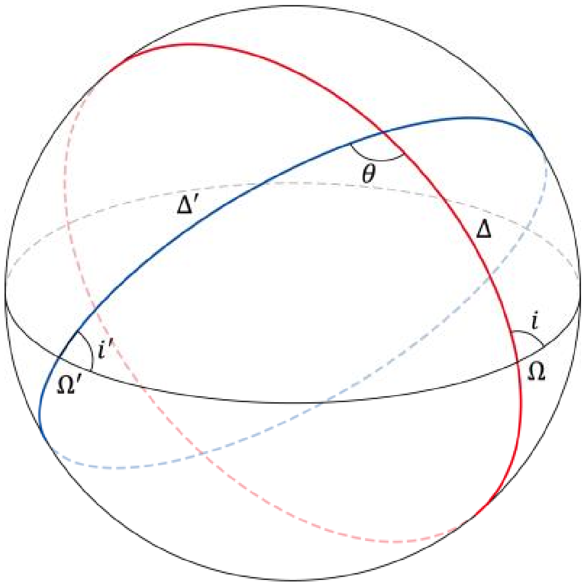
Geocentric Declination at the Time of Detection, cont’d



Relative Orientation of Orbital Planes



Red: Orbit of a measurement satellite (variables w/o prime)

Blue: Orbit of a piece of fragment (variables w/ prime)

i: Inclination

Ω: RAAN

Δ: Argument of true latitude

θ: Relative inclination

Condition for Geocentric Declination at the Time of Detection to Be Maximum or Minimum

Since $\sin\delta = \sin i \sin\Delta$, the geocentric declination at the time of detection can be maximum or minimum when $d\Delta/dt = 0$. The rate of change in the argument of true latitude at the time of detection (Δ) may be given by

$$\sin\theta \frac{d\Delta}{dt} = \sin i' \cos\Delta' \left(\frac{d\Omega}{dt} - \frac{d\Omega'}{dt}\right) + \sin\Delta' \frac{di'}{dt} - \sin\Delta \cos\theta \frac{di}{dt}$$

Except for special conditions such as $\sin i' = 0$ and $d\Omega'/dt = d\Omega/dt$, therefore, we have

$$\cos\Delta' = 0 \text{ or } \Delta' = \pm\frac{\pi}{2}$$

because the inclinations (i' and i) are not supposed to change over time.

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Condition for Geocentric Declination at the Time of Detection to Be Maximum or Minimum, cont'd

Let $\delta_{max} (> 0)$ be the maximum geocentric declination at the time of detection. Substituting δ_{max} and $\Delta' = \pm\pi/2$ into $\sin\delta = \sin i' \sin\Delta'$, then we have

$$i' = \delta_{max} \text{ and } i' = \pi - \delta_{max}$$

Thus, the inclination of broken-up object can be determined from the maximum geocentric declination at the time of detection. Note that this approach cannot work when $\delta_{max} = i$ and $\pi - \delta_{max} = i$. All we can know is that the inclination of broken-up object is between δ_{max} and $\pi - \delta_{max}$.

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Nonlinear Model

Δ in $\sin\delta = \sin i \sin\Delta$ can be calculated by

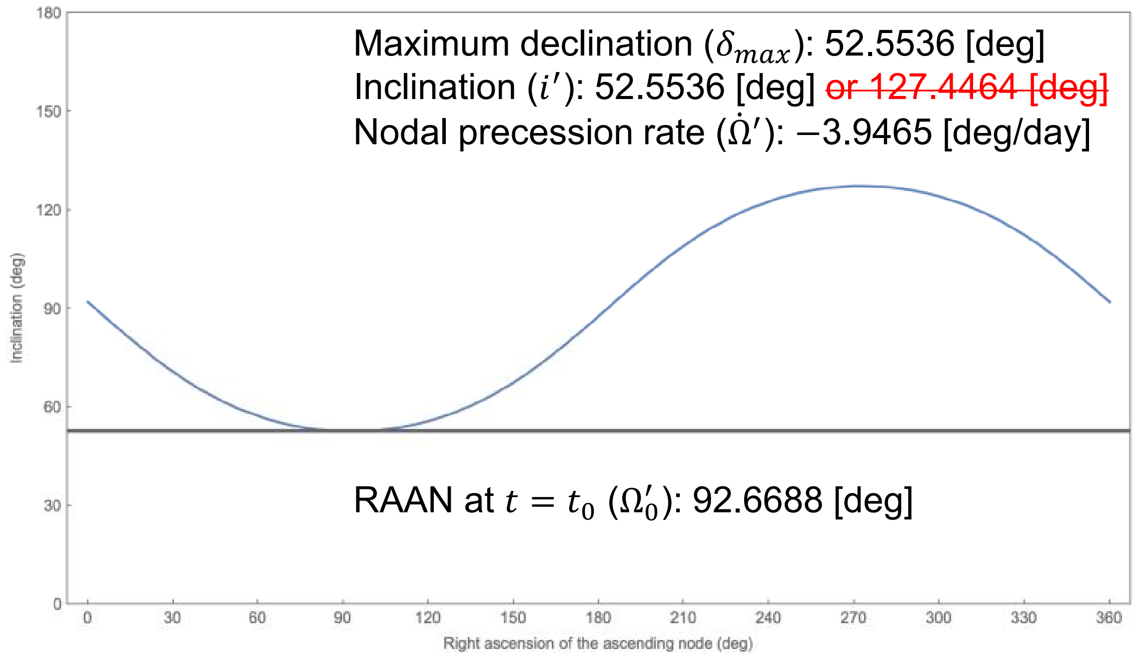
$$\sin\Delta \sin\theta = \sin(\Omega - \Omega') \sin i'$$
$$\cos\Delta \sin\theta = \cos i' \sin i - \sin i' \cos i \cos(\Omega - \Omega')$$

The rate of change in RAAN is mainly determined by J_2 perturbation and is constant. Thus,

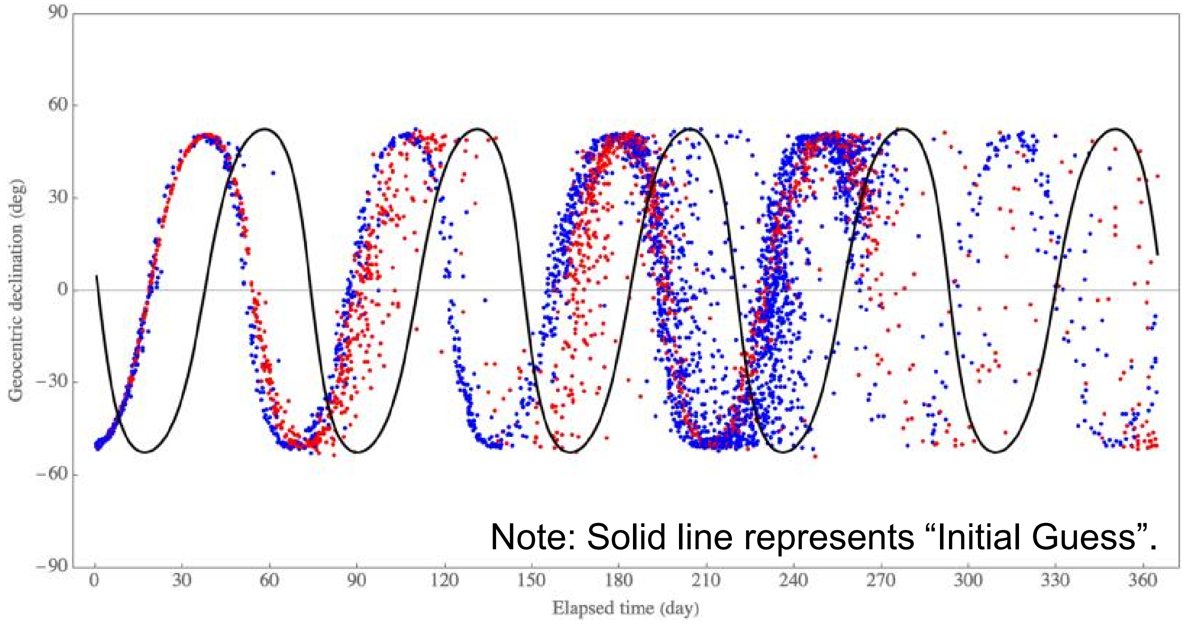
$$\begin{aligned} \Omega - \Omega' &= \Omega_0 + \dot{\Omega}(t - t_0) - [\Omega'_0 + \dot{\Omega}'(t - t_0)] \\ &= \Omega_0 - \Omega'_0 + (\dot{\Omega} - \dot{\Omega}')(t - t_0) \\ &\equiv \alpha + \omega(t - t_0) \end{aligned}$$

Now, parameters to estimate are $\alpha = \Omega_0 - \Omega'_0$ and $\omega = \dot{\Omega} - \dot{\Omega}'$.

Constraint on Ω'_0 and i' when $\dot{\Omega}' = -3.9465$ [deg/day]



Nonlinear Model Fit to Geocentric Declination at the Time of Detection



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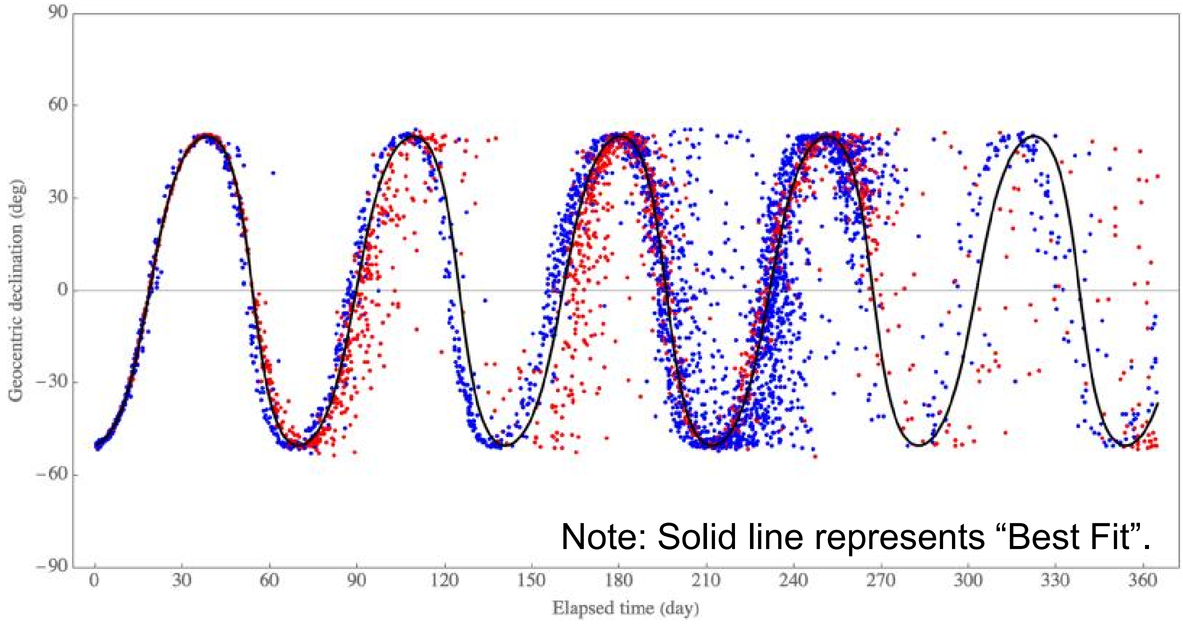
Nonlinear Model Fit to Geocentric Declination at the Time of Detection, cont'd



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True Values and Best Fit Parameters

Orbital Parameters	True Values	Initial Values	Best Fit Parameters
i' (deg)	50.6433	52.5536	50.4879
Ω'_0(deg)	1.6779	92.6688	1.6582
$\dot{\Omega}'$(deg/day)	– 4.0659	– 3.9465	– 4.0872

Conclusions

This paper has proposed a new approach to estimate some orbital parameters of on-orbit satellite fragmentations from in-situ debris measurements.

The new approach applied a nonlinear model fit to the history of geocentric declination at the time of detection.

This paper also verified that the new approach works effectively using measurements generated by close approach.

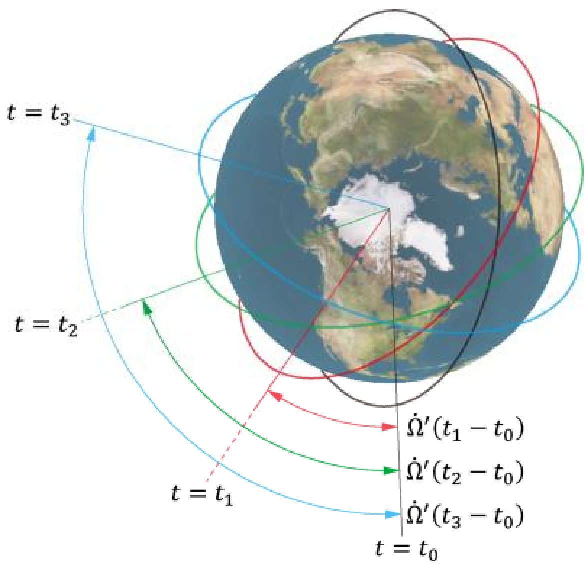
Constraint Equation

Substituting $\Omega'(t) = \Omega'_0 + \dot{\Omega}'(t - t_0)$ into the constraint equation and reducing it gives

$$\left(\left[C^3_{\dot{\Omega}'(t-t_0)}\right]\boldsymbol{r}\right) \cdot \begin{pmatrix} \sin\Omega'_0 \sin i' \\ -\cos\Omega'_0 \sin i' \\ \cos i' \end{pmatrix} = 0$$

where $[C\ \ ]$ is the rotation matrix about an axis specified by the superscript with an angle given by the subscript. Note that $\left[C^3_{\dot{\Omega}'(t-t_0)}\right]\boldsymbol{r}$ is on the plane defined by Ω'_0 and i' since $(\sin\Omega'_0 \sin i', \ -\cos\Omega'_0 \sin i', \cos i')^T$ is $\boldsymbol{e}'_W$ at the time of t_0 .

Constraint Equation, cont'd



$\left[C^3_{\dot{\Omega}'(t_1-t_0)}\right]\boldsymbol{r}_1$, $\left[C^3_{\dot{\Omega}(t_2-t_0)}\right]\boldsymbol{r}_2$, and $\left[C^3_{\dot{\Omega}(t_3-t_0)}\right]\boldsymbol{r}_3$ are all on the same plane defined by Ω'_0 and i', so that the rate of change in RAAN of the broken-up object may be constrained by

$$\left[C^3_{\dot{\Omega}'(t_1-t_0)}\right]\boldsymbol{r}_1 \cdot \left[\left(\left[C^3_{\dot{\Omega}(t_2-t_0)}\right]\boldsymbol{r}_2\right) \times \left(\left[C^3_{\dot{\Omega}(t_3-t_0)}\right]\boldsymbol{r}_3\right)\right] = 0$$

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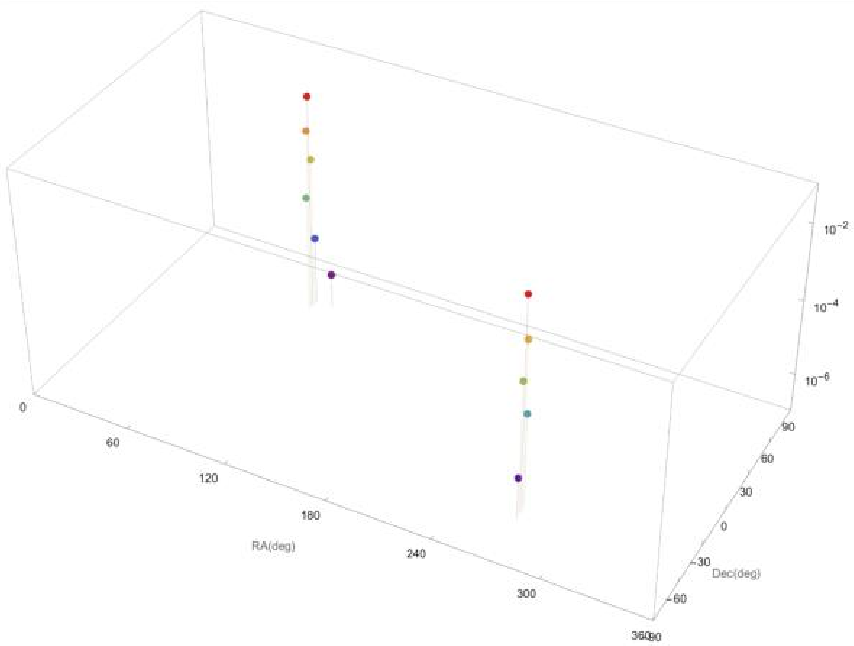
Collision Flux of Fragments from a Breakup along the Orbit of an In-situ Debris Measurement Satellite



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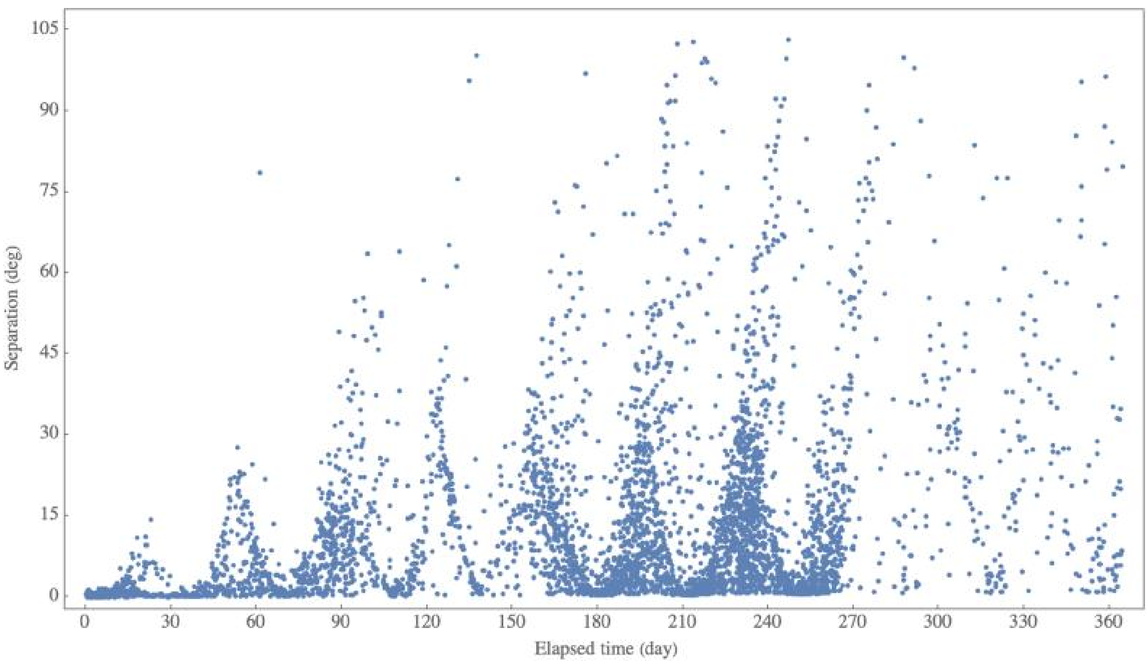
Separation from the Intersection



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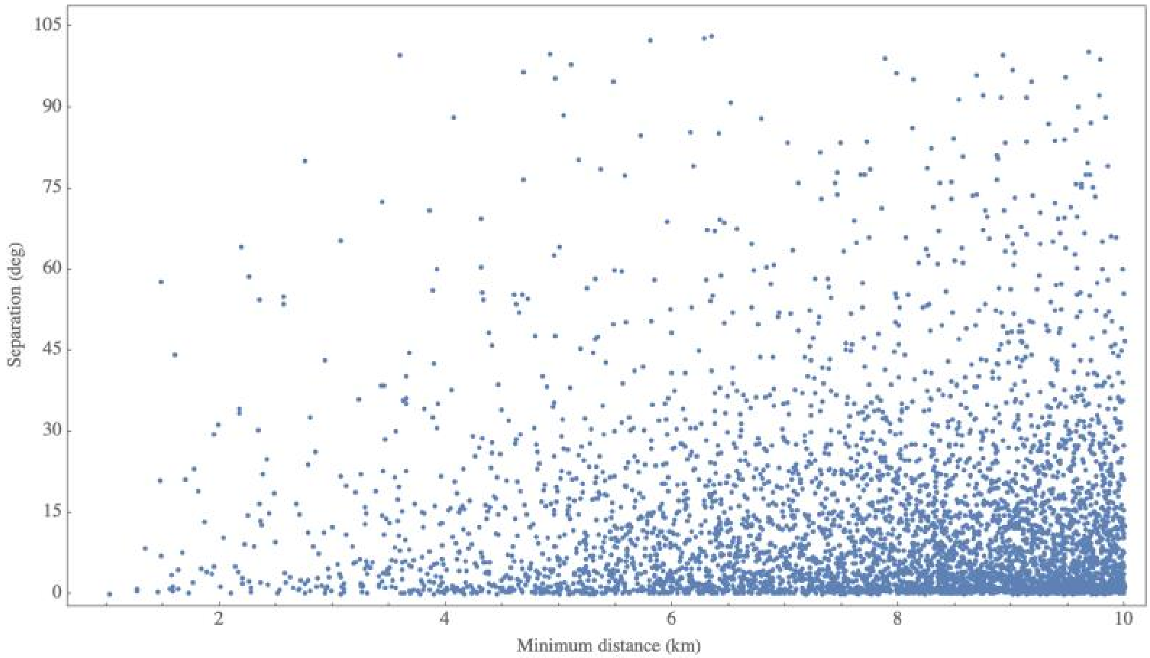
Separation from the Intersection, cont'd



Condition for Geocentric Declination at the Time of Detection to Be Maximum or Minimum, cont'd

Let $\delta_{min}(< 0)$ be the minimum geocentric declination at the time of detection. Substituting δ_{min} and $\Delta' = \pm\pi/2$ into $\sin\delta = \sin i' \sin\Delta'$, then we have

$$i' = -\delta_{min} \text{ and } i' = \pi + \delta_{min}$$

Thus, the inclination of broken-up object can be determined from the minimum geocentric declination at the time of detection. Note that this approach cannot work when $-\delta_{min} = i$ and $\pi + \delta_{min} = i$. All we can know is that the inclination of broken-up object is between $-\delta_{min}$ and $\pi + \delta_{min}$.

Condition for Geocentric Declination at the Time of Detection to Be Maximum or Minimum, cont'd

Let $\delta_{max} (> 0)$ and $\delta_{min} (< 0)$ denote the maximum and minimum geocentric declinations, respectively. Substituting δ_{max} and $\Delta' = \pm\pi/2$ or δ_{min} and $\Delta' = \pm\pi/2$ into $\sin\delta = \sin i' \sin\Delta'$, then we have

$$i' = \delta_{max}, i' = \pi - \delta_{max}, i' = -\delta_{min}, \text{ and } i' = \pi + \delta_{min}$$

Thus, the inclination of broken-up object can be determined from the maximum or minimum geocentric declination at the time of detection. Note that this approach cannot work when $\delta_{max} = i$, $\pi - \delta_{max} = i$, $-\delta_{min} = i$, and $\pi + \delta_{min} = i$. All we can know is that the inclination of broken-up object is between δ_{max} and $\pi - \delta_{max}$ or $-\delta_{min}$ and $\pi + \delta_{min}$.

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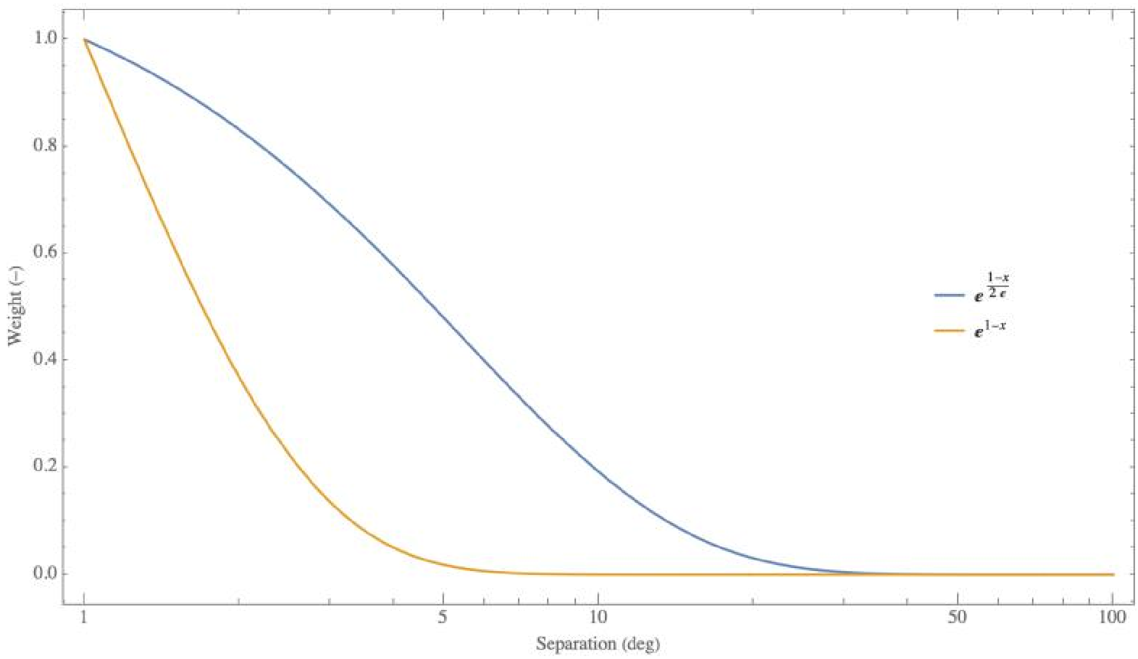
Weightings



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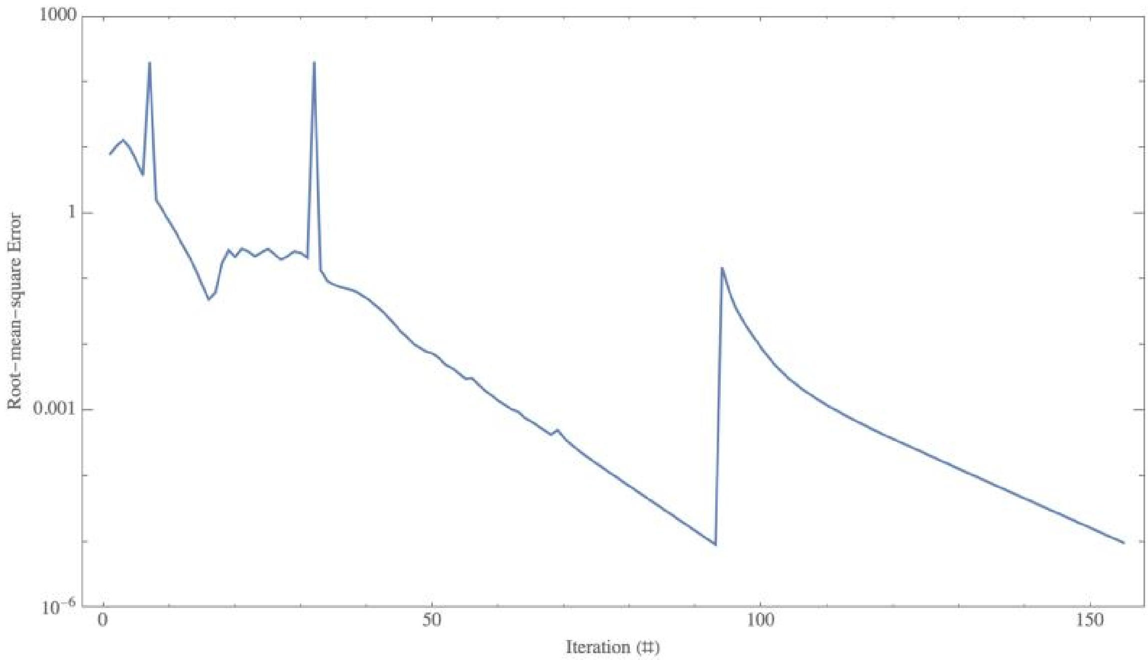
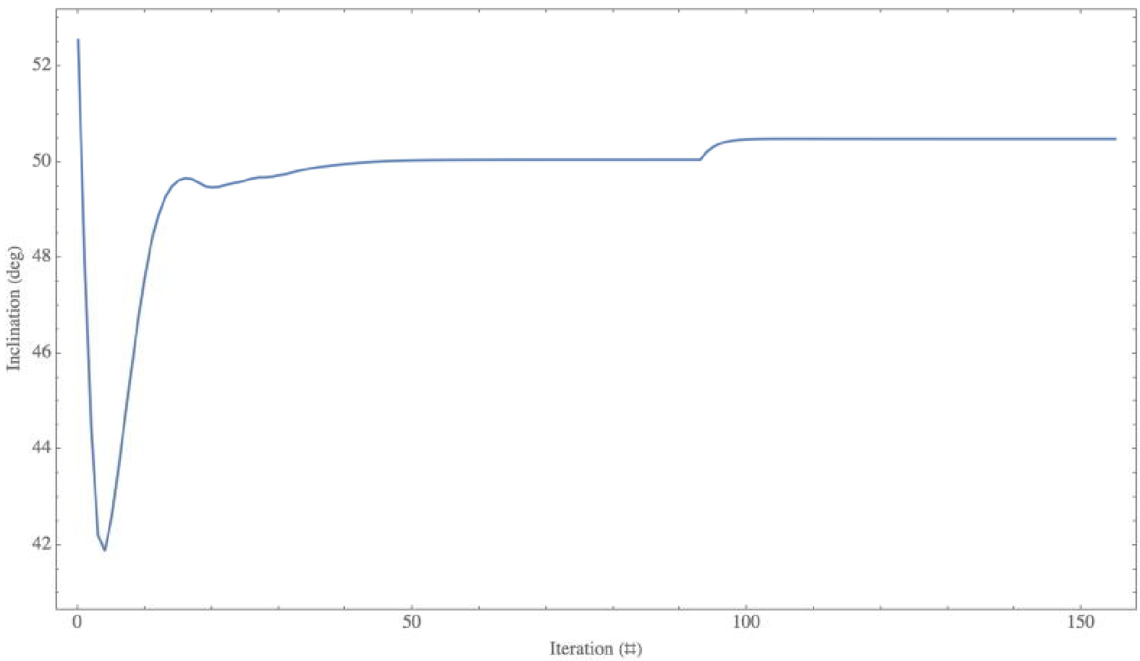
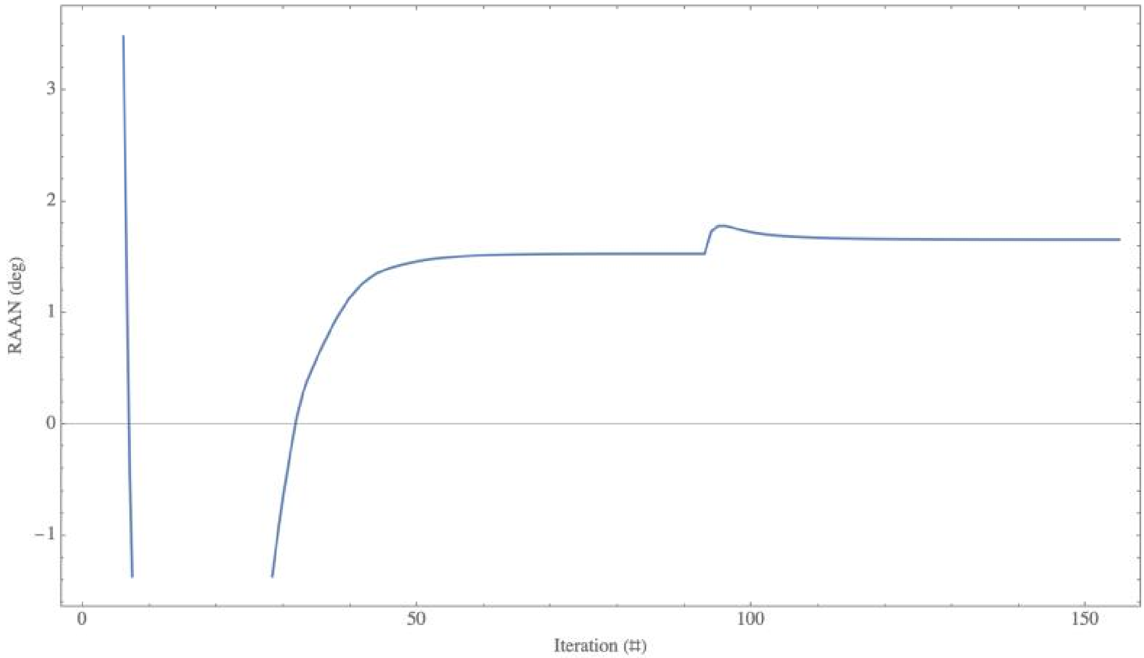
Root-mean-square Error



Inclination (i') Iterations



RAAN at $t = t_0$ (Ω_0') Iterations



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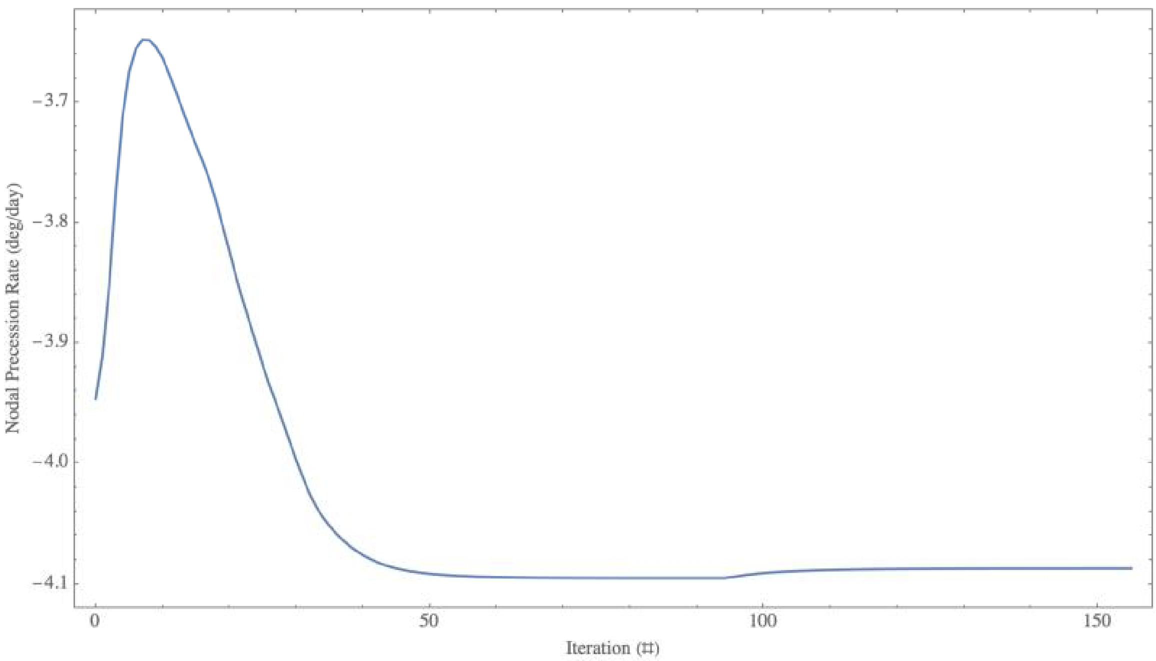
Nodal Precession Rate ($\dot{\Omega}'$) Iterations



November 30, 2022

C02

模擬衛星を用いた爆発源位置による影響評価と実例による考察
Effect of Source Location on Mock-up Satellite Fragmentation

○波多英寛，井ノ口凪紗（熊本大），仁田工美，佐藤健一（JAXA 安信部），花田俊也（九州大）
○HATA Hidehiro, INOKUCHI Nagisa (Kumamoto Univ.), NITTA Kumi,
SATO Kenichi (JAXA Safety and Mission Assurance Department), HANADA Toshiya (Kyushu Univ.)

衝突や爆発によって発生する破片を表す破砕モデルのうち，本研究では人工衛星が爆発破砕した場合を対象とした爆発破砕モデルについて検討を行っている．簡易的な真空容器中にて模擬衛星を用いた爆発破砕実験を行い，破砕後の破片回収ならびに高速度撮影結果より，破片寸法，飛散速度を計測し，爆発破砕モデルを検討する．爆発源としてはエネルギー推測が可能な PETN 爆薬を用いている．今回の講演では，爆発源の設置位置を模擬衛星の内部と外部に変化させた結果を比較し，爆発源の位置による破壊様相ならびに爆発破砕モデルへの影響を検討し，同一エネルギーでも爆発源の位置により異なった結果が得られたことを報告する．また，爆発破砕した事例である Ekran2 およびその破片の状況について検討し，爆発源が外部にあると考えた方が実情に合致する可能性について報告する．

The Breakup model includes cases for collisions and explosions, and this study examines the breakup model for satellite explosions. Explosive fragmentation experiments were conducted using a mock-up satellite in a simple vacuum vessel. Then, the fragment size and typical velocity are measured using the high-speed photographing results and recovered fragments after the experiment, and an explosion breakup model is examined. A PETN explosive have predictable explosive energy is used as the explosion source. In this presentation, comparison of the results obtained by changing the location of the explosion source inside and outside the mock-up satellite. Then, the effect of the location of the explosion source on the broken condition and the breakup model is examined. And It is reported that different results were obtained depending on the location of the explosion source. In addition, situation of Ekran2 and its fragments was examined as a case of breakup. As a result, the source of the explosion may be outside.

Effect of Source Location on Mock-up Satellite Fragmentation
（模擬衛星を用いた爆発源位置による影響評価と実例による考察）

〇Hidehiro Hata, Nagisa Inokuchi (Kumamoto Univ.),
Kumi Nitta, Kenichi Sato
(JAXA Safety and Mission Assurance Department),
Toshiya Hanada (Kyushu Univ.)

28-30 Nov. 2022 10th Space Debris Workshop

Background

〇Breakup model（Prediction of physical properties of fragments generated）

NASA standard breakup model 2001 revision

・Collision

・Explosions

↑ Examination of on-orbit explosion fragmentations

↑ Propellant-induced explosions of upper stages

〇The Russian EKRAN 2 (International Designator 1977-092A) spacecraft exploded

・Only fewer fragments

・Small delta velocity of fragments

⬇

Development of an explosion breakup model for satellites

※ Energy, Source Location

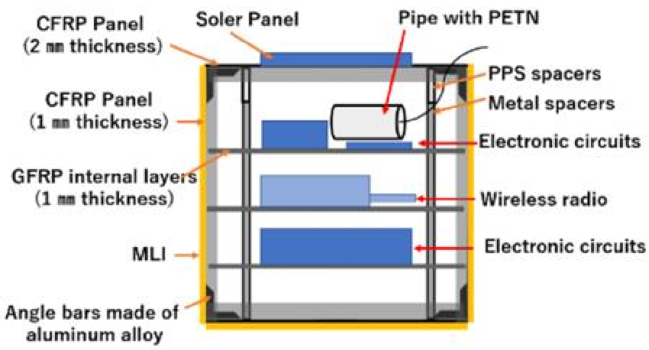
Kumamoto University Space and Shock Engineering Lab.

Mock-up Satellite

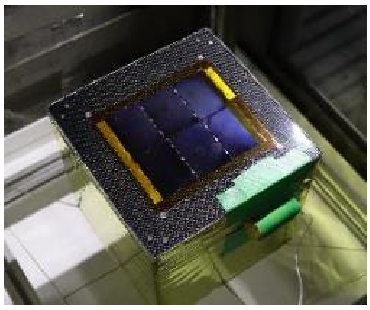
Explosive source : PETN(5.71kJ/g)

Size :
20 by 20 by 20cm
Mass :1,558 g

(a) Inside (PETN1.0 g, 0.3 g)

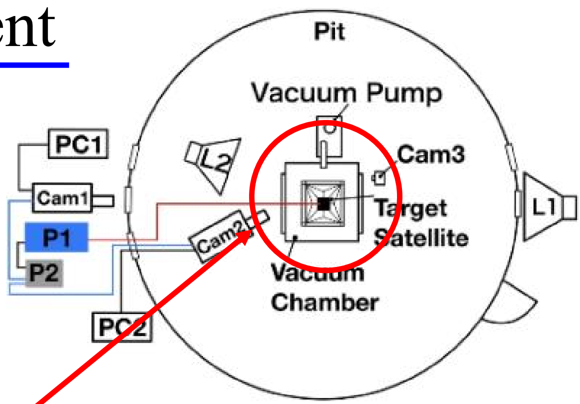


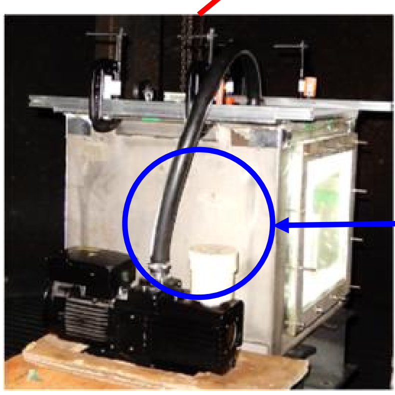
(b) Outside (PETN1.0 g)

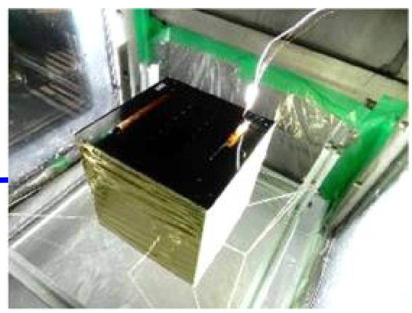


Experimental arrangement

- Use of explosives
  →Explosion pit A at K.U.
- Fracture condition + fragment velocity
  → High speed video camera
- Space environment simulation
  +
  Fragments collection
  → measurement
  ↓
  simple vacuum vessel







Fragments collection result 1

(a) Inside（PETN 1g）

(b) Outside（PETN 1g）

Effect of Source Location (Inside → Outside)

CFRP : Only the setting part broken
Solar Cell : Not broken up
MLI : Only the setting part is broken
Main body : Not broken up

Fragments collection result 2

	Inside (PETN 1g)				Outside (PETN 1g)			
	Number	%	Mass(g)	%	Number	%	Mass(g)	%
CFRP	41,392	95.69	77.38	4.97	8040	96.73	0.38	0.03
Solar Cell	1693	3.91	5.11	0.33	0	0	0	0
Electric device & Metal	48	0.11	174.01	11.17	0	0	0	0
Plastic	18	0.04	2.89	0.19	0	0	0	0
MLI	94	0.22	0.25	0.02	271	3.26	0.82	0.06
Main Body, Mix	10	0.02	1298.44	83.34	1	0.01	1479.31	99.94
Total	43,255		1558.08	99.95	8312		1480.51	99.07

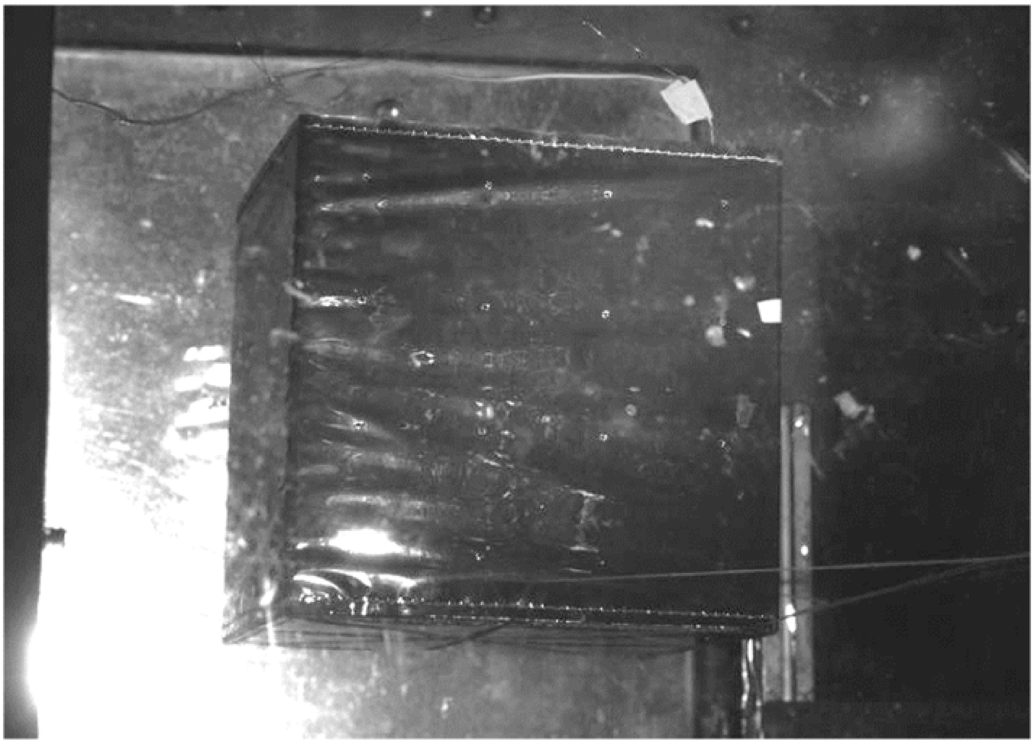
Effect of Source Location (Inside → Outside)

CFRP : Decreased
Solar Cell : Not broken up
MLI : Increased
Main body : Not broken up

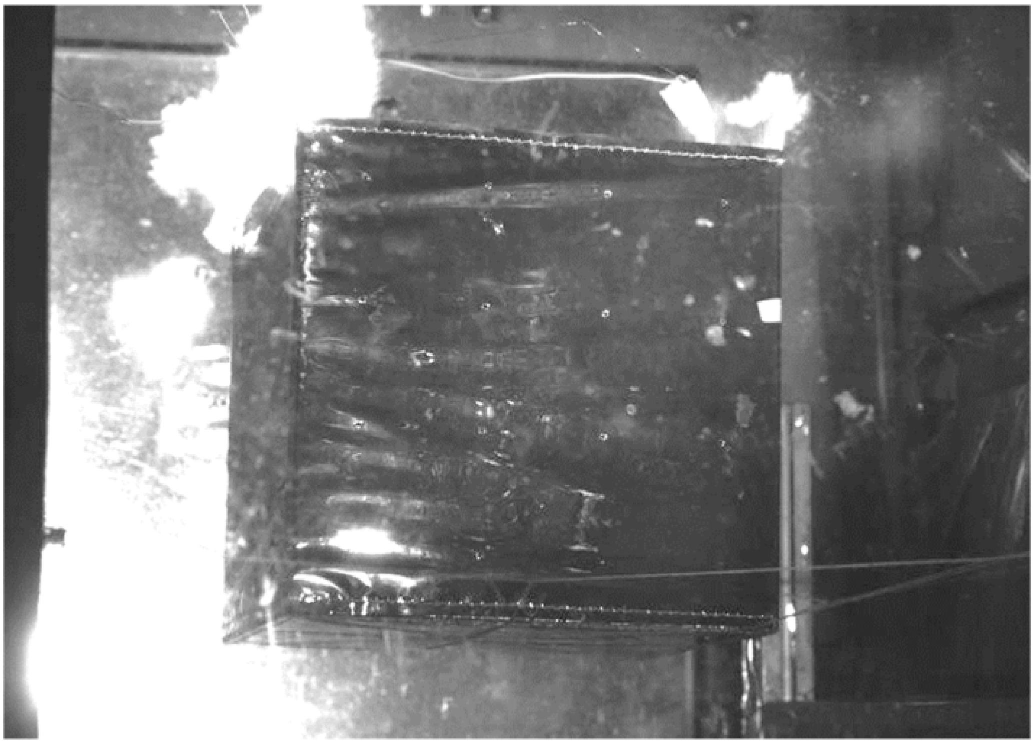
Reduced
total number
&
big fragments

Result of high-speed photography (Inside)

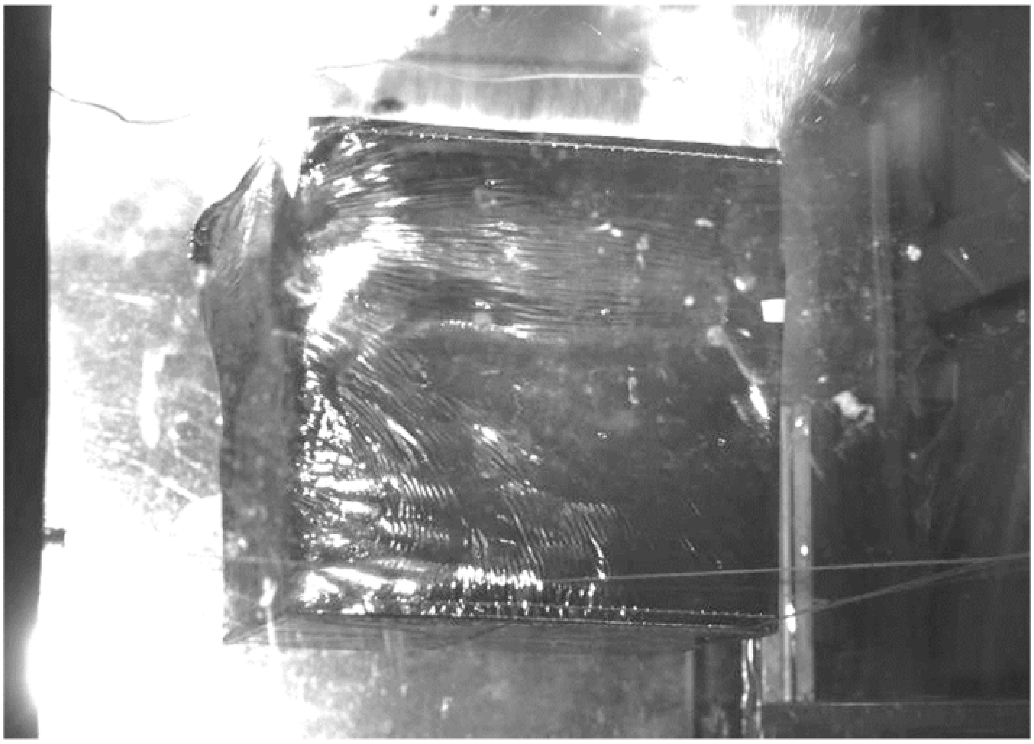
Result of high-speed photography(Inside)



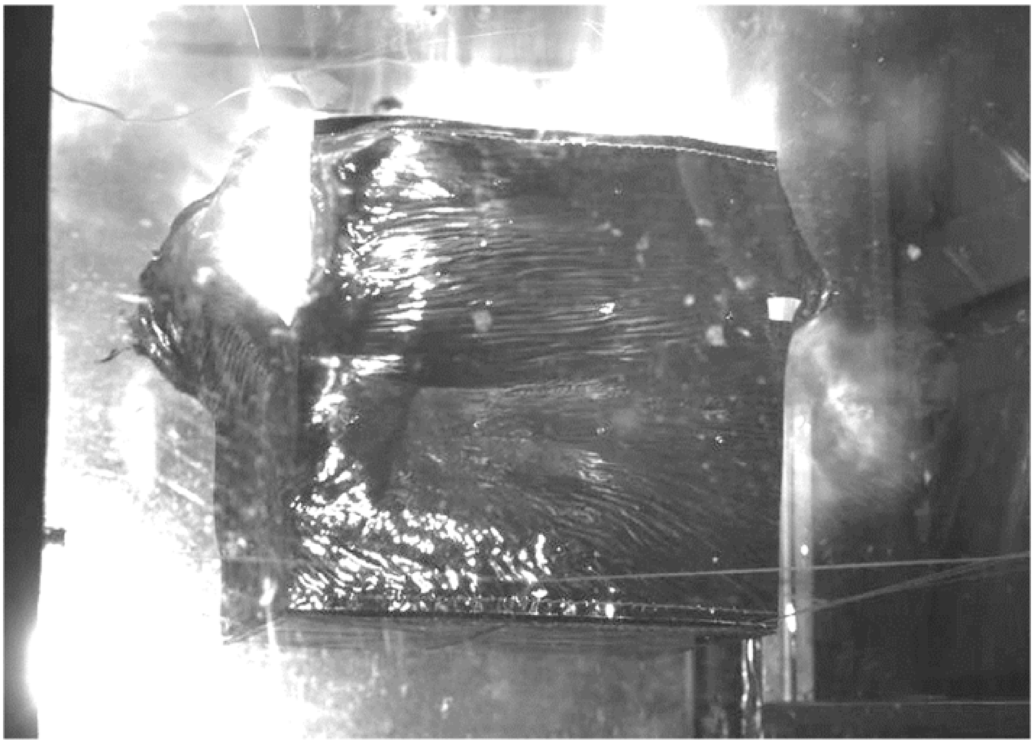
Result of high-speed photography(Inside)



Result of high-speed photography(Inside)

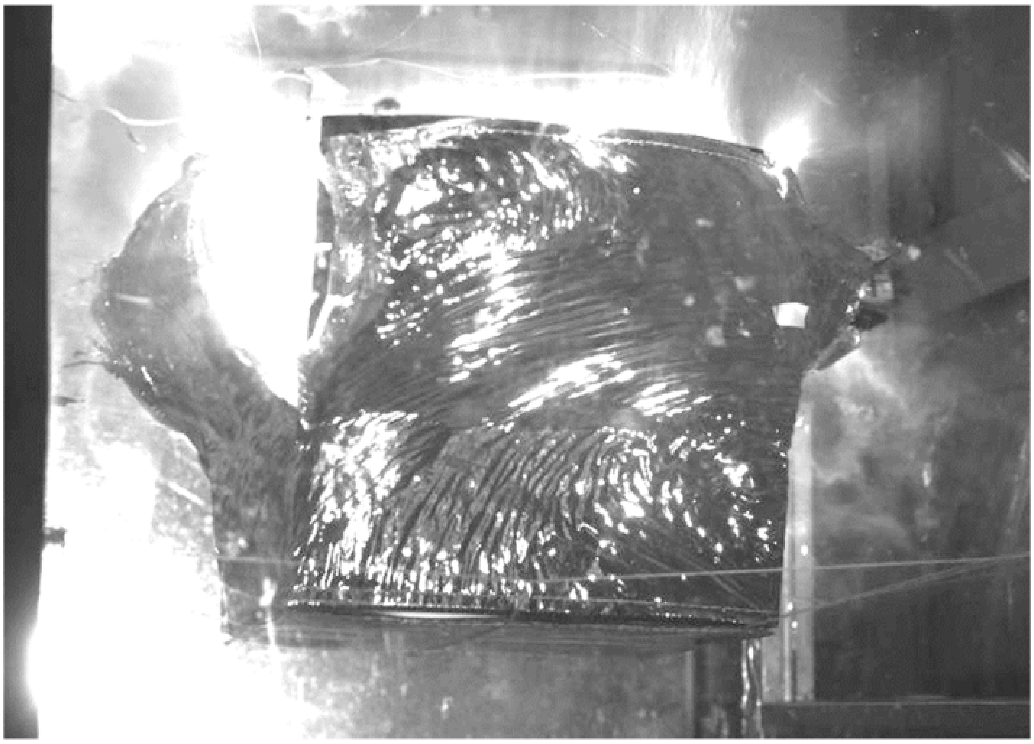


Result of high-speed photography(Inside)



28-30 Nov. 2022 10th Space Debris Workshop

Result of high-speed photography(Inside)



Kumamoto University
Space and Shock Engineering Lab.

Result of high-speed photography(Inside)

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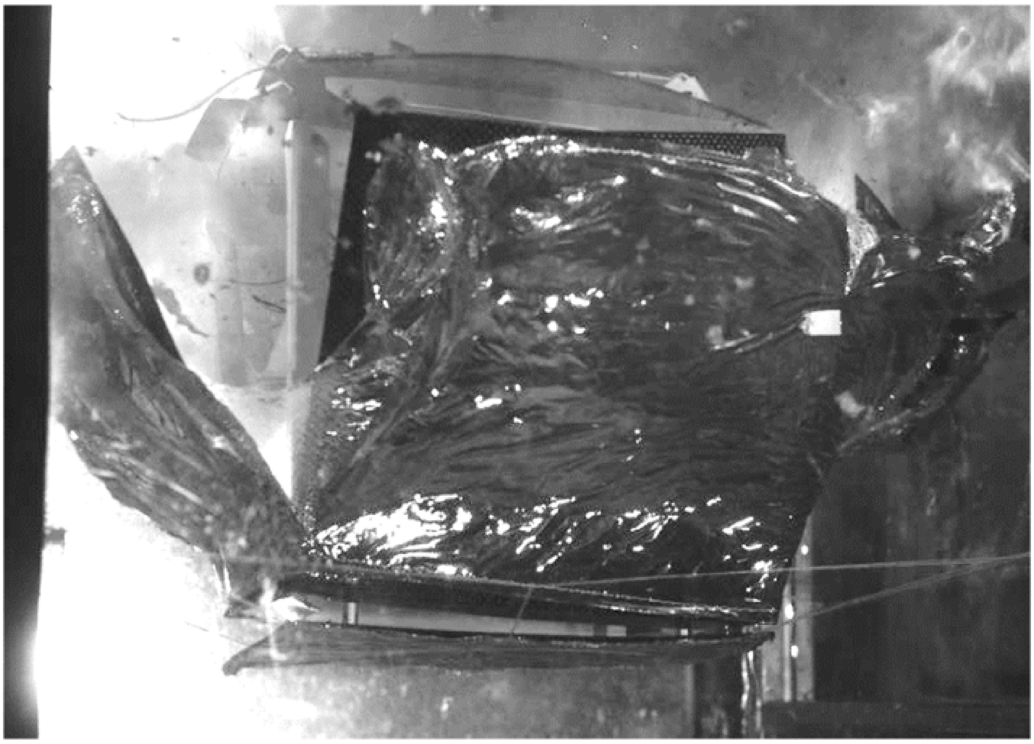
Result of high-speed photography(Inside)

Result of high-speed photography(Inside)



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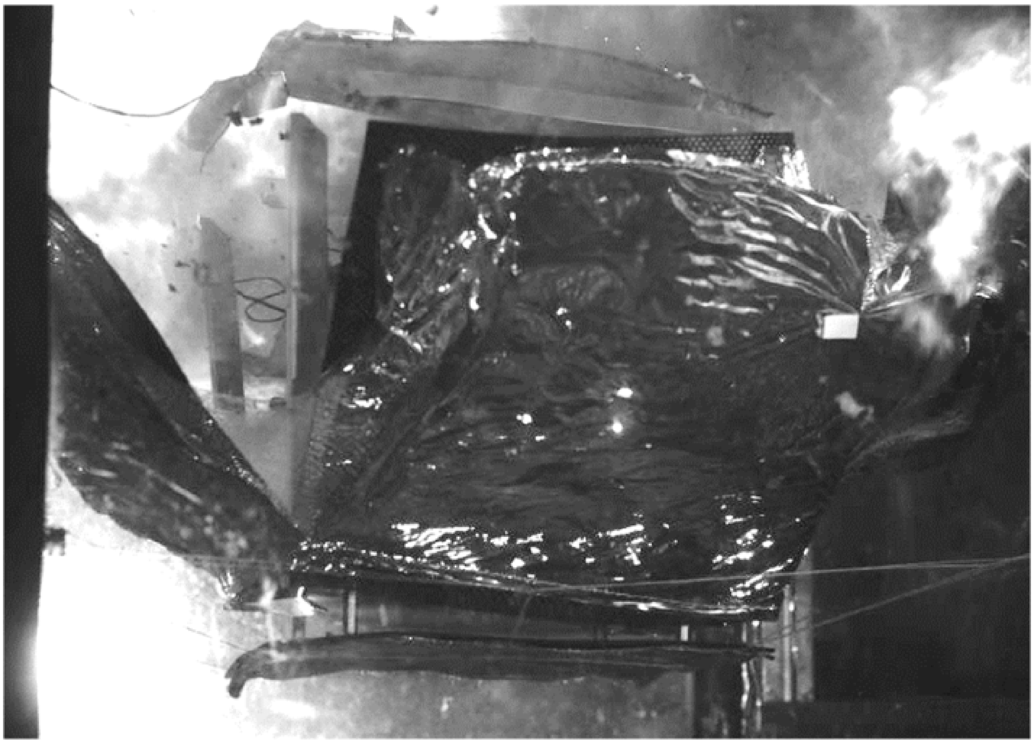
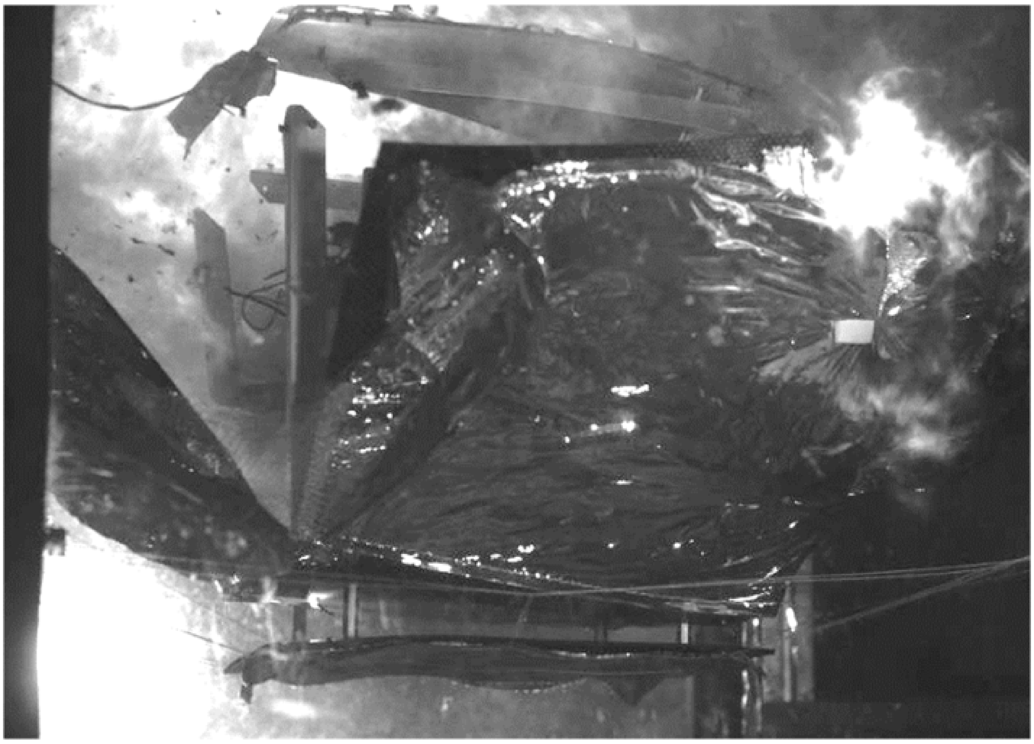
Result of high-speed photography(Inside)



Kumamoto University
Space and Shock Engineering Lab.

Result of high-speed photography(Inside)



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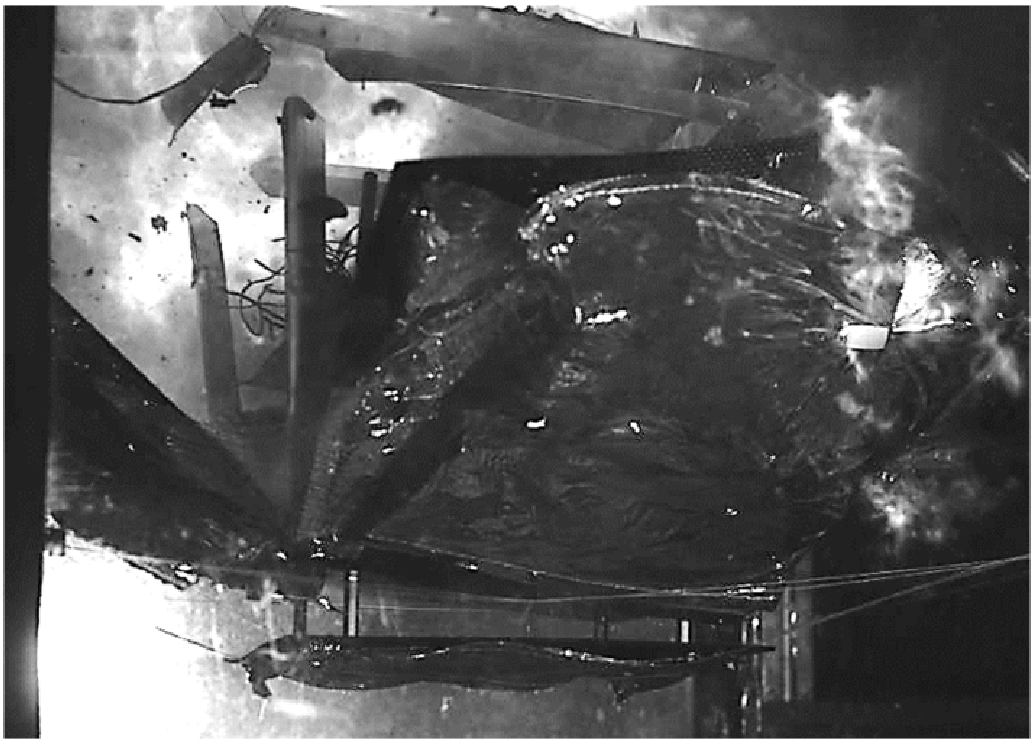
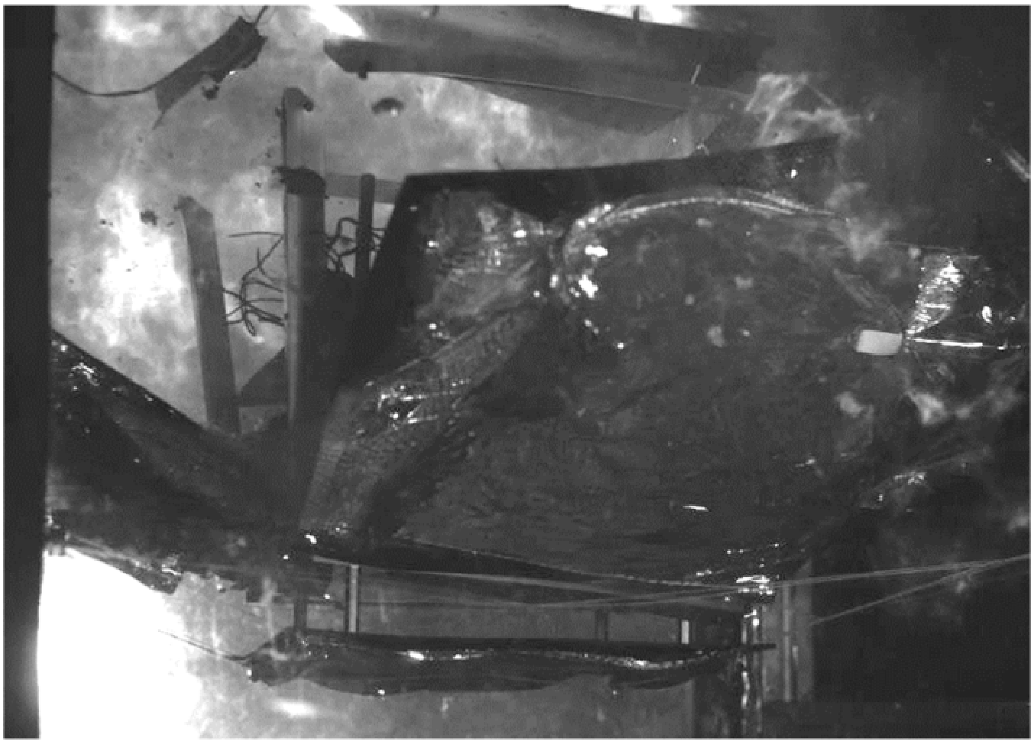
Result of high-speed photography(Inside)



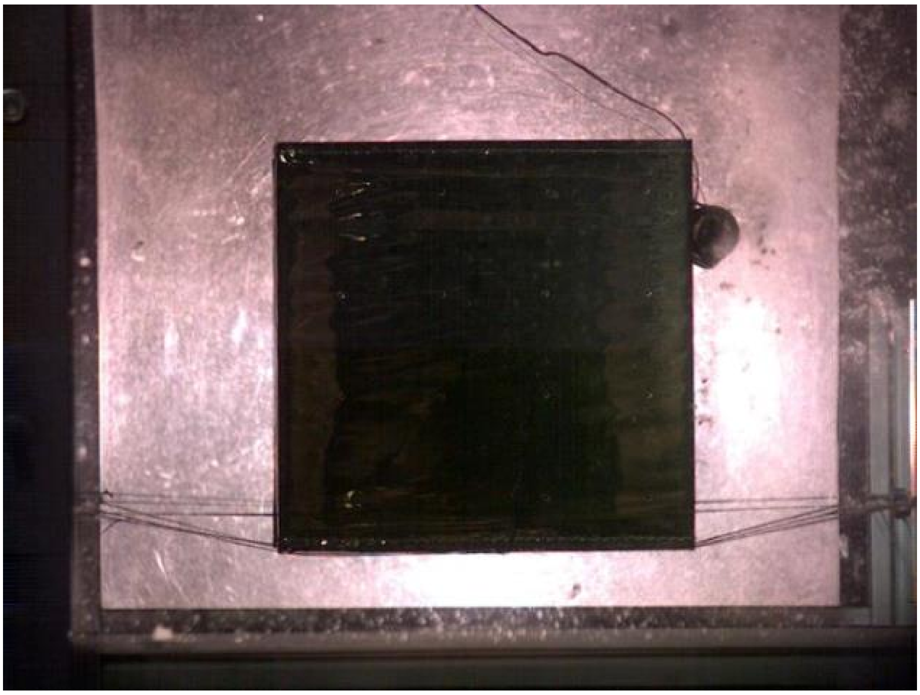
Kumamoto University Space and Shock Engineering Lab.

Result of high-speed photography(Inside)

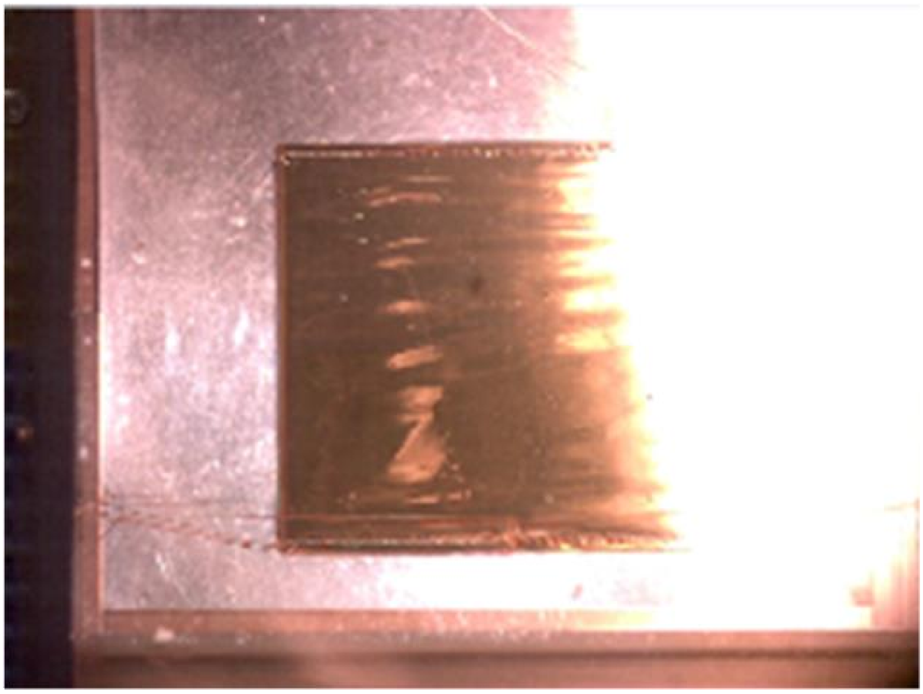


Result of high-speed photography (Outside)

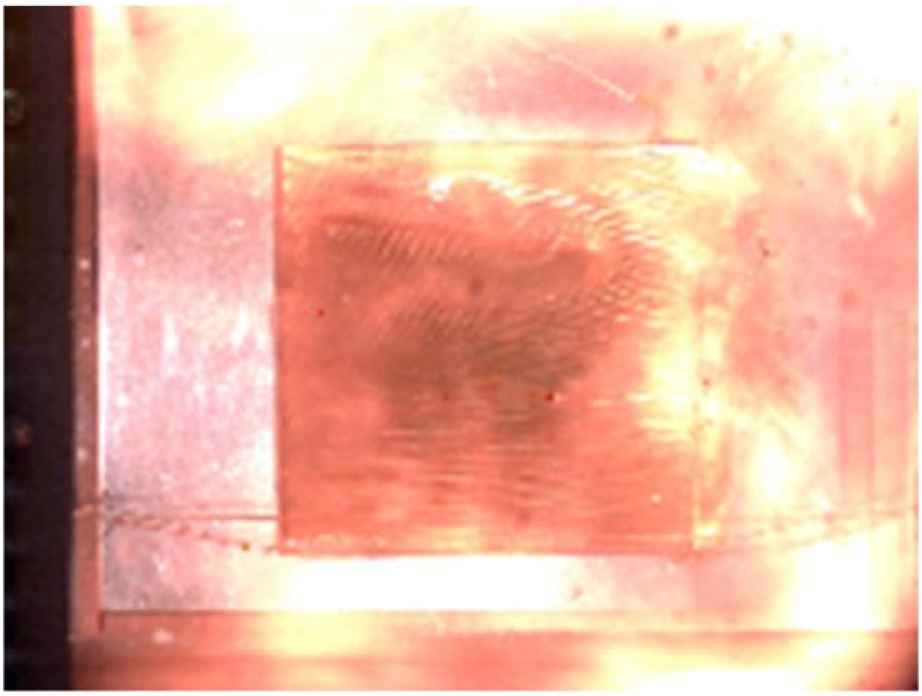
Result of high-speed photography(Outside)



Result of high-speed photography(Outside)



Result of high-speed photography(Outside)



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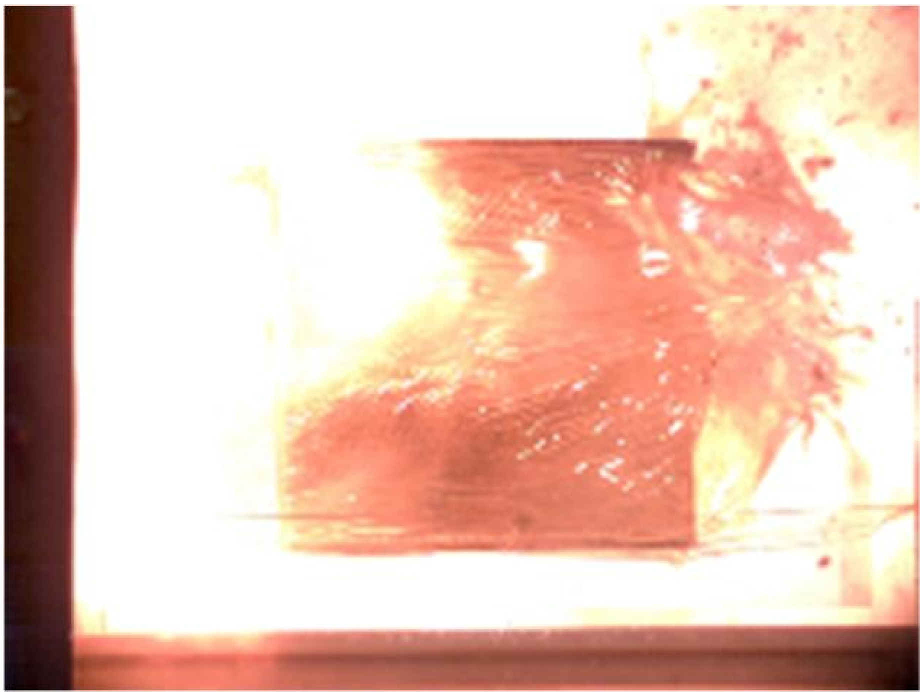
Result of high-speed photography(Outside)



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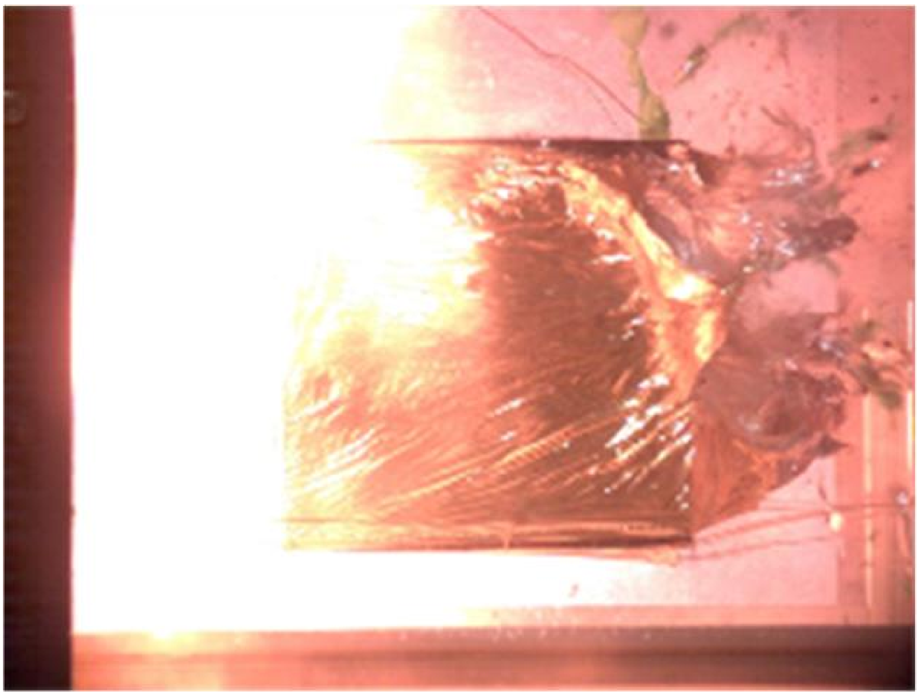
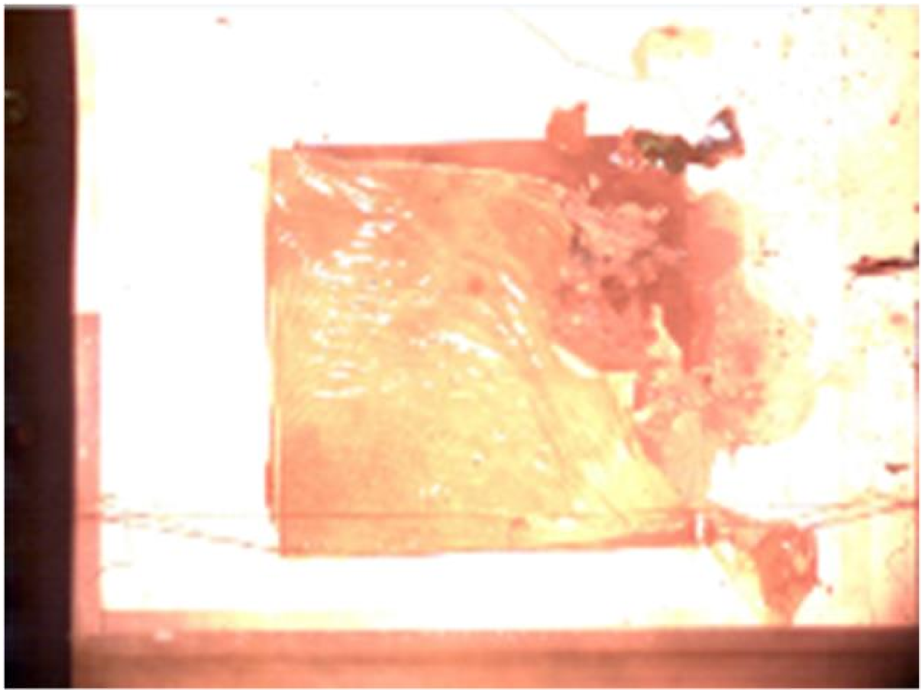
Result of high-speed photography(Outside)



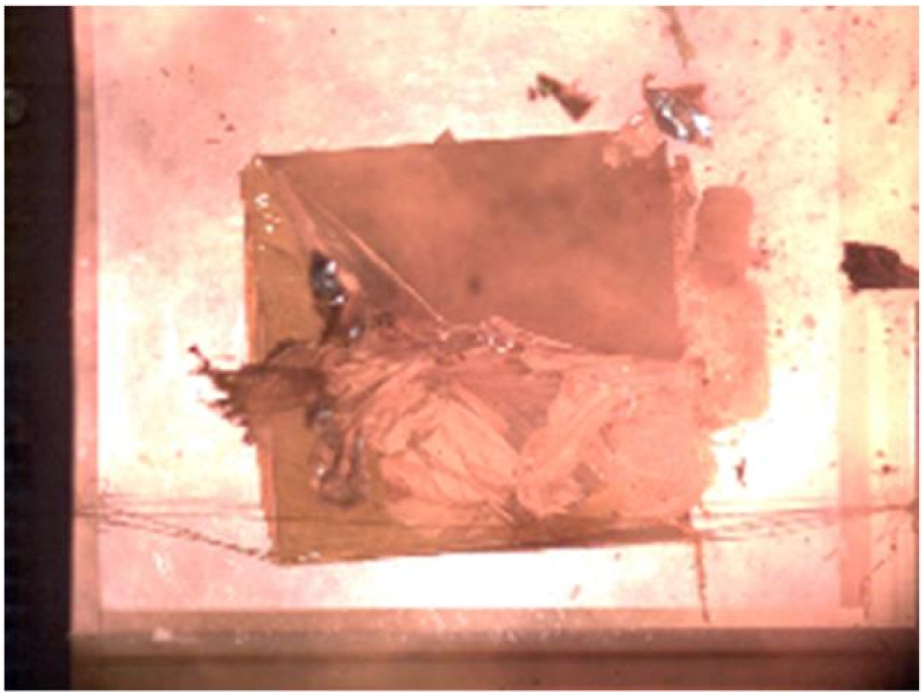
28-30 Nov. 2022 10th Space Debris Workshop

Result of high-speed photography(Outside)



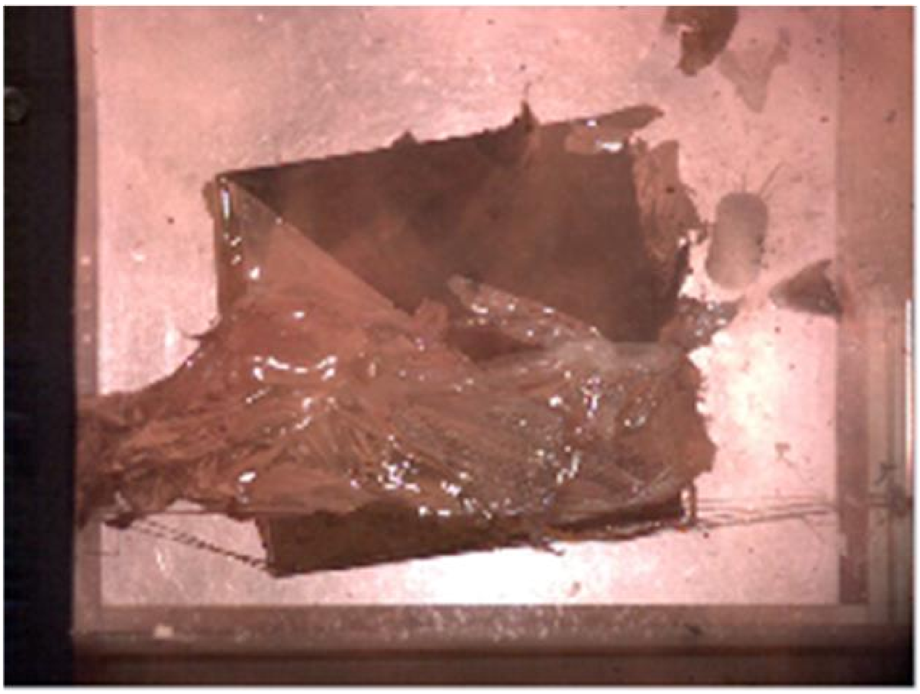
Kumamoto University Space and Shock Engineering Lab.

Result of high-speed photography(Outside)



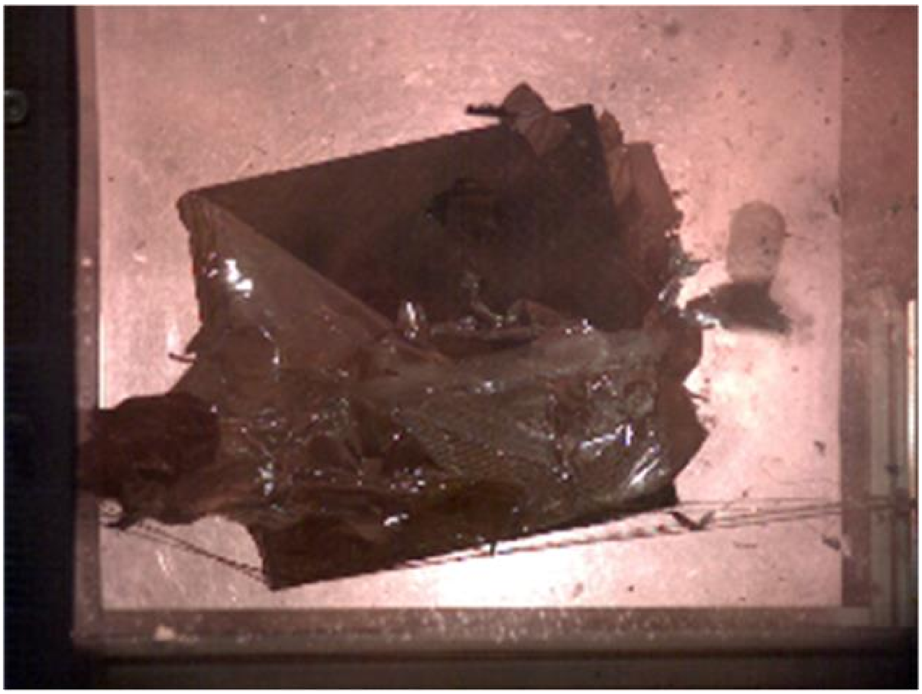
28-30 Nov. 2022 10th Space Debris Workshop

Result of high-speed photography(Outside)



Kumamoto University
Space and Shock Engineering Lab.

Result of high-speed photography(Outside)



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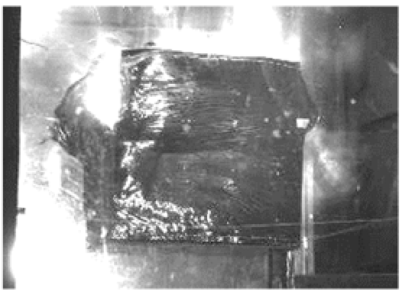
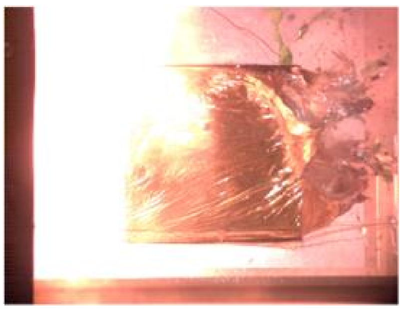
Result of high-speed photography

(Inside)



Destroyed by being pushed from the inside（parts do not fragment）

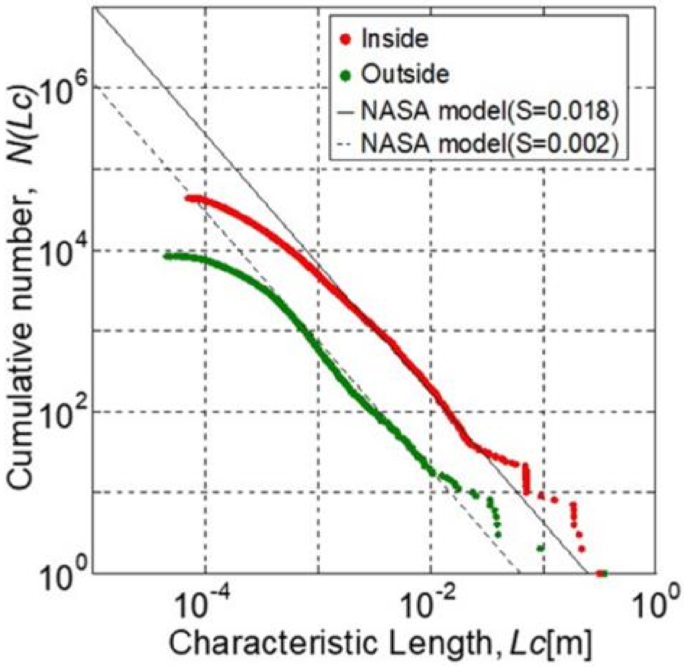
(Outside)



Only the contact part is destroyed

Kumamoto University Space and Shock Engineering Lab.

Size distributions

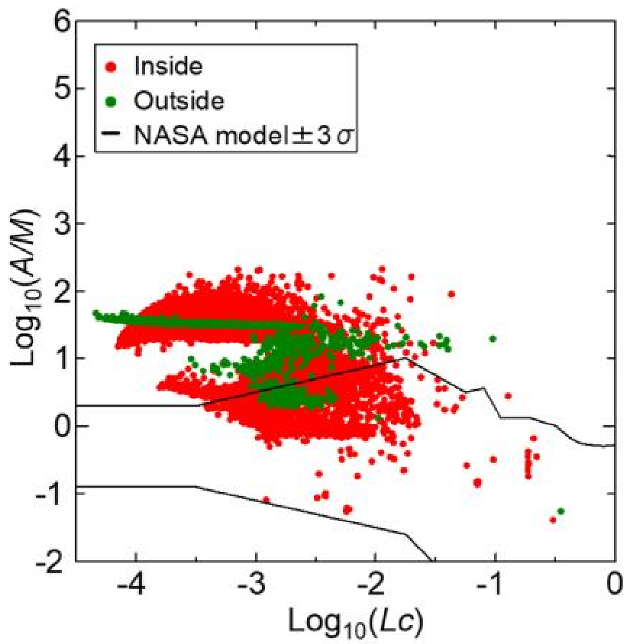


$N(Lc) = 6\ S\ Lc^{-1.6}$

Inside : S=0.080
Outside : S=0.002

Effect of Source Location

Area-to-mass ratio distributions



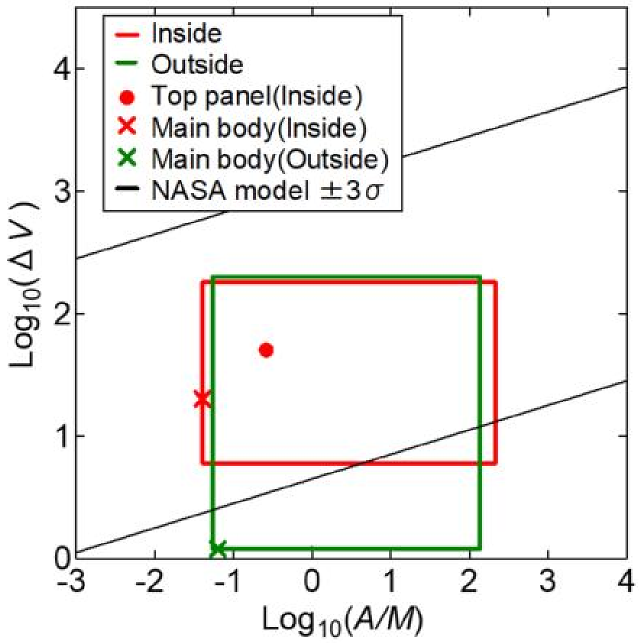
Effect of Source Location
→ None

Fragment shape
→ Influenced by materials and structures

Distributed on top

Difference in materials
→ Density : AL＞CFRP
→ High A/M

Delta velocity distributions



Low distribution

1. Upper stage
→ pressure hold
+
High energy
↓
Delta velocity up

2.Difference in materials
→ Density : AL＞CFRP
→ High A/M

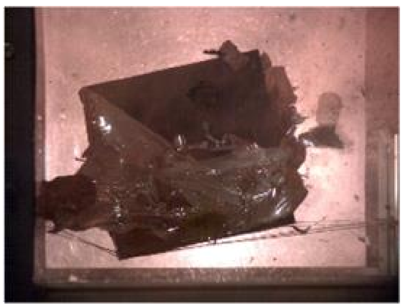
Minimum velocity
Inside ＞ Outside

Effect of
Source Location

Fragment Velocity

(Inside)

(Outside)



	Inside	Outside
Max velocity	180 m/s	199 m/s
Main body	20 m/s	**1.2 m/s**
Top panel	50 m/s	-

・Velocity measurement using multiple images
・ Less depth movement
→Focus on the top panel and main body

・Max Velocity
Inside ≒ Outside
→Small fragments

・Main body
Inside ＞ Outside
※ Open space
(installation position only)

・Main body ＜ Top panel
↑ mass difference
→ Velocity difference

Ekran 2 ?

Ekran2 Break-up fragment

- ・Only fewer fragments observed
- ・Small delta velocity of fragments (<～1.5 m/s)

(a)Inside

- ・Large delta velocity
- ・Generates large fragments
  ＋Delta velocity difference
- ・Many fragments

or

(b)Outside

- ・Small delta velocity
- ・Not large fragments
- ・Fewer fragments

Outside Possibilities
(Large fragments are generated by separation?)

Conclusion

Development of an explosion breakup model for satellites
→ Evaluate effect of source location

- ・Destruction differs depending on the location of the explosion source
- ・The source of the explosion is outside
  → Fewer fragments, Small delta velocity
- ・The Russian EKRAN 2
  → the source of the explosion may be outside.

Acknowledgments

・This work was supported by JSPS KAKENHI Grant Number JP20H02355 & Sponsored Research with JAXA
・Using the Explosion test facility at Institute of industrial nanomaterials, Kumamoto University
・本研究に協力：九州大学大学院　高橋雄文君
熊本大学技術職員の渡邉直人様に感謝の意を表す.

C03

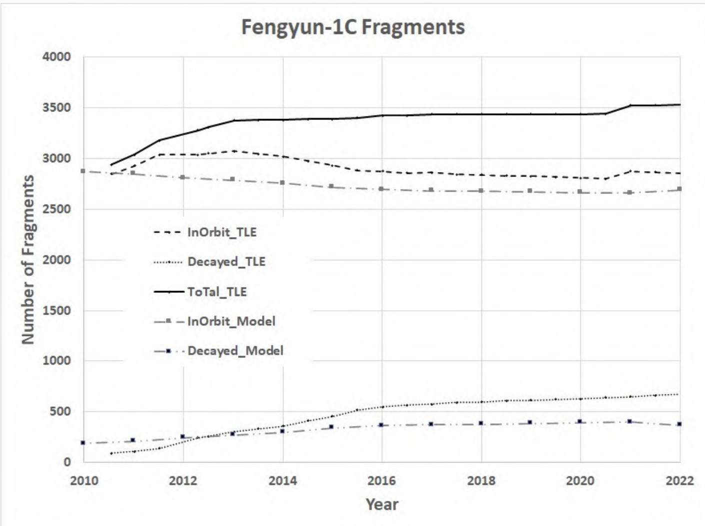
軌道上デブリ推移モデルを用いた軌道上破砕片の推移解析

Analysis of Orbital Debris Environment Using Debris Evolutionary Model

○長岡 信明、河本 聡美、原田 隆佑、北川 康弘（JAXA 研開部門）、花田 俊也（九州大学）
○NAGAOKA Nobuaki, KAWAMOTO Satomi, HARADA Ryusuke,
KITAGAWA Yasuhiro (JAXA Research and Development Directorate), HANADA Toshiya (Kyushu Univ.)

JAXA 研開部門では九州大学と共同開発してきた軌道上デブリ推移モデル（NEODEEM）を用いて軌道上環境変化の長期予測を行っている。この推移モデルには軌道上での衝突や爆破によって生じる破砕片の生成機能があり、この機能により軌道上環境における破砕片の影響の評価を行うことが出来る。また、この機能を用いる事で軌道上で生じた衝突や爆発事象のモデルによる推定を行う事も出来、昨今問題となっている ASAT なども模擬的に現象を生じさせることが出来る。この報告では、推移モデルの応用の例として、これらの破砕片生成に基づく種々の解析例を紹介する。

JAXA has been evaluating the future space debris environment using debris evolutionary model named NEODEEM, developed in collaboration with Kyushu University. This evolutionary model is able to generate orbital debris generated by on-orbit collisions and explosions, and also to estimate and evaluate the impact of debris to the long time orbital environment. In addition, by using this model, ASAT event also may simulate and evaluate, which has become a problem in recent years, can also be simulated. In this presentation, various analysis examples based on this evolutionary model are introduced.



第10回スペースデブリワークショップ

C03_軌道上デブリ推移モデルを用いた軌道上破砕片の推移解析

Analysis of Orbital Debris Environment Using Debris Evolutionary Model

長岡 信明、河本 聡美、原田隆佑、北川 康弘（JAXA）
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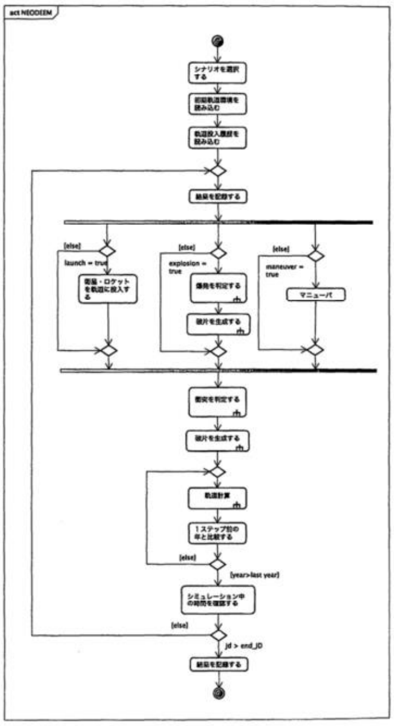
KITAGAWA Yasuhiro (JAXA) HANADA Toshiya (Kyushu Univ.)

Preface

1. JAXA研開部門では軌道上環境の変化や長期的な推移の予想を軌道上デブリ推移モデル（NEODEEM）を用いて検討を行っている。この推移モデルには軌道上での衝突や爆破によって生じる破砕片の生成機能があり、この機能により軌道上環境における破砕片の影響の評価を行うことが出来る。
2. この機能を用いる事で軌道上で生じた衝突や爆発事象のモデルによる推定を行う事も出来、昨今問題となっている ASAT なども模擬的に現象を生じさせることで状況の推定が出来る。この報告では、推移モデルの応用の例として、これらの破砕片生成に基づく種々の解析例を紹介する。

1. JAXA Research and Development Division is studying the orbital environment evolution and predictions of long-term trends using the orbital debris environment evolutionary model (NEODEEM). This evolutionary model has the function of generating simulated debris generated by in-orbit collisions and explosions, and this function can be used to evaluate the impact of orbital debris environment.
2. By using this function, it is also possible to estimate ASAT events by simulating a phenomenon. In this report, as an example of application of the environment evolutionary model, various analysis examples based on the generation of these fragments are presented.

NEODEEM* （Near-Earth Orbital Debris Environment Evolutionary Model）



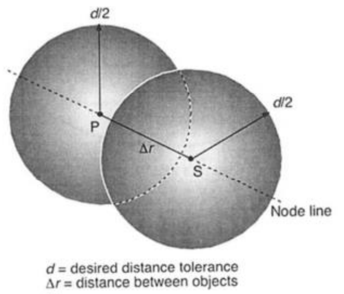
Initial Input：
　Set the scenario
　Initial population

Population Transfer: (Selectable)
　Traffic Model: New Launch（8-year cycle）
　<u>Explosion: Anz-Meador Model(MC)</u>
　<u>Maneuver: PMD(MC)、ADR(MC)</u>

MC: Monte Carlo Simulation

　<u>Collision: Anz-Meador Model(MC)</u>
　Collision avoidance

Propagation:
　Earth Gravity（Zonal, Tesseral:4th）
　Air Drag（Jacchia-Roberts）
　Solar・Lunar attraction
　Solar Pressure



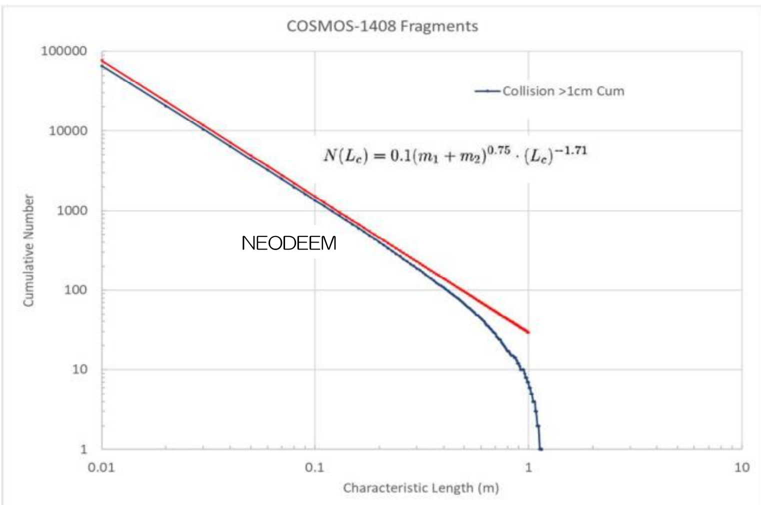
Collision Sphere Model

＊Developed by JAXA and Kyushu University

2

Generation of Fragments

1.　破砕片数（観測値）から衝突物体の質量を想定し、衝突モデルで破砕片を生成。
2.　大きな破砕片では有限サイズの影響で少なくなっている。



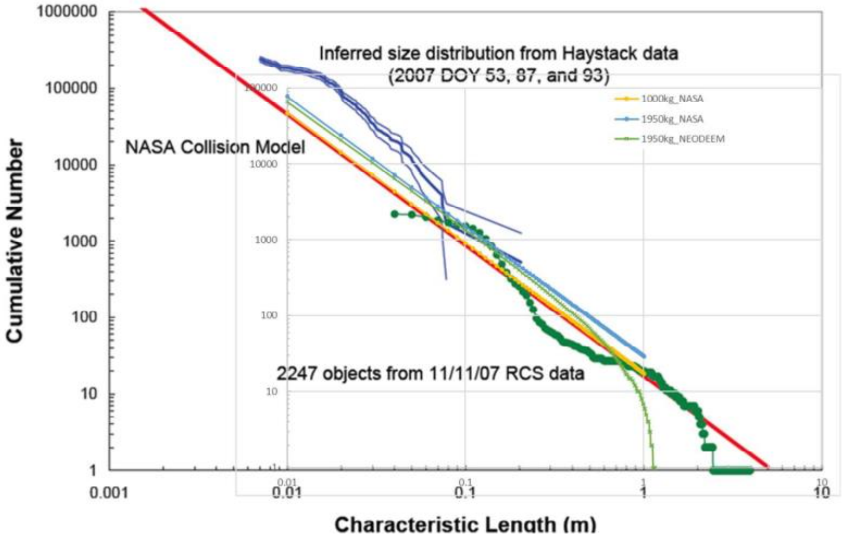
注／Notice:
モデルにおける10cm以下の破砕片の生成数は検証されていない。
The number of fragments less than 10 cm in the model has not been validated.

Assuming the mass of the colliding object from the number of fragments (observed data).
Fragments are generated by the collision model.
Due to finite size effect large size fragments are fewer than NASA model.

3

Generation of Fragments～Fengyun-1C Case

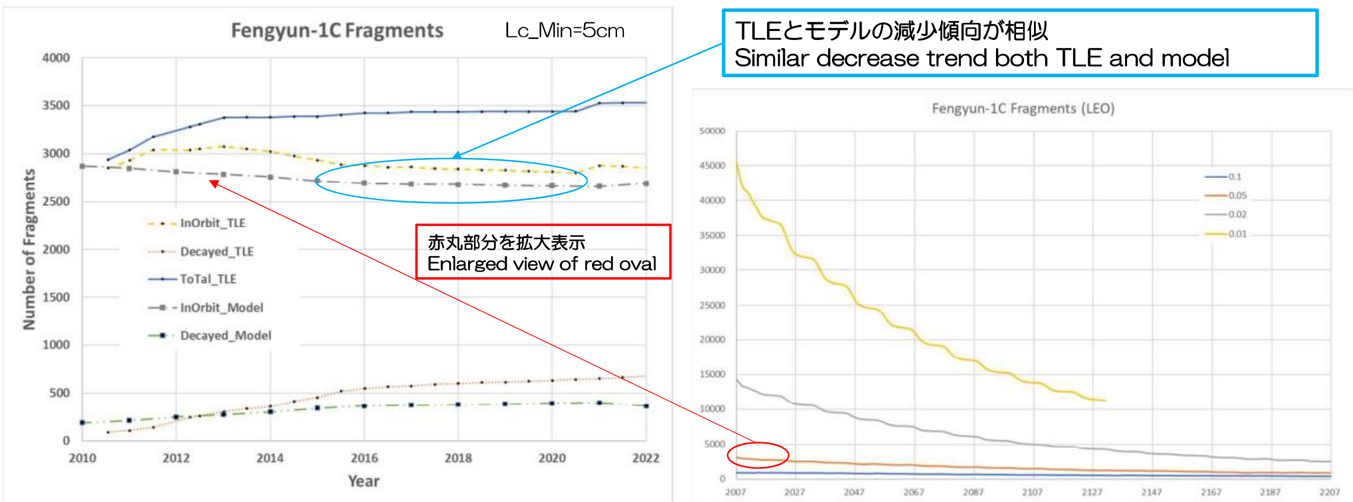
1. Fengyun-1Cの観測値との比較
2. 破砕片数から、衝突のトータル質量を1950kg想定



Comparison with Fengyun-1C observation data.
From the observation number of fragments, the total mass of the collision is assumed to be 1950kg.

Comparison between observation and model data

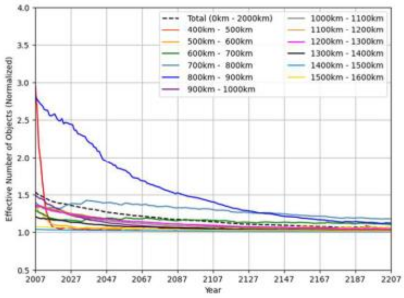
1. Fengyun-1C DEBのTLE推移とNEODEEMでの生成破砕片との比較
2. 観測値が安定している領域での破砕片数変化には相関がみられる。

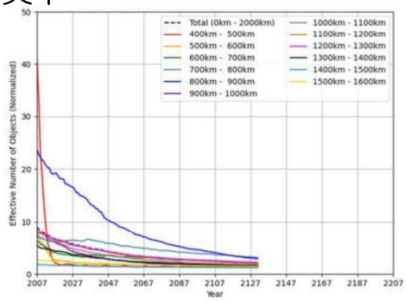


Comparison of TLE data of Fengyun-1C DEB and fragments generated by NEODEEM.
There is a correlation between changes in the number of both observed and generated fragments.

Estimated Number of Fengyun-1C fragments

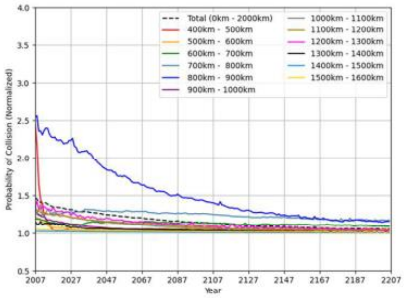
1. 破砕片サイズによる軌道上破砕片数の推移と積算衝突率

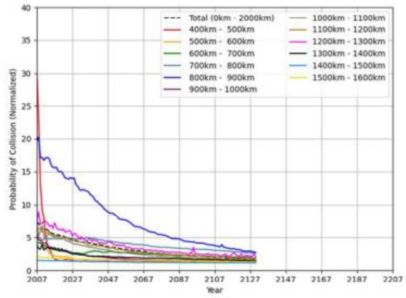




Lc_Min=5cm

Lc_Min=1cm





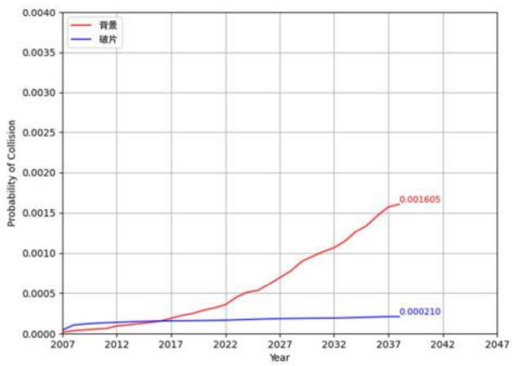
The number of on-orbit fragments and cumulative collision rate by fragment size

6

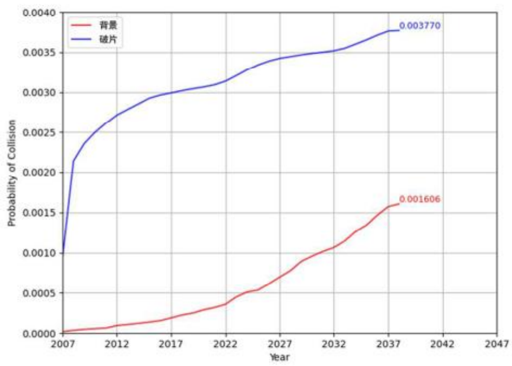
Probability of Collision to ISS（Fengyun-1C）

1. 破砕片サイズによる積算衝突確率の差異
2. 赤線はFengyun-1Cの破砕片以外による衝突率

Lc_Min=5cm



Lc_Min=1cm

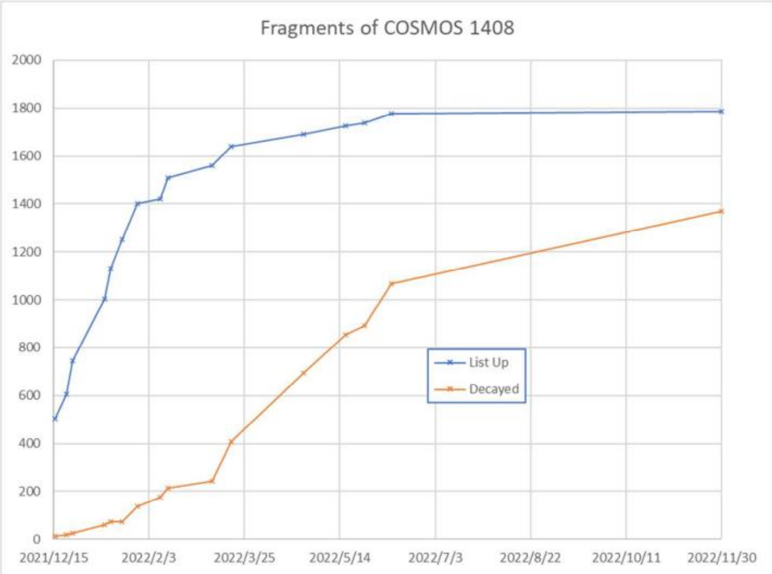


Difference in cumulative collision probability due to fragment size.
The red line is the collision rate due to fragments other than Fengyun-1C fragments.

7

Fragments of COSMOS-1408 (Current Status)

1. Destroyed on 2021/11/15
2. Observed Fragments with TLE

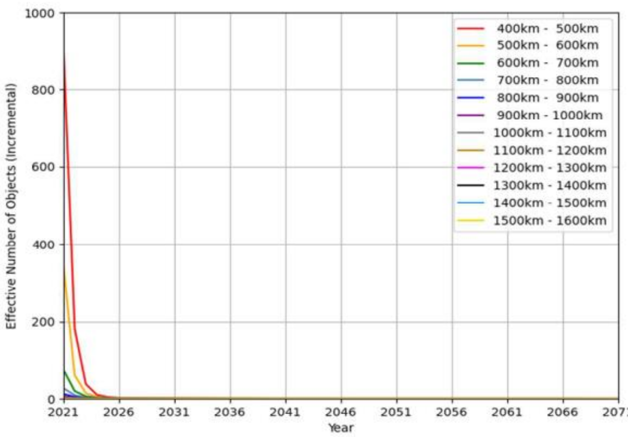


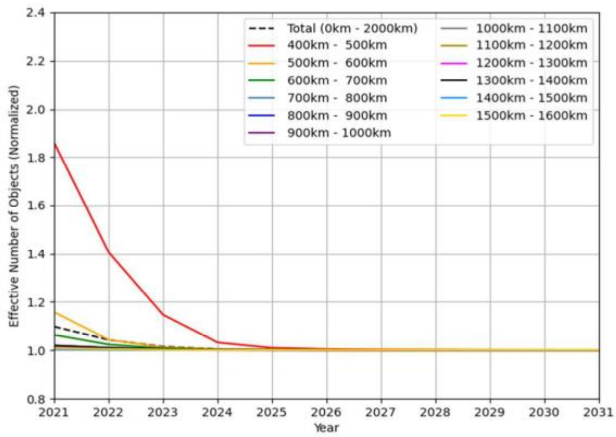
DATE	List Up	Decayed	Decayed Rate
2021/12/16	503	12	2.39
2021/12/22	606	20	3.30
2021/12/25	744	25	3.36
2022/1/11	1002	62	6.19
2022/1/14	1130	73	6.46
2022/1/20	1250	74	5.92
2022/1/28	1400	137	9.79
2022/2/9	1419	176	12.40
2022/2/13	1510	213	14.11
2022/3/8	1560	242	15.51
2022/3/18	1641	407	24.80
2022/4/25	1690	694	41.07
2022/5/17	1727	854	49.45
2022/5/27	1739	892	51.29
2022/6/10	1777	1067	60.05
2022/11/30	1787	1368	76.55

Estimated Number of COSMOS-1408 Fragments

1. 衝突高度の400-500kmの物体数は衝突直後約900個増加するが、数年のうちに大部分は落下し以前の状態に戻ると予想される。

Lc_Min=10cm

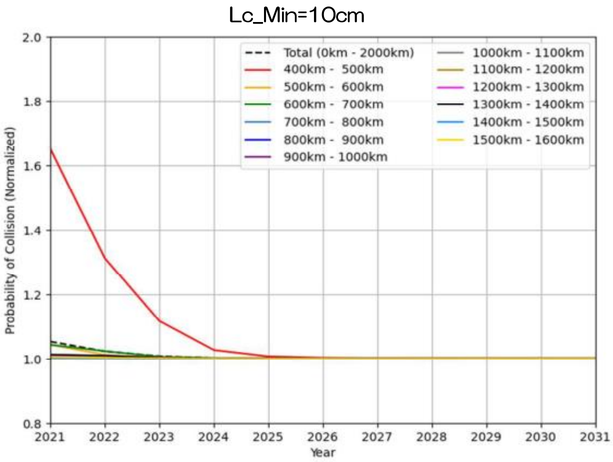


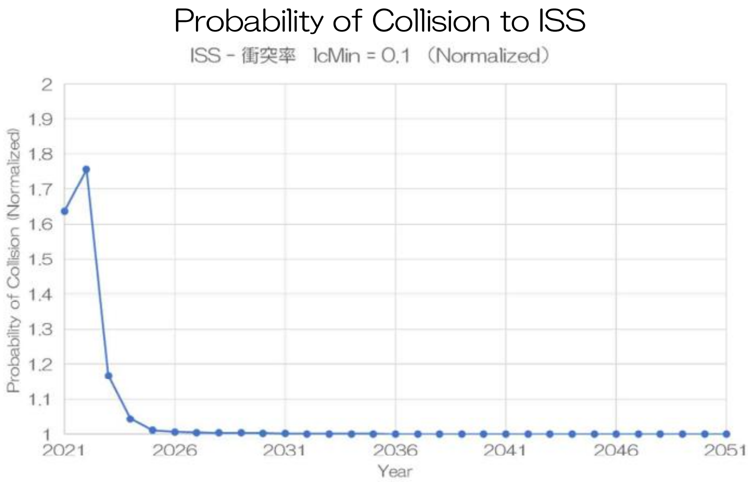


The number of objects at a collision altitude of 400-500 km will increase after the collision.
But most of these fragments are expected to decay, and the orbital environment return to the previous state within a few years.

Probability of collision （COSMOS-1408）

1. ISSへの衝突確率は衝突直後は約1.65倍、１年後には1.75倍となるが、長期的には影響がほとんどない。



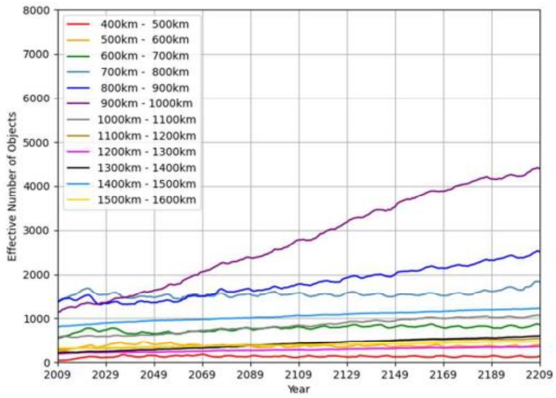


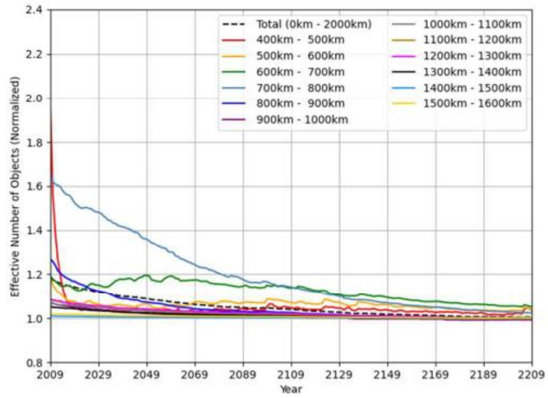
The collision probability to ISS is about 1.65 times immediately after the collision and 1.75 times one year later, but there is almost no impact over the long term.

Estimated Number of Fragments （Iridium33 – COSMOS2251）

1. 衝突は高度789kmで発生。
2. 破砕片は発生高度から徐々に降下、衝突高度が高いので長期的に影響が残る

Lc_Min=10cm



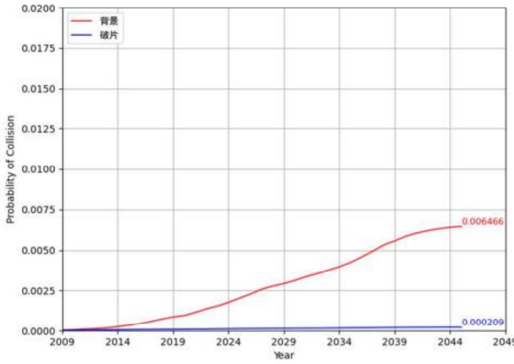


The collision occurred at an altitude of 789 km.
Fragments decay gradually from the generated altitude.
Orbital impacts remain for a long time due to the high collision altitude.

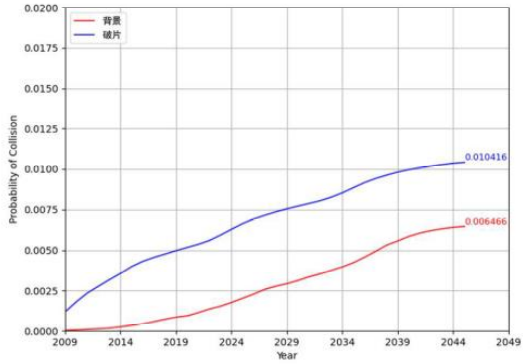
Probability of collision （Iridium33 – COSMOS2251）

1. 破砕片サイズによるISSへの積算衝突率の差異
2. 10cmサイズの破砕片による衝突率はあまり大きくならないが、1cmまで考慮すると1.6倍の影響が予想される。

Lc_Min=10cm



Lc_Min=1cm



Difference in cumulative collision rate to ISS by fragment size.
The collision rate of more than 10cm-sized fragments is not so large,
But more than 1cm-sized fragments effect is expected to be 1.6 times larger.

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Summary

1. 推移モデルを用いて破砕片生成とその後の破砕片の挙動を推定する一手法を示した。
2. モデルによる破砕片の挙動は、実測結果と統計的な傾向として類似性が見られる。
3. 軌道上イベント発生時に観測結果からその後の軌道環境の予想を行う一手法として利用が可能である。

1. A method for estimating fragment generation and subsequent fragment behavior by using an environment evolutionary model is presented.
2. The modeled fragment behavior is similar to the actual measurement results as a statistical trend.
3. It may be used as a method to predict the orbital environment after an In-orbit event from observation results.

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C04

軌道上デブリデータベースの更新状況　―PMD および異常検知への応用―

Update Status of the On-orbit Objects Database
--Application for Detecting PMDs and Anomalies of Orbit--

○上田 裕子、中原 雄樹、八田 真児（MUSCAT スペース・エンジニアリング）、
小林 泰三（秋枞）、長岡 信明、河本 聡美、原田 隆佑（JAXA 研究開発部門）
○UEDA O. Hiroko, NAKAHARA Yuki, HATTA Shinji (MUSCAT Space Engineering),
KOBAYASHI Taizo (AcisomA), KAWAMOTO Satomi, NAGAOKA Nobuaki,
HARADA Ryusuke (JAXA Research and Development Directorate)

JAXA 研究開発部門では推移モデルのための軌道上デブリデータベースの更新を継続して行っている。その一環として TLE 軌道履歴をサーベイし、TLE 履歴から A/M の推定を行い、デブリ環境モデルと比較するなどしてサイズや質量を割当てている。また TLE 履歴をサーベイすることで、個々の衛星の運用終了や PMD を行ったことによる軌道変化、および衝突・破砕等による異常な変化やそのタイミングを知ることができる。
そこで TLE 履歴に表れる特徴から、制御を継続している衛星か運用終了やデブリの状態であるか、さらに軌道変化が運用による制御か運用終了や PMD であるか、または衝突・破砕によるイベントかを自動判別、分類する試みを行っている。今後、それらの精度向上のために機械学習を取り入れることも検討している。

JAXA continues to update the on-orbit objects database for the debris evolutionary model. As part of the work, we survey TLE orbit histories, estimate A/M from TLE histories, and compare them to debris environment models to assign sizes and masses. By surveying TLE histories, it is possible to determine orbital changes due to the termination of operations or PMD of individual satellites, as well as anomalous changes due to collisions, etc. and their timing.
We have worked to automatically identify and classify whether a satellite is still under control or out of operation, and whether the orbit change is due to operational control, PMD, or a collision event, based on the characteristics that appear in TLE histories. We are considering incorporating machine learning methods to improve their accuracy.

Update Status of the On-orbit Objects Database --Application for Detecting PMDs and Anomalies of Orbit--

軌道上デブリデータベースの更新状況 ―PMDおよび異常検知への応用―

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上田 裕子、中原 雄樹、八田 真児 (MUSCAT スペース・エンジニアリング)、
小林 泰三 (秋灿)、長岡 信明、河本 聡美、原田 隆佑 (JAXA研究開発部門)

Outline

■JAXA on-orbit objects database

■Updating the database

- estimate A/M from surveyed TLE orbit histories
- assign sizes and masses for debris comparing to debris environment models (MASTER)

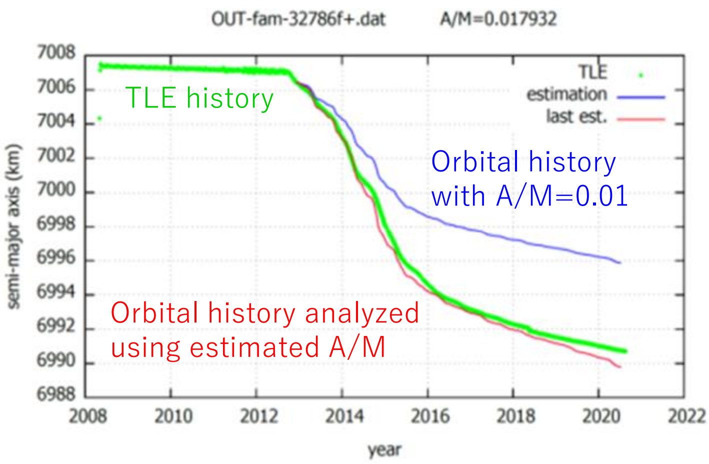
■Application of TLE orbit history survey

- identify PMD of satellites
- detect anomalous orbital changes

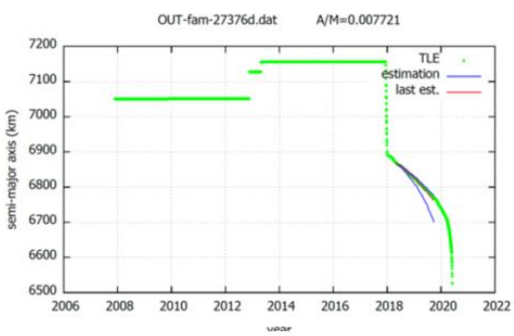
JAXA On-orbit Objects Database

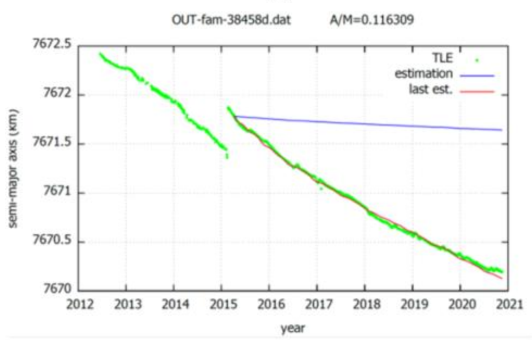
- Baseline file for the debris evolutionary model; NEODEEM
- Over 24000 objects data is maintained, about 20,000 available from TLE data by space-track.org, uncataloged objects from ground observations
- Based on the breakup history, fragment objects supposed to be in the orbit are added
- Orbital elements, mass and the other characteristics of the objects are contained
- Area-to-mass ratios(A/M) of cataloged objects are estimated from TLE orbit histories
- Mass and size of fragments are randomly set to match the A/M with fragments generated by NASA standard breakup model

A/M Estimation from Surveyed TLE History



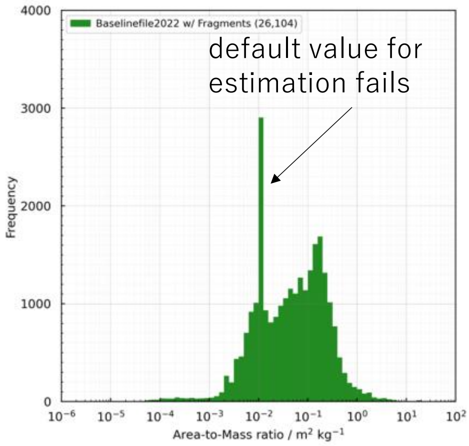
- Daily update TLEs and A/M estimation
- Automatic detection of suitable intervals for analysis



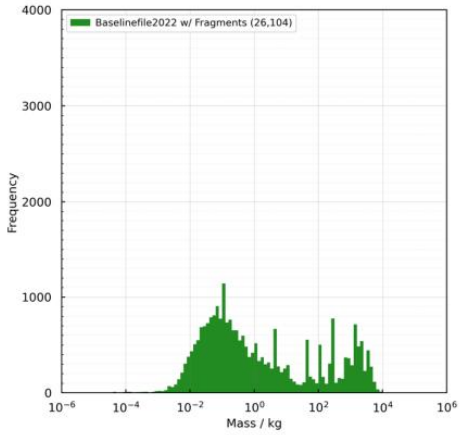


Mass and Size Assignment for Debris

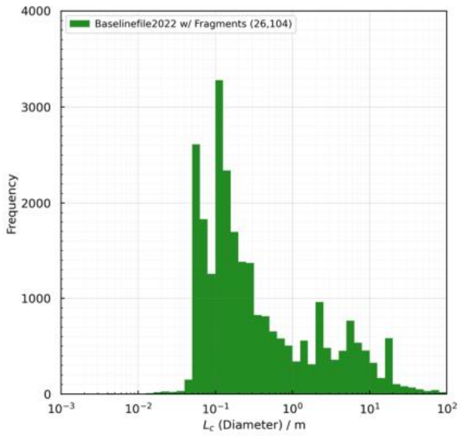
- Masses and sizes of debris are assigned according to that relation between A/M and those of ESA MASTER-8 debris sources
- Explosion fragments generated by NASA standard breakup model are added



A/M distribution

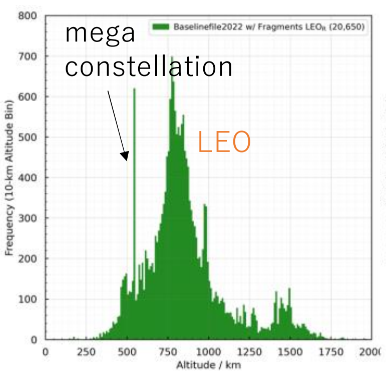


Mass distribution

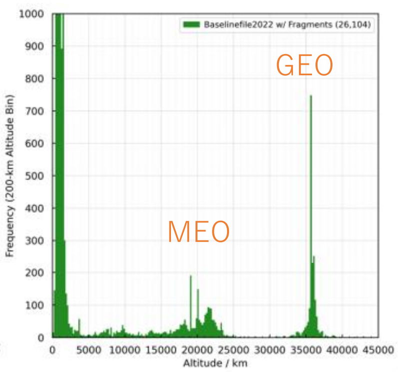


Diameter distribution

Characteristics of the Database

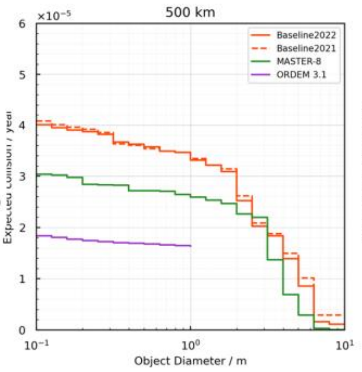


0-2000km

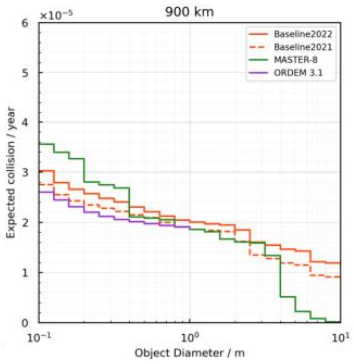


0-45000km

Attitude Distribution



500km



900km

Expected Collision Probability

Application of TLE Orbit History Survey

- TLE of satellite shows each condition such as under operation, end of operation, deployment of deorbit devices, control for PMD.
- TLE of the others may show anomalies such as collisions, explosions, generation of new debris, disappearance from TLEs, etc.
- Objective is to detect those by surveying

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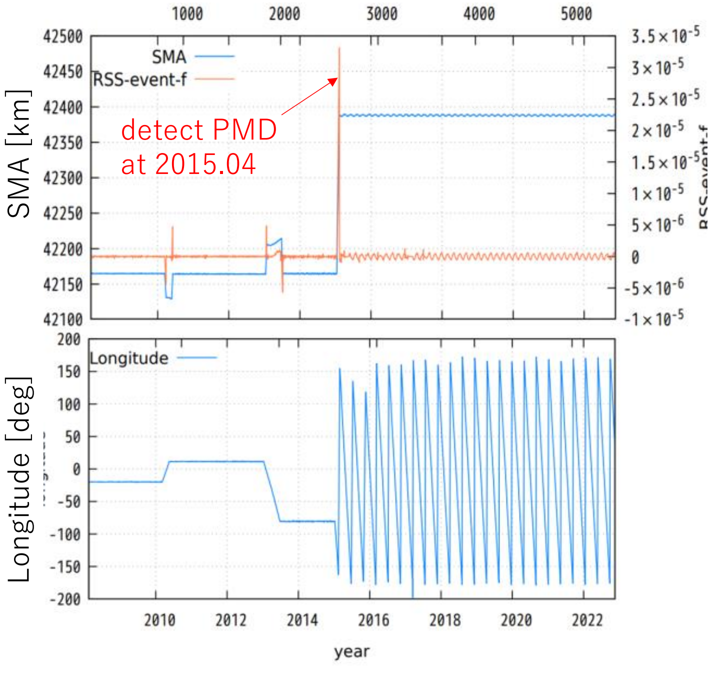
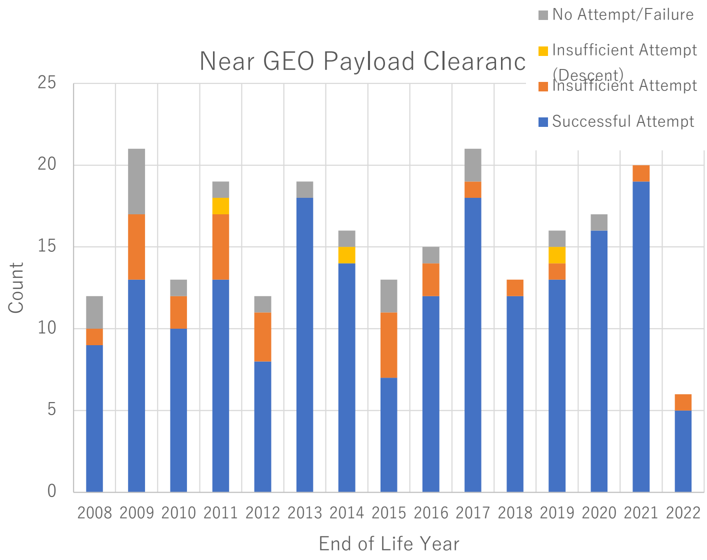
PMD Identification from TLE History : GEO

Orbit History of a GEO Sat.

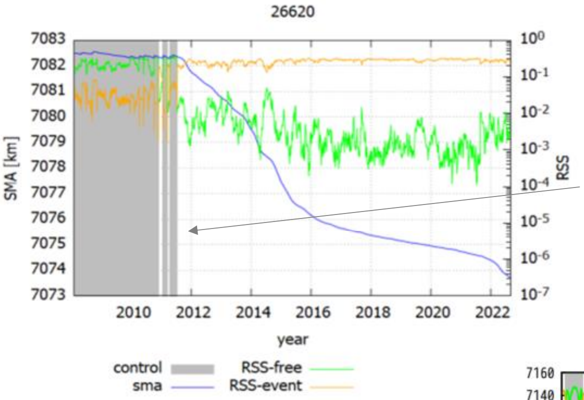


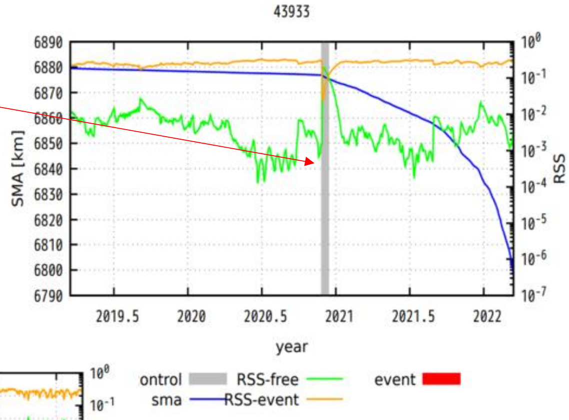


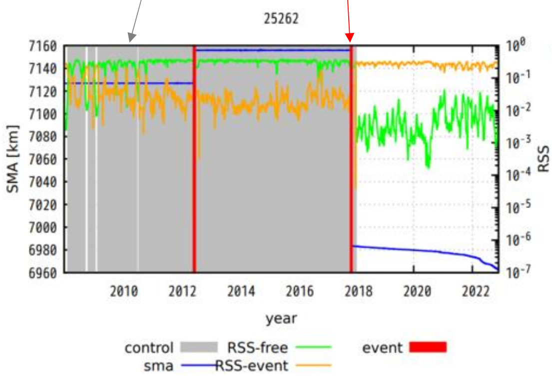
213 PMDs identified automatically

8

PMD Identification from TLE History : LEO



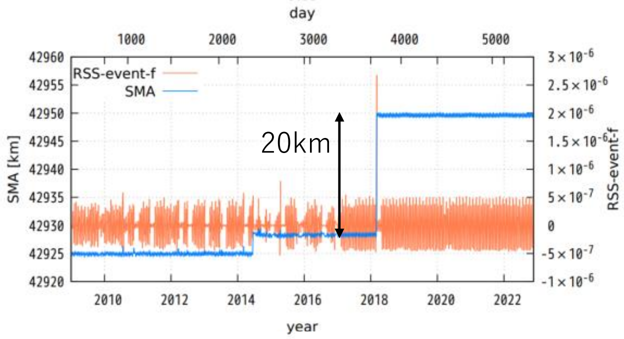




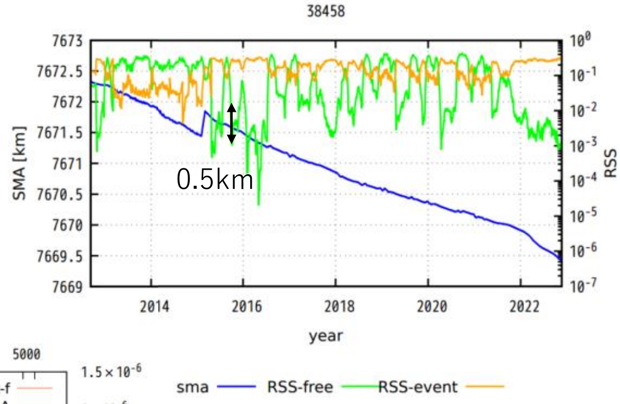
- Orbit histories have **variety of patterns**
- Machine learning will be effective for accurate identification

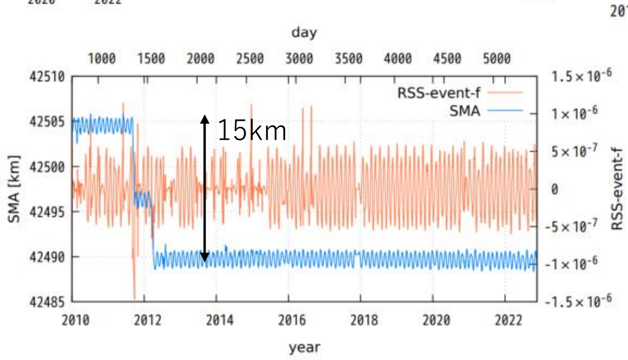
Future Work

Detection of **anomalous** orbital changes by TLEs daily check



TITAN 3C TRANSTAGE R/B (GEO)





GOES 10 (GEO)

OPS 4682 DEB (LEO)

Summary

- JAXA's original database for debris evolutionary model have been developed
- We have updated it by analyzing TLEs and add observation data to improve the completeness
- An application of TLE survey, we identified PMD of GEO satellites with sufficient accuracy, and work on using machine learning to improve accuracy for LEO satellites
- Detecting anomalous orbital changes is another objective

C05

大気上層の長期変動を考慮した宇宙開発の持続可能性評価
Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

〇清水貴裕、吉村康広（九州大）、河本聡美、原田隆佑（JAXA 研開部門）、
花田俊也（九州大）
〇SHIMIZU Takahiro, YOSHIMURA Yasuhiro (Kyushu Univ.),
KAWAMOTO Satomi, HARADA Ryusuke (JAXA Research and Development Directorate),
HANADA Toshiya (Kyushu Univ.)

本研究は，熱圏の長期的な密度減少に起因する軌道環境の変化が，今後の宇宙開発に与える影響について評価することを目的としている．近年問題となっている温室効果が，宇宙機が多く運用されている高度 800 km までの熱圏で寒冷化を引き起こし，それによる大気密度の減少が報告されている．大気密度の減少を考慮せずに長期的な軌道環境の予測を行うと，低軌道におけるスペースデブリの数や軌道寿命が過小評価される恐れがある．本研究では，JAXA と九州大学が共同開発・運用している軌道環境推移モデルを用いて，大気密度減少化における長期的な軌道上のスペースデブリ数，スペースデブリの軌道寿命，及び宇宙機やスペースデブリの衝突確率を予測する．また，軌道環境の変化に対応可能となるよう，25 年ルールを満たす高度や必要増速量，能動的デブリ除去の効果を計算し，衛星運用の安全性向上のための方策について提案する．

There is a growing concern about climate change caused by greenhouse gases. Especially, carbon dioxide has significant influences not only on the lower atmosphere but also on the upper atmosphere such as the thermosphere where space objects are orbiting. One of the problems of increasing carbon dioxide is that it reduces the density of the thermosphere, resulting in less atmospheric drag on space objects. This paper evaluates the long- term influence of decreasing the atmospheric drag on the space environment and space activities using an orbital debris evolutionary model. In this study, Jacchia-Roberts 1971 atmospheric model is used to calculate the atmospheric density. In addition, this study makes correction to atmospheric density with considering the long-term density decrease. This paper also reveals the long-term impact of density decrease on space activity by calculating the debris number transition, the extension of debris orbital lifetime, and collision probability with debris. Furthermore, this study shows the change of delta-v and the collision probability with other objects to satisfy the 25-year rule.

C05
大気上層の長期変動を考慮した宇宙開発の持続可能性評価

Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

Kyushu University
◯Shimizu Takahiro, Yoshimura Yasuhiro, Hanada Toshiya
Japan Aerospace Exploration Agency (JAXA)
Harada Ryusuke, Kawamoto Satomi

11/30/2022
The 10th Space Debris Workshop

九州大学

The Changes in Low-Earth Orbit ①

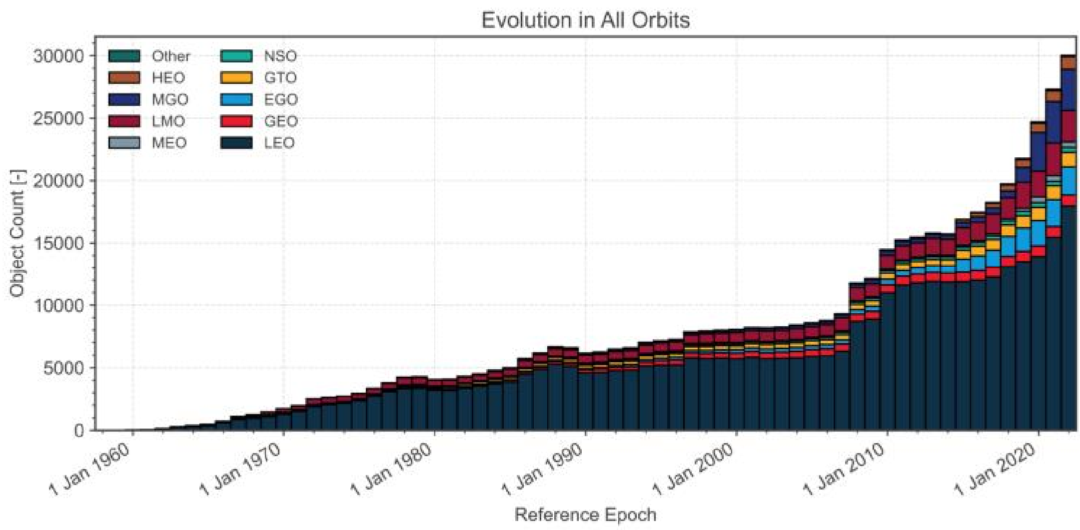


Figure 1. Evolution of number of objects in geocentric orbit[ESA, 1]

- The number of objects in Low-Earth orbit(LEO) has increased significantly since 2010 because of constellation and debris.

The Changes in Low-Earth Orbit ②

- The increase of CO_2 and cooling in the thermosphere
  - Thermosphere have been **cooling** due to the “greenhouse effect”.
  - Thermospheric density decreases because of cooling.
  - ✓ The upper atmospheric data show the **long-term decrease of density**.[2–4]

➡ **Atmospheric drag is reduced in the altitude where many satellite are present.**

- The impact of reduced atmospheric drag is…
  - Extension of the objects’ lifetime in LEO
  - It is advantage to satellite manager in terms of fuel savings, but satellite at the end of operation may be less likely to deorbit.

C05 Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere
1. Background 2. Method 3. Result 4. Conclusion

The Motivation of this study

- There are little examples of cooling in the thermosphere **applied to the engineering field**.

The Objective of this study

- Assessing the impact of density reduction associated with thermospheric cooling **on the orbital environment**

Study flow

- Apply density decrease to **atmospheric models**
- Analyze by **NEODEEM** and comparison with the previous result
- Verify Post-Mission Disposal(PMD) effects
- Analyze **orbital lifetime and 25-year rule**

The Calculation of Long-Term Change in Thermosphere

◆ Thermospheric density trend is -2 to -5 %/decade

- Several studies using orbital data since the 1960s suggest this trend
- This trend will keep because the CO_2 concentration keep increasing

□ Calculation Method

- ρ is the atmospheric density
- ν is the trend of density

$$d\rho = \nu \rho dt \Rightarrow \rho_c = \rho_0 e^{\nu(t-t_0)}$$

ρ_c : Atmospheric density **after** correction

ρ_0 : Atmospheric density **before** correction

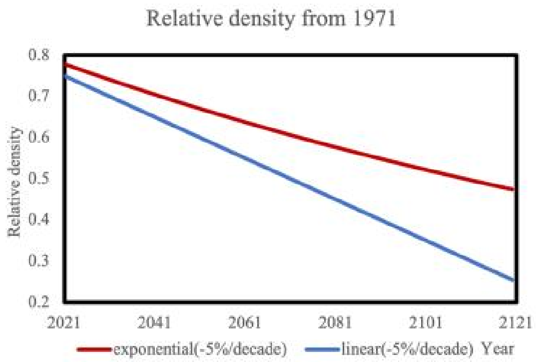


Figure 2. Relative density after correction

Orbital Environment Simulation ①

□ Condition in NEODEEM

- This study uses the density calculated by the Jacchia-Roberts 1971 atmospheric model and corrected by above-mentioned formula.
- PMD rate is 0, 0.3, 0.6, and 0.9
- PMD is trying to drop to an altitude that would fall in 25 years, assuming JR 1971 (uncorrected) is right.

Table 1. Simulation condition

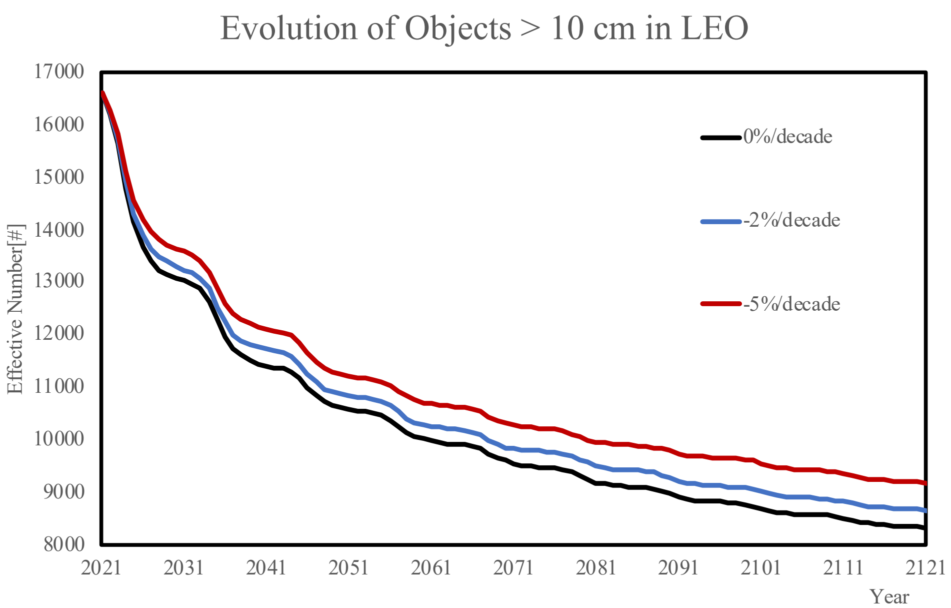
Parameters	Conditions
Initial Population	Objects in 2021 (≥10 cm)
Span	2021 – 2120
MC Runs	150
Atmospheric Model	Jacchia-Roberts 1971
Perturbations	Air drag, SRP, Third body, Geopotential
Space activity	New launch PMD, Collision
Density trend ν	0, -2, -5 %/decade

Orbital Environment Simulation ②

- Evaluation items
  - **Population of objects more than 10 cm in LEO**
  - Spatial density as a function by altitude
  - Effectiveness of PMD
- Analysis and evaluation based on orbit propagation results
  - **Lifetime** of initial objects
  - Relationship between **lifetime**, **area-to-mass ratio** and **initial altitude**

Evolution of Initial Population

No Collisions, PMD, and New Launches



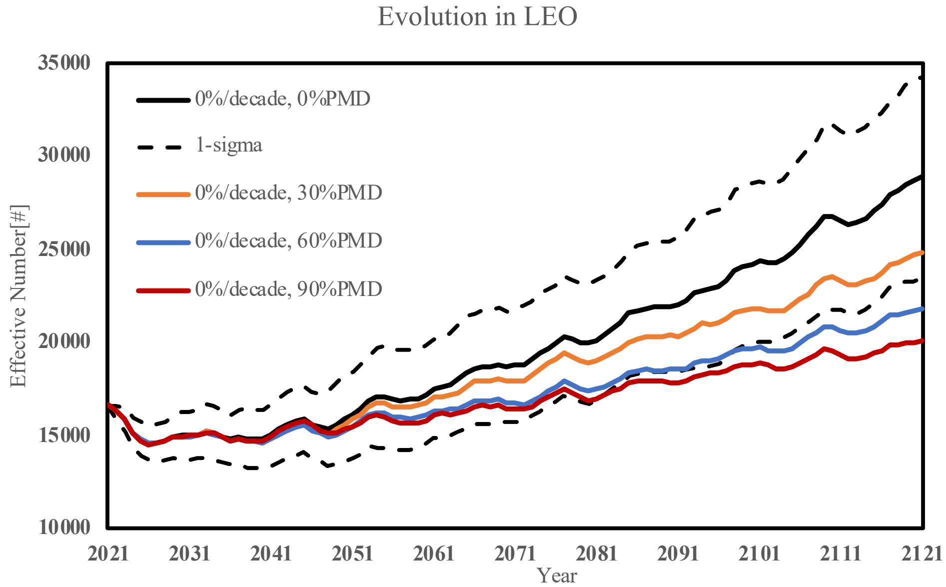
➢ Greater density decreasing trends lead to more objects remaining.

C05 Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

1. Background 2. Method **3. Result** 4. Conclusion 8

Evolution in LEO ①

With Collisions and New Launches



- 90% PMD(this is the obligation to make effort regarding PMD success rates set by IADC Space Mitigation Guidelines[5]) is effective to lessen the objects in LEO.

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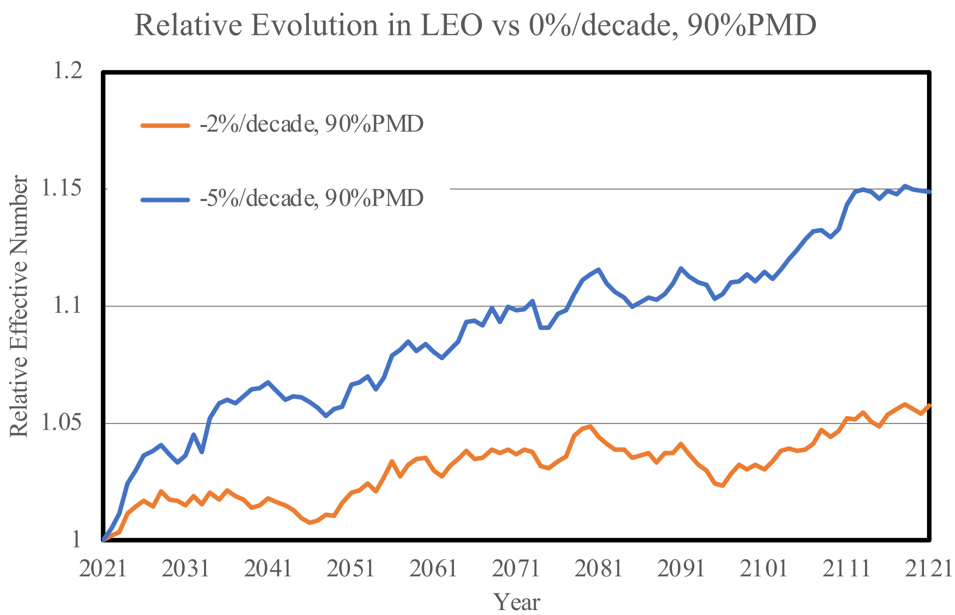
1. Background 2. Method **3. Result** 4. Conclusion 9

Evolution in LEO ②

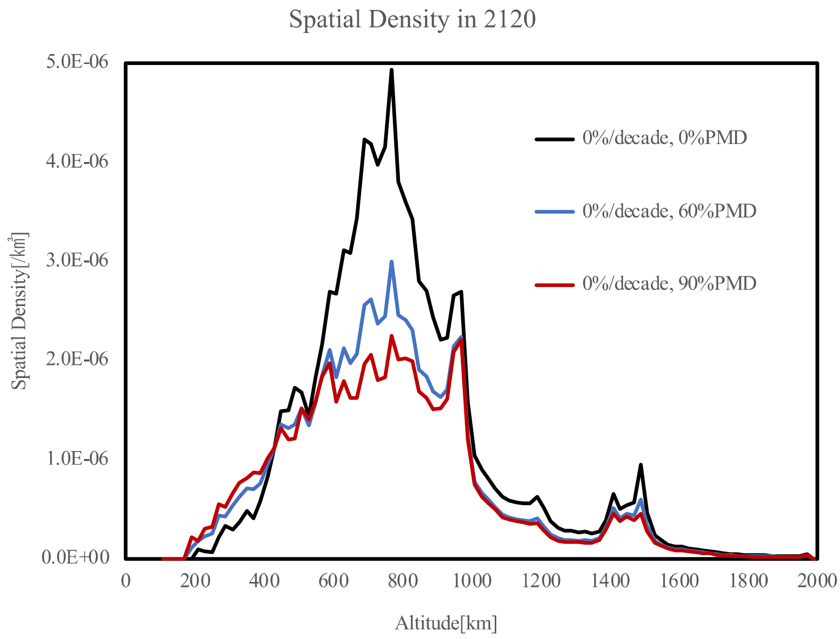
With Collisions and New Launches



- Density decrease in the thermosphere can diminish the effectiveness of PMD.

Spatial Density by Altitude ①

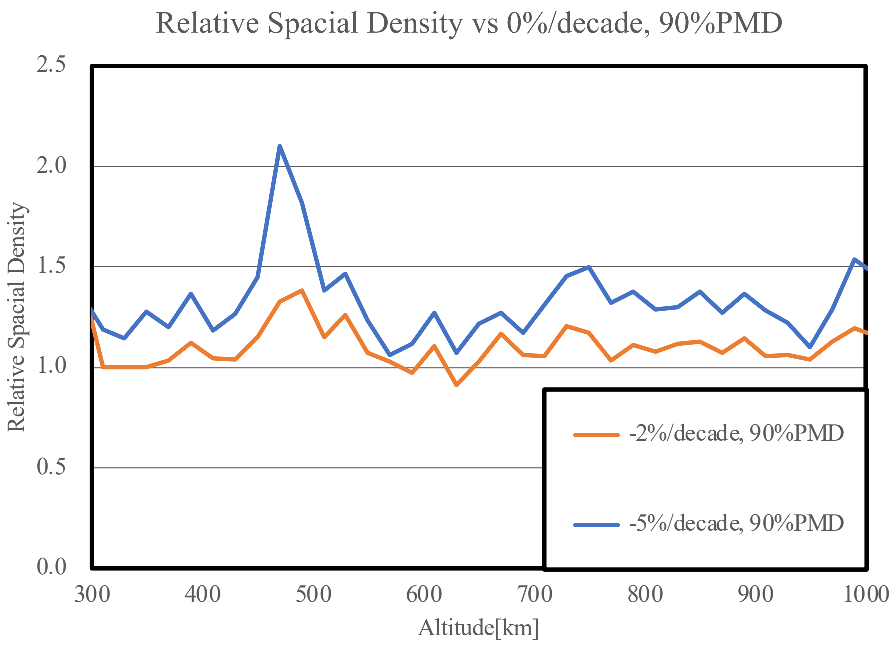
With Collisions and New Launches



➢ Spatial density <u>at altitudes above 600 km</u> decreases due to PMD

Spatial Density by Altitude ②

With Collisions and New Launches

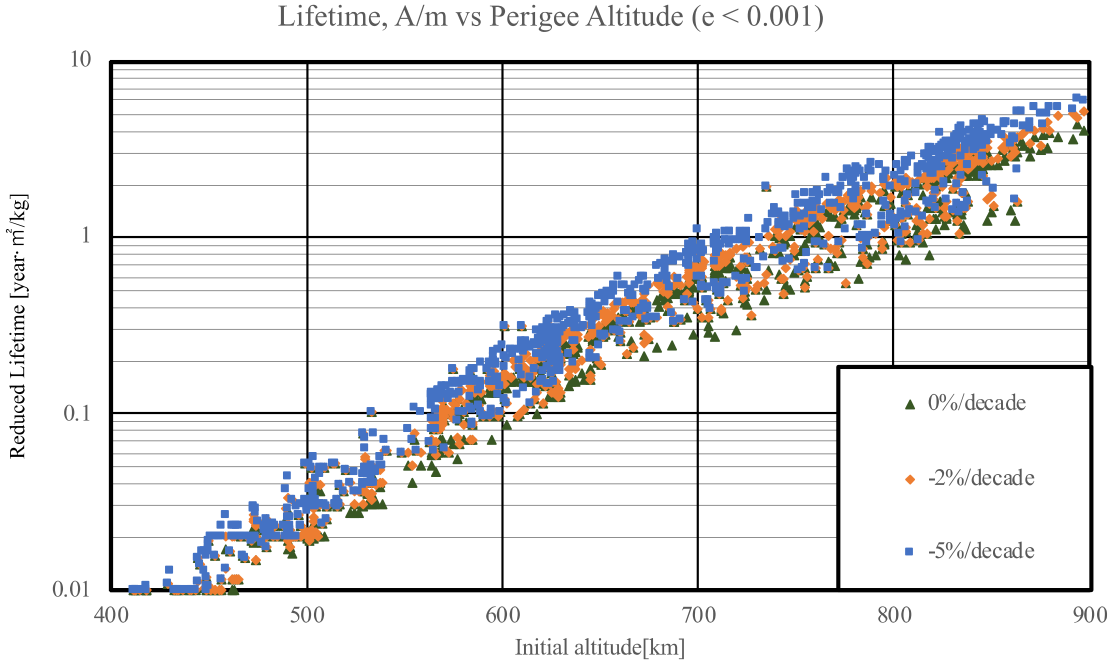


➢ <u>Density decrease in the thermosphere can diminish the effectiveness of PMD</u>.

C05 Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

1. Background 2. Method **3. Result** 4. Conclusion 12

Analysis of Lifetime and 25-year rule



- The vertical axis is the **product of A/m and lifetime**

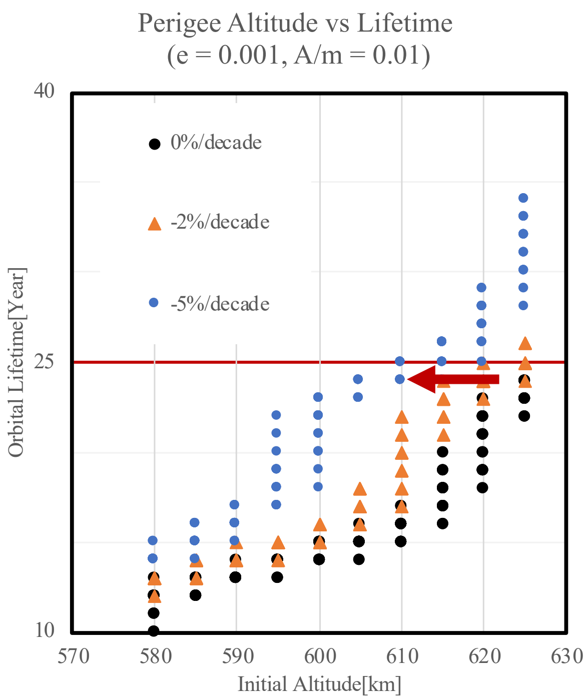
C05 Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

1. Background 2. Method **3. Result** 4. Conclusion 13

Analysis of Lifetime and 25-year rule

- The right figure is the propagation result of objects, which have the A/m = 0.01, e = 0.001, and inclination angles every 5 degrees, from 0 to 100 degrees.
- Spacecraft must lose more altitude to meet the 25-year rule.

→ **PMD Cost Rise**



Summary

☐ Impact of density decrease on LEO

- In LEO, the stronger density decrease trend, the greater debris increase.
- Especially, **spatial density at the lower altitude** increases significantly.

☐ Effectiveness of PMD

- 90% PMD is effective in the debris reduction at altitude above 600 km
- Density decrease in the thermosphere can diminish the effectiveness of PMD.

☐ Lifetime of satellites and 25-year rule compliance

- The stronger density decrease trend, the lower initial altitude must be.
- To comply with 25-year rule, the perigee altitude must be reduced more.

Reference

[1] ESA Space Debris Office, "ESA's Annual Space Environment Report," 2022.

[2] Emmert, J. T. (2015), Altitude and solar activity dependence of 1967–2005 thermospheric density trends derived from orbital drag, J. Geophys. Res. Space Physics, 120, 2940–2950, doi:10.1002/ 2015JA021047.

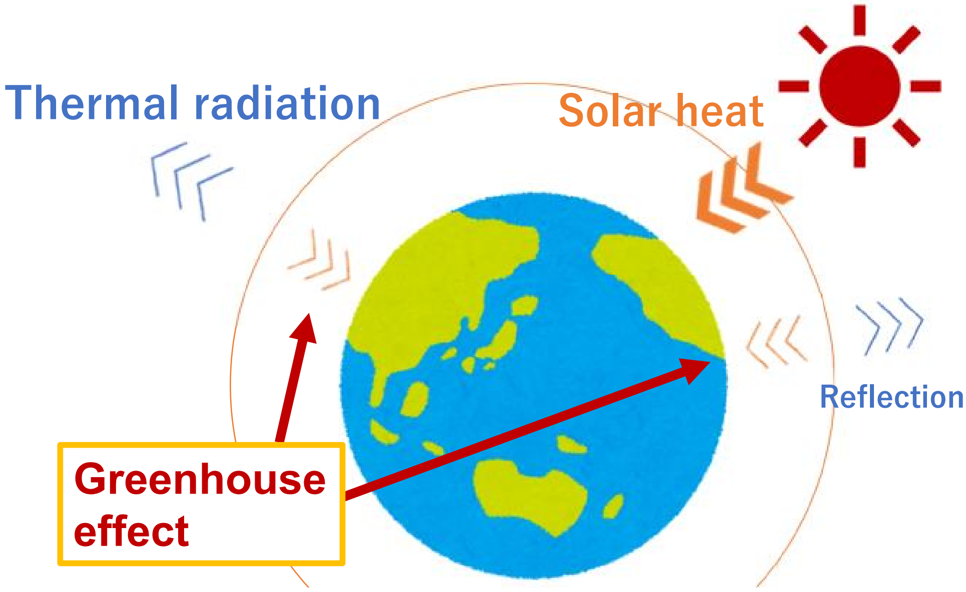
[3] Emmert, J. T., J. M. Picone, J. L Lean, and S. H. Knowles (2004), Global change in the thermosphere: Compelling evidence of a secular decrease in density, J. Geophys. Res., 109, A02301, doi:10.1029/2003JA010176.

[4] Brown, M. K., Lewis, H. G., Kavanagh, A. J., & Cnossen, I. (2021). Future decreases in thermospheric neutral density in low Earth orbit due to carbon dioxide emissions. *Journal of Geophysical Research*: *Atmospheres*, *126*, e2021JD034589.

[5]https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf

The diagram of cooling in the thermosphere

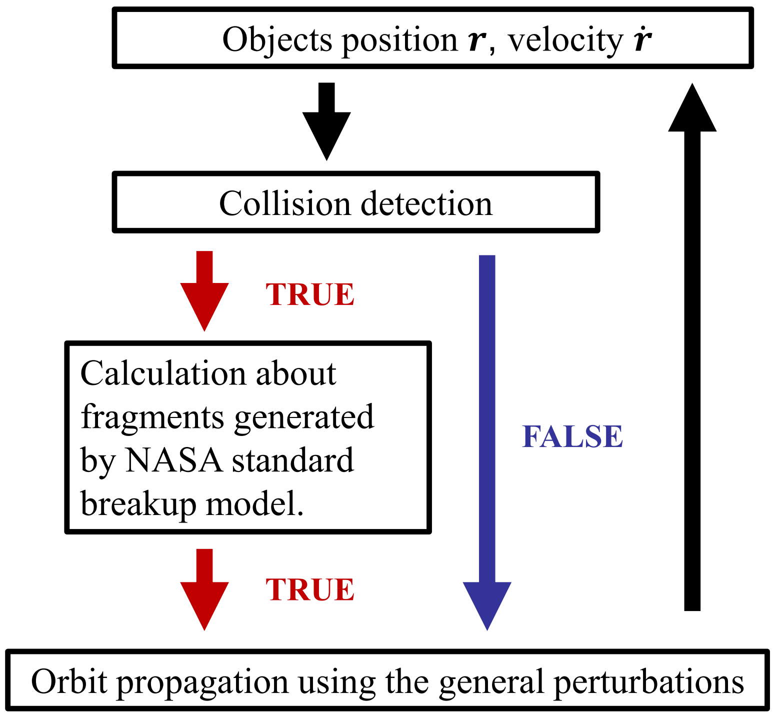
- ☐ Some of the heat returns to the surface due to the nature of CO_2
- ➢ In the thermosphere, the supply of heat is reduced, and cooling occurs.



Orbital Environment Simulation

☐ NEODEEM

- NEODEEM can predict the orbital environment with the assumption of new launch, collisions, and more.
- The diagram on the right shows the flow of an orbit environment simulation using NEODEEM.



The summary of density trends calculated by orbital data[2]

	Study 1[6]	Study 2[3]	Study 3[7]	Study 4[2]
Density trends [%/decade]	-4.9 ± 1.3	-2.8 ± 1.0	-1.7 ± 0.2	-2.0 ± 0.5

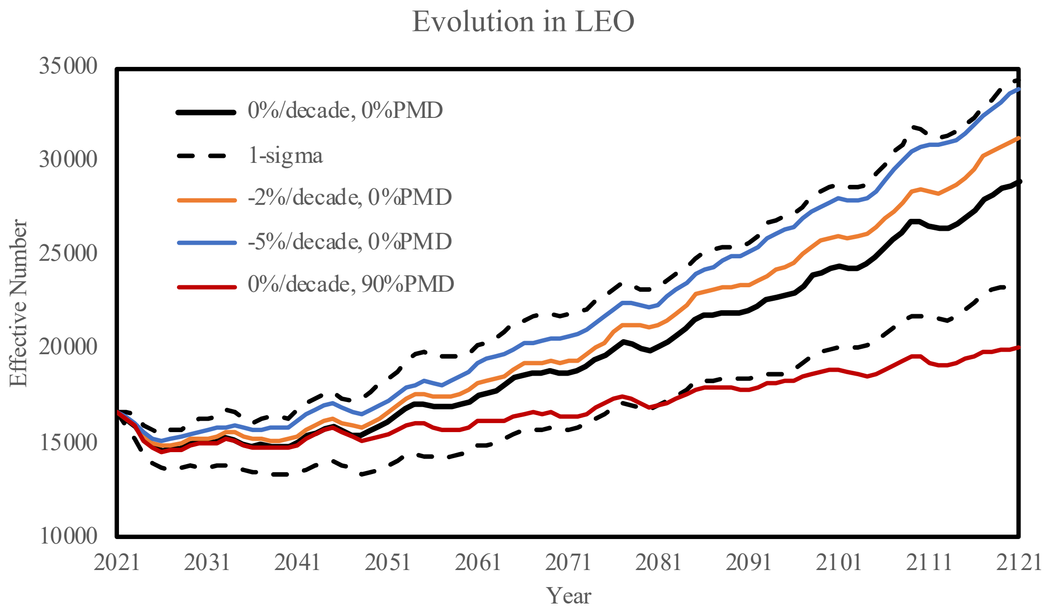
◆ The thermospheric density trend is -2 to -5 %/decade

[6] Keating, G. M., R. H. Tolson, and M. S. Bradford (2000), Evidence of long term global decline in the Earth's thermospheric densities apparently related to anthropogenic effects, Geophys. Res. Lett., 27, 1523–1526, doi:10.1029/2000GL003771.

[7] Marcos, F. A., J. O. Wise, M. J. Kendra, N. J. Grossbard, and B. R. Bowman (2005), Detection of a long-term decrease in thermospheric neutral density, Geophys. Res. Lett., 32, L04103, doi:10.1029/2004GL021269.

Evolution in LEO

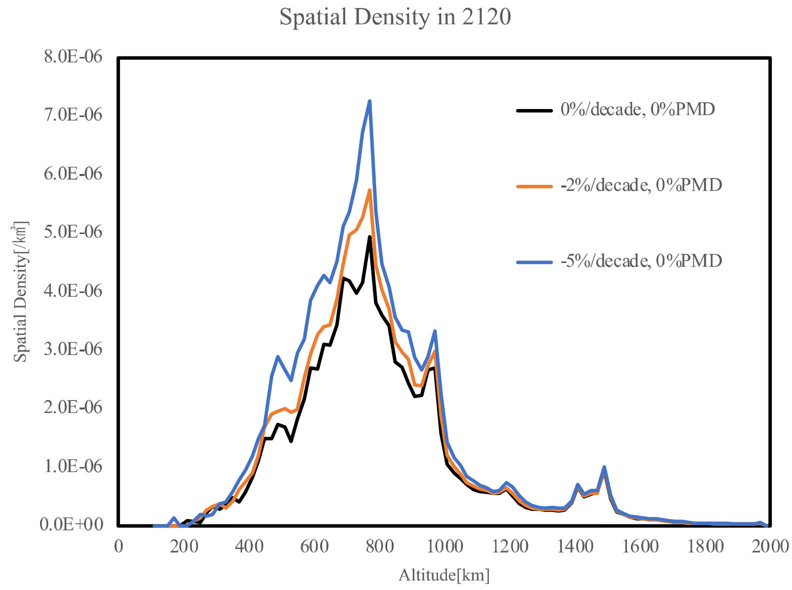
With Collisions and New Launches



➢ The number of objects is greater by the stronger density decrease trend.

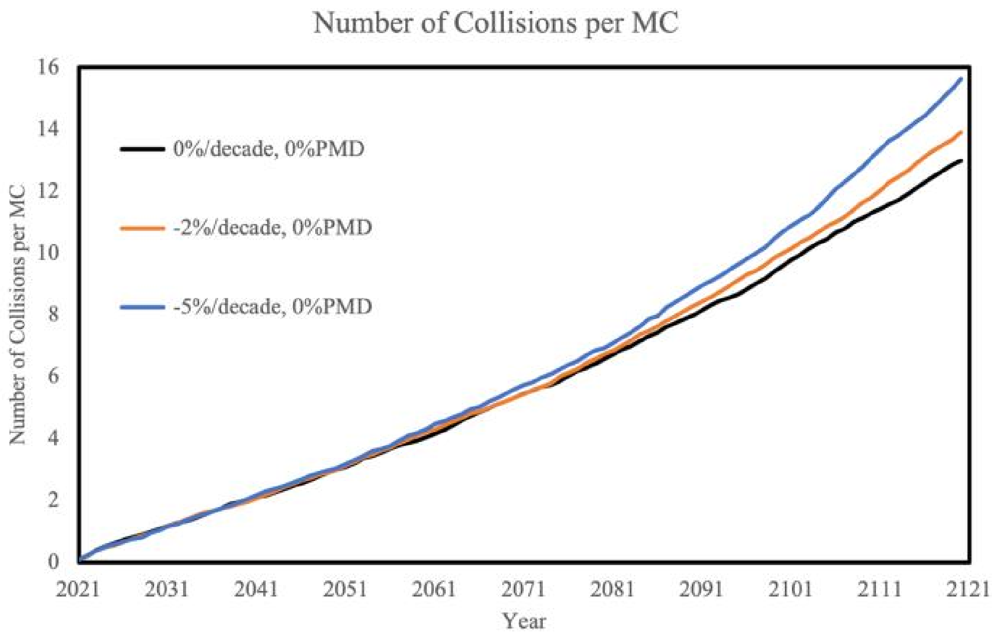
Spatial Density by Altitude

With Collisions and New Launches



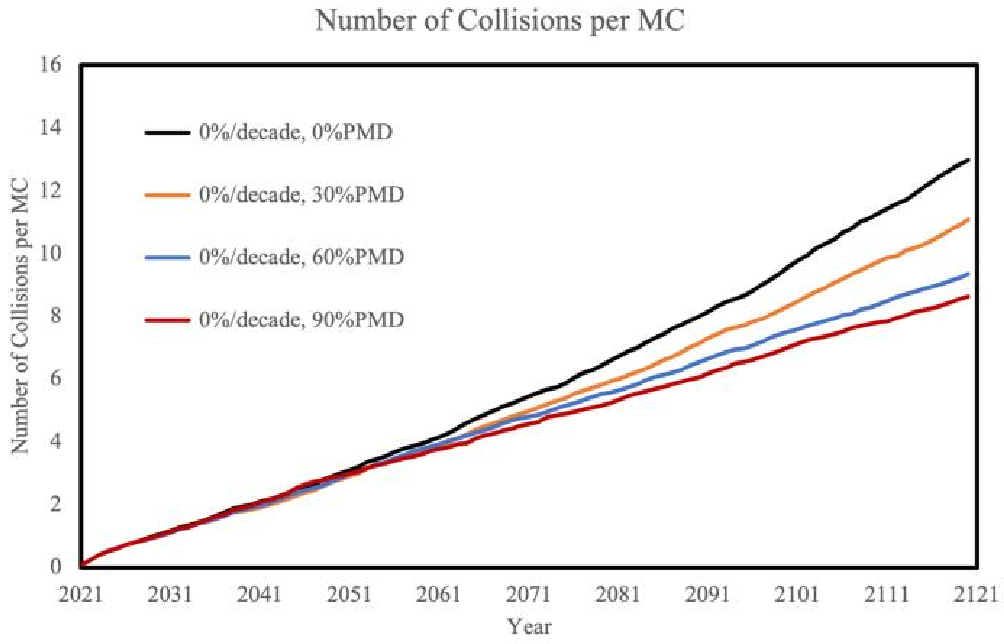
- Spatial density up to 1000 km altitude range increases because of density decrease

Number of Collisions up to 1,000 km ①



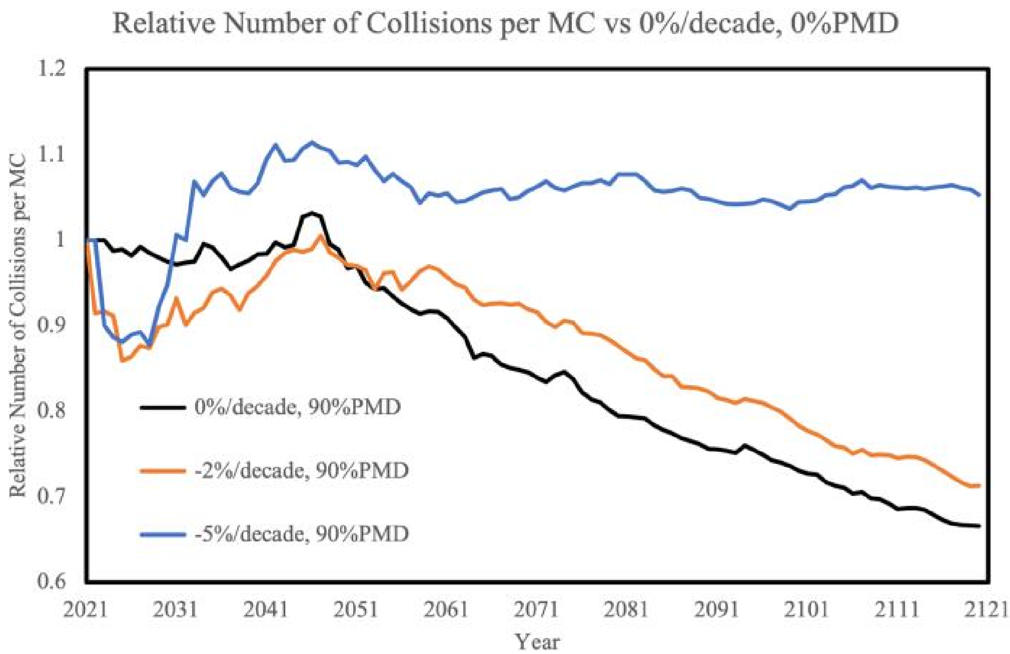
- The stronger density decrease trend can cause the long-term increase of breakups

Number of Collisions up to 1,000 km ②



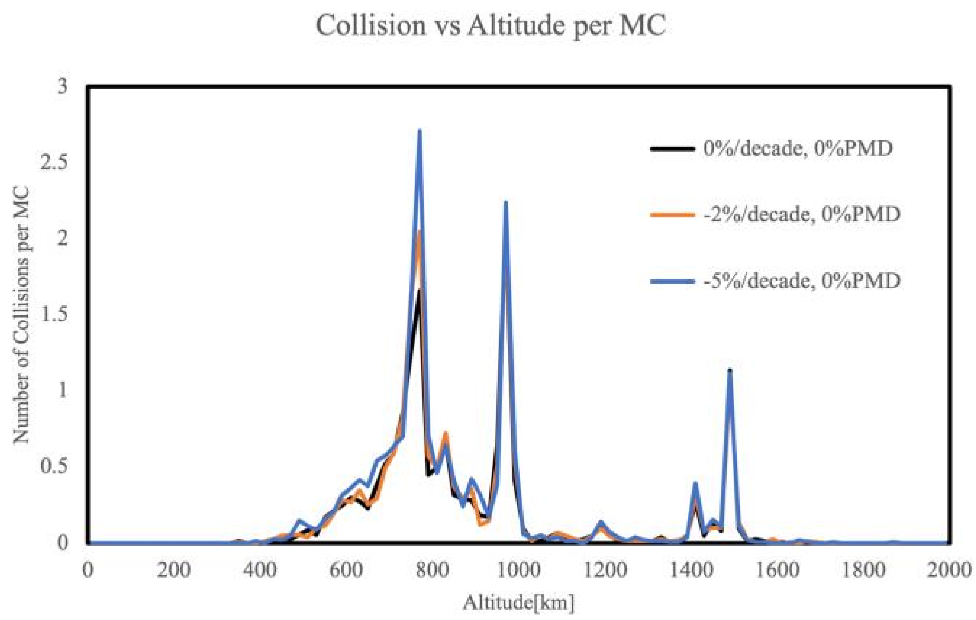
➢ PMD is effective in the reduction of long-term breakups

Number of Collisions up to 1,000 km ③



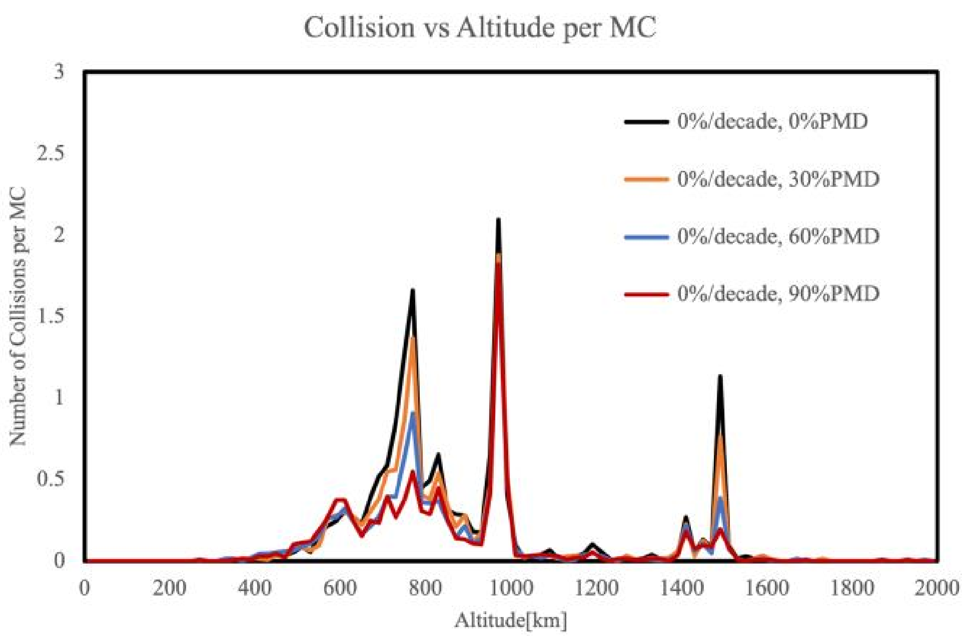
➢ The strong density decrease trend leads to more breakups despite high PMD rate.

Number of Collisions by Altitude ①



- The greater density decrease trend leads to the increase of collisions at the low altitude

Number of Collisions by Altitude ②



- The higher PMD rate reduces the collisions at altitude around 700 km

C05 Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

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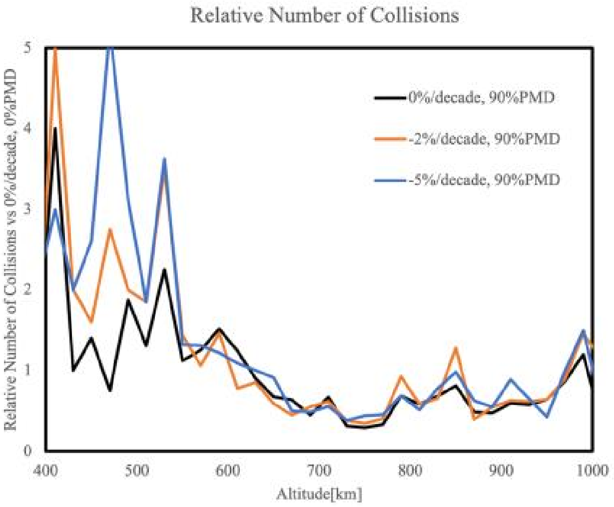
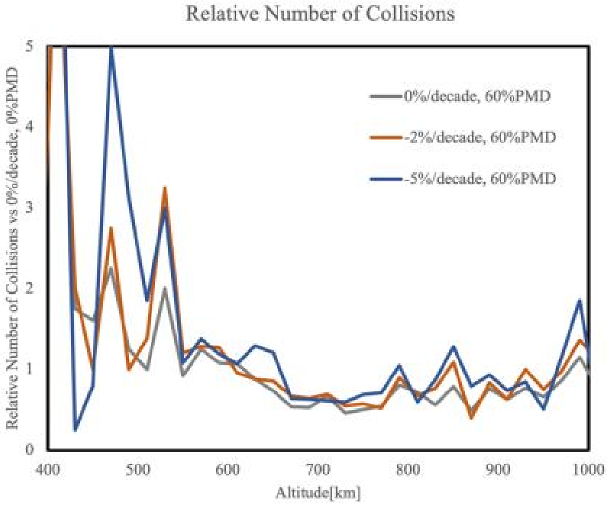
Number of Collisions by Altitude ③

PMD 90%



PMD 60%



- Higher PMD rate prevents collisions occurring, especially around 700 km.
- However, lower PMD rate (60 %) do not work enough to decrease collisions.

C05 Evaluation of Sustainable Space Development with Considering Long-term Change in Upper Atmosphere

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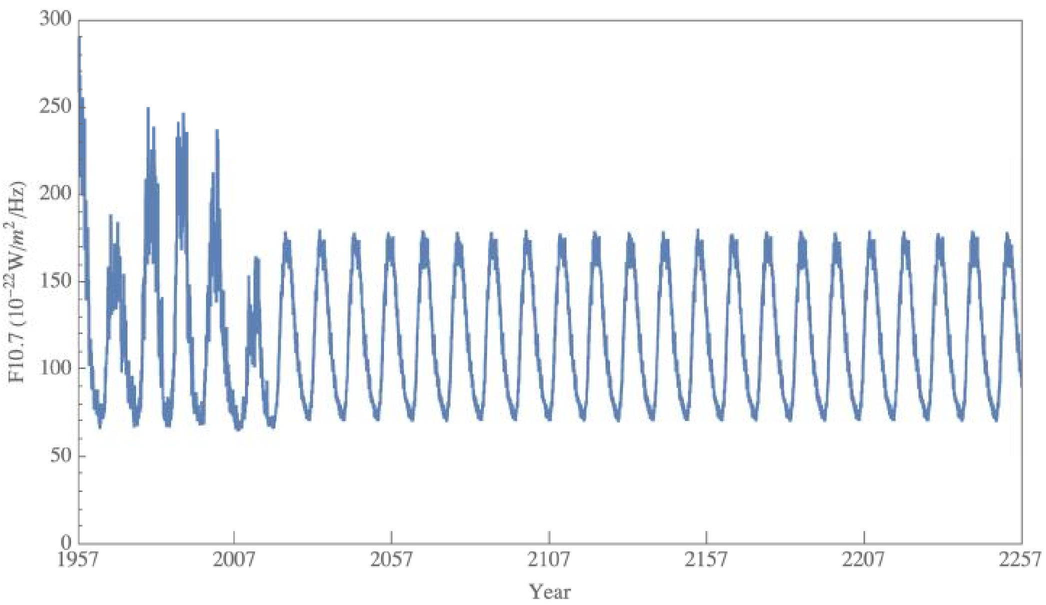
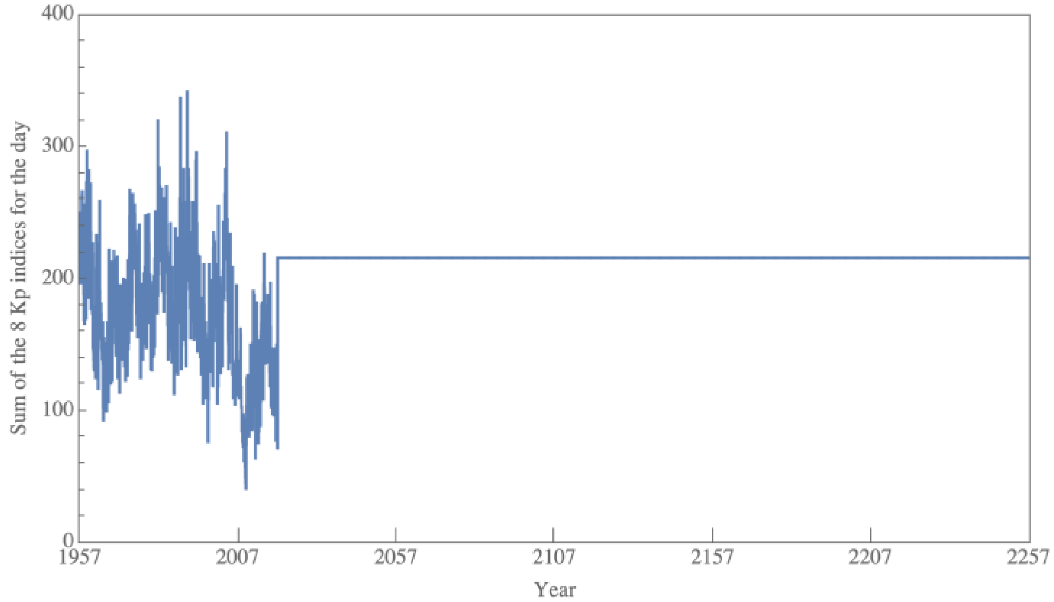
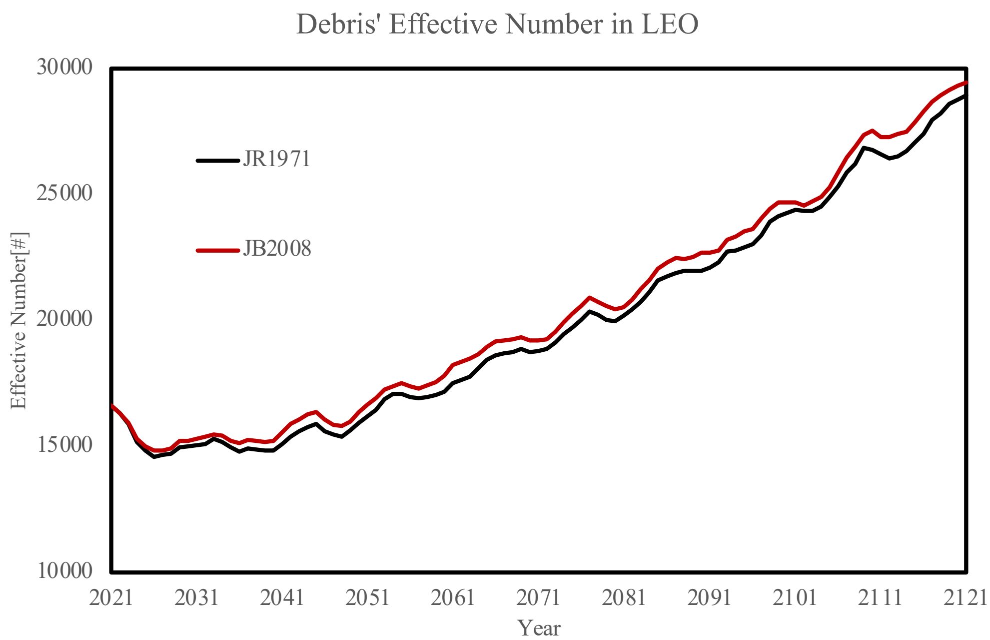
Space Data ① (Solar Cycle)



Space Data ② (Kp index)



Evolution in LEO



- The difference between atmospheric models (Jacchia-Roberts 1971 vs Jacchia-Bowman 2008)

C06

スペースデブリインデックスの活用及び定式化に関する検討

A Study of Utilization and Formulation of Space Debris Index

○原田隆佑、河本聡美、長岡信明(JAXA 研開部門)、
花田俊也(九州大学)
○HARADA Ryusuke, KAWAMOTO Satomi, NAGAOKA Nobuaki
(JAXA Research and Development Directorate),
HANADA Toshiya (Kyushu University)

JAXA 研開部門デブリモデリングチームでのペースデブリインデックス検討状況について紹介する。デブリインデックスは宇宙機やミッションの環境負荷などを示す指標として関心を集め、国際的に議論や研究がなされている。モデリングチームではデブリインデックスの定義及び用途を整理し、宇宙機が環境に与える影響のうち、どのような特徴を評価すべきかまとめた。またこの結果から考慮すべき特徴を絞り込み、インデックス式の検討を行っている。インデックス式は軌道環境に対する短期的影響及び長期的影響の観点から、それぞれ定式化を検討した。またインデックスが示す値が宇宙機が軌道環境に与える影響を正しく表せているか確認するための環境評価基準についても検討行っている。本発表では検討したインデックス式に基づき軌道上の物体を評価し、上位 100 位の物体が軌道環境に与える影響についての考察を紹介する。

This presentation describes the status of the Space Debris Index study by the debris modeling team of JAXA's Research and Development Directorate. The debris index which indicates the environmental impact of spacecraft or missions has been the subject of international discussion and research. The modeling team organized the definitions and applications of the debris index, and summarized which characteristics of the environmental impact of spacecraft should be evaluated. From this result, we narrowed down the features to be considered, and are working on an index formulation. The index is formulated in terms of short-term and long-term effects on the orbital environment. The environmental evaluation criteria are also discussed to confirm that the index values correctly represent the impact of spacecraft on the orbital environment. This presentation evaluates orbital objects based on the index formulas being considered by our modeling team and present a discussion of the impact of the top 100 objects on the orbital environment.

The 10th Space Debris Workshop 2022 11/28mon → 30wed

10th JAXA Space Debris Workshop, Chofu, Japan, 28-30 November 2022.

JAXA Explore to Realize

C06: A study of utilization and formulation of space debris index
スペースデブリインデックスの活用及び定式化に関する検討

HARADA Ryusuke, KAWAMOTO Satomi, NAGAOKA Nobuaki (JAXA),
HANADA Toshiya (Kyushu Univ.)

Space Debris Index

JAXA Explore to Realize

- **Space Debris Index**
- The value associated to a spacecraft(S/C) or mission that assess the impact to orbital environment.
- Several studies* and discussions have been conducted to formulate index (especially in Europe).
- Formulations, evaluation methods and criteria have not been established yet.

- **Possible Uses Cases**

1. Adjustment of the requirement of mitigation guidelines according to the environmental impact
2. Selection of ADR targets
3. Rating of mission and S/C

***Studies of Space debris index**
1. F. Letizia et al., Assessment of breakup severity on operational satellites, Advances in Space Research 58 (2016) 1255–1274
2. A. Rossi et al., The criticality of spacecraft index, Advances in Space Research 56 (2015) 449–460
3. F. Letizia et al., Assessment of environmental capacity thresholds through long-term simulations, IAC-21-A6.4.1, 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.
4. Darren McKnight et al, Identifying the 50 statistically-most-concerning derelict objects in LEO, Acta Astronautica 181 (2021) 282–291
5. S. KAWAMOTO et al, Considerations on the Lists of the Top 50 Debris Removal Targets, IAC-21-A6.2.5, 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.

etc..

Space Debris Index

➢ **Possible component of Index**

Parameter	Contribution to debris environment
Operational, transfer, and disposal orbit	Collision probability, number of collision avoidance, orbital lifetime ,,
Effective area and mass of spacecraft	Collision probability, the number of new fragments,,
Failure probability due to explosion or collision	Fragmentation events, decrease of PMD compliance rate,,
PMD capability	Orbital lifetime, Collision probability,,
Collision avoidance capability Disposal strategy	Collision probability,,

Two Steps to Establish Index

Step 1. Definition of Criteria

- Criteria for judging how “good” or “bad”
- Debris evolutionary model or other sophisticated calculations are required

Examples:

< for short-term effects >

- Number of conjunctions for nearby operational satellites by fragments
- Collision rate of lethal non-trackable debris

< for long-term effects>

- Effective number of objects in 200 years
- Cumulative collision rate until reentry
- Expected number of debris to be generated
- Decrease in the number of debris when removed
- Increasing trend when constellation is injected

Pros: Meaningful values allow for comparative evaluation of how good or bad the object is and some threshold can be set.
Cons: Cannot evaluate without evolutionary model

Step 2. Formulation of the Space Debris Index

How to formulate the index:
1) Consider index that can be evaluated using evolutionary model (e.g. $eFRG \times Life$)

2) Assess whether the index is appropriate using the criteria defined in Step 1. (cf. p.15)

3) Modify the index formulas that can be evaluated without using environment evolutionary model (e.g. $Pc \times M \times Life$)

4) Check whether formulas 1) and 3) are essentially the same evaluation by using the evaluation criteria in Step 1.(cf. p.16, 17)

Pros: Easily evaluated by anyone without using evolutionary model
Cons: Threshold cannot be determined from this index alone

Concept of Index Formulation

➢ **Short-term effect:**

Short-term safety features such as collision avoidance frequency and collision probability with non-trackable debris.

Example of short-term effect index:
- eFRG → Expected number of fragments (JAXA's index in top 50 selection[Ref. 1])
- eFRG x Φ → Expected number of fragments x Spatial Density (Altitude only)
- NOC → Number of conjunctions

➢ **Long-term effect**:

Long-term environmental stability due to accumulation of fragments.

e: Euler's number = 2.718281...
a = 14.18
b = 0.1831
c = -42.94

Example of long-term effect index:
- eFRG x Life_AM0.012 → The orbital lifetime is calculated with altitude, assuming that A/M for all objects is 0.012[Ref.2].
  (*Life* [yr] =e^(a x *Altitude*^b + c) When the *Altitude* >= 1000 km, its altitude is assumed as 1000 km (upper limit))
- eFRG x Life → The orbital life is calculated based on altitude, taking into account the A/M of each object.
  (*Life* [yr] =e^(a x *Altitude*^b + c) x 0.012/(A/M) When the *Altitude* >= 1000 km, its altitude is assumed as 1000 km (upper limit))
- eFRG x Life_MAX1000yr → The orbital life is calculated based on altitude, taking into account the A/M of each object.
  (*Life* [yr] =e^(a x *Altitude*^b + c) x 0.012/(A/M) When the *Life* >= 1000 yr, its lifetime is assumed as 1000 yr (upper limit))

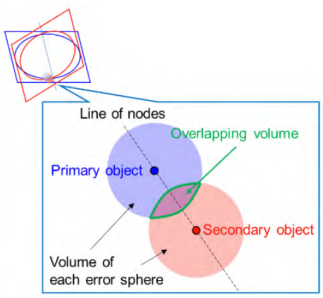
It is also necessary to define **how to evaluate "good" or "bad"** in the short-term or long-term, respectively.

Ref. 1 Darren McKnight et al, Identifying the 50 statistically-most-concerning derelict objects in LEO, Acta Astronautica 181 (2021) 282–291
Ref. 2 A Rossi et al, Cliticality of Spacecraft Index, Advances in Space Research 56 (2015) 449 460

NEODEEM: Debris Evolutionary Model

NEODEEM (Near-Earth Orbital Debris Environment Evolutionary Model)

- developed jointly by Kyushu University and JAXA.
- Calculates the trajectories of all objects larger than 10 cm in 5 day-steps by considering such orbital perturbations as air drag and geo potential.
- Simulates a collision between each object using a random number when each error sphere overlaps.
- Generates fragments (≥ 10cm) according to the NASA standard breakup model.
- Outputs the average of 100 Monte Carlo simulation runs.



Collision probability

$$C_{12}=\frac{p_2 \Delta V}{V}\frac{p_1}{V}A_{12}U_{12}$$

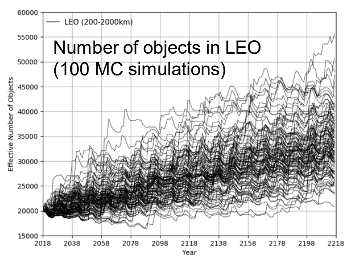
Number of fragments by collision

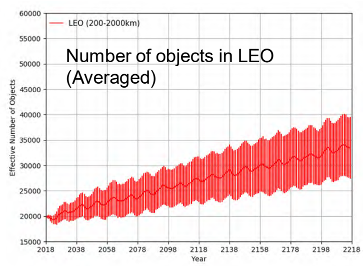
Catastrophic

$$N(L_c)=0.1(M_1+M_2)^{0.75}L_c^{-1.71}$$

Non-catastrophic

$$N(L_c)=0.1(M_2 U_{12}^2)^{0.75}L_c^{-1.71}$$





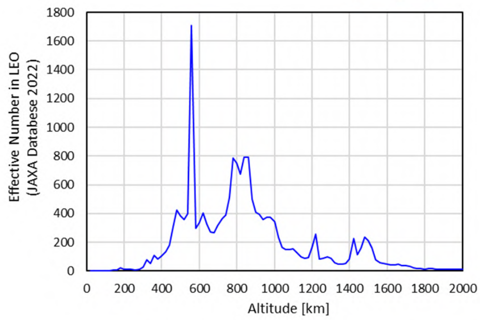
Initial Population & Background Environment

JAXA database as of 2022:

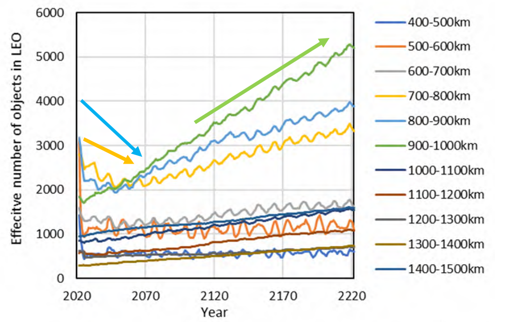
- Two-Line Elements (TLE) obtained from Space Track
- Optical observations using JAXA telescopes
- Breakup models

Prediction of Background Environment

- Assumptions
  - 90 % of PMD success rate, accidental collision, and a repeat of recent eight-year launches
  - No explosion
- Result
  - Total number of objects will increase, especially at altitudes **900-1000 km**
  - Number of objects and the collision probabilities in the altitude bands of **700**–**800** km were high
    -> Decay shortly due to atmospheric drag but return to increase.



Background objects distribution as of 2022



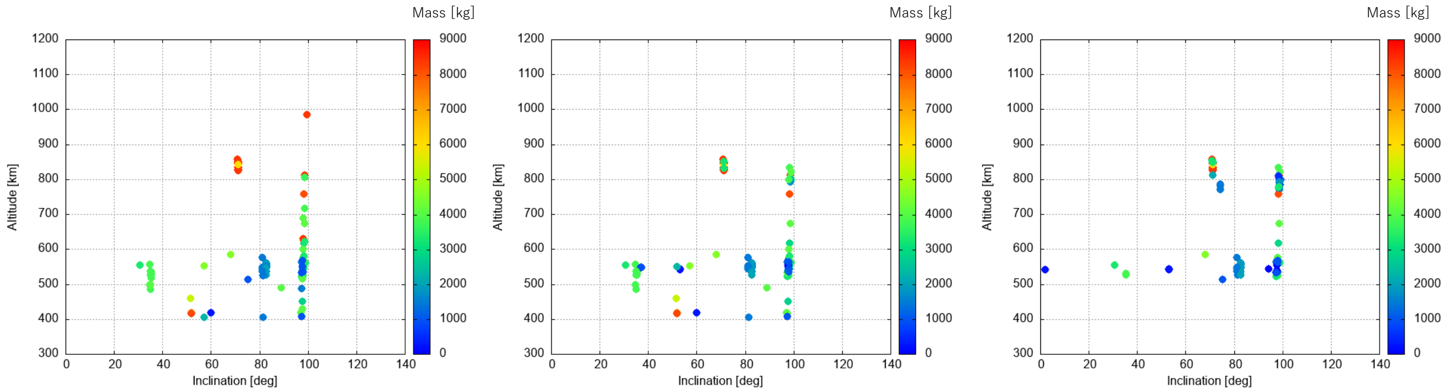
Future population in LEO from 2022 to 2222

Comparison of Short-term Index

<Numerical Simulation>

Three indexes (eFRG, eFRGxΦ, NOC) that assess **Short-term** effects are considered.

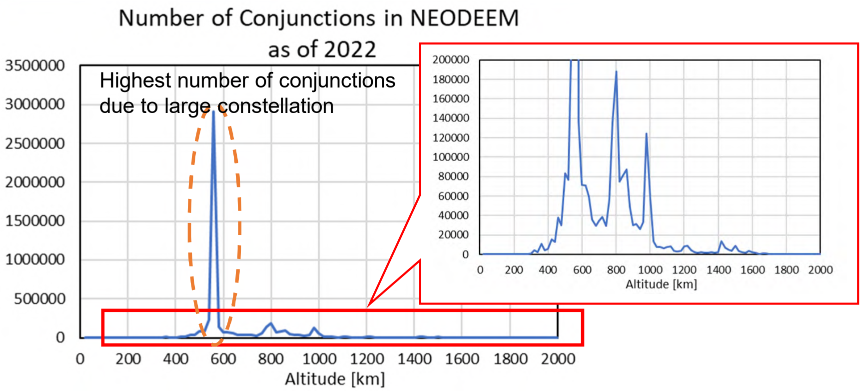
Top 100 objects are defined from JAXA_Database_2022, and assessed the number of conjunctions with these objects for 10 years



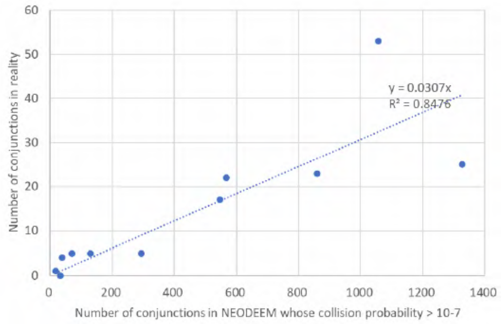
eFRG **eFRG xΦ** **NOC**

Orbital distribution of top 100 objects selected from JAXA_Database_2022 by short-term index

Number of Conjunctions in NEODEEM



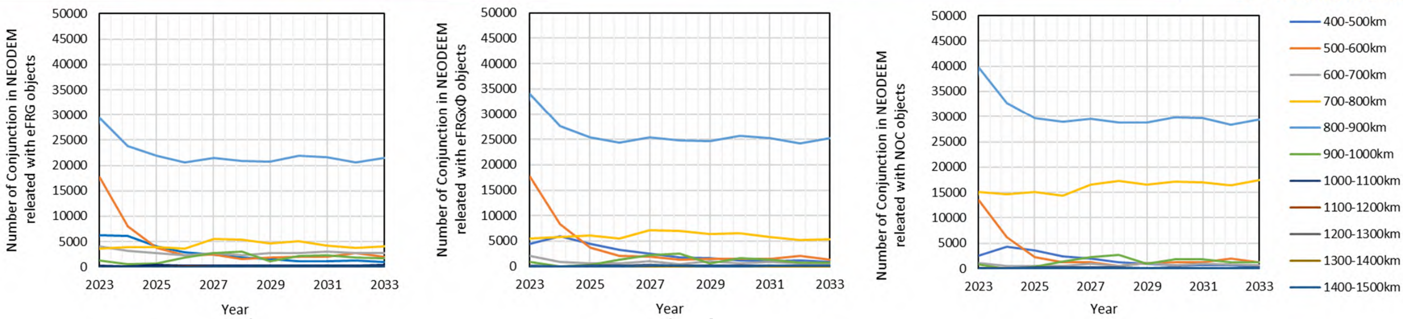
Number of Conjunctions in NEODEEM as of 2022

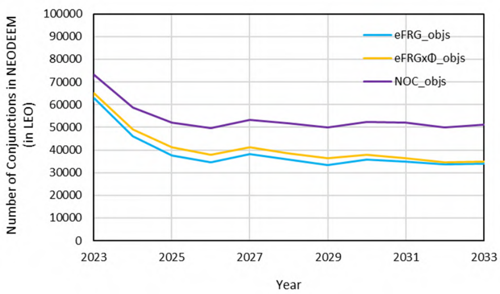


Correlation between the number of conjunctions in NEODEEM and the actual number of conjunctions for several JAXA satellites (Ref, S. KAWAMOTO et al, IAC-21-A6.2.5, 72nd IAC, Dubai)

- NEODEEM can only predict the average number of conjunctions and collisions.
- However, there is a sufficient correlation between the number of conjunctions in NEODEEM for several JAXA satellites and the number of actual times necessary to consider collision avoidance maneuvers.

Comparison of Short-term Index: Number of Conjunction





Number of conjunctions with selected objects for 10 years in each altitude band (upper) and in LEO (bottom)

Parameter	Value
Initial population	JAXA database 2022
Future launch	past 8 years launch cycle
Background objects conditions	90 % of PMF success rate, accidental collision, and no explosion

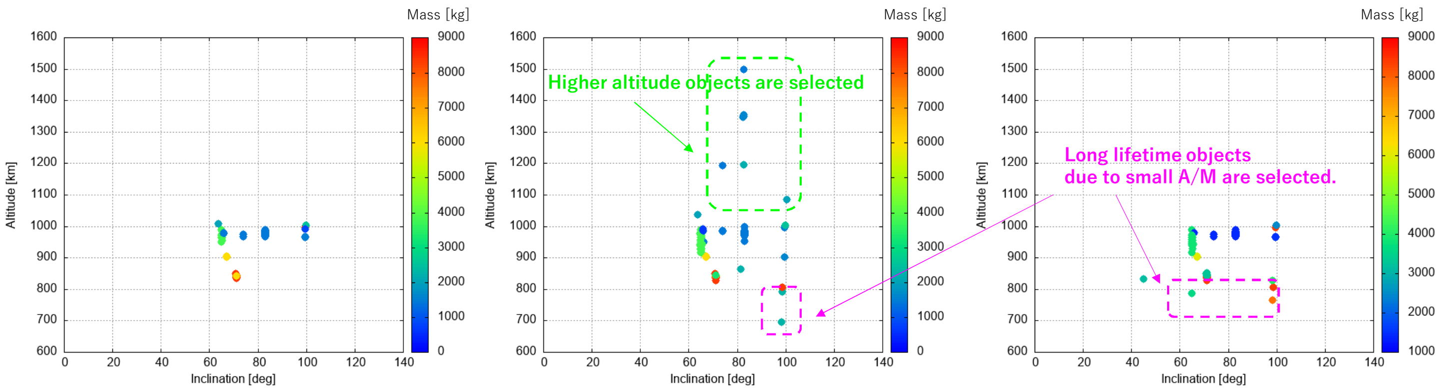
- NOC shows the largest effects in a short-term.
- eFRG and eFRGxΦ have mostly same contribution.

Comparison of Long-term Index

<Numerical Simulation>

Three indexes (eFRG x Life_AM0.012, eFRG x Life, eFRG x Life_MAX1000yr) that assess **Long-term** effects are considered.

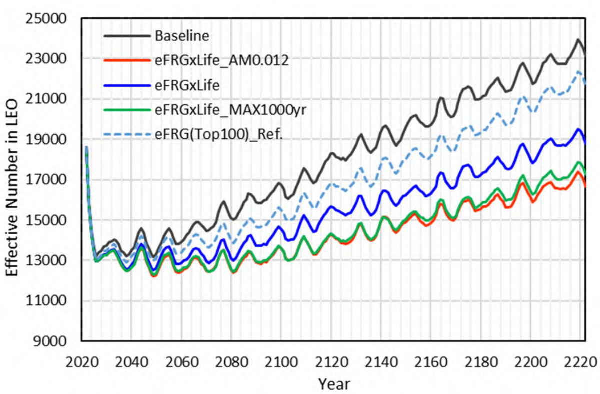
Top 100 objects are defined from JAXA_Database_2022, and removed at the beginning of 2022.



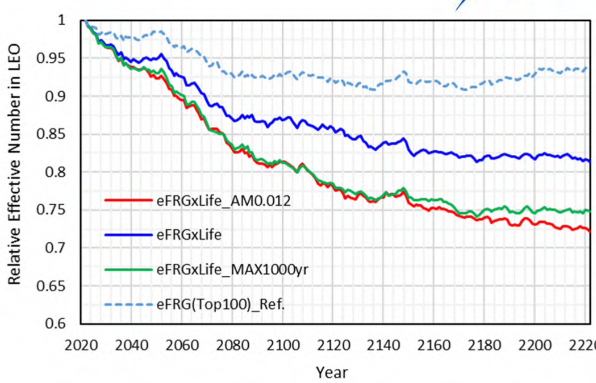
eFRG x Life_AM0.012 | eFRG x Life | eFRG x Life_MAX1000yr

Orbital distribution of top 100 objects selected from JAXA_Database_2022 by long-term index

Comparison of Long-term Index: Effective Number (in LEO)



Predictions of the effective number of debris objects for 200 years with and without ADR of each top 100 objects (average of 300 MC runs).

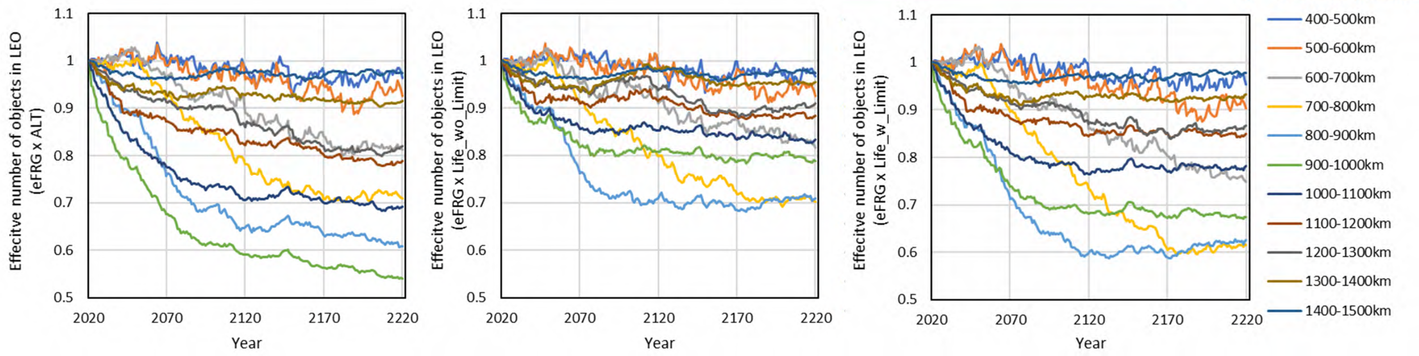


Relative effective number of debris objects for 10 years with ADR of each top 100 objects (average of 300 MC runs).

Cumulative decreasing rate [%]	for 200 yrs
eFRG x Life_AM0.012	-32
eFRG x Life	-21
eFRG x Life_MAX1000yr	-29

- eFRG x Life shows the lowest improvement effects in a long-term.
- eFRGxLife_AM0.012 and eFRGxLife_MAX1000yr have mostly same effectiveness (in 3% difference).

Comparison of Long-term Index: Effective Number (in Each Altitude Band)



eFRG xLife_AM0.012 **eFRG x Life** **eFRG x Life_MAX1000yr**

Relative effective number of objects for 200 years with ADR of each top 100 objects in each altitude band

- eFRGxLife selects objects higher than 1,000km in altitude. However, the number of objects in orbits over 1,000km is not so much and the increment of population is smaller than lower altitude. -> Less effectiveness
- eFRGxLife_AM0.012 mainly selects objects in altitude of 900-1000 km, and that makes the best effectiveness. However, the difference between eFRGxLife_AM0.012 and eFRG x Life_MAX1000yr is quite small.
- eFRG x Life_MAX1000yr can select long lifetime objects even though its altitude are not so high.

Conclusion

1. The definition and applications of the debris index are sorted out.
- Adjustment of the requirement of mitigation guidelines according to the environmental impact
- Selection of ADR targets
- Rating of mission and S/C

2. Two steps to establish index are suggested
- Definition of Criteria
- Formulation of the Space Debris Index

3. The effects of short / long–term effects are simulated
- Short-term index: Number of conjunctions with collision probability larger than 1e-07
- Long-term index: eFRG x Life_MAX1000yr

Backup

Space Debris Index

Index: The value associated to a spacecraft(S/C) or mission that assess the impact to orbital environment.
＜Possible Use Cases＞

1. Adjustment of the requirement of mitigation guidelines according to the environmental impact

For examples:

- Designers and Operators can choose their mission orbits (altitudes or inclinations) with smaller environmental impact, or limit the number of S/Cs depending on the operating orbit.
- For large constellation, required PMD success rate and the altitude of disposal orbit might be changed depending on the orbit and number of S/Cs.
- The index can evaluate which operation has less impacts, operating 200 S/Cs of 300kg each at 500 km alt. or 600 S/Cs of 100kg each at 450 km alt.

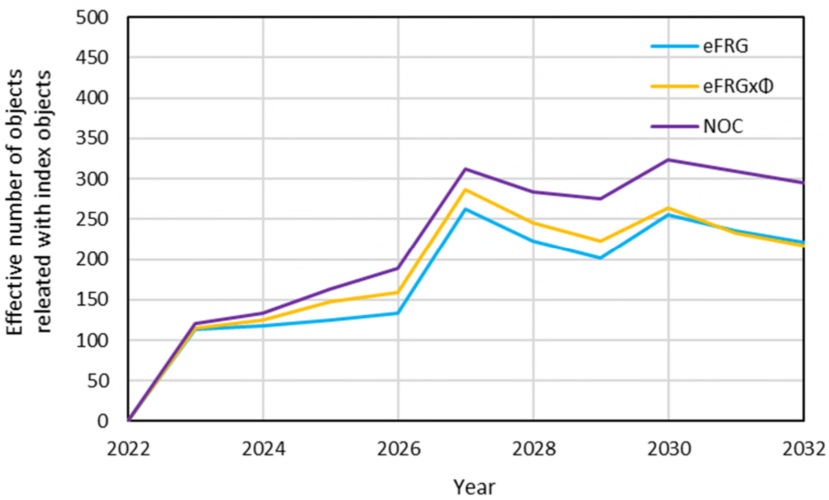
2. Selection of ADR targets

- ADR provider can identify the high-risk objects in order to maximize the ADR effects.
- For example, if the same total index value means same ADR effects, then cost-effectiveness comparison can be made.
  Plan 1) Sat.-A 1pt, Sat.-B 9pt -> Total 10pt
  Plan 2) Sat.-A 1pt, Sat.-C 5pt, Sat.-D 4pt -> Total 10pt
  Plan 3) Sat.-A 1pt, Sat.-D 4pt, Sat.-E 2pt, Sat.-F 2pt -> Total 10pt

3. Rating of mission and S/C

- Evaluators can rate missions by environmental impact, establish insurance premiums, etc.

Comparison of Short-term Index: Effective Number (in LEO)



Predictions of the effective number of debris objects for 10 years with top 100 objects (average of 300 MC runs).

10th Space Debris WS, Chofu, 30 Nov. 16

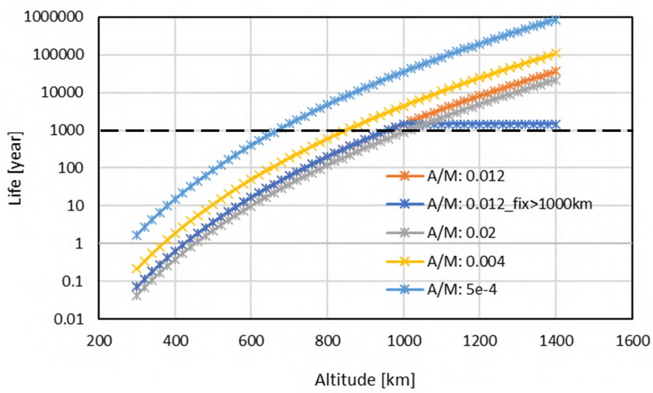
Orbital Lifetime of Objects

Orbital lifetime is calculated based on the below equation that assumed A/M =0.012 in original*.
This study takes into account A/Ms of each object.

$$\log(lifetime) = a * Altitude^{b} + c \ / \ (\text{A/M of each objs})$$

Original equation

a: 14.18
b: 0.1831
c: -42.94
with A/M=0.012



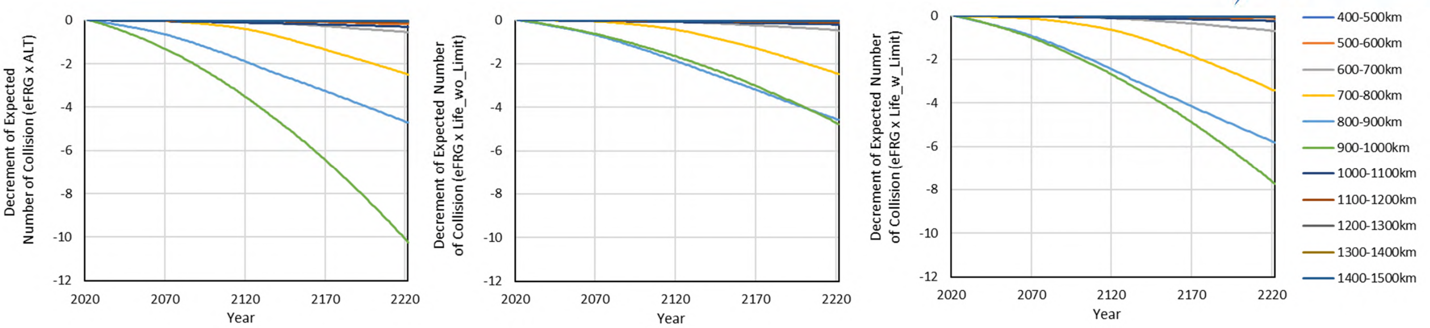
As the altitude of objects becomes higher or the A/M becomes smaller, the orbital lifetime would be long.

➡ Is it more effective to remove objects of which lifetime are greater than 1000 year for Long-term environmental stability?

10th Space Debris WS, Chofu, 30 Nov. 17

*A Rossi et al, Cliticality of Spacecraft Index, Advances in Space Research 56 (2015) 449–460

Comparison of Short-term Index: Expected Number of Collision



eFRG xLife_AM0.012 eFRG x Life eFRG x Life_MAX1000yr

Decrement of expected number of collision for 200 years in each altitude band

Decrement of expected number of collision	for 200 yrs
eFRG x Life_AM0.012	-18.7
eFRG x Life	-12.8
eFRG x Life_MAX1000yr	-18.4

- eFRGxLife_AM0.012 and eFRGxLife_MAX1000yr have mostly same effectiveness (in 3% difference).
- According to the future population and the collision risk, the long-term effects of these two indexes can be considered the same.

C07

静止軌道太陽光発電衛星実現に向けたデブリ衝突時のイジェクタ評価

Ejecta Evaluation of Debris Impact for Realization of Geostationary Earth Orbit Photovoltaic Satellite

○大保颯野、赤星保浩、内田岳志、北黒裕麻、藤井理紀、高良隆男（九工大)、河本聡美，上土井大助，
木本雄吾，長岡信明，原田隆佑（JAXA 研開部門)、泉山卓，福重進也（IHI)、北澤幸人
○DAIBO Soya, AKAHOSHI Yasuhiro, UCHIDA Takeshi, KITAGURO Yuma, FUJII Masanori,
KOURA Takao (Kyutech), KAWAMOTO Satomi, JOUDOI Daisuke, KIMOTO Yugo, NAGAOKA Nobuaki,
HARADA Ryusuke (JAXA Research and Development Directorate), IZUMIYAMA Taku,
FUKUSHIGE Shinya (IHI), KITAZAWA Yukihito

微小宇宙ごみやメテオロイドが人工衛星の表面に衝突すると，イジェクタと呼ばれる二次デブリが発生する。高高度軌道では，衝突確率が低いため現時点では大きな問題とみなされていない。一方で，近年静止軌道でも太陽発電衛星等の大型構造物が検討されており，大型衛星が増え続けると衝突確率が無視できなくなる可能性がある。このため，イジェクタ発生を抑制／防止に向けた対策の１つとしてバンパ構造が提案されている。そこで著者らは，静止軌道上での大型構造物の実用化に先立ち，静止軌道での高速衝突現象の基礎的知見の蓄積を図るとともに，バンパ構造実現に向けた衝突特性の把握を計画している。具体的には，静止軌道太陽光発電衛星で使用が予想される構造材料に１ｍｍのアルミ球を衝突させた際に発生するイジェクタ量の計測実験を計画している。本講演ではこの実験計画ならびに実験結果の速報値を紹介する予定である。

When small space debris or meteoroids impact the surface of a spacecraft at hypervelocity, secondary debris called “ejecta” are generated. Currently, ejecta are not considered a major issue due to the low collision rate in high-altitude orbits. However, recently, large-scaled structures such as space solar power satellites (SSPS) in geostationary orbit (GEO), have been studied, and if the number of large satellites continues to increase, the collision rate of small debris cannot be ignored. For this reason, a bumper structure has been proposed as one of the measures for preventing ejecta. Before large-scaled structures on geostationary orbit are developed, we have an experimental plan to examine the hypervelocity collision characteristics for future design of “Bumper Structures” using space materials which might be used in the future SSPS on GEO. In this talk, quick reports of some preliminary experimental results will be addressed in advance to protection design of “Bumper Structures” against small debris impacts.

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Doc.No. KIT-SSPS1-22-0300

静止軌道太陽光発電衛星実現に向けたデブリ衝突時のイジェクタ評価

Ejecta evaluation of Debris Impact for Realization of Geostationary Earth Orbit Photovoltaic Satellite

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河本聡美, 上土井大助, 木本雄吾, 長岡 信明, 原田隆佑 (JAXA研開部門)、

泉山卓, 福重進也 (IHI)、

北澤幸人

2022/12/14

赤星研究室

国立大学法人 九州工業大学

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研究背景 Research background

Space Solar Power Systems(SSPS)

太陽光エネルギーをマイクロ波またはレーザー光に
変換して地球に伝送するシステム

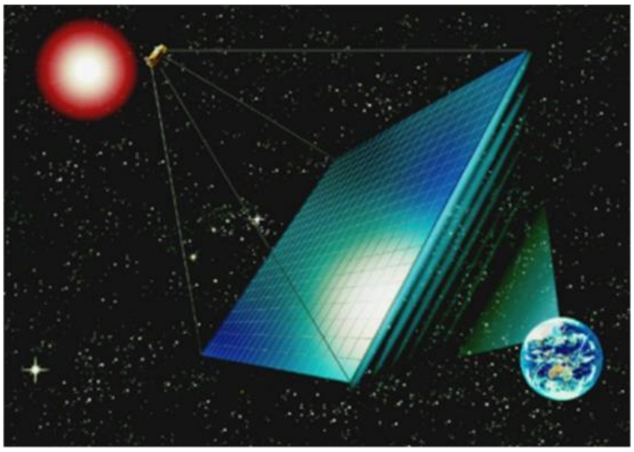
Converting solar energy into microwave or laser light into microwave or laser light and transmit it to the earth.

SSPSの特徴

feature of SSPS

○静止軌道上に数km四方の
　面積を要する

SSPS need several kilometers square in Geostationary Earth orbit(GEO).



s.Kawamoto, IAC-22-B6.5.10,(2022)

研究背景 Research background

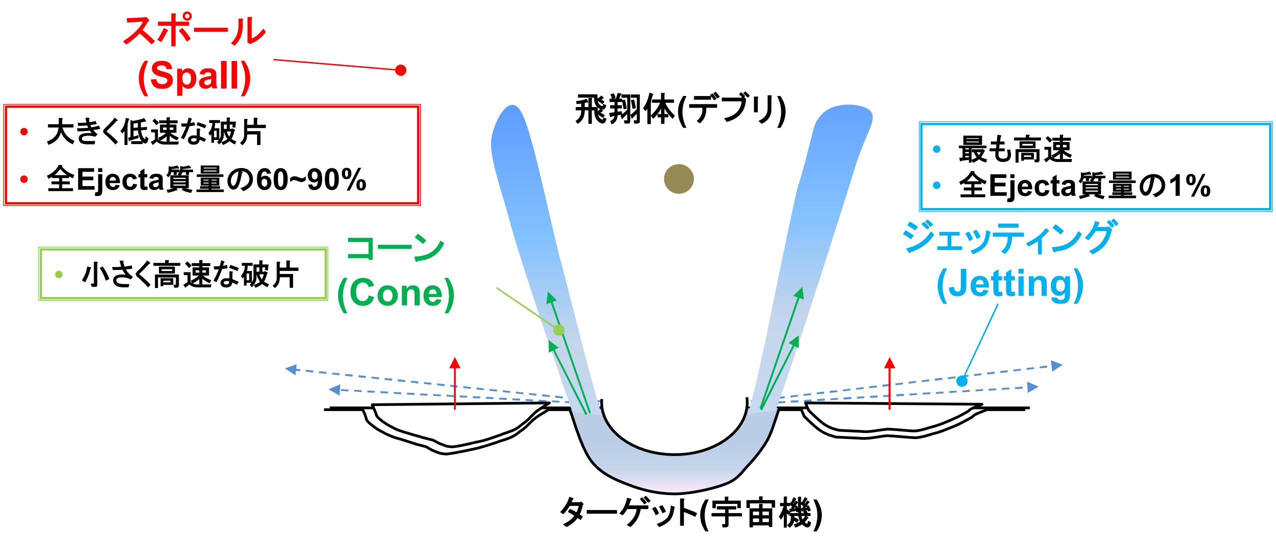
低軌道でのデブリは大気圏に突入
Debris in LEO enters the atmosphere
→自然除去が可能
Natural removal is possible

一方、静止軌道でのデブリは、大気抵抗が少なく永久的に残り続ける可能性がある
On the other hand, debris in GEO has less atmospheric resistance and may remain permanently
→自然除去が見込めない
Natural removal is not expected.

静止軌道での宇宙構造物では、
デブリ発生抑制を検討する必要がある
Space structures in GEO must control debris generation

研究背景 Research background

Ejecta
スペースデブリが宇宙機等に衝突した際に生じる二次的なデブリ
Secondary debris created when space debris impact with spacecraft, etc.



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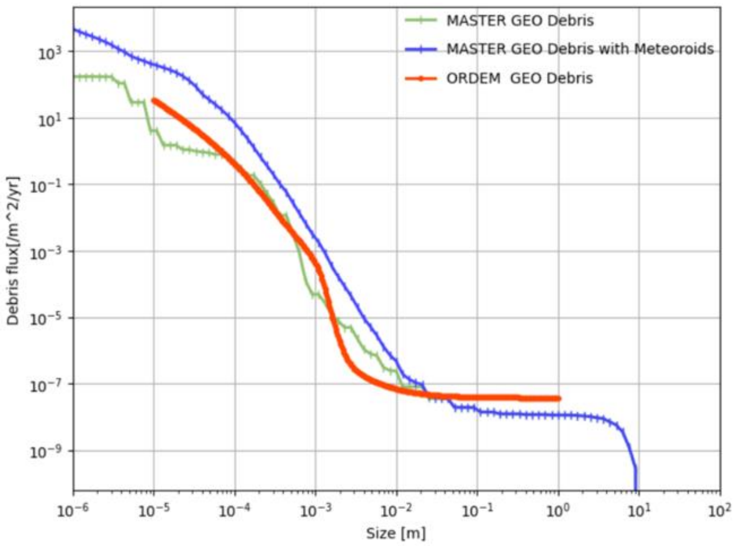
研究背景 Research background

静止軌道でのデブリ環境モデル

Debris flux in (GEO)

SSPSの面積が6km²場合
If SSPS area is 6 km2
MMODとの衝突
Impact between SSPS and MMOD
○100μm以上　数千万回
100 μm or more
Tens of millions of times
○1mm,1cm以上 数千回
1mm,1cm or more
Thousands of times

Ejecta発生の可能性
Possible Ejecta Occurrence



Debris flux in GEO analyzed with different debris environment models

S.Kawamoto, IAC-22-B6.5.10,(2022)

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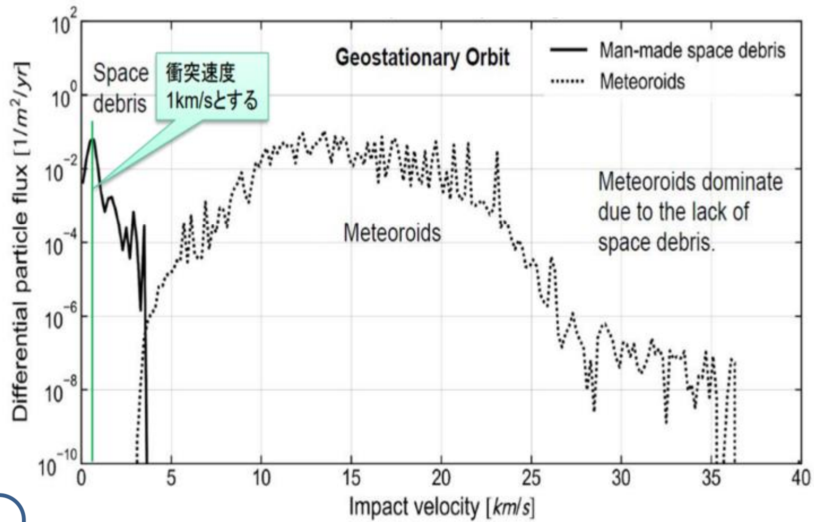
研究背景 Research background

静止軌道でのデブリ環境モデル

Debris flux in (GEO)

静止軌道では
衝突速度1km/sにおいて
衝突確率頻度が高い
Impact velocity of debris
at the largest debris flux
in GEO is about 1km/s

衝突速度1km/s付近での
イジェクタ評価が必要



ESA MASTER-8Model
Differential mean flux (11/2015-11/2016),objects>0.1mm
Earth-oriented GEO (35,786km),leading front surface

C.Widermann et al., 9th Space Debris Workshop(2021)

研究目的 Research Purpose

衝突実験を用いた静止軌道上でのイジェクタ評価
Evaluation of ejecta in GEO using impact experiments

イジェクタ評価
Evaluation of ejecta

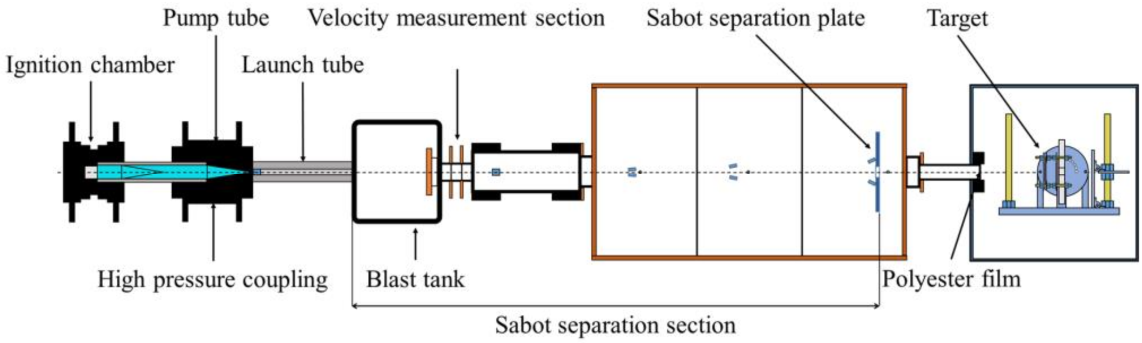
- 質量
  Ejecta mass
- 個数
  Number of ejecta
- 分布
  Distribution of ejecta

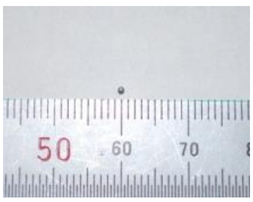
現状把握実験
Exp. w/o capture

イジェクタ抑制実験
Exp. w/ capture

実験装置 Experimental equipment

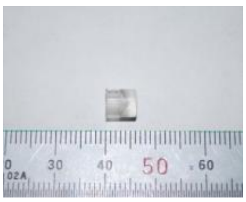
二段式軽ガス銃
Two stage light gas gun





Material : A2017
Diameter : φ1.0±0.1mm
Mass : 1.5 mg

Projectile



Material : PC
Diameter : φ6.0mm
Mass : 120 mg

Sabot

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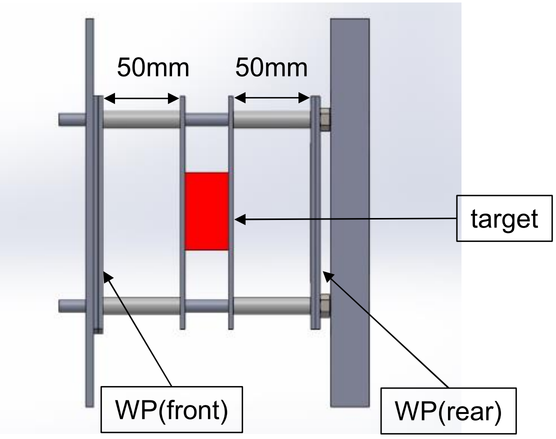
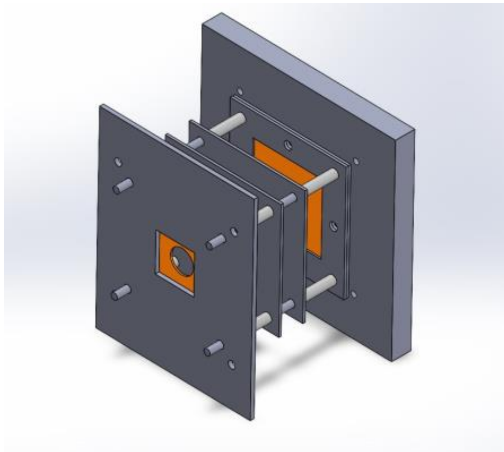
実験条件 Experimental conditions





Target	Spacecraft Materials
Impact Velocity	1.2±0.2km/s
Witness Plate	Copper Plate (C1100-O)

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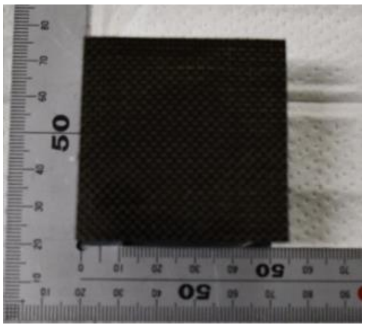
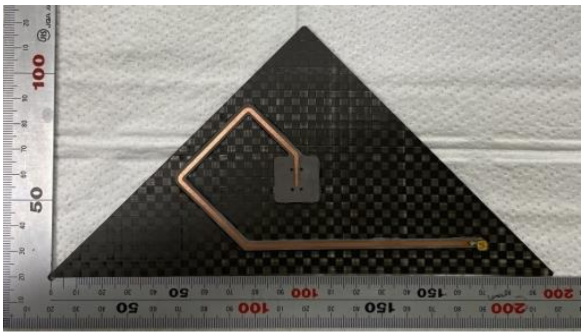
実験条件 Experimental conditions

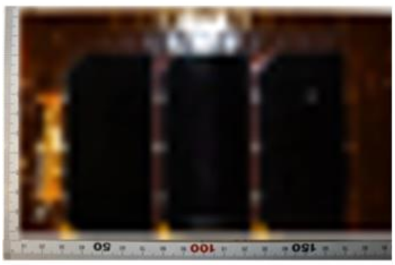
Target



Honeycomb



Triangular antenna



Solar cell front

Solar cell rear

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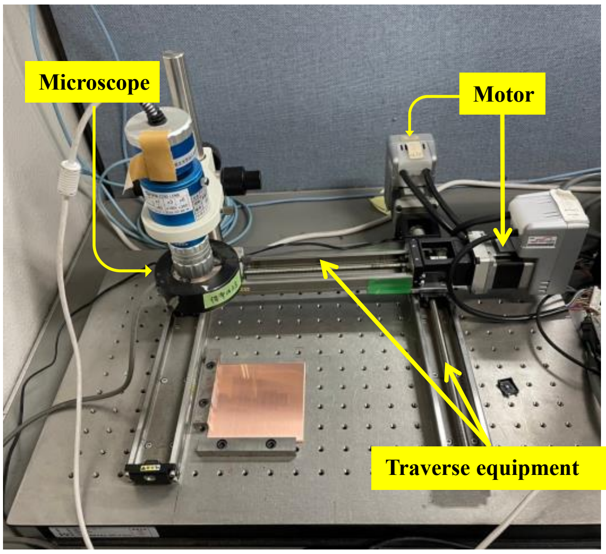
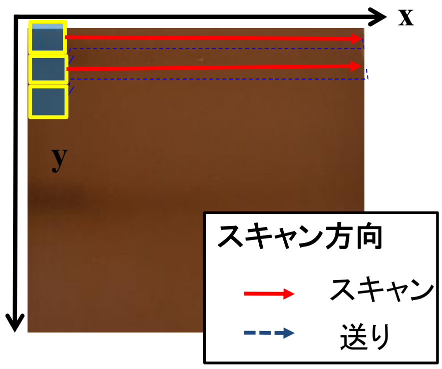
WP解析方法 WP Analysis Method



Microscope Systems

Magnification	Resolution [pixels]
60 ~ 360	1600 x 1200



Analysis Procedure

Scanning of the entire surface of the Witness Plate before and after the experiment

▼

Differential processing before and after experiment

▼

Detect impact scar coordinates and size

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実験結果 Experimental results

現状把握実験(Exp. w/o capture)		
Experiment Number	Target	Impact Velocity[km/s]
#1STS22-40	Honeycomb	1.2±0.2
#2STS22-41	Antenna	
#3STS22-42	Solar cell (front→rear)	
#4STS22-46	Solar cell (rear→front)	

実験結果 Experimental results

#1(honeycomb)
STS22-40

Impact Velocity(km/s)	1.23
Projectile mass(mg)	1.5
Ejecta mass(mg)	0.5
Penetrating hole(mm)	
front	0.967×0.949
rear	0.813×0.700

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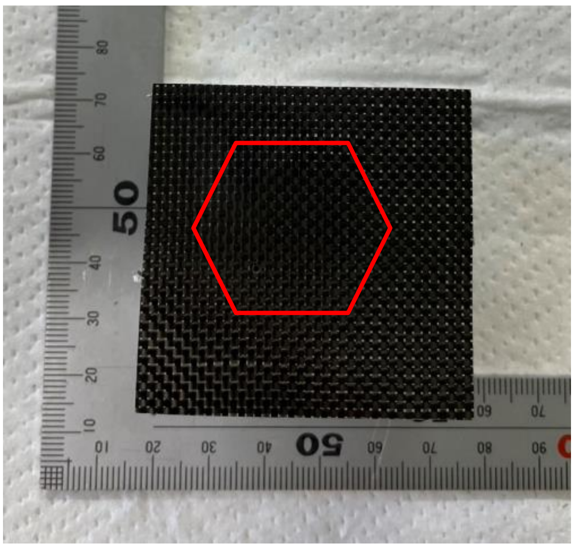
実験結果 Experimental results

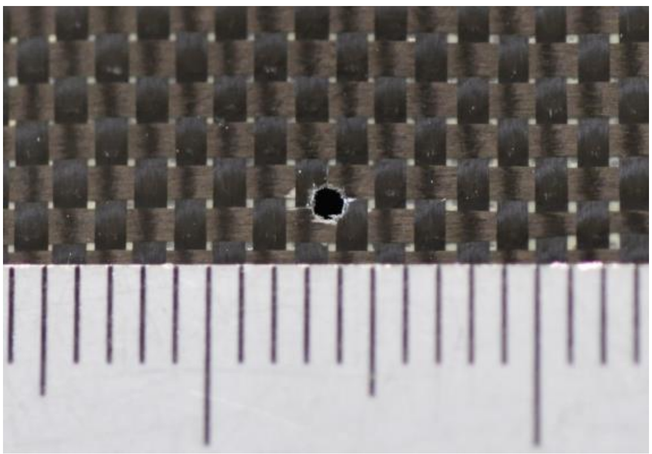
#1(honeycomb)
STS22-40

Front hole
0.967×0.949mm



Overall view

impact side

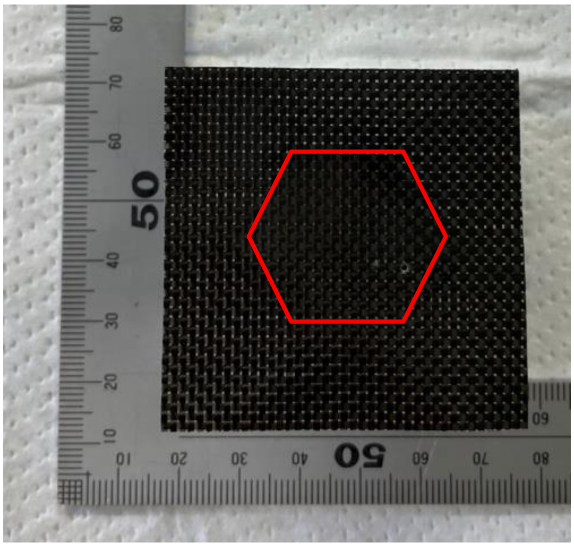


Enlarged view

実験結果 Experimental results

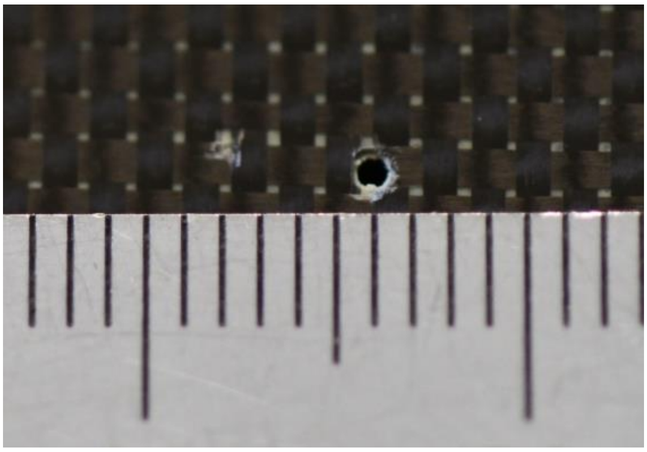
#1(honeycomb)
STS22-40

Rear hole
0.813×0.700mm



Overall view

rear side



Enlarged view

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実験結果 Experimental results

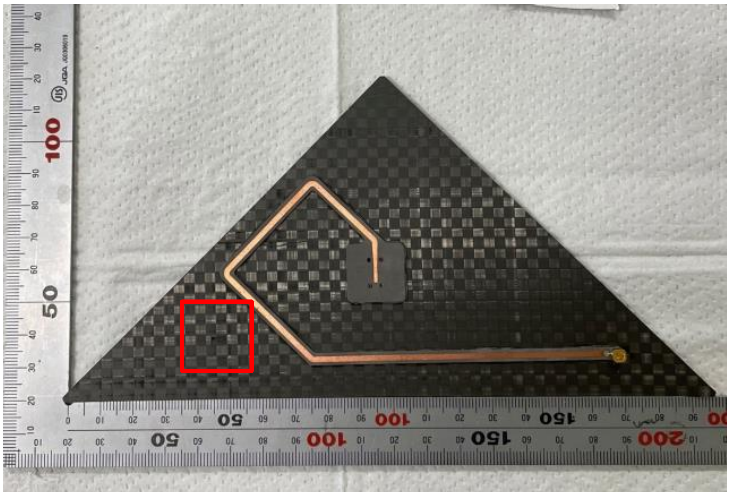
#2(Antenna)
STS22-41

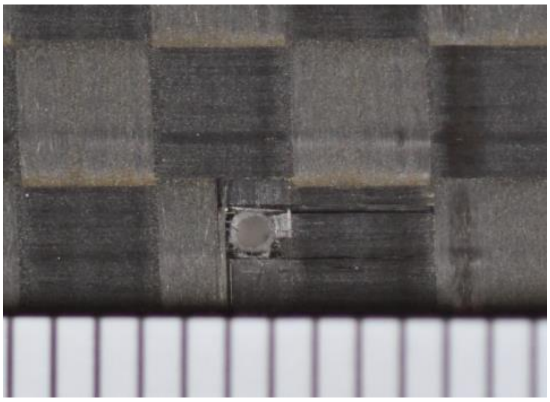
Impact Velocity(km/s)	1.19
Projectile mass(mg)	1.5
Ejecta mass(mg)	2.5
Penetrating hole(mm)	
front	0.750×0.717
rear	0.803×0.755

実験結果 Experimental results

#2(Antenna)
STS22-41

Front hole
0.750×0.717mm





Overall view

Enlarged view

impact side

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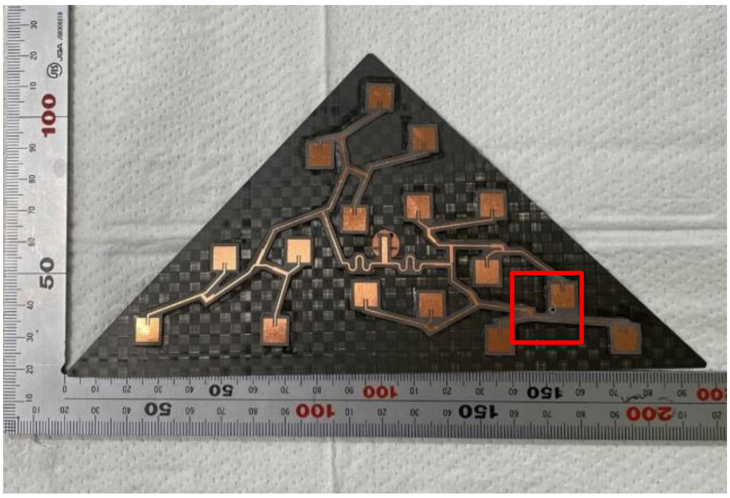
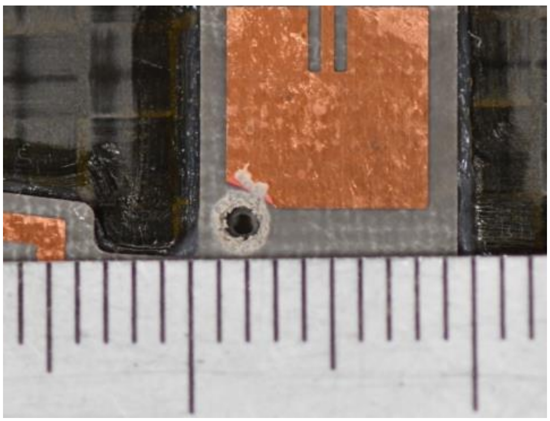
実験結果 Experimental results

#2(Antenna)
STS22-41

Rear hole
0.803×0.755mm





Overall view

Enlarged view

rear side

実験結果 Experimental results

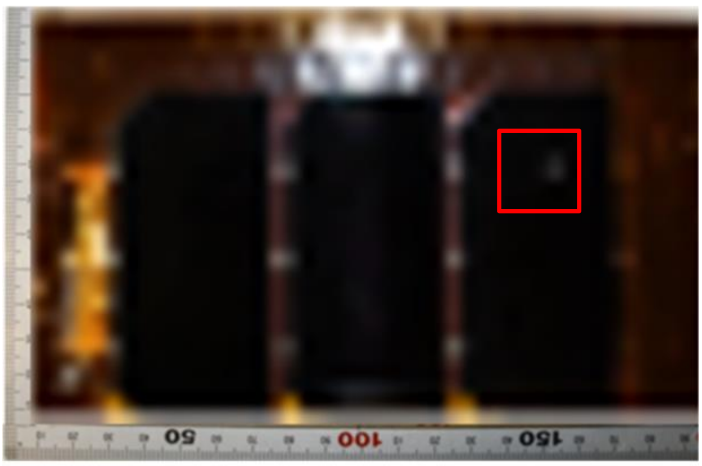
#3(Solar cell front→rear)
STS22-42

Impact Velocity(km/s)	1.07
Projectile mass(mg)	1.5
Ejecta mass(mg)	2.9
Penetrating hole(mm)	
front	0.477×0.468
rear	2.194×2.296

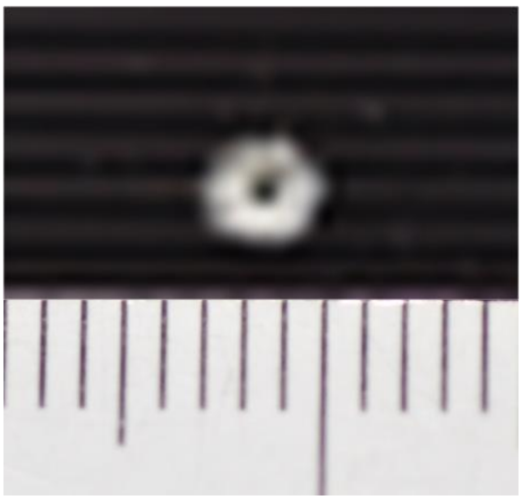
実験結果 Experimental results

#3(Solar cell front→rear)
STS22-42

Front hole
0.477×0.468mm



Overall view



Enlarged view

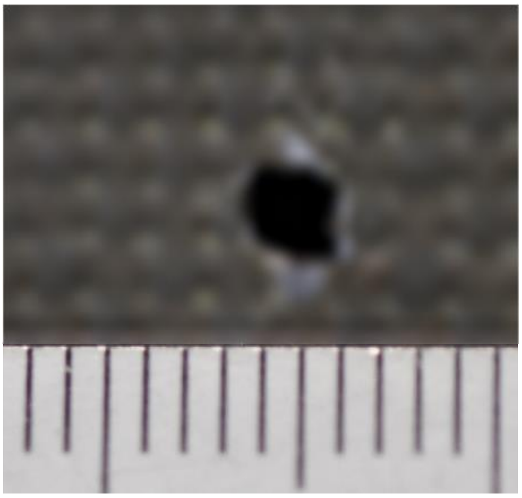
impact side

実験結果 Experimental results

#3(Solar cell front→rear)
STS22-42

Front hole
2.194×2.296mm

Overall view



Enlarged view

rear side

実験結果 Experimental results

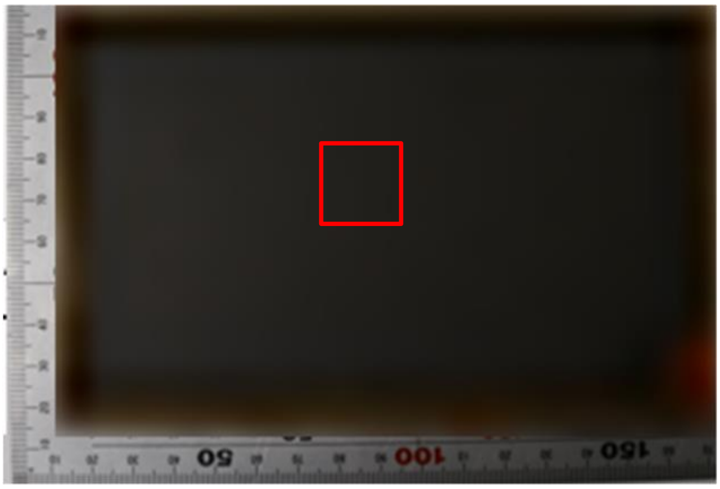
#4(Solar cell rear→front)
STS22-46

Impact Velocity(km/s)	1.35
Projectile mass(mg)	1.5
Ejecta mass(mg)	7.5
Penetrating hole(mm)	
front	0.986×0.976
rear	0.608×0.608

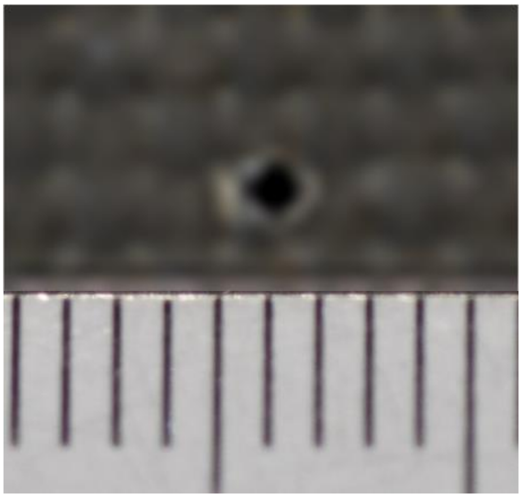
実験結果 Experimental results

#4(Solar cell rear→front)
STS22-46

Front hole
0.986×0.976mm



Overall view



Enlarged view

impact side

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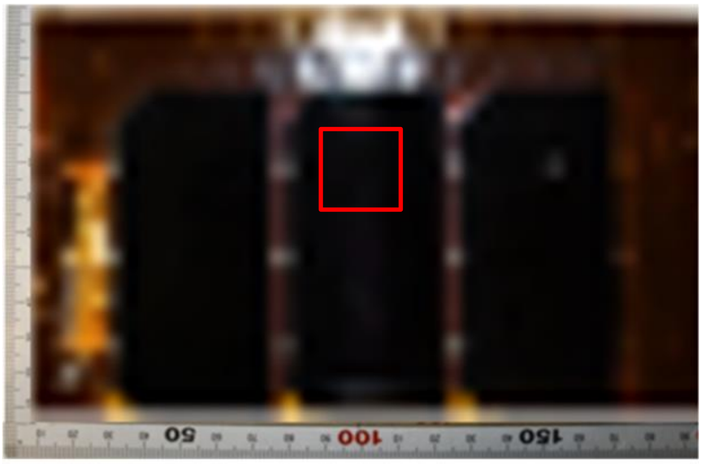
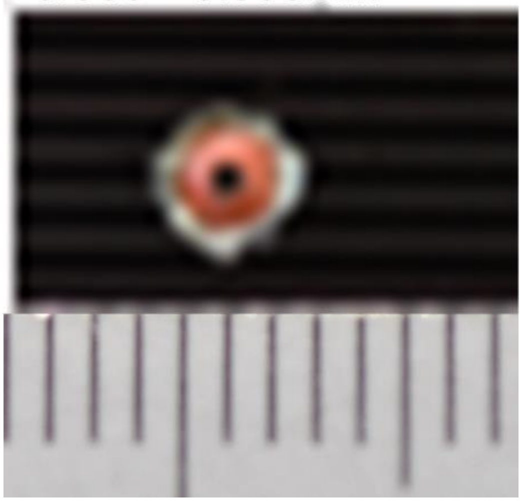
実験結果 Experimental results

#4(Solar cell rear→front)
STS22-46

Front hole
0.608×0.608mm



Overall view



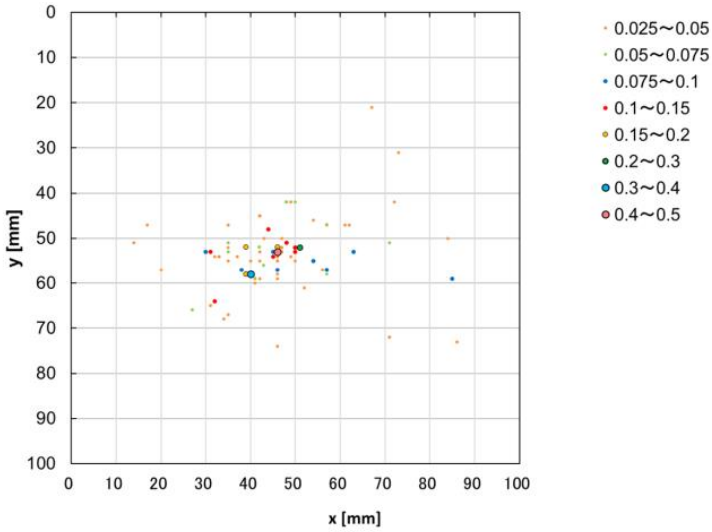
Enlarged view

rear side

実験結果 Experimental results

WP分布図
#2(Antenna)STS22-41

WP Overall view

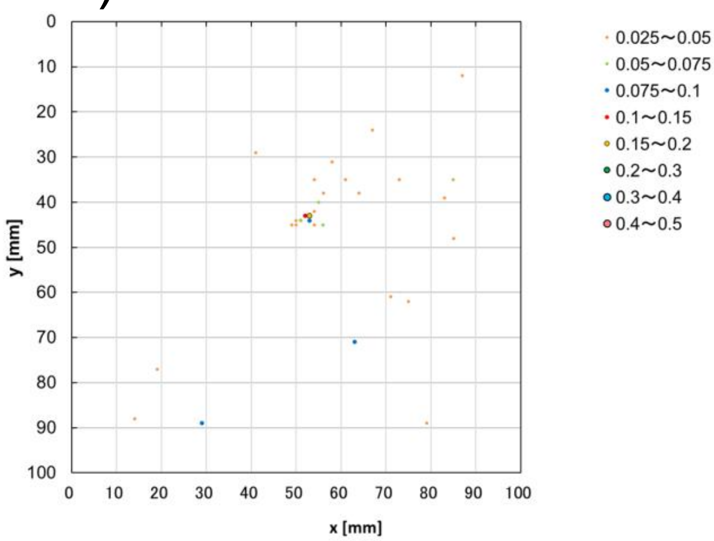


crater distribution on WP

実験結果 Experimental results

WP分布図
#3(Solar cell front→rear)STS22-42

WP Overall view



crater distribution on WP

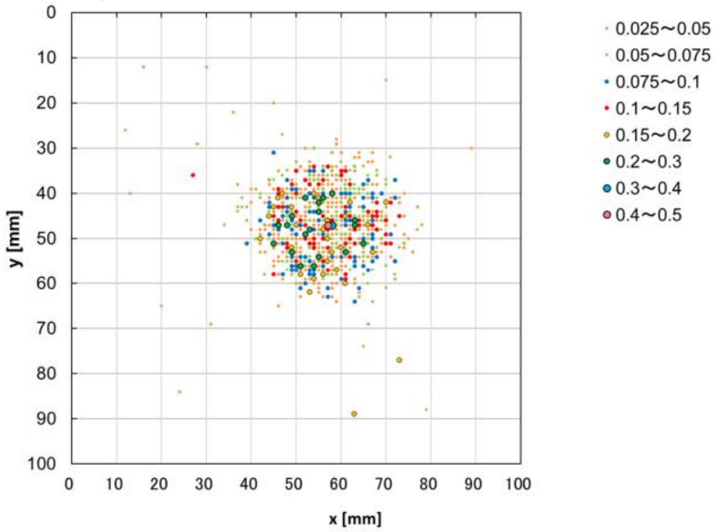
国立大学法人 九州工業大学

第10回スペースデブリワークショップ(11/28-30)@JAXA調布

実験結果 Experimental results

WP分布図
#4(Solar cell rear→front)STS22-46

WP Overall view



crater distribution on WP

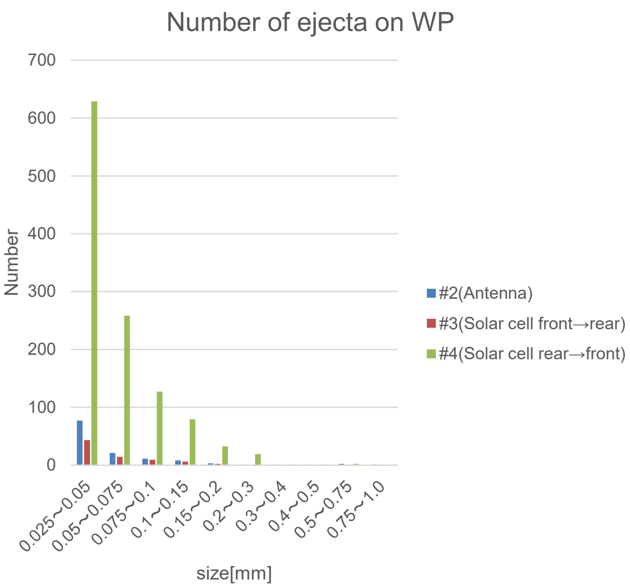
2022/12/14 26 赤星研究室

国立大学法人 九州工業大学

第10回スペースデブリワークショップ(11/28-30)@JAXA調布

実験結果 Experimental results

Number of ejecta on rear WP



	Number of Ejecta		
Ejecta size(mm)	#2(Antenna)	#3(Solar cell front→rear)	#4(Solar cell rear→front)
0.025～0.05	77	43	629
0.05～0.075	21	14	258
0.075～0.1	11	9	127
0.1～0.15	**8**	**6**	**79**
0.15～0.2	**3**	**2**	**32**
0.2～0.3	**1**	**0**	**19**
0.3～0.4	**1**	**0**	**1**
0.4～0.5	**1**	**0**	**1**
0.5～0.75	**2**	**0**	**2**
0.75～1.0	**1**	**0**	**0**

2022/12/14 27 赤星研究室

実験結果 Experimental results

Ejecta mass and number

Experiment number	Ejecta mass(mg)	Number of ejecta on rear WP(0.1 mm or more)
#1(Honeycomb)	0.5	-
#2(Antenna)	2.5	17
#3(Solar cell front→rear)	2.9	8
#4(Solar cell rear→front)	7.5	134

今後の実験計画 Plan of experiment

	Target	Impact Velocity[km/s]
現状把握実験 (Exp. w/o capture)	Honeycomb Antenna Solar cell (front→rear) Solar cell (rear→front) Irradiated honeycomb Irradiated Solar cell (front→rear) Irradiated Solar cell (rear→front)	About 3.5
イジェクタ抑制実験 (Exp. w/ capture)	Solar cell + capture	1.2±0.2

C08

耐 AO コーティング／ポリイミド CFRP からのイジェクタに与える電子線・原子状酸素の影響

Effects of Electron Beam and Atomic Oxygen Irradiation on Ejecta from Anti-AO Coating Polyimide CFRP

○西田政弘，木村大地（名古屋工業大学），古田尚正，岩瀬賢明（東亜合成株式会社），
東出真澄，石田雄一（JAXA）
○NISHIDA Masahiro (Nagoya Institute of Technology), KIMURA Daichi (Nagoya Institute of Technology),
FURUTA Naomasa (Toagosei Co., Ltd.), IWASE Yoshiaki (Toagosei Co., Ltd.), HIGASHIDE Masumi
(JAXA Research and Development Directorate), ISHIDA Yuichi (JAXA Research and Development Directorate)

炭素繊維強化複合材料（CFRP）は宇宙機にも多く使われているが，スペースデブリが超高速で衝突すると，破砕し，多くの破片（イジェクタ）が飛散する．耐原子状酸素（AO：atomic oxygen）コーティングを塗布することにより，イジェクタを低減する CFRP を提案し，そのイジェクタに与える電子線および原子状酸素照射の影響を報告する．

Carbon fiber reinforced plastic (CFRP) plates are widely used in spacecraft. When space debris strike them at very high velocities, CFRP was broken and many fragments (ejecta) were scattered. Our group proposed anti-atomic oxygen (AO) coating polyimide CFRP to decrease ejecta from CFRP. The effects of electron beam and atomic oxygen irradiation on AO coating polyimide CFRP were examined.

C08

第10回スペースデブリワークショップ
2022年11月28日～30日（JAXA調布航空宇宙センター）

耐AOコーティング／ポリイミドCFRPからのイジェクタに与える電子線・原子状酸素の影響

Effects of Electron Beam and Atomic Oxygen Irradiation on Ejecta from Anti-AO Coating Polyimide CFRP

○ 西田政弘，木村大地（名古屋工業大学）
古田尚正，岩瀬賢明（東亞合成株式会社）
東出真澄，石田雄一（宇宙航空研究開発機構）
Masahiro Nishida, Daichi Kimura (Nagoya Institute of Technology)
Naomasa Furuta, Yoshiaki Iwase (Toagosei Co., Ltd.)
Masumi Higashide, Yuichi Ishida (JAXA)

1

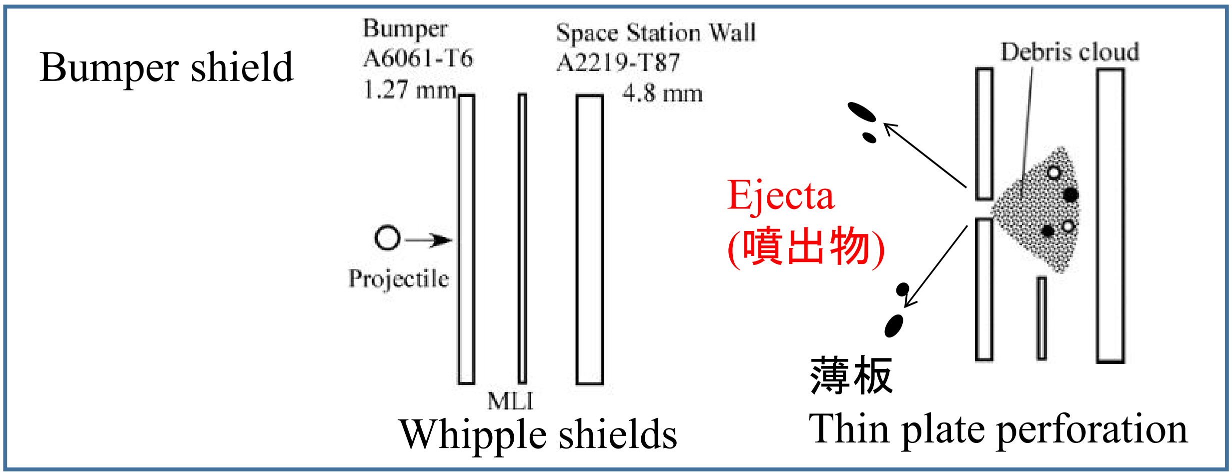
Perforation of Thin Plates

International Space Station

Courtesy of NASA
http://spaceflight.nasa.gov/gallery/images/shuttle/sts-127/html/s127e011212.html

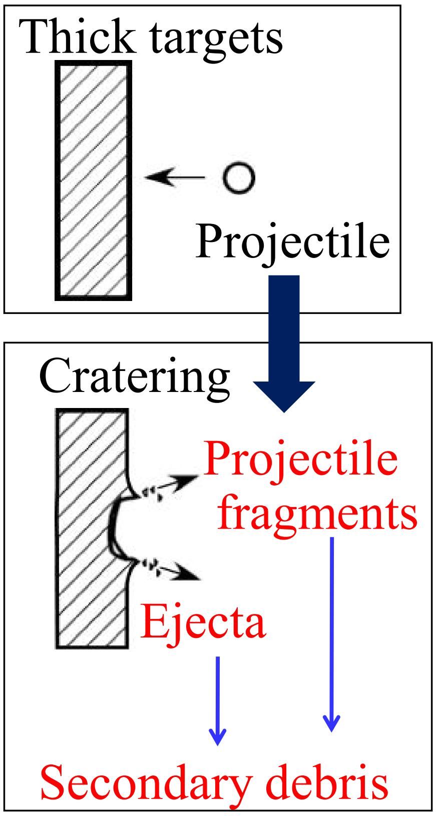
JEM

Courtesy of JAXA
http://www.jaxa.jp/projects/iss_human/kibo/index_j.html



2

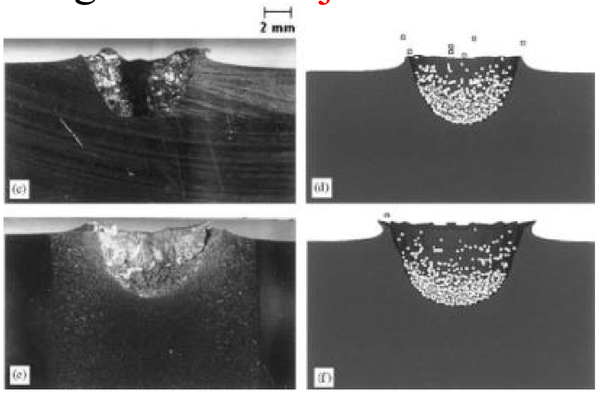
Penetration into Thick Plates



Composition of ejecta

Numata, Kikuchi, Sun, Kaiho, Takayama, Proc JSSW, (2006), pp. 221-222.

Projectile fragments and ejected materials



Murr, Int. J Impact Eng., (2006), pp. 1981-1999.

3

Flux of Space Debris

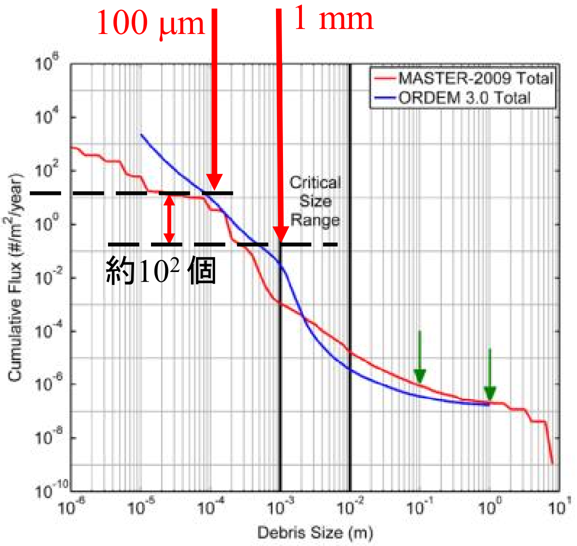


Fig. 1. ORDEM 3.0 and MASTER-2009 orbital debris fluxes for the ISS orbit in 2014.

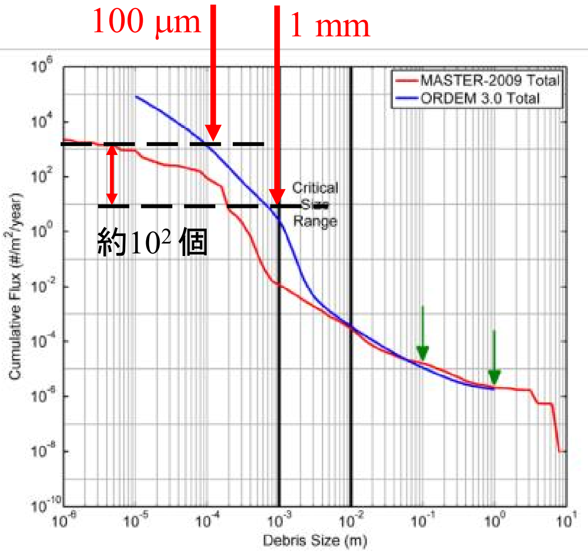


Fig. 4. ORDEM 3.0 and MASTER-2009 orbital debris fluxes for the SSO orbit in 2014.

P. H. Krisko, S. Flegel, M. J. Matney, D. R. Jarkey, V. Braun, ORDEM 3.0 and MASTER-2009 modeled debris population comparison, Acta Astronautica, Vol. 113, 2015, pp. 204-211.

=> Micro-space debris

(Never repeat the issue of microplastics in the ocean) 4

Purpose : Reduction of Forward Ejecta （イジェクタの低減）

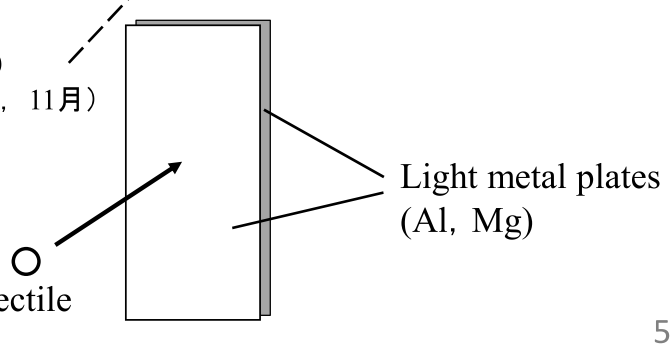
1) Coating / CFRP plates（コーティング / CFRP板）
2021 Symposium on Laboratory Experiment for Space Science
（宇宙科学に関する室内実験シンポジウム，2021年3月）
（第9回スペースデブリワークショップ，2021年2月）

2) Organic fiber reinforcement composites
（有機繊維補強複合材料）
（宇宙科学に関する室内実験シンポジウム，2020年3月）
（第9回スペースデブリワークショップ，2021年2月）

3) Aluminum alloy clad materials
（宇宙科学に関する室内実験シンポジウム，2019年3月）

4) Mg/Al clad materials
（材料学会 第71期学術講演会， 2022年5月）
（第66回宇宙科学技術連合講演会， 2022年， 11月）

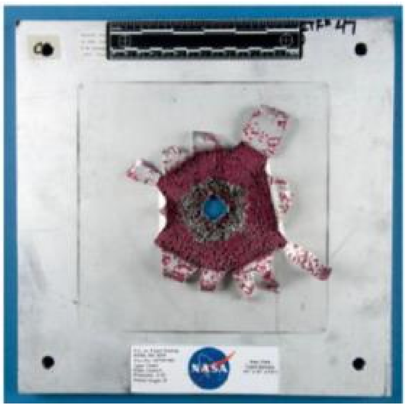
Less ejecta &
better shielding performance



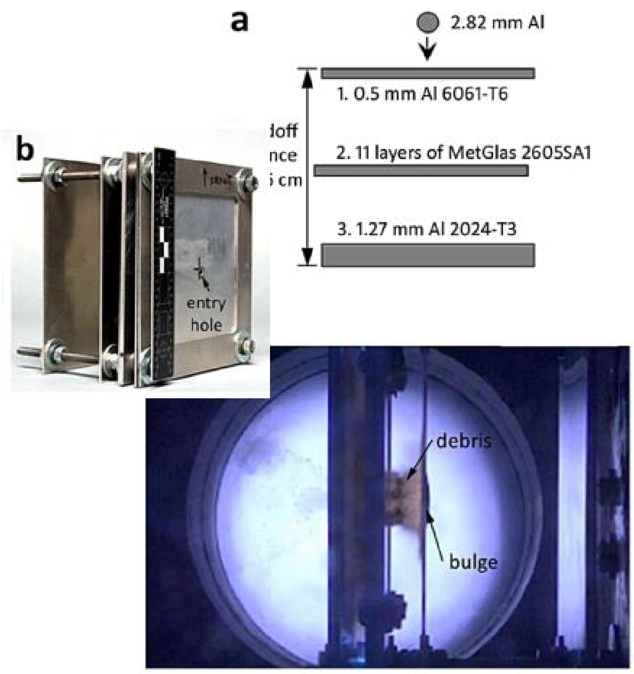
5

Earlier Studies of Debris Shielding (1/3)

0.833 cm Al sphere → Double-layer foam
6.9 km/s



Ryan *et al.*, NASA/TM–2009–214793



D. C. Hofmann, et al, Advanced Engineering Materials, 2015

Earlier Studies of Debris Shielding (2/3)

PBI coating/CFRP

Polybenzimidazole (PBI):
Atomic Oxygen Protective Coating

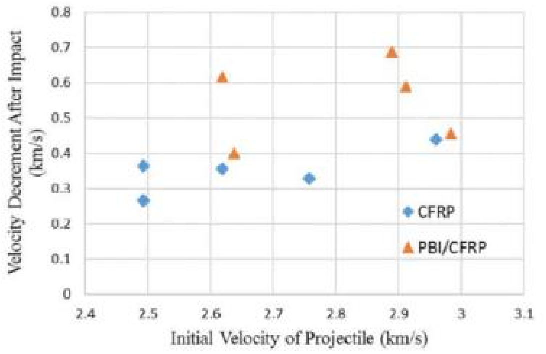
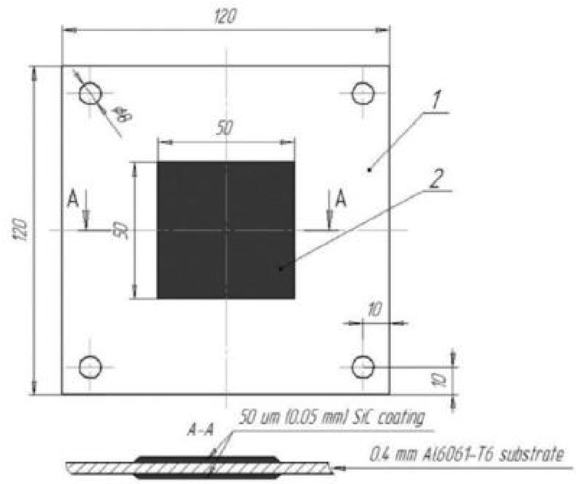


Fig. 5. Velocity decrement of the projectile after impact with CFRP and PBI/CFRP.

Sarath Kumar Sathish Kumar, et al., Polybenzimidazole (PBI) film coating for improved hypervelocity impact energy absorption for space applications, Composite Structures 188 (2018) 72–77

SiC coating/Al



Aleksandr Cherniaev, Igor Telichev, Sacrificial bumpers with high-impedance ceramic coating for orbital debris shielding, International Journal of Impact Engineering, 119 (2018) 45–56

Earlier Studies of Debris Shielding (3/3)

Ti-Al nylon impedance-graded materials

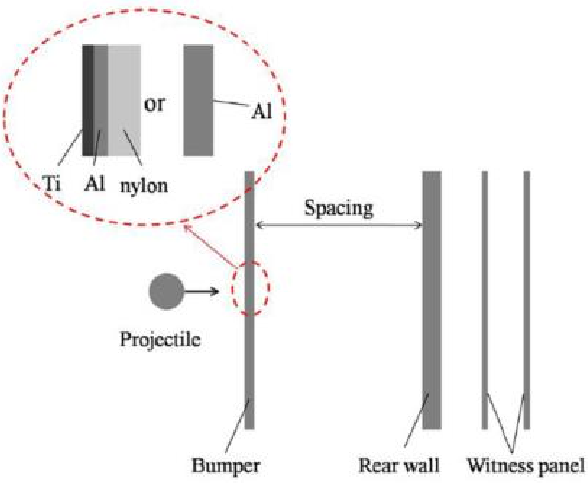


Fig. 1. Experiment schematic diagram.

Zhang P.L., et al., Study of the shielding performance of a Whipple shield enhanced by Ti-Alnylon impedance-graded materials, International Journal of Impact Engineering 124 (2019) 23–30

Al/ Mg impedance-graded-material-enhanced shields

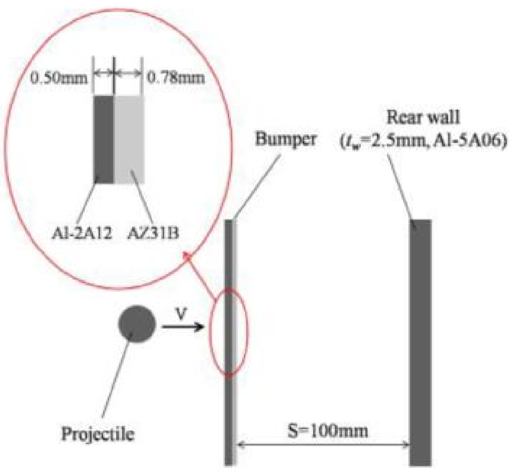


Fig. 1. Experimental configuration.

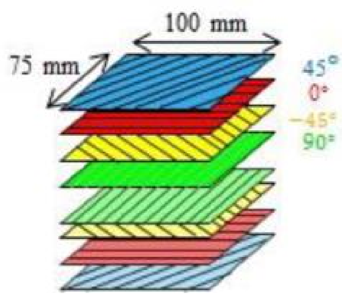
Zhang Pinlian, et al., Comparison of shielding performance of Al/Mg impedance-graded-material-enhanced and aluminum Whipple shields, International Journal of Impact Engineering Vol.126, (2019) pp. 101-108.

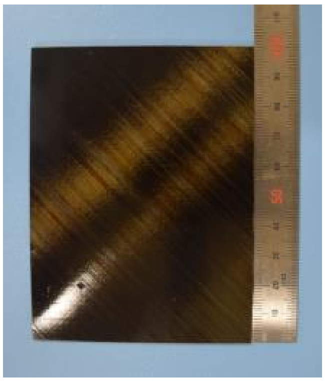
→ Multi-material structure

Anti-Atomic Oxygen (AO) Coating / Polyimide CFRP
耐原子状酸素（AO）コーティング/ポリイミドCFRP板

Polyimide CFRP

Polyimide CFRP（Prepreg from JAXA*）
Size：75 mm×100 mm
Thickness：1.0 mm（8 ply）
Quasi-isotropic [45º/0º/−45º/90º]s
（擬似等方性）



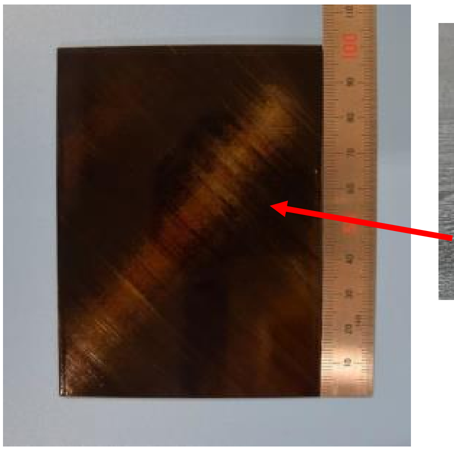


* 石田雄一，耐熱高分子基複合材（耐熱 CFRP）の適用技術研究，日本航空宇宙学会誌, 68(2), 2020, pp. 38-42.
Miyauchi, M., Ishida, Y., Ogasawara, T. and Yokota, R., Highly soluble phenylethynyl-terminated imide oligomers based on KAPTON-type backbone structures for carbon fiber-reinforced composites with high heat resistance, Polymer J., 45, 2013, 594-600.

Atomic Oxygen（AO）Protective Coating

Coating
Sil-sesqui-oxane derivative
（シルセスキオキサン誘導体）
（Toagosei）
Thickness 25 μm

Composition formula $[(RSiO_{1.5})_n]$, intermediate material of inorganic silica $[SiO_2]$ and organic silicone $[(R_2SiO)_n]$
Density 1.14 g/cm^3
Storage modulus 1×10^9 Pa (1 Hz, 0°C)

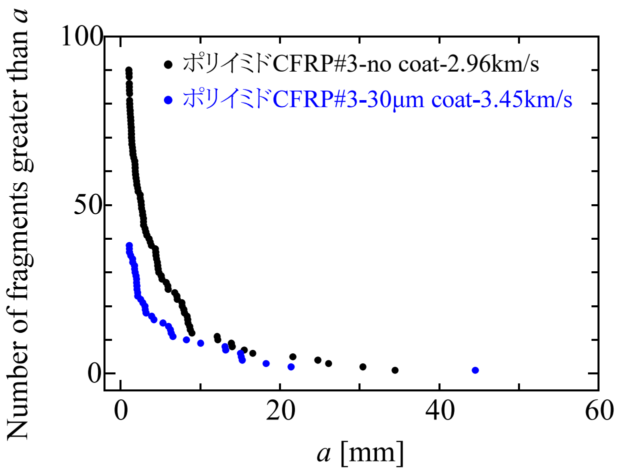


Atomic oxygen（AO） protective coating

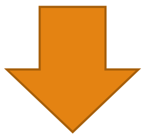
bar-coating method
⇒ Ultraviolet curing

Thickness 25 μm
=> Areal density 1.7% up

Earlier Studies of Our Group



Reduction of forward ejecta by coating



Effects of space environment

西田ほか，材料力学カンファレンス講演論文集 (2022)

Impact Tests

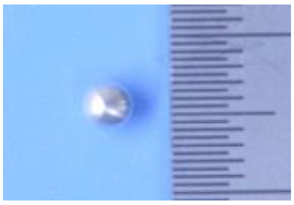
Two stage gas gun

JAXA/ISAS

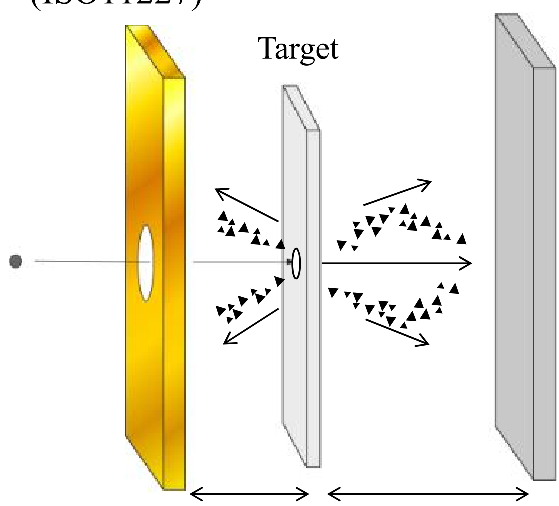
Impact velocity
2 km/s – 7 km/s

N. Kawai, K. Tsurui, S. Hasegawa, E. Sato, Rev Sci Instrum 81 (11) (2010) 115105.

Projectile
Aluminum alloy sphere
A2017-T4
Diameter： 1.6 mm
（3 km/s）



Experimental Setup



Space Environment (1/2)

Low Earth orbit

1) Vacuum, 真空

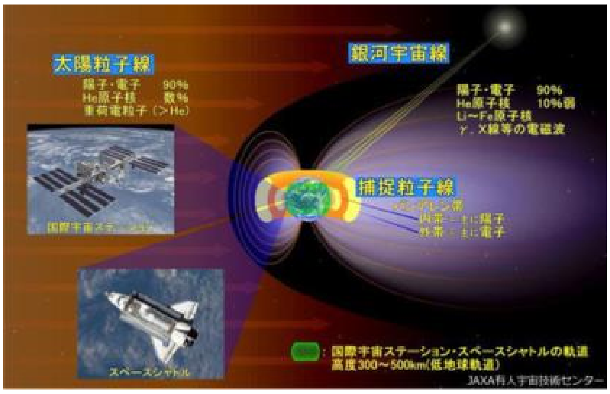
2) Atomic Oxygen (AO), 原子状酸素

3) Ionizing radiation, 放射線
   Electron beam, γ ray

4) Ultraviolet Radiation, 紫外線

5) Temperature and thermal cycling,
   温度と熱サイクル

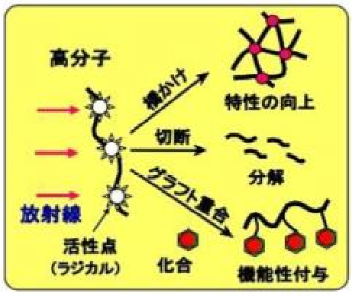
6) Micrometeoroid/Orbital Debris Impact,
   宇宙ゴミ，宇宙塵の衝突



https://iss.jaxa.jp/med/research/radiation/

Space Environment (2/2)

a) Electron beam (EB)

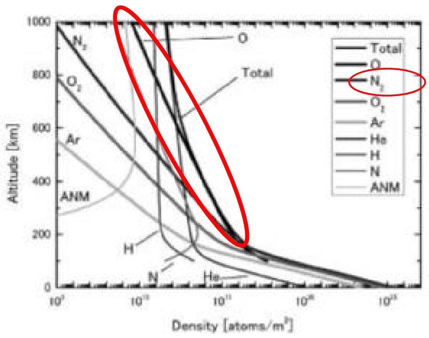


JAEA，放射線を利用したものづくり “放射線による橋かけ”
（財）群馬県産業支援機構「企業サポートぐんま」より一部編集），
2003年11月

QST 高崎量子応用研究所（1号加速器）
Dose rate (線量率) 2 kGy/s
Total dose (線量) 20.0 MGy, 34.9 MGy
Argon gas

Polyimide CFRP 25 μm coating

b) Atomic Oxygen (AO), 原子状酸素

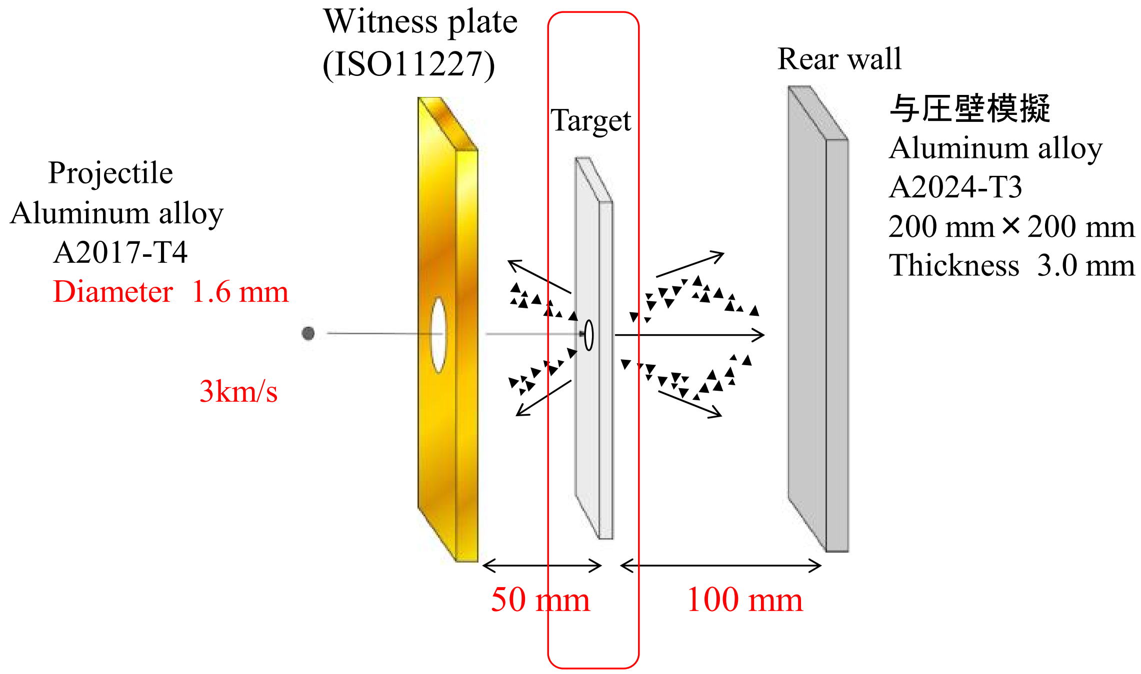


木本雄吾，宮崎英治，石澤淳一郎，島村宏之，低軌道における宇宙用材料への原子状酸素の影響とその地上評価, J. Vac. Soc. Jpn., 52(9) (2009) 475-483.

神戸大学（田川研）

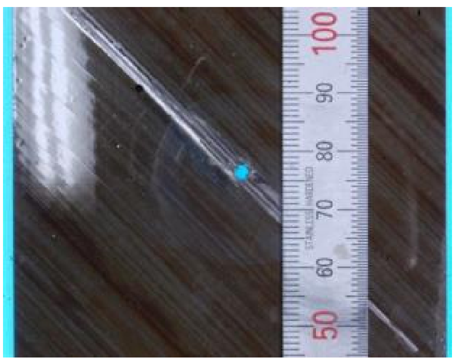
AO flux 1.64E+15 (atoms/cm^2/shot)
Shot number 82,530
AO fluence 1.40E+20 (atoms/cm^2)

Experimental Setup

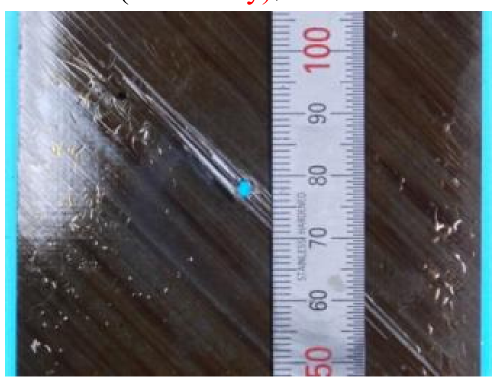


CFRP Surfaces （実験後の試験片写真）

Polyimide CFRP 20 μm coating, 3.47 km/s

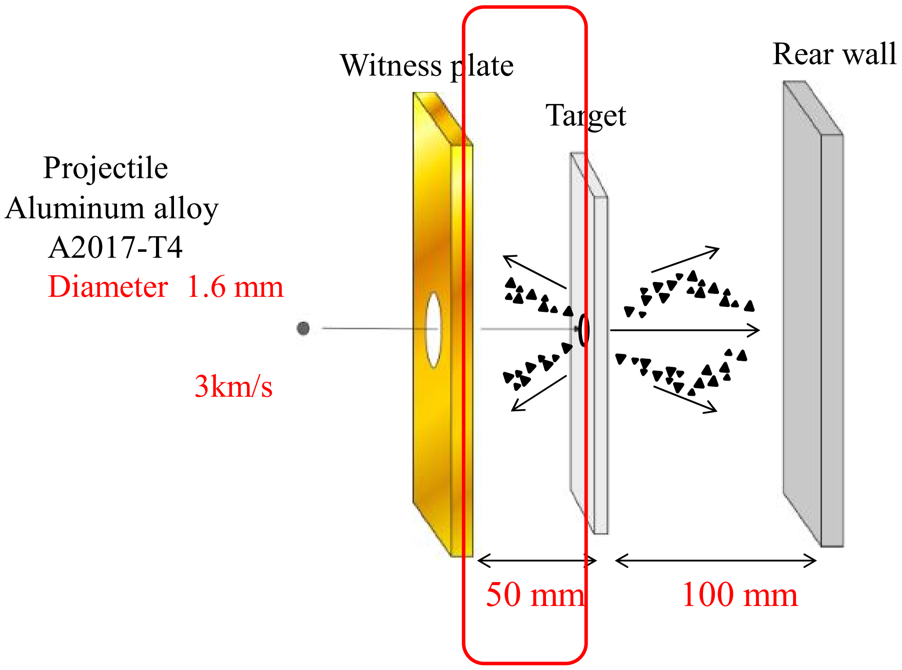


Polyimide CFRP 25 μm coating +EB (34.9 MGy), 3.12 km/s



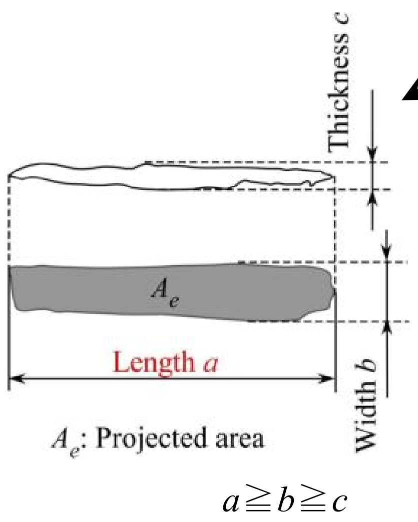
西田ほか，第13回複合材料会議材料，JCCM-13 講演論文集 (2022)

Results of Ejecta

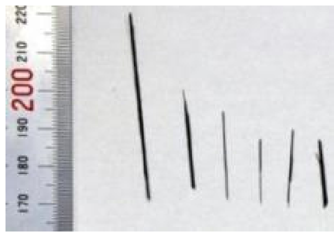


Evaluation of Ejecta (Direct method)

Image analysis software
ImageJ

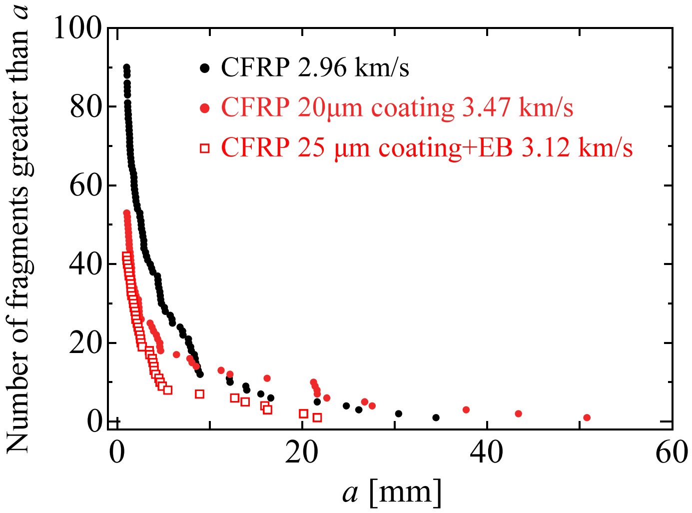


Fragments from CFRP plates



Main target: $a \geqq 1$ mm

Results by Direct Method (Cumulative number distribution of ejecta)



EB: Decreased

Anti-AO coating increased space environment resistance

西田ほか, 第13回複合材料会議材料, JCCM-13 講演論文集 (2022)

Conclusions（まとめ）

Anti-AO Coating /Polyimide CFRP was proposed as a debris bumper. The effects of electron beam (EB) and atomic oxygen (AO) were examined.

Forward ejecta：EB: Decreased

Future plans：

1） Chemical analysis (XPS)

2） Surface observation (SEM)

Acknowledgments

本研究を進めるにあたり，コーティングに関しまして，名古屋工業大学 栗山　晃 特任教授に，アドバイスいただきました．

本実験にあたり，宇宙航空研究開発機構 宇宙科学研究所 スペースプラズマ共同研究設備を利用しました．ここに記して謝意を表します．本研究は，JSPS 科研費19K04072の助成を受けたものです．

C09

MLI 用耐 AO 性材料に対するデブリ衝突の影響評価の取り組み

Initiative for Evaluation of Space Debris Impact on AO-Resistant Materials for MLI

〇久保優子、木本雄吾（JAXA 研開部門）、梅田花織（株式会社エイ・イー・エス）、
長谷川直（JAXA 宇宙科学研究所）
〇KUBO Yuko, KIMOTO Yugo (JAXA Research and Development Directorate), UMEDA Kaori
(Advanced Engineering Services), HASEGAWA Sunao (JAXA Institute of Space and Astronautical Science)

JAXA では多層断熱材（Multi-Layered Insulation; MLI）用の材料の研究開発を行ってきた。優れた耐宇宙環境性から、有機材料の１つであるポリイミドが MLI 用の材料として広く使用されてきたが、ポリイミドも低高軌道に存在する原子状酸素（Atomic Oxygen; AO）による浸食を受け劣化することが判明している。そこで我々は耐 AO 性を有する MLI 用材料の研究開発を行い、軌道上曝露実験等も経て、その機能を実証しつつある。一方で、ポリイミド材料にデブリが衝突するとポリイミド材料の耐 AO 性が低下する可能性を示唆する先行研究がある。そこで我々は研究開発中の耐 AO 性ポリイミドを中心とした耐 AO 性材料に対し、模擬デブリを衝突させる地上実験（超高速衝突実験）を行い、耐 AO 性の変化を評価する取り組みを行った。本発表では、我々が行った取り組みを紹介すると共に現在までに得られた結果を報告する。

JAXA has been studied and developed materials for Multi-Layered Insulation (MLI). With its excellent space environmental resistance properties, polyimide, an organic material, is used to fabricate MLI. However, polyimide is degraded by Atomic Oxygen (AO), which is present in low earth orbit. To reduce degradation of MLI, we have developed AO-resistant materials, AO-resistant polyimide in particular. Our materials are proving themselves through orbital experiments and ground tests. Previous studies have suggested that debris impact on polyimide materials degrades their AO resistance. We evaluated the changes in the tested materials through ground hypervelocity impact tests that simulated debris impacts. In this presentation, we will report our work and the current results.

[C09]

MLI用耐AO性材料に対する デブリ衝突の影響評価の取り組み

Initiative for evaluation of space debris impact on AO-resistant materials for MLI

〇久保 優子*、木本 雄吾*、梅田 花織**、長谷川 直*
Yuko Kubo Yugo Kimoto Kaori Umeda Sunao Hasegawa

*国立研究開発法人 宇宙航空研究開発機構
Japan Aerospace Exploration Agency (JAXA)

** 株式会社 エイ・イー・エス
Advanced Engineering Services Co., Ltd.,

2022年11月30日
30 Nov. 2022

第10回スペースデブリワークショップ
10th Space Debris Workshop

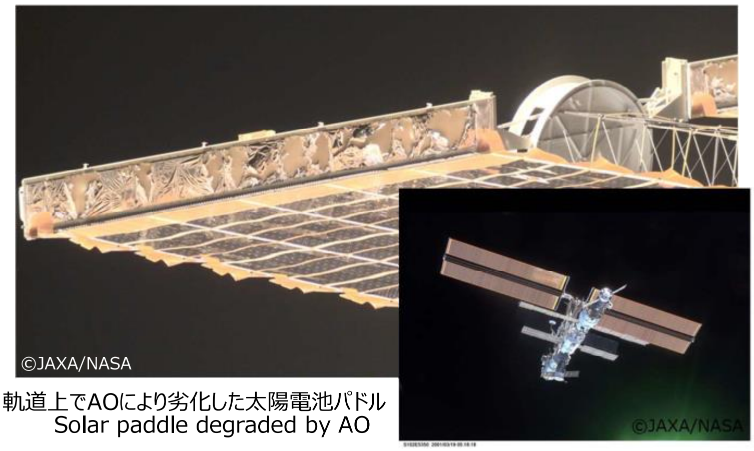
10th Space Debris Workshop

目次
Outline

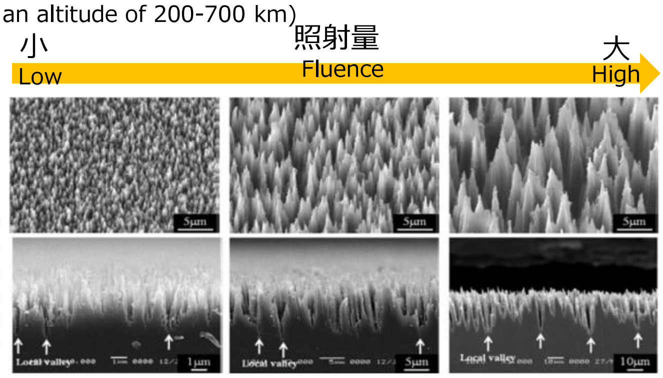
1． 背景と目的 Introduction

■ **原子状酸素（Atomic Oxygen: AO）による有機材料（ポリイミド等）表面の劣化**
Degradation of a surface of organic materials (including polyimide) by Atomic Oxygen (AO)

- 酸素分子が紫外線により分解したもの
  Oxygen molecules decomposed by UV
- 高度200-700km（低軌道）の主な大気成分
  Main atmospheric constituents of low Earth orbit (at an altitude of 200-700 km)



軌道上でAOにより劣化した太陽電池パドル
Solar paddle degraded by AO



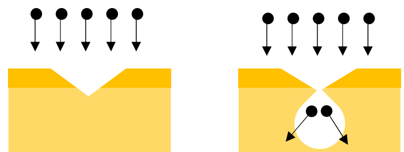
AOにより劣化したポリイミド表面及び断面＊
The surfaces and cross sections of polyimides degraded by AO

＊島村宏之, 中村孝、Investigation of Degradation Mechanisms in Mechanical Properties of Polyimide Films Exposed to a Low Earth Orbit, Vol. 95, pp. 21–33.2010

1． 背景と目的 Introduction

■ **劣化対策 Anti-degradation measures**

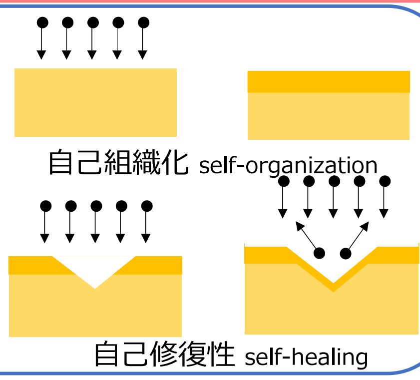
表面コーティング Surface-coating methods
無機材料等による表面の保護 Coating by inorganic materials
×損傷部分を起点とした劣化の進行 AO erosion spreading from damaged areas
・製造時の欠陥（ピンホール） Manufacturing defects (e.g., pinholes)
・ハンドリング時のクラック Cracks caused by handling



AOの照射を受けるとサンプル表面に自ら耐AO性の層（酸化物層）を生成する
Exposure to AO forms an AO-resistant layer (an oxide layer).

自己組織化Self-organization／自己修復性Self-healing
耐AO性材料（ポリイミド／コーテ…材）
AO-resistant materials (… ating agent)
◎損傷が生じて…

一度生成した耐AO性の層（酸化物層）が損傷しても、
再度AOの照射を受けることによって自ら耐AO性の層を修復する
Subsequent exposure to AO regenerates even a damaged oxide layer.



地上、軌道上では実証されつつあるが、
デブリとの衝突後も同様に耐AO性（自己組織化、自己修復性）特性が発揮されるか？
Are AO-resistant (including self-organizing, self-healing) properties the same after a collision with debris?

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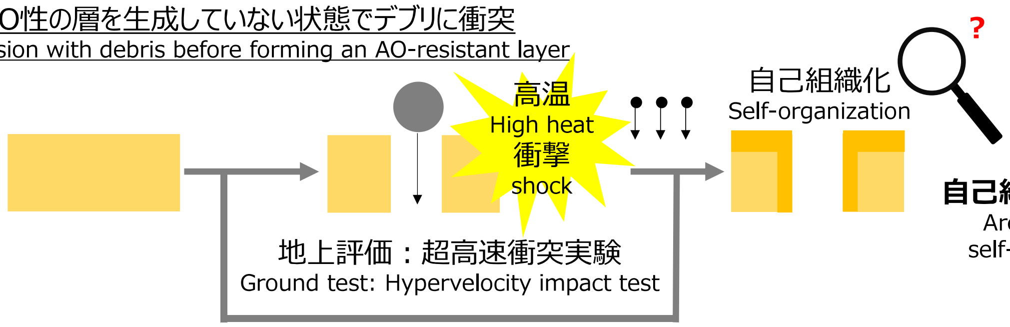
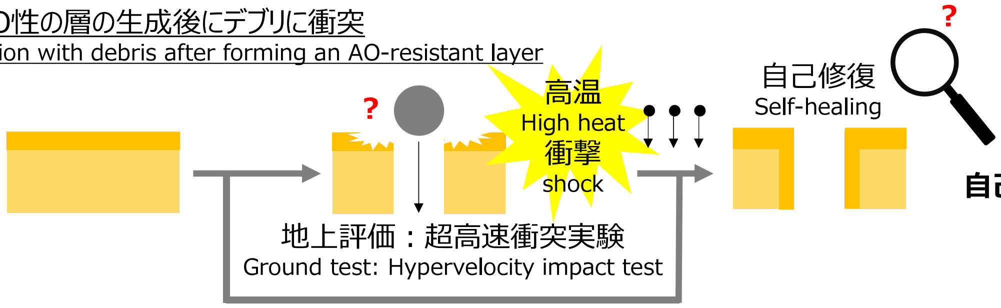
2. 試験計画
Experimental plan

耐AO性の層を生成していない状態でデブリに衝突
Collision with debris before forming an AO-resistant layer



自己組織化に影響はあるか？
Are there any effects on self-organization property?

耐AO性の層の生成後にデブリに衝突
Collision with debris after forming an AO-resistant layer



自己修復性に影響はあるか？
Are there any effects on self-healing property?

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3.試験方法 Experimental method

AO照射試験 AO irradiation test

- プラズマアッシャー装置を用いて宇宙空間でのAO環境を簡易的に模擬
  Simplified simulation of AO environment in space by plasma asher

試験条件 Test conditions

照射量 Flux (atoms/cm²)	6×10²⁰
	1.2×10²¹
	1.8×10²¹
	2.5×10²¹

AO照射設備
AO irradiation machine

超高速衝突実験 Hyper velocity impact test

- デブリとの衝突を模擬した地上試験 Simulation of colli
- JAXA宇宙科学研究所にて実施 conducted at ISAS, JAXA

アルミ片(10 km/s)との衝突を模擬＊
Simulated collision with a piece of aluminum flying at 10 km/s

試験条件 Test conditions

パラメータ Parameters	条件 Conditions
衝突速度 Velocity	6 km/s
模擬デブリサイズ Size of projectile	0.3 mmφ
模擬デブリ材質 Material of projectile	鋼球（ステンレス） steel
照射方法 Shooting method	散弾法 shotgun

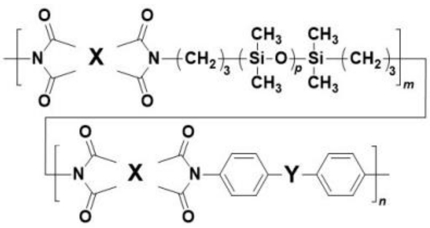
東出真澄ら、MLIの微小デブリ防御性能、第59回宇宙科学技術連合講演会講演集、JSASS-2015-4586, 2015

サンプル設置状況
Sample setup

3.試験方法 Experimental method

シロキサン変性ポリイミド （BSF-30） Polysiloxane-block-polyimide

- 日鉄ケミカル＆マテリアル株式会社様との共同研究で作製 Created by NIPPON STEEL Chemical & Material Co., LTD. and JAXA.
- 主にMLI用のフィルムとして使用することを想定 Developed for use as a film of MLI.
- AOの照射を受け、表面に耐AO性の酸化物層（SiO_x層）を生成 Exposure to AO forms an AO-resistant layer (SiOx layer).
- 自己組織化／自己修復性を有する Self-organization and self-healing properties exist.
- ポリイミドとポリジメチルシロキサンの共重合体 Copolymer of polyimide and polydimethylsiloxane



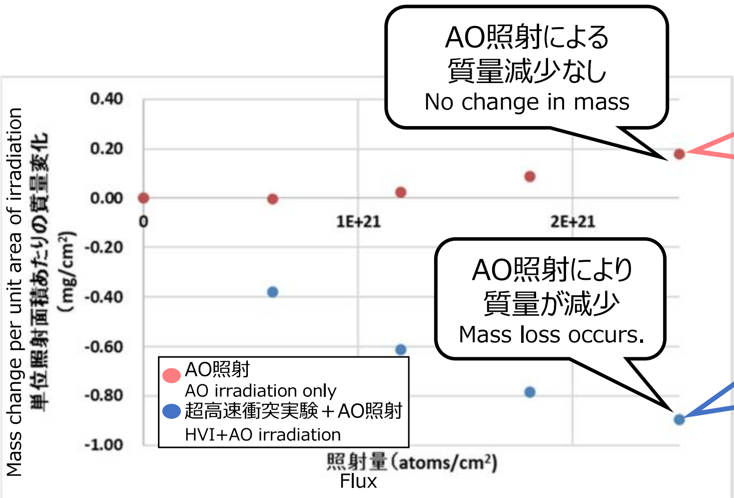
（X,Yの構造は非公開）
Construction of X and Y are not disclosed.
BSF-30化学構造
Chemical construction of BSF-30

サンプル外観
Sample appearance

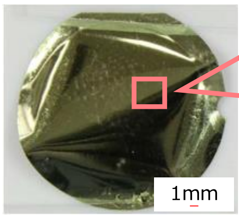
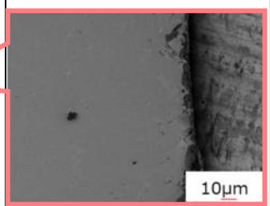
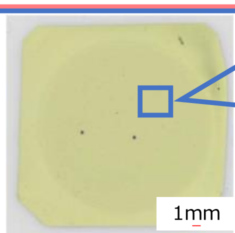
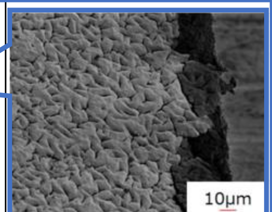
4.試験結果（BSF-30/Al評価結果） Result of BSF-30

- 模擬デブリの衝突があったサンプルではAOの照射による質量減少が発生。表面に生成する酸化物層には無数のクラックが発生。
  Mass loss occurs at hypervelocity impact test (HVI)+AO sample and this sample forms an AO-resistant layer with many cracks.

⇒耐AO性（含、自己組織化）の低下を確認した
AO-resistant properties (including self-organization property) are degraded.



外観変化 Change in sample appearance

	外観 appearance	表面 surface
AO 照射 AO irradiation only	 	
超高速 衝突実験 ＋ AO HVI+AO irradiation	 	

久保優子、木本雄吾、梅田花織、長谷川直；耐AO性フィルムに対するデブリ衝突の影響評価、第66回宇宙科学技術連合講演会（2022）

5. 発表まとめ Summary of the presentation

- **耐AO性ポリイミドフィルムに対するデブリ衝突の影響評価の取り組みについてご紹介した。**
  Introduced our plans for evaluating the impact of space debris on AO-resistant materials for MLI.
- **デブリの衝突により耐AO性ポリイミドフィルムの耐AO性（自己組織化）が低下することを示唆する結果が得られた。**
  This evaluation suggests that space debris impact degrades the AO-resistant properties of our samples.
- **現在も評価を実施しており、それらの結果をもとに結論を導きたい。**
  We have been conducting the evaluations and we will offer a conclusion based on the result thereof.

謝辞 Acknowledgments

- **本研究はJAXA宇宙科学研究所スペースプラズマ共同利用（超高速衝突実験施設）を用いて実施されました。ご協力いただいた超高速衝突実験施設の皆様に感謝いたします。**
  This study was supported by the Hypervelocity Impact Facility, (former facility name: the Space Plasma Laboratory) ISAS, JAXA.
- **本研究にサンプルをご提供いただいた日鉄ケミカル＆マテリアル株式会社様に感謝いたします。**
  We gratefully acknowledge NIPPON STEEL Chemical & Material Co., Ltd. for their help in supplying samples.
- **サンプルの測定及び分析を担当していただいた株式会社エイ・イー・エスのエンジニア各位に感謝いたします。**
  We also thank Advanced Engineering Services Co., Ltd. for their kind support in these experiments.

ご清聴ありがとうございました
Thank you for your attention.

C10

ELSA-d 軌道上実証成果について

ELSA-d Demonstration Results in Orbit

小林裕亮、瀬戸裕基、〇飯塚清太（アストロスケール）
KOBAYASHI Yusuke, SETO Yuki, 〇IIZUKA Seita (Astroscale Japan Inc.)

ELSA-d (End-of-Life Services by Astroscale - demonstration)は、デブリ除去に係る一連のコア技術を実証する世界初の商業ミッションである。2021 年 3 月に無事打上げ・軌道投入に成功し、2021 年 8 月に試験捕獲ミッションを完了した。2022 年 4 月には約 1,600km 離れた位置から 159m まで絶対航法を実施後、搭載センサを用いた相対航法への移行に成功した。これは ELSA-d ミッションにおいて最も困難な運用であり、また軌道上サービスの運用において実現することが最も難しい機能の 1 つとして広く認識されている。

ELSA-d (End-of-Life Services by Astroscale - demonstration) is the world's first commercial mission to prove the core technologies necessary for on-orbit satellite servicing in LEO. The spacecraft was successfully launched into an orbit in March 2021, and the test capture mission was completed in August 2021. In April 2022, absolute navigation from 1,600km to 159m was conducted, then a transition to relative navigation using on-board sensors was enabled successfully. This handover has been the most challenging operation of the ELSA-d mission and is widely recognized as one of the more difficult capabilities to prove for satellite servicing operations.

ELSA-D-220006

Astroscale

The 10th Space Debris Workshop
～ELSA-d Demonstration Results in orbit～

Astroscale Japan Inc.
Director of Programs
Seita Iizuka

November 30th, 2022

Table of Contents

1. Summary of Astroscale

Global company solving a global problem

5 Offices

360+ Team Members
*70% Engineers; 35% female.

$300 million raised

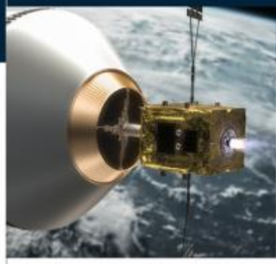
30+ awards

Multiple Global Leadership Roles

4 Service Lines
EOL, ISSA, ADR, LEX

Our services

EOL
End-of-Life Services
Preventing future debris through installation of pre-launch docking plates and de-orbiting prepared client spacecrafts
Customer Type: Commercial Constellations + Others



ADR
Active Debris Removal
Reducing current debris by de-orbiting crafts unprepared for servicing
Customer Type: Government

LEX
Life Extension Services
Extending client satellite life through relocation and fleet management
Customer Type: Commercial + Government

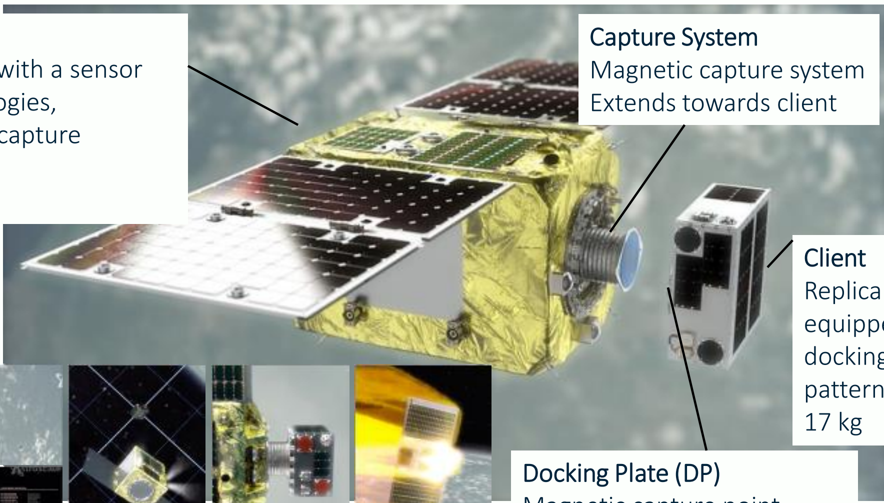
ISSA
In-situ Space Situational Awareness
Surveying client objects and orbital environments at a variety of ranges
Customer Type: Commercial + Government

Astroscale Proprietary 5

2. ELSA-d Operation Results

ELSA-d mission

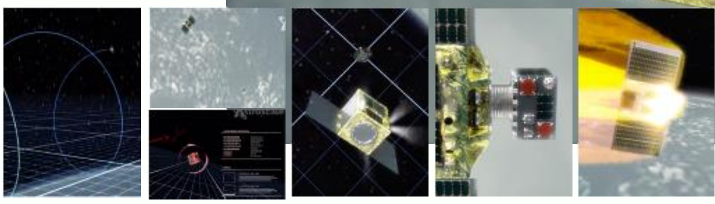
Servicer
Satellite equipped with a sensor suite, RPO technologies, & a ferromagnetic capture mechanism
175 kg



Capture System
Magnetic capture system
Extends towards client

Operation Timeline
Mar 22, 2021: Launch & Orbit Insertion
Aug 25, 2021: Test Capture
Jan 25, 2022: Autonomous Capture

Client
Replica debris/defunct satellite equipped with ferromagnetic docking plate & unique fiducial pattern
17 kg



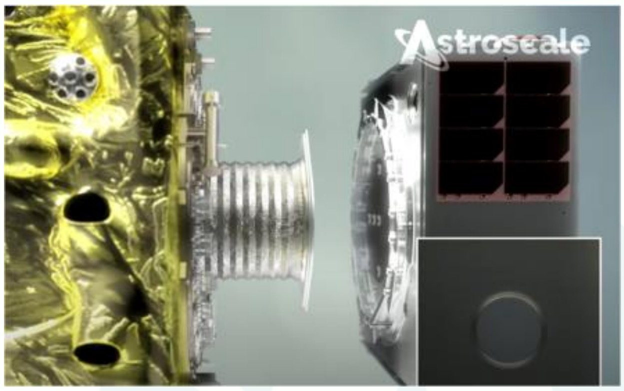
Rendezvous | Diagnose | Synchronize | Capture and stabilize | De-orbit

Docking Plate (DP)
Magnetic capture point

Test Capture

Phase 3a: Test Capture【Complete】

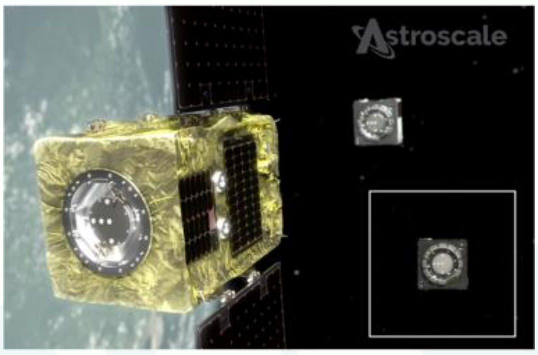
- **Results**
  - Client would be released manually and be captured
- **Key technologies which have been demonstrated**
  - Magnetic capture mechanism using a docking plate
  - Releasing the Client gently
  - Functionality of capture mechanism
  - Sensors’ output required for relative navigation
  - Validity of Operation team, Ground stations and Ground segment
  - Validity of testing platform



Autonomous Capture

Phase 3b: Autonomous capture

- **Plan**
  - After releasing the Client, absolute navigation (30m Home Position → 10m Point A → 5m Point B) would be completed using the onboard sensors
  - At Point B, relative attitude synchronization would be executed. Then, capture would be completed.
- **Results**
  - 30m Home Position Keeping for several orbits
  - Attitude anomaly during Home Position Keeping. Triggered an abort.
  - Found out 4 thrusters out of 8 were failed
  - Max Servicer – Client distance: 1600km
  - Reapproached to 159m using the remaining 4 thrusters based on absolute navigation. Then, onboard sensors detected the Client and started relative navigation.
- **Key technologies which have been demonstrated**
  - Autonomous guidance, navigation and control algorithms,
  - Closed loop control with on-board navigation sensors,
  - Autonomous thruster rendezvous maneuvering and attitude control,
  - Navigation of a servicer spacecraft from 1,600 km to within 160 m of a client using absolute navigation techniques (GPS and ground-based observations),
  - Transition from absolute navigation to relative navigation using on-board LPR (Low Power Radio) sensor, and
  - More than one year of servicer and client satellite in-orbit mission operations



Phase 3b Original plan vs. Actual operation

Original plan

Servicer
Client

0m
1. Separation
30m
2. Autonomous tracking
~~4. Recapture~~
~~3. Rendezvous from 30m~~

Anomaly during autonomous tracking
- Rotation rate was too fast
- One of the thrusters stopped firing

→
- Executed contingency procedures to abort safely

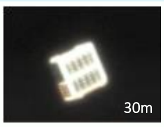
Anomaly after active abort
- 4 out of 8 thrusters were failed

→
- Used high-fidelity simulator to validate absolute navigation operation using remaining thrusters

Actual operation

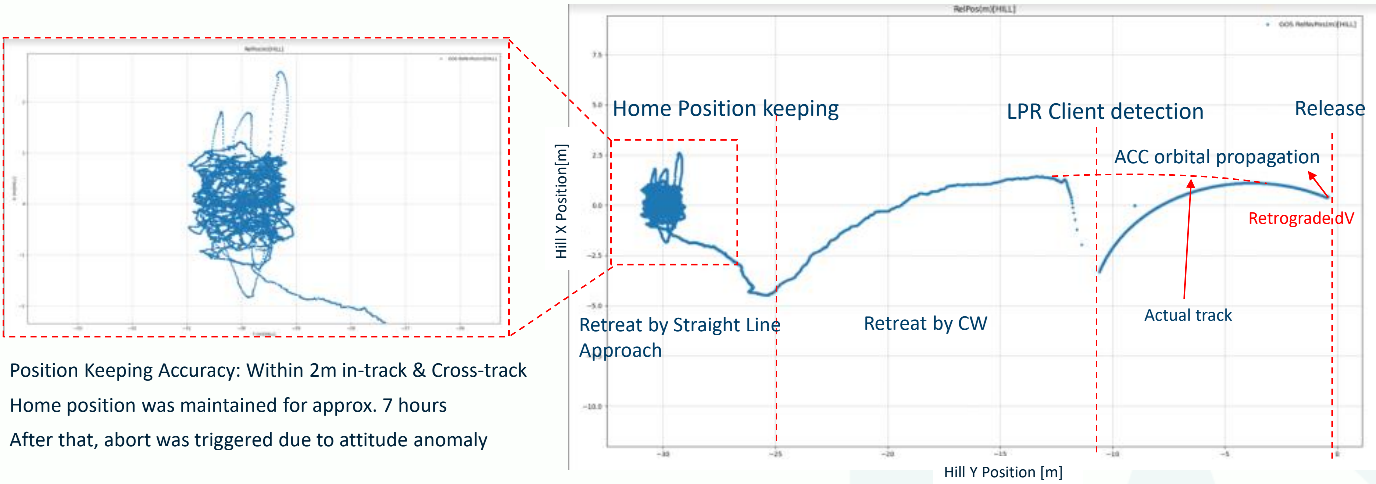
0m*
1. Separation
30m
2. Autonomous tracking
3. Attitude & Thruster Anomaly Active Abort
160m
1,600km
4. Stop drifting
5. Absolute Navigation
6. Relative Navigation

* Distance between servicer and client



Result in orbit: Separation ～ Autonomous Tracking

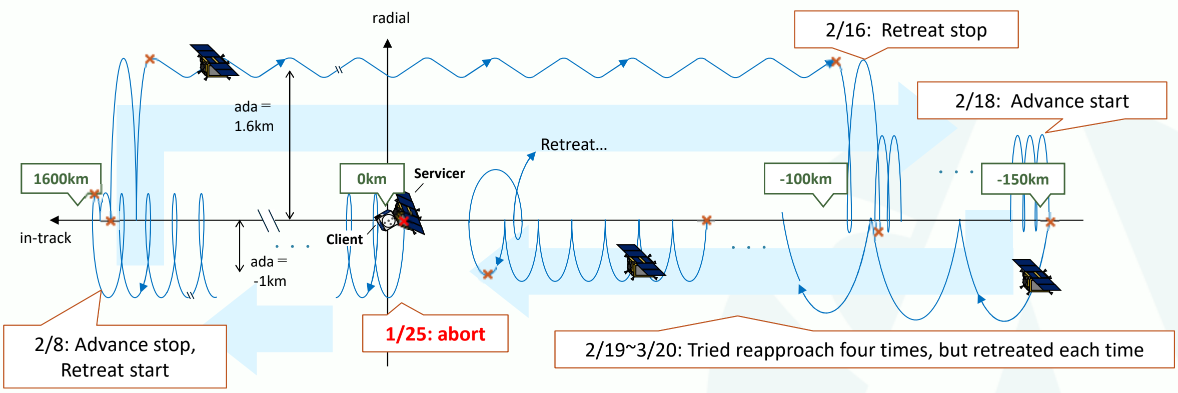
- Jan 25th, 2022: Client release, Retreat to Home position (-30 m) from Client, and Home position keeping



- Position Keeping Accuracy: Within 2m in-track & Cross-track
- Home position was maintained for approx. 7 hours
- After that, abort was triggered due to attitude anomaly

Result in orbit: Post Abort No.1

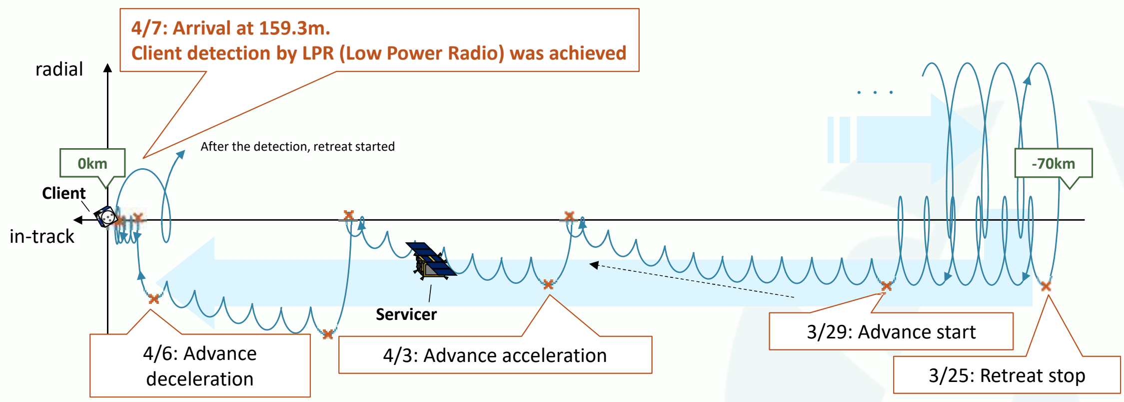
- Maximum distance between the Servicer and the Client: 1600km
- After retreat to -100km, we have attempted reapproach four times until March 20th. However, we had to pause each trial.



January 25th to March 20th, 2022

Result in orbit: Post Abort No.2

- After March 29th, we have struggled with the adjustment of differential drag. Ada has been adjusted multiple times.
- On April 7th, the LPR (Low Power Radio) on the Servicer detected the Client successfully, and relative navigation was initiated.

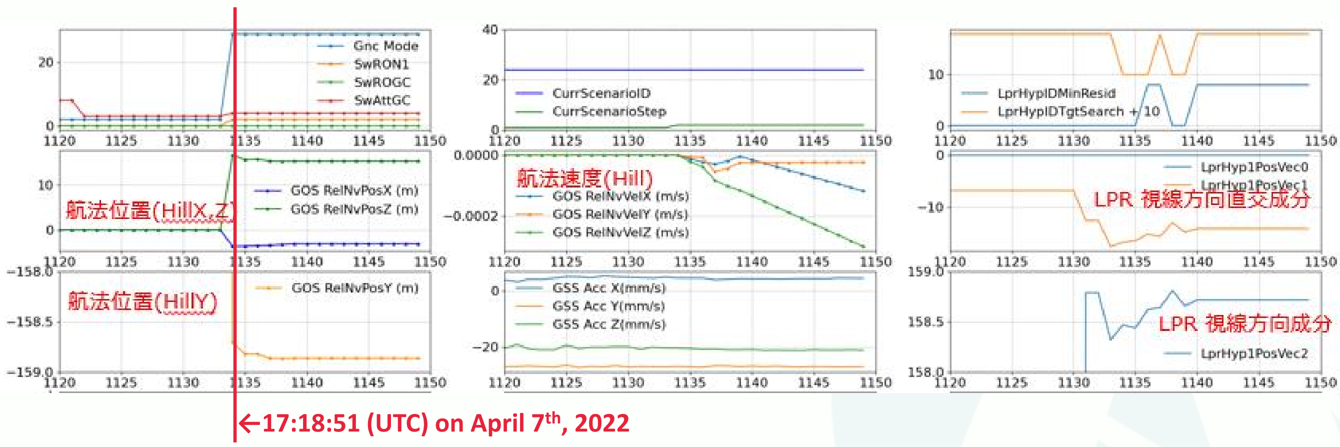


March 20th to April 7th, 2022

Result in orbit: Client detection by LPR (Low Power Radio)

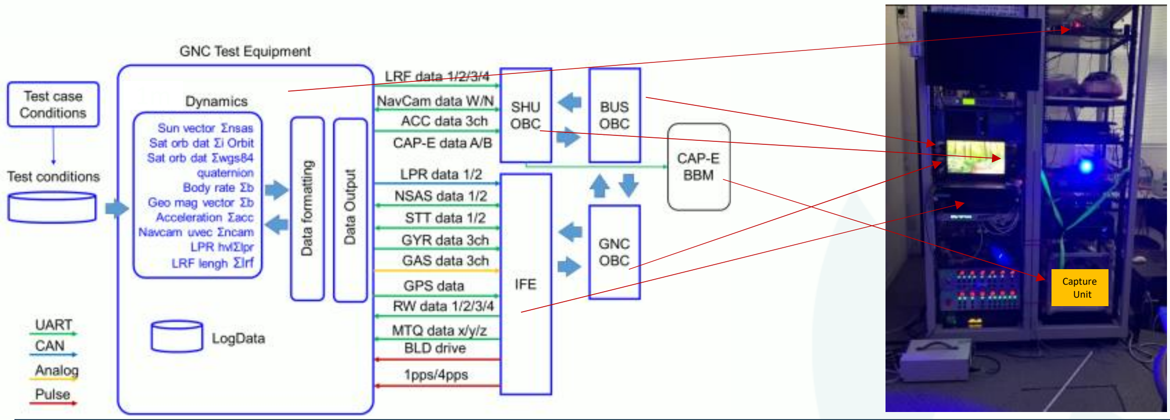
Navigation output after LPR detection

- At 17:18:51 (UTC) on April 7th, 2022, the client data was obtained
- Estimated position by navigation : [R, I, C] = [-3.14,-158.86,15.32]m



Introduction of testing platform

- We have developed a high-fidelity end-to-end testing platform which includes actual OBCs, sensors, capture mechanism, ground segment and orbit environmental simulator
  - Actual hardware was required to conduct tests for switching between primary and redundant lines
  - “Close-loop testing” was necessary to verify electrical interface between sensors and OBCs with flight software, and to confirm their inputs
  - **This platform was very valuable not only for the verification of onboard function but also for validation of operation procedures and operation trainings**



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ADRAS-J プロジェクトステータス
- 世界初大型デブリ除去実証プロジェクトの開発進捗 -

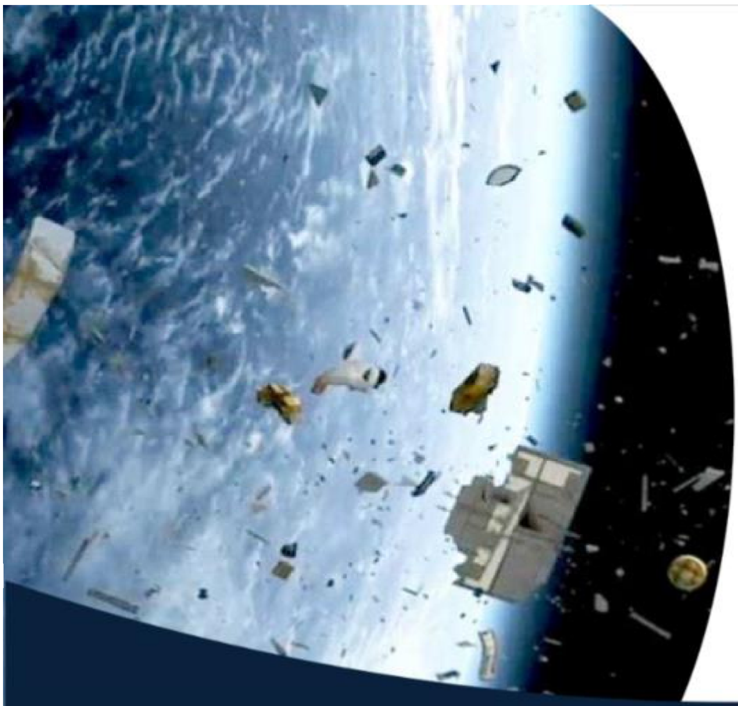
Status of ADRAS-J Project　- Development Progress of ADR -

○新 栄次朗（株式会社アストロスケール）
○ATARASHI Eijiro (Astroscale Japan Inc.)

本講演では、スペースデブリ除去の商業化を大きく前進させる画期的な JAXA ミッションの意義について述べる。2020 年 3 月、JAXA は、日本の大型スペースデブリの観測、特性評価、そして最終的な除去に焦点を当てた CRD2 プログラム　フェーズ 1 に資金提供することを発表した。CRD2 フェーズ 1 では、日本の上段ロケット本体の位置確認、接近、ランデブーに続き、デブリの運動特性をより深く理解するためのデータ取得が行われる。
CRD2 フェーズ 1 は、2022 年度末までに打ち上げられる予定であり、JAXA は、このフェーズ 1 の実施事業者として、アストロスケール社と同社の ADRAS-J（Active Debris Removal by Astroscale-Japan）衛星を選定した。本講演では、ADRAS-J プロジェクトの技術的背景、運用概念、開発状況について紹介する。

This presentation will address the implications of a groundbreaking JAXA mission that is a significant step forward in commercializing space debris removal. In March 2020, JAXA announced that it would fund the first phase of a mission line focused on the observation, characterization, and eventual removal of a large piece of Japanese space debris. The initial phase of the mission line includes the location, close approach and rendezvous with a Japanese upper stage rocket body, followed by the acquisition of in-situ data to better understand the movement characteristics of the debris.
The first phase of the mission is scheduled to launch by the end of the Japan Fiscal Year (JFY) 2022 (March 2023). JAXA has selected Astroscale and its Active Debris Removal by Astroscale-Japan (ADRAS-J) satellite as the commercial partner for the first phase of this mission. This presentation will focus on the technical background, concept of operations and the development status of ADRAS-J project.

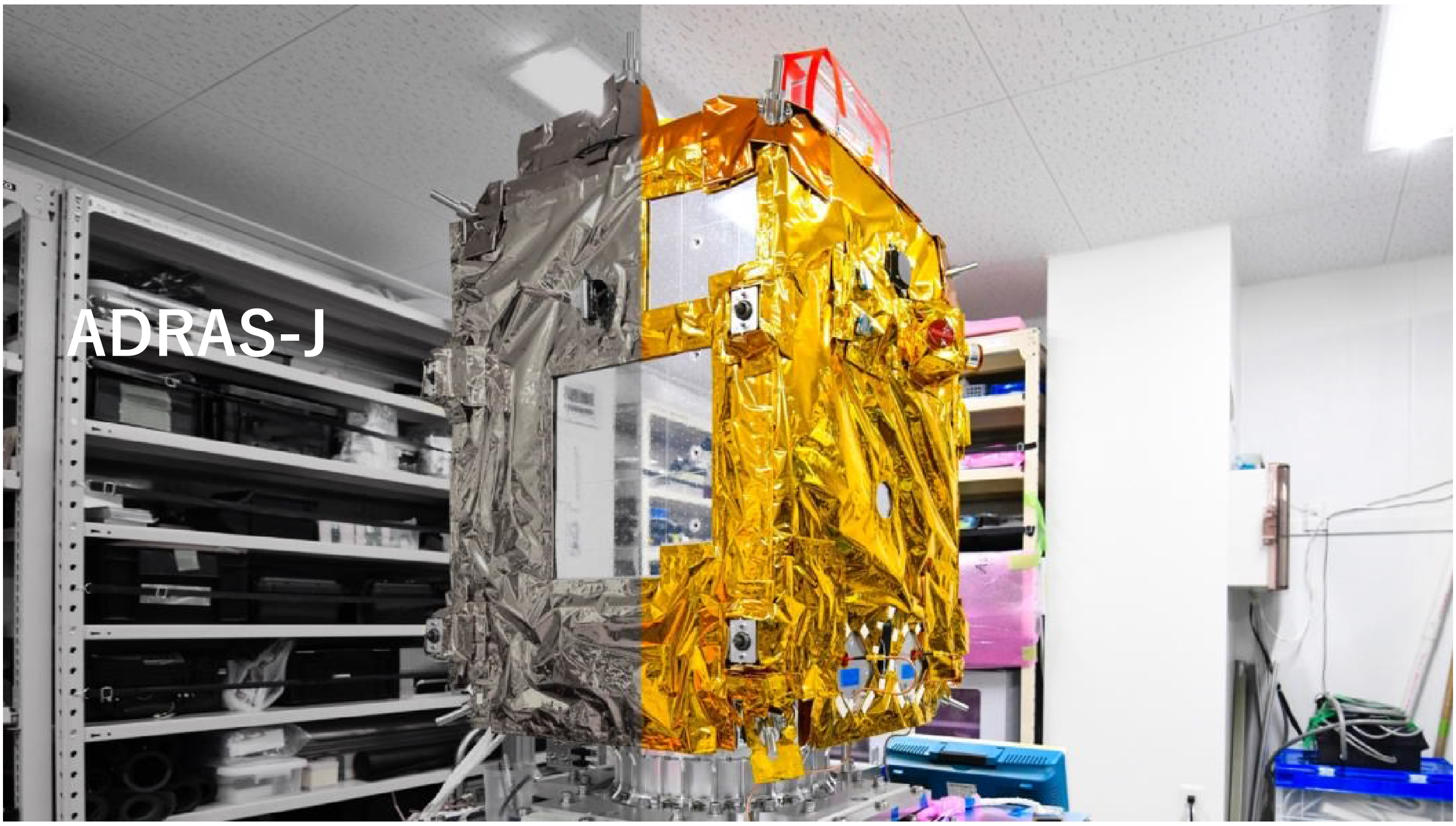
10th Space Debris Workshop
Program ID : C11



Astroscale

Status of ADRAS-J Project
- Development Progress of ADR -

30th November 2022
ASTROSCALE JAPAN inc.
Eijiro Atarashi



ADRAS-J Project Overview

■ ADRAS-J Project Overview

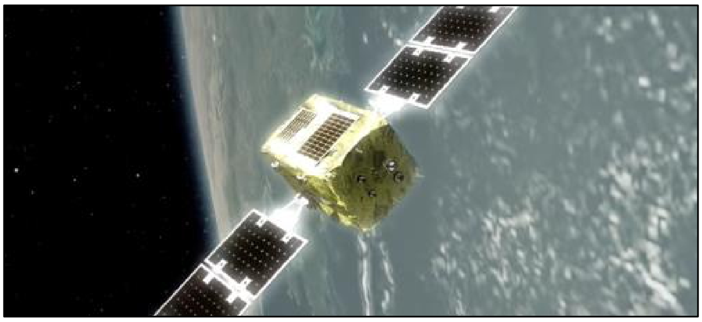
- **What is ADRAS-J Project？**
  - Project aims to demonstrate on-orbit debris removal technology
  - Selected as a private-sector implementation partner for JAXA's CRD2 Phase I ＊CRD2=Commercial Removal of Debris Demonstration
- **Objectives of CRD2**
  - World’s first technology demonstration of large debris removal
  - Development of ADR business by private companies
- **CRD2 consists of two phases**

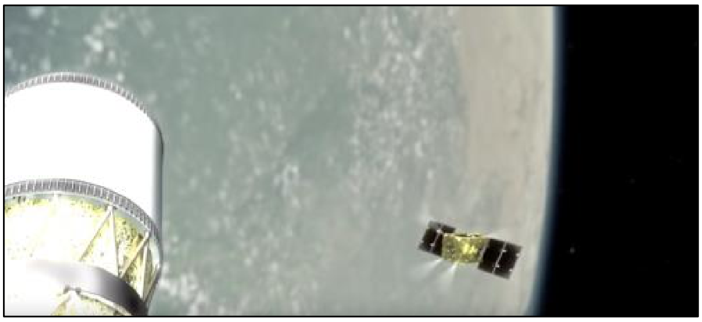
ADRAS-J Project

■ ADRAS-J Project Overview

■ Objectives of ADRAS-J (Active Debris Removal by Astroscale-Japan) Project

- ■ Demonstration of ADR Core Technology
  - Proximity approach and operation to non-cooperative objects
  - Observation and image capturing of target non-cooperative objects
  - In addition to JAXA missions, Astroscale's own technology demonstrations

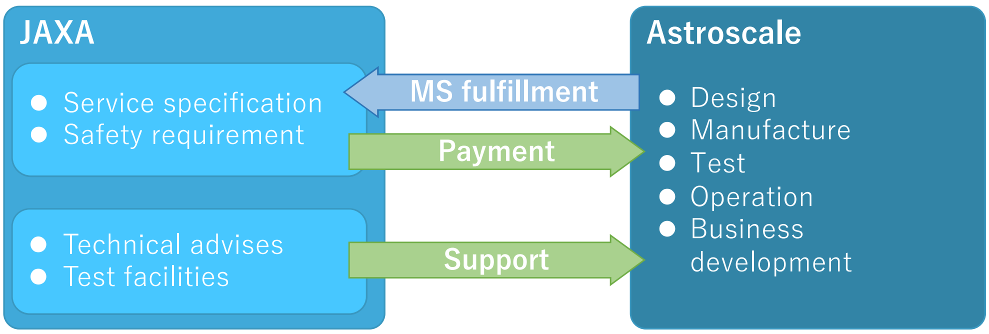




■ ADRAS-J Project Overview

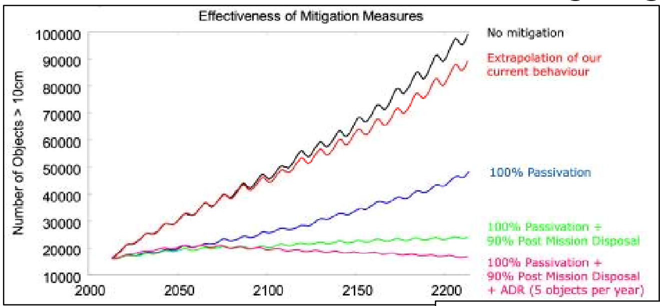
■ CRD2 Framework

- ■ Brand-new partnership scheme with JAXA
- ■ Astroscale designs and operates the whole satellite system and provides the service to JAXA
- ■ Payments are made based on the results of milestone (MS) reviews



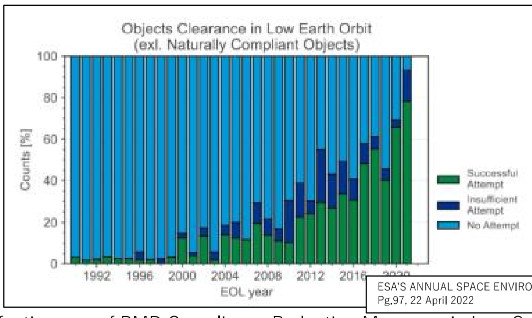
ADRAS-J Project Overview

- **Background on the need for ADR**
  - Increased risk of accidents involving active satellites due to congestion of the space environment
  - Conditions for Space Environment Improvement
    1. Achieve 100% passivation
    2. Achieve 90% PMD (Post Mission Disposal)
    3. Continuous removal of (large, high-risk) debris, 5 pieces per year, for 200 years



Effectiveness of debris reduction measures

H. Krag, Head of ESA's Space Debris Office at SWF Summit for Space Sustainability, June 26, Pg.10-11,2019



ESA'S ANNUAL SPACE ENVIRONMENT REPORT, Pg.97, 22 April 2022

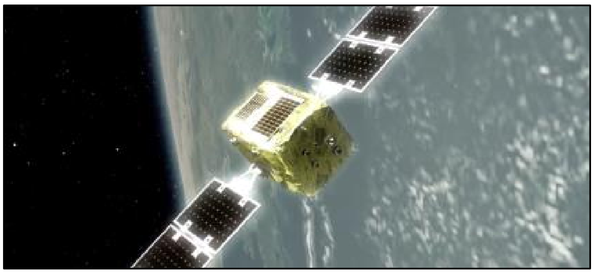
Effectiveness of PMD Compliance Reduction Measures in Low Orbit

In addition to achieving #1 and #2, it is essential to achieve #3 (= Active Debris Removal)

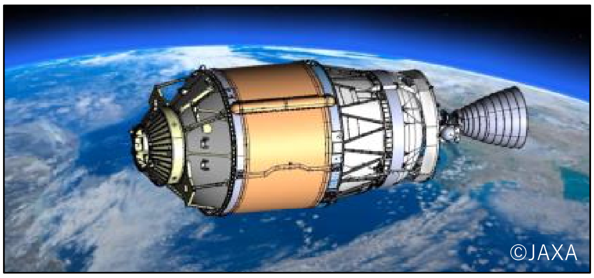
ADRAS-J Mission Overview

ADRAS-J Mission Overview

Servicer
- Mass (wet) :
  Approx. 180Kg
- Sizing :
  Approx. 3,700mm x 800mm x 1,200mm



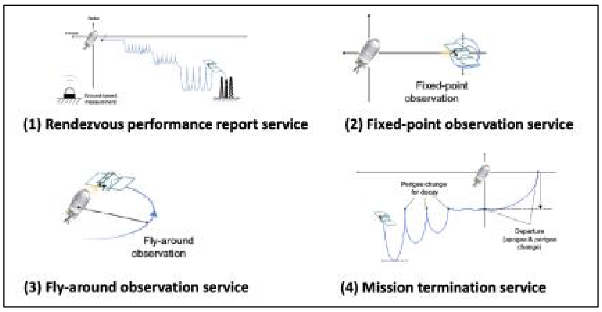
Client candidate
- H2A upper stage existing in low orbit
- Altitude about 600 km



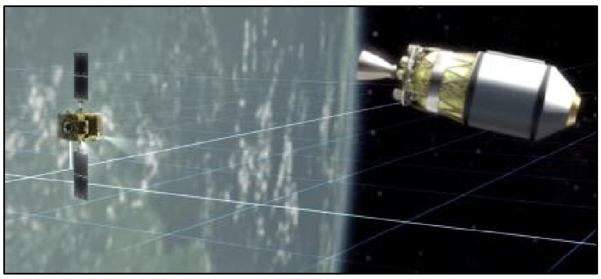
ADRAS-J Mission Overview

ADRAS-J Mission

JAXA Mission
- Report of performance against debris approach plan
- Fixed-point observation of target debris
- Fly-around observation of the target debris
- Mission completion processing

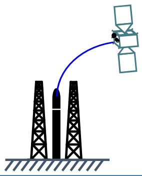


Astroscale Mission
- Inspection and diagnosis of target debris
- Extreme proximity approach to target debris
- Extra mission



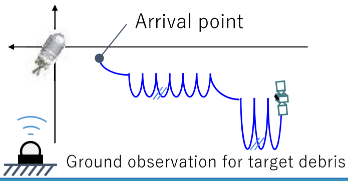
ADRAS-J Mission Overview

ADRAS-J Mission Scenario



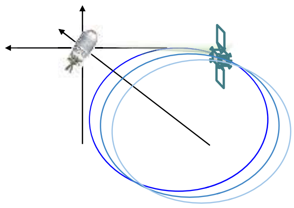
【Launch and Early Operation (LEOP) & commissioning】

The Servicer is inserted into its initial orbit and initial checks of functions are performed. The initial orbit is determined based on the phase angle of the Client at the time of launch.



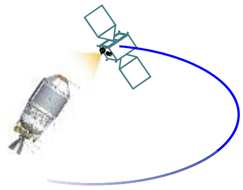
【Rendezvous】

By executing orbital maneuvers, the phase angle, orbital altitude and orbital plane of the Servicer is matched to that of the Client, and the Servicer arrives behind the Client.



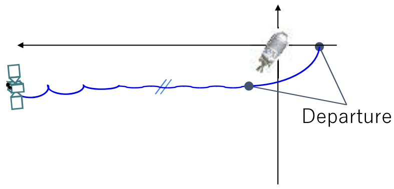
【Proximity approach】

Through relative navigation using the Servicer's optical sensors, the Servicer approaches to behind the Client.



【Proximity operation】

Fixed-point observation and fly-around observation of the Client, and testing of final approach to the PAF section of the rocket upper stage is conducted. In addition, extra mission will be carried out.



【Departure】

Through orbital maneuvers, the Servicer will break away from the Client proximity, move to an orbit below the Client, and end the mission.

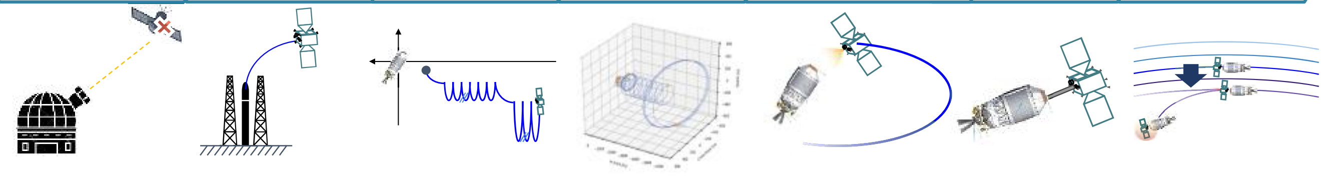
Core technologies and features

Core technologies and features

ADRAS-J's key technologies

RPO technology (Rendezvous and Proximity Operations)

① Observe client	② Launch	③ Far-range approach	④ Short-range approach	⑤ Short-range approach	⑥ Capture	⑦ De-orbit



① Observe client	② Launch	③ Far-range approach	④ Short-range approach	⑤ Short-range approach	⑥ Capture	⑦ De-orbit
Observe and determine the Client orbit.	Define the injection orbit and launch epoch/window.	Absolute navigation approach from a distance. Match the phase, altitude, and orbital plane of the client.	Relative navigation approach with the client as a point using the on-board sensors.	Fixed point and fly-around observation. And match the momentum(tumbling).	Capture with the servicer's capture system. Stabilize attitude assuming a center of gravity when docked.	Performs a de-orbit maneuver to reduce the client altitude and re-entry. Put on target sea area when necessary.

CRD2 Phase I Scope

CRD2 Phase II Scope

Key technologies and features

ADRAS-J's features

Full-range RPO system

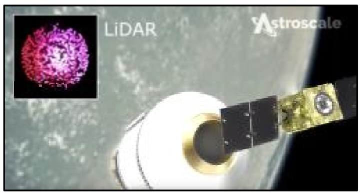
- **Full-range RPO technology to approach non-cooperative objects**
  ※Full range = the entire range from the far end to the near end of the range
- **On orbit safety is ensured by 1 Fail Safe**

Low-cost design for commercialization

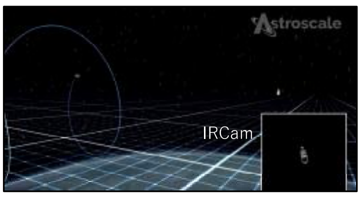
- **COTS sensors**
  - Adopting COTS products as rendezvous sensors to realize RPO
  - Conduct various tests on COTS sensors using the latest technology and verify their feasibility for space use.
- **Collaboration with NewSpace Companies**
  - Contract with Rocket Lab as launch provider

Inheriting RPO Technology

- **Utilization of ELSA-d performance**
  - Utilization of technology/knowledge and on-orbit operation experience gained from ELSA-d, the world's first debris capture technology demonstration project



ROCKET LAB



ADRAS-J development status

ADRAS-J development status

■ Outline of development schedule

FY2020	FY2021	FY2022	FY2023
Preliminary Design	Critical Design	AIT	Operation
MS1 (PDR) Completed	MS2 (CDR) Completed	MS3 (PQR/PSR)	▼Launch MS4 (Service Report)

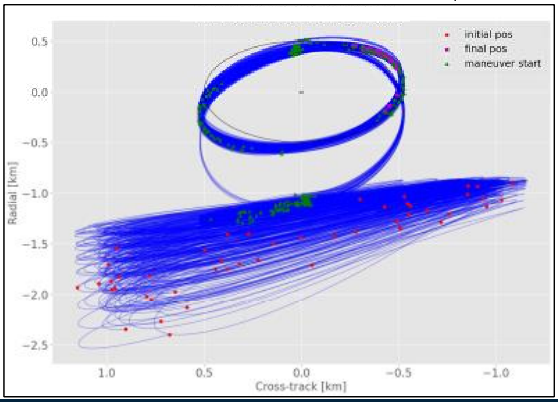
- Achieved MS1 and MS2
- Currently, satellite system tests and various verification works are in progress

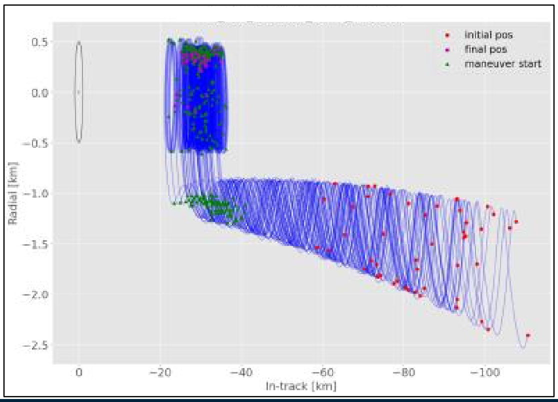
■ ADRAS-J development status

■ Major progress/achievements

- ■ MS1/MS2 achieved
- ■ On-orbit safety of both JAXA and Astroscale mission confirmed by simulation in MS2 (=CDR)
- ■ QT/AT tests for all subsystems completed
- ■ System environment tests are ongoing

Examples of orbit simulation results

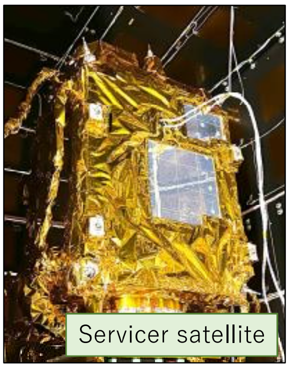




■ ADRAS-J development status

■ Current Status

- ■ System AIT in progress
  - ■ Currently, conducting various environmental tests
- ■ Various verification works in progress for MS3
  - ■ On-orbit safety verification based on updated mission design
  - ■ Finalizing safety design including FDIR
  - ■ Proximity approach verification using JAXA test facility “SATDyn”
  - ■ Operation verification using Ground Segment tools



Conclusion and Outlook

Conclusion and Outlook

- ADRAS-J Project Demonstrates ADR Core Technologies
  - Proximity approach and operation to non-cooperative objects
  - Observation and image capturing of target non-cooperative objects
  - In addition to JAXA missions, Astroscale's own technology demonstrations
- Develop technology to acquire ADR technology by utilizing the knowledge gained from this project, and promote commercialization of large debris removal.
- In addition, Astroscale intends to promote international standardization and institutionalization by establishing ADR technology ahead of the rest of the world.

■ Acknowledgements: ADRAS-J Marketing Partnership

ADRAS-Jプロジェクトは、以下のパートナー会社より支援を頂きSpace Sustainabilityの実現を推進しています

The ADRAS-J project is promoting the realization of Space Sustainability with support from the following partner companies.

www.astroscale.com

C12

当社のデブリ除去の取り組みと デブリ捕獲システム超小型実証衛星（DRUMS）の運用状況

Our Debris Removal Efforts and the Operational Status of the Debris Removal Unprecedented Micro-Satellite (DRUMS)

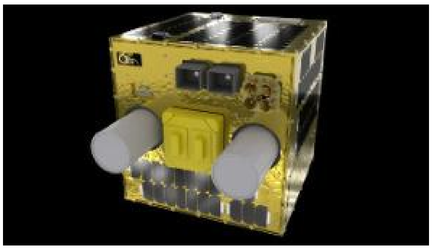
〇菅原靖敬，松下悠里，山崎裕司，森田大地，町野泰章，丸山辰也，田中稔久
（KHI 航空宇宙システムカンパニー）
〇SUGAWARA Yasutaka, MATSUSHITA Yuri, YAMASAKI Hiroshi, MORITA Daichi, MACHINO Yasuaki, MARUYAMA Tatsuya, TANAKA Toshihisa
(Space Systems Engineering Department, Kawasaki Heavy Industries, Ltd.)

我々のデブリ除去の取り組みと、軌道上での要素技術実証のために開発したデブリ捕獲システム超小型実証衛星（DRUMS）の運用状況について報告する。

We will report on our debris removal efforts and the operational status of the Debris Removal Unprecedented Micro-satellite (DRUMS) we developed for demonstrating elemental technologies on-orbit.

C12　　22KT021307

Our Debris Removal Efforts and the Operational Status of the Debris Removal Unprecedented Micro-Satellite(DRUMS)
当社のデブリ除去の取り組みとデブリ捕獲システム超小型実証衛星（DRUMS）の運用状況




10th Space Debris Workshop, November 30th, 2022
Kawasaki Heavy Industries, Ltd.
2022/11/30 @第10回スペースデブリワークショップ　川崎重工業株式会社

Kawasaki
Powering your potential

What is DRUMS　はじめに

DRUMS（***Debris Removal Unprecedented Micro-Satellite***）

・Kawasaki Heavy Industries, Ltd. developed DRUMS for demonstrating elemental on-orbit technologies of ADR.
　川崎重工業はADR要素技術の軌道上実証を目的として、超小型衛星DRUMSを開発

・DRUMS was launched on November 9th 2021 as one of the payloads of “Innovative Satellite Technology Demonstration Program”.
　革新的衛星技術実証プログラム２号機に選定され、2021年11月9日にイプシロンロケット5号機にて軌道投入

Agenda 目次

1．Background 背景
2．Overview of mission and DRUMS system
　ミッション概要とDRUMSシステム
3．Operation　運用
4．Evaluation results by on-orbit measurements
　軌道上評価
5．Conclusion　おわりに

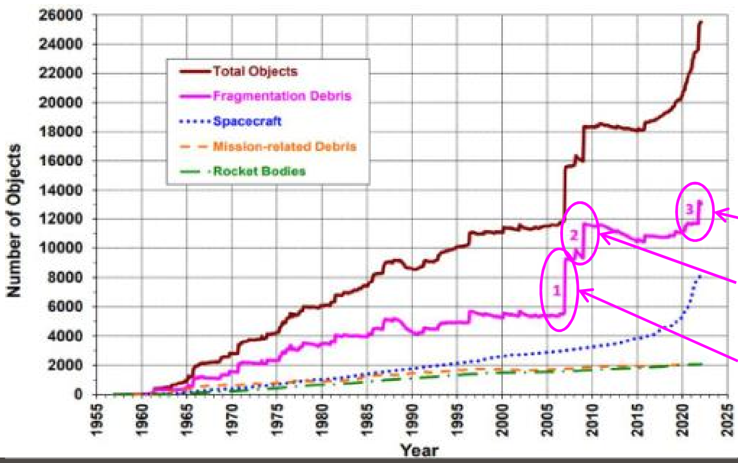
Work at launch site（Aug. 2021）
射場作業（2021/8）
https://fanfun.jaxa.jp/topics/detail/19220.html

launch（Nov. 9th 2021）
打上げ（2021/11/9）
https://www.mext.go.jp/b_menu/daijin/detail/1421560_00002.html

1．Background　背景
1．1　Increasing space debris　スペースデブリの増加

Negative impact of debris collision/explosion in orbit　軌道上でデブリが衝突／爆発する悪影響
①Debris collision with an operational satellite can cause catastrophic damage.
運用中の衛星にデブリが衝突した場合、致命的な損傷を引き起こす可能性がある
②Deteriorated orbital environment will constrain future satellite launches
軌道環境が悪化し、将来衛星の打上制約となる

Current orbital environment　現状の軌道環境
・Collision flux between debris and operational satellite is approximately 0.01/m²/year in SSO at 600-800km altitude.
600−800km帯の太陽同期軌道では、デブリと運用衛星の衝突フラックスは0.01/m²/年オーダー
・The number of orbital objects has been increasing due to large constellation.
近年は大規模コンステレーションの構築等で打上物体数が増加
⇒The risk of Kessler Syndrome is growing　このまま軌道環境を放置するとケスラーシンドロームが発生する危険性



Improvement of orbital environment is an urgent issue.
軌道環境改善は喫緊の課題

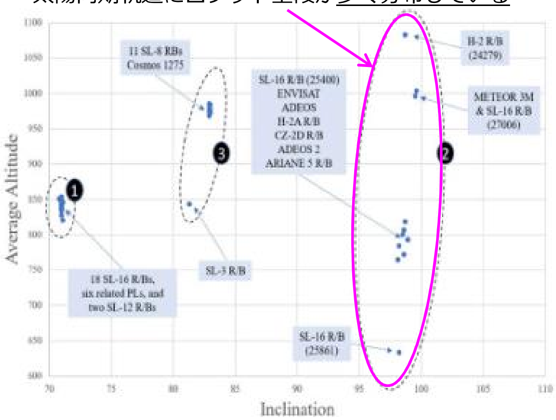
Russia's ASAT test (2021)
ロシア衛星破壊兵器実験(2021)
2009 satellite collision
米露通信衛星の衝突事故(2009)
China's ASAT test (2007)
中国衛星破壊兵器実験(2007)

NASA Orbital Debris Quarterly News, Vol.26, Issue 1, pp. 2, 2022.

1．Background　背景
1．2　Target debris　対象物体

Improvement of orbital environment in LEO　低軌道の軌道環境改善
・Larger debris removal (ex. upper stages, large satellites) with a risk of large impact in collision occurrence are effective to avoid Kessler Syndrome.
大型デブリ（ロケット上段、大型衛星）の除去が有効
・Most conventional upper stages have no deorbit functions.
既存大型デブリの多くは自身で軌道離脱するシステムを持たない／機能していない
⇒ADR servicing is required, which contains rendezvous, capture and deorbit.
⇒除去衛星がデブリ付近まで接近・捕獲・軌道降下する一連のADRサービスが必要

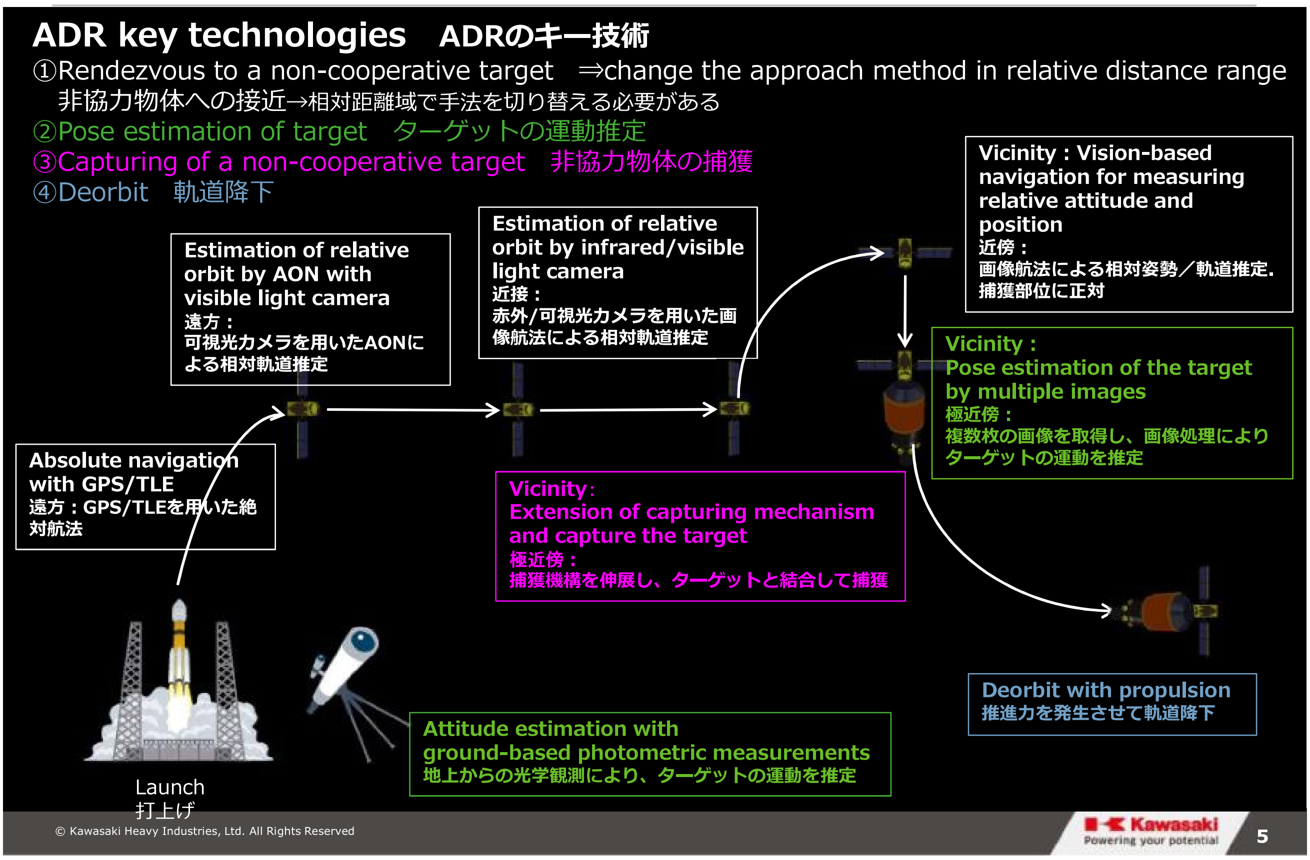
Upper stages of rockets ロケット上段
・Upper stages have similar characteristics in their shapes and the satellite separation parts. These characteristics enable to share a capturing mechanism.
形状が類似しており、ミッションごとに形態が異なる衛星と比較して捕獲しやすい
・Many upper stages are distributed in SSO
太陽同期軌道にロケット上段が多く分布している



KHI aims to realize ADR for upper stages in SSO
KHIは**太陽同期軌道**の**ロケット上段**を対象としたADR実現を目指す

D. McKnight, et al.: 'Updating the Massiue Collision Monitoring Activity – Creating a Collision Risk Continuum', 8th European Conference on Space Debris, Vol.8, Issue 1, 2021.

1．Background　背景
1．3　Key technologies　キー技術



2．Overview of mission and DRUMS system　ミッション概要とDRUMSシステム
2．1　Mission requirement　ミッション要求

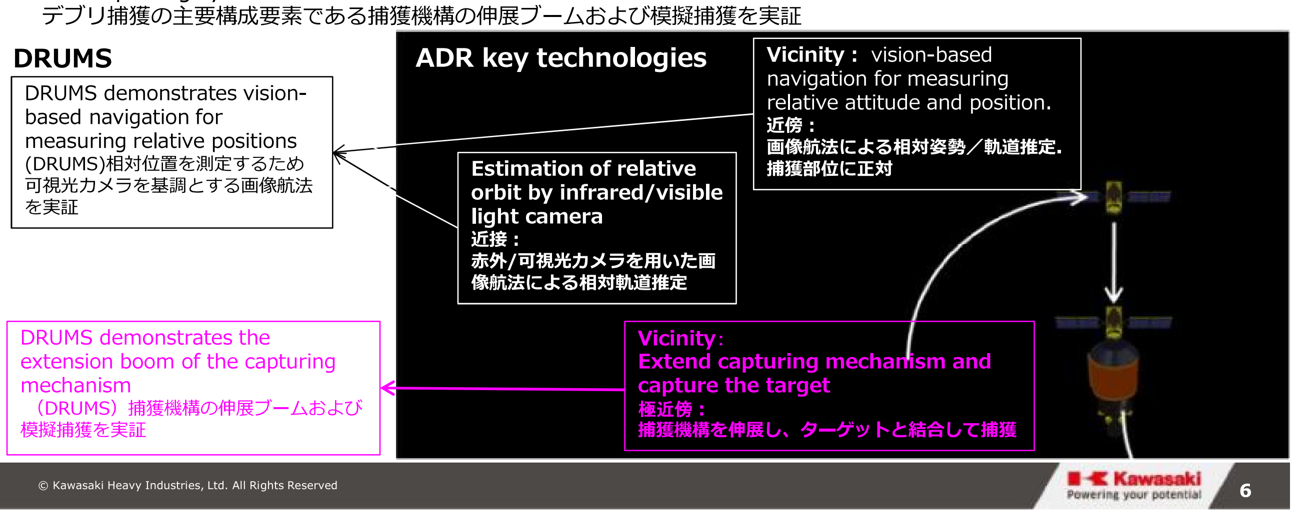
・Since a micro satellite system has limited resources, two essential technologies (mission requirements) to be demonstrated were selected among many technologies to provide ADR servicing in orbit.　ADR衛星のキー技術のうち、地上での実証が難しい技術をDRUMSで軌道上実証する。DRUMSは50kg級超小型衛星で、搭載できる機器が限られていることを考慮し、２点のミッション要求を設定。

(a) Non-cooperative approach :　**非協力物体への接近技術**

DRUMS demonstrates vision-based navigation for measuring relative positions between satellites and uncooperative objects in the vicinity of the target.
衛星と非協力物体の相対位置を測定するため、可視光カメラを基調とする画像航法を実証

(b) Capturing technology :　**非協力物体の捕獲技術**

DRUMS demonstrates the extension boom of the capturing mechanism, which is the main component of the debris capturing system.
デブリ捕獲の主要構成要素である捕獲機構の伸展ブームおよび模擬捕獲を実証

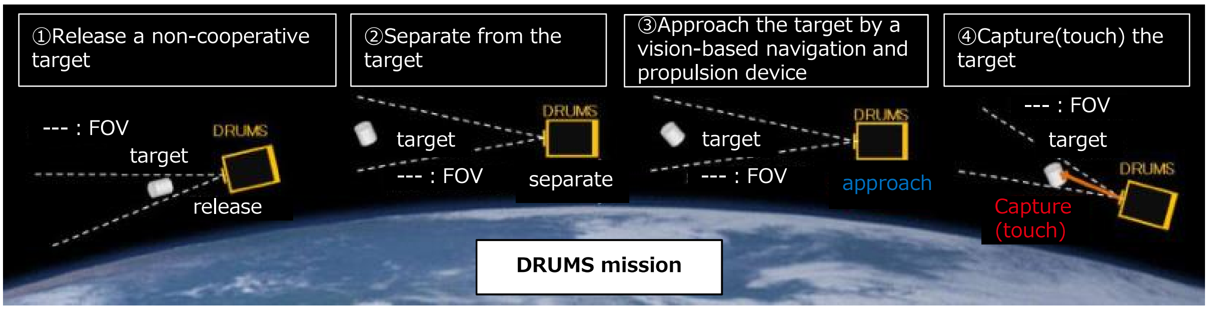


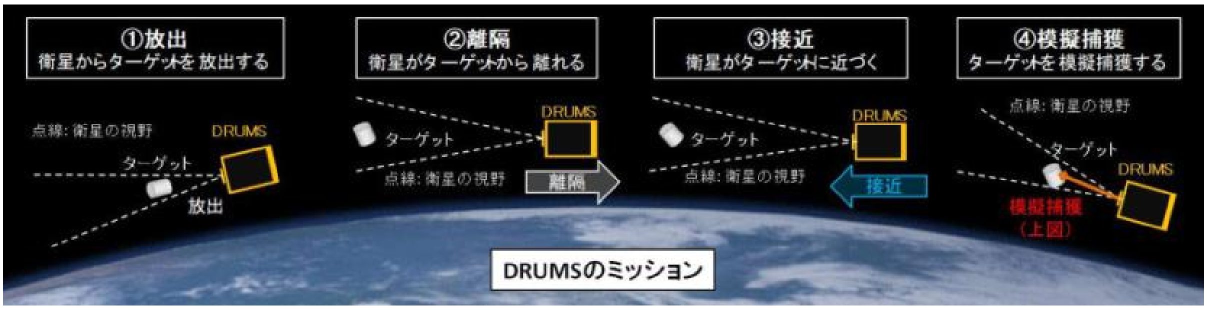
2. Overview of mission and DRUMS system　ミッション概要とDRUMSシステム
2．2　Mission sequence　ミッションシーケンス

On-orbit demonstration of ADR key technologies　ADR要素技術の軌道上実証

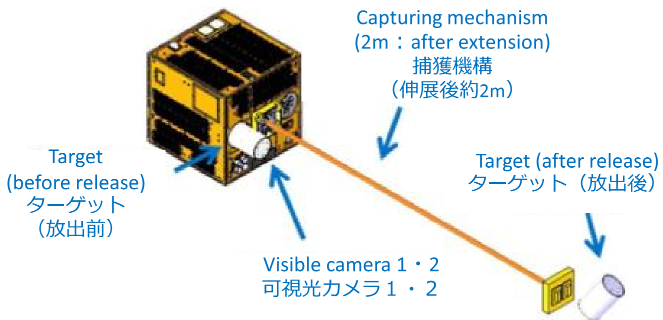
・Relative orbit control from proximity approach to capture is identical to ADR satellite operation

DRUMSの近接接近から模擬捕獲までの相対軌道制御は、ADR衛星運用と同一





2. Overview of mission and DRUMS system　ミッション概要とDRUMSシステム
2．3　DRUMS system　DRUMSのシステム構成



Overview of DRUMS and main mission component
DRUMS外観と主要なミッション機器

Specification of DRUMS
DRUMS主要諸元

Size 寸法	600mm×600mm×800mm
Mass 質量	65kg
Orbit 軌道	SSO（太陽同期軌道），560km

Attitude control sensors
3軸姿勢制御に使用するセンサ組み合わせ

Solar intensity = 100% 日照	Sun sensor, Magnetic sensor, Gyro sensor 太陽センサ，地磁気センサ，ジャイロセンサ
Solar intensity < 100% 日陰	Earth sensor, Magnetic sensor, Gyro sensor 地球センサ，地磁気センサ，ジャイロセンサ

Bus system　バス系

・The bus system has the basic subsystems, such as the attitude control subsystem, the power control subsystem, the heat control subsystem, and the communication subsystem
姿勢制御、電源・熱制御、地上局との通信機能等、衛星の基本機能を担当

・The attitude control subsystem has sensors (three SSs, a GAS, a three-axis GYRO, an ES, a GPS)
姿勢センサとして、太陽センサ、地磁気センサ、ジャイロセンサ、地球センサを搭載

Mission system　ミッション系

・Orbit control is demonstrated in addition to attitude control
ミッションでは、姿勢制御に加えて軌道制御も実施

・The mission system has the navigation sensors (an IMS, and three-axis ACC), actuators (12 thrusters), the capturing mechanism, and the target release mechanism
航法センサ（画像センサ、加速度センサ）、アクチュエータ（スラスタ）、捕獲機構、ターゲット放出機構を搭載

2．Overview of mission and DRUMS system　ミッション概要とDRUMSシステム

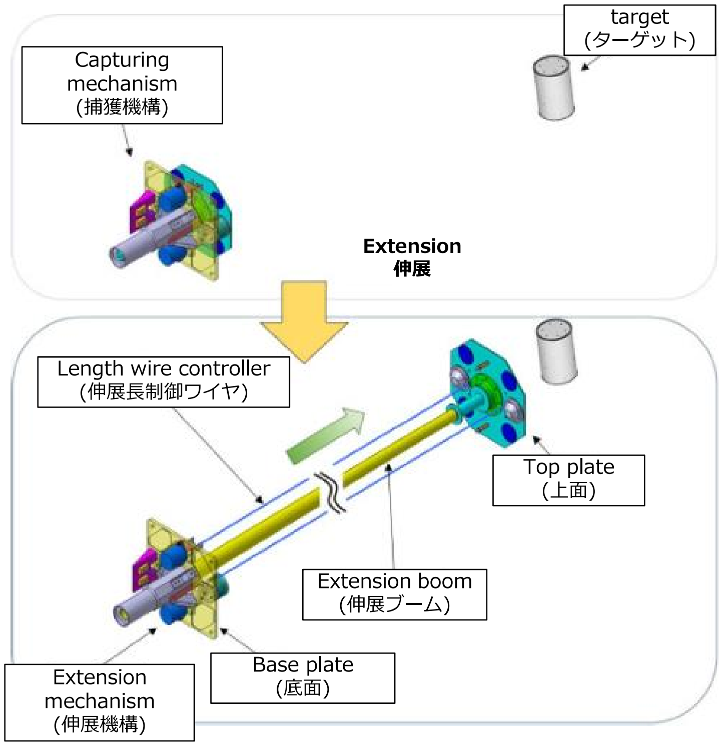
2．3　DRUMS system　DRUMSのシステム構成

Capturing mechanism　捕獲機構

・DRUMS has the basically same functional system as that for actual ADR missions. Equipment consists of top plate, base plate, extension mechanism, length wire controller and extension boom.
DRUMSの捕獲機構は、実際のADRミッションにおける捕獲機構と、基本的な構成は同じ（上面、底面、伸展ブーム、伸展長制御ワイヤから構成）

・The boom is extended when it is determined that the target has stabilized within the assumed range of distance and direction.
ターゲットの距離および方向が想定される範囲内で安定したとき、伸展ブームを伸展する。

・The state of capturing is planned to record by using visible camera in order to confirm whether the capturing system functions successfully.
捕獲機構が正常に作動しているか、モニタカメラで確認する。



3．Operation　運用

Ground Station　地上局

・A control room was established at Kawasaki Heavy Industries' Gifu Plant to operate DRUMS.
川崎重工業岐阜工場内に管制室を設置し、DRUMSを運用

・Operators uses monitors produced in-house
自社製の運用モニタを使用

・In parallel with the DRUMS project, ground station is also used to analyze and provide satellite data
DRUMSプロジェクトと並行し、衛星データの解析や提供等にも活用

<KHI Ground Station>
Manufacturer: SAFRAN (France)
Parabola diameter: 3.7 m
Weight: 1t
Tracking: Program & Auto Tracking
Frequency: S-band (2GHz band) Send/Receive
X-band (8GHz band) Receive

・Ground station sharing service is also implemented
地上局のシェアリングサービスも実施

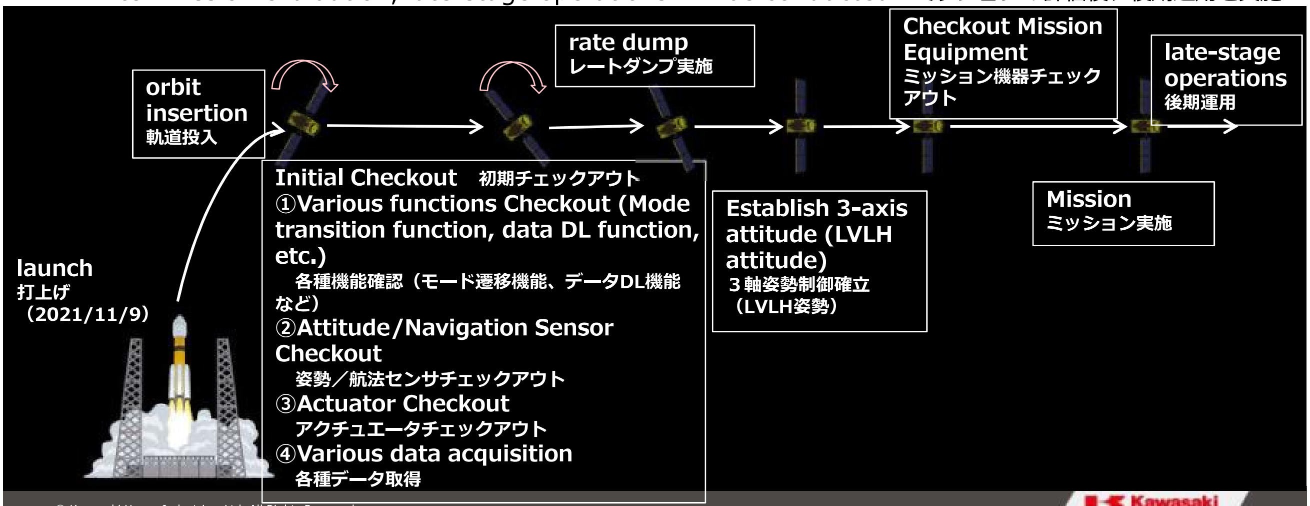
Ground Station (Gifu Plant KHI)
地上局（川崎重工業岐阜工場内）

Operation room
管制室

3．Operation　運用

Overview of DRUMS operations　DRUMS運用の全体像

・After launching from the rocket and entering orbit, an initial check-out was conducted to confirm the basic functions of the satellite
ロケットから打上げ、軌道投入後、衛星の基本機能を確認する初期チェックアウトを実施
・Rate dump operation and 3-axis attitude control operation were conducted to stabilize DRUMS attitude
DRUMSの姿勢安定化のため、レートダンプ運用、３軸姿勢制御運用を実施
・Checkout of mission equipment was conducted prior to mission
ミッション実施前にミッション機器のチェックアウトを実施
・Mission will be implemented　ミッションを実施
・After mission evaluation, late-stage operations will be conducted　ミッションの評価後、後期運用を実施



4．On-orbit evaluation　軌道上評価

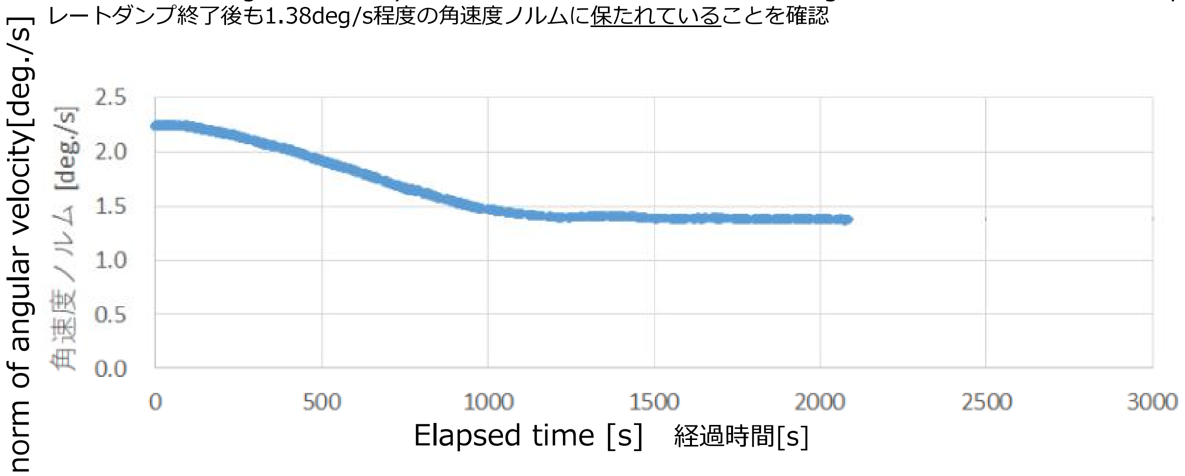
4．1　Evaluation of Rate Dump functions　レートダンプ機能評価

rate dump operation　レートダンプ運用

・After the launch, a rate dump operation was conducted to reduce the angular velocity of the satellite.
打上後、衛星の角速度を低減するため、レートダンプ運用を実施

・After starting the rate dump, the angular velocity was reduced to the set value of 1.38 deg/s in about 1200 seconds.
レートダンプ開始後、約1200秒で設定値の1.38deg/sの角速度ノルムに低減

・The norm of angular velocity was maintained at about 1.38 deg/s even after the rate dump.
レートダンプ終了後も1.38deg/s程度の角速度ノルムに保たれていることを確認



4．On-orbit evaluation　軌道上評価
4．2　Verification of Control Functions　制御機能の確認

Three-axis attitude control operation　3軸姿勢制御運用

・Establish three-axis (sun-oriented and Earth-oriented) posture with LVLH as reference posture
LVLH姿勢を基準姿勢とする、3軸姿勢（太陽指向及び地球指向）を確立
・Confirm that both the power balance and communication with the ground station are stable
電力収支および地上局との通信、ともに安定した状態であることを確認

Function of thruster checkout　スラスタの機能確認

・By blowing thrusters and checking the rotational motion with a gyro-sensor, confirm all channel thrusters work properly
スラスタを噴射し、ジャイロセンサで回転運動の様子を確認することで、全チャンネルのスラスタが正常に機能することを確認

Checking the directional control function　指向制御機能の確認

・Confirm that DRUMS can be directed to the moon and earth
月や地球方向にDRUMSを指向制御できることを確認
Directional accuracy is currently being evaluated
指向精度は現在評価中

4．On-orbit evaluation　軌道上評価
4．3　Image acquisition by image sensor and monitor camera
画像センサ、モニタカメラによる画像取得

Moon image by image sensor
画像センサによる月画像

Earth image by monitor camera
モニタカメラによる地球画像

Currently, we are preparing for the mission by performing the following on image sensors used for image navigation and monitor cameras for capture demonstration recording.
現在、画像航法に使用する画像センサ、捕獲実証記録用のモニタカメラに対して下記を実施し、ミッションに向けた準備を実施している。

・Confirmation of relative position calculation function using moon as a target
月をターゲットに見立てた相対位置計算機能の確認
・Exposure time, gain adjustment
露光時間、ゲイン調整

5．Conclusion　おわりに

- The on-orbit evaluation results of DRUMS are presented.
  DRUMSの軌道上評価結果を示した

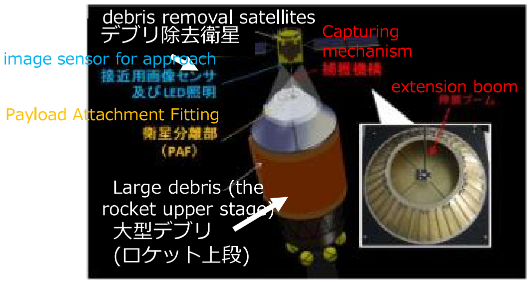
  The rate dump function, the 3-axis attitude control function, and the imaging function of the monitor camera were confirmed to operate as designed.
  レートダンプ機能、３軸姿勢制御機能、モニタカメラの撮像機能等が設計通りに作動していることを確認した

- We will acquire ADR key technology in DRUMS.
  DRUMSでADRキー技術を獲得する

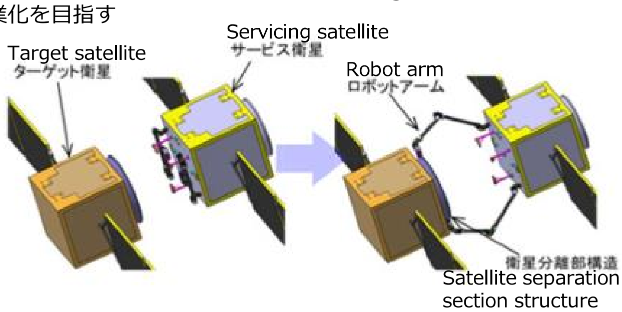
  

  We will demonstrate "Approaching non-cooperative objects" and "Capturing non-cooperative objects" in orbit.
  「非協力物体への接近技術」、「非協力物体の捕獲技術」の軌道上実証をする

- We aim to commercialize future debris removal satellites and on-orbit servicing satellites.
  将来のデブリ除去衛星、軌道上サービス衛星の実用化／事業化を目指す



Future debris removal satellites
将来デブリ除去衛星



Orbital service satellite
軌道上サービス衛星

Kawasaki Powering your potential

世界の人々の豊かな生活と地球環境の未来に貢献する

“Global Kawasaki”

Kawasaki Powering your potential

C13

持続可能なデブリ除去運用コンセプトと 商業デブリ除去実証フェーズⅡの技術実証シナリオの検討

Study of Technology Demonstration Scenarios of CRD2 Phase2 Aiming Sustainable Debris Removal

○中村涼，岡本博之，山元透（JAXA 研究開発部門）
○NAKAMURA Ryo, OKAMOTO Hiroyuki, YAMAMOTO Toru (JAXA Research and Development Directorate)

JAXA の商業デブリ除去実証（CRD2）は，日本由来の大型デブリの除去を，民間企業と協力して実施することで，スペースデブリの積極的除去（Active Debris Removal: ADR）に係る国際的議論の具体的な進展と，日本企業の軌道上サービス市場における国際的競争力向上の実現を目指している．これら 2 つの目的を達するためには，CRD2 で実証するデブリ除去技術は，ビジネスとして持続可能である，つまり低コストであることが 1 つの要件となる．そこで具体的なターゲットを想定したうえで，将来の ADR 事業のアーキテクチャ及び運用コンセプトについてデブリ 1 個当たりの除去コストの観点で検討を行い，その結果に基づき CRD2 フェーズⅡの技術実証シナリオを検討した．

JAXA's Commercial Debris Removal Demonstration (CRD2) aims to improve the international competitiveness of Japanese companies in new markets such as the on-orbit service market and to lead concrete progress in international discussions on space debris removal (ADR) by removing large debris of Japanese origin in cooperation with the private sector. To achieve these two objectives, one of the requirements of the debris removal technology to be demonstrated in CRD2 is that it must be sustainable as a business, meaning that the practical use of the technology makes the debris removal feasible at low cost. This paper studies operational concept of the future ADR project with specific debris in terms of removal cost per piece of debris, and based on those studies, proposes technology demonstration scenarios of CRD2 phase2.

CRD2 Phase II

Study of Technology Demonstration Scenarios of CRD2 Phase2 Aiming Sustainable Debris Removal

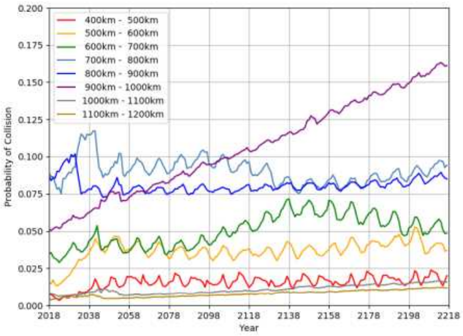
Ryo Nakamura, Hiroyuki Okamoto, Toru Yamamoto
(JAXA)

Contents

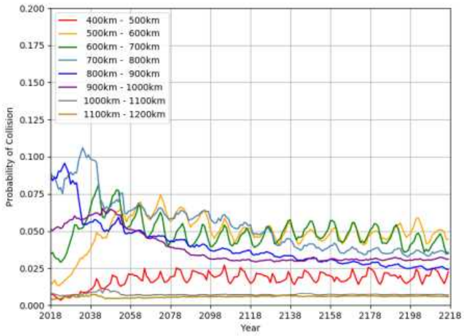
- Background
- CRD2 and Objective of this study
- Concerning derelict objects
- Future ADR architecture and operational concept
  - ➢Simple evaluation
  - ➢Example scenarios with specific targets
  - ➢Discussion on Russian Rockets
- Summary

Background

- ■ Space debris has been increasing year by year and in the future is expected to interfere with human space activities.
- ■ Removal of massive space debris in crowded orbit (800-1000km) is effective.



Collision probability of each altitude band with 90% PMD, and no ADR



ADR of five debris objects per year

Kawamoto, Satomi, et al. "Impact on collision probability by post mission disposal and active debris removal." Journal of Space Safety Engineering 7.3 (2020): 178-191.

Commercial Removal of Debris Demonstration (CRD2)

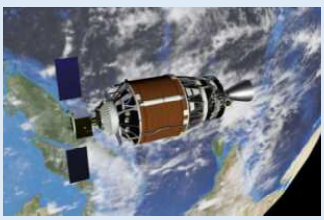
Aiming at the world's first Active Debris Removal in partnership with private sectors
Demonstration of the removal of large space debris left in orbit in two phases

- ■ **To improve the international competitiveness of Japanese companies in new markets such as the on-orbit service market**
- ■ **To lead concrete progress in international discussions on space debris removal (ADR)**

Phase-I Planned for launch in FY2022
Key technologies demonstration

- **Non-cooperative rendezvous, proximity operation, inspection**

Phase-II FY2025~
ADR demonstration



- Non-cooperative rendezvous, proximity operation, inspection
- **Removal of 2nd stage of launch vehicle**

CRD2 New partnership-type contract and ofjective of this study

New partnership-type contract

JAXA

- Service specifications
- Safety requirements

- Technical advices
- Test facilities
- Intellectual properties

Fulfillment ←

→ Payment

→ Support

Private sectors

- Design
- Manufacture
- Test
- Operation
- Business development

Objective of this study

- To achieve two objectives of CRD2, one of the requirements of the debris removal technology to be demonstrated in CRD2 is that it must be sustainable as a business, meaning that the practical use of the technology makes the debris removal feasible at low cost.
- The objective of this study is to study operational concept of the future ADR project with specific debris in terms of removal cost per piece of debris, and based on those studies, proposes technology demonstration scenarios of CRD2 phase2.

Concerning derelict objects

Table 4
The composite top 50 SMC are summarized below.

Ranking	Score	SATNO	Number of Lists	SATNAME	APOGEE, km	PERIGEE, km	INCL., deg	MASS, kg	COUNTRY	LAUNCH
1	4048	22,566	11	SL-16 R/B	848	837	71.0	9000	CIS	3/26/1993
2	3710	22,220	10	SL-16 R/B	848	827	71.0	9000	CIS	11/17/1992
3	3500	31,793	10	SL-16 R/B	846	843	71.0	9000	CIS	6/29/2007
4	3470	26,070	9	SL-16 R/B	854	827	71.0	9000	CIS	March 2, 2000
5	3330	16,182	10	SL-16 R/B	844	833	71.0	9000	CIS	10/22/1985
6	3300	20,625	10	SL-16 R/B	853	834	71.0	9000	CIS	5/22/1990
7	2880	27,006	8	SL-16 R/B	1006	986	99.5	9000	CIS	October 12, 2001
8	2862	23,705	9	SL-16 R/B	852	831	71.0	9000	CIS	10/31/1995
9	2826	25,407	9	SL-16 R/B	844	835	71.0	9000	CIS	7/28/1998
10	2800	23,405	10	SL-16 R/B	845	838	71.0	9000	CIS	11/24/1994
11	2547	17,974	9	SL-16 R/B	846	823	71.0	9000	CIS	5/13/1987
12	2412	23,088	8	SL-16 R/B	845	841	71.0	9000	CIS	4/23/1994
13	2296	22285	8	SL-16 R/B	844	840	71.0	9000	CIS	12/25/1992
14	2240	22,803	8	SL-16 R/B	850	823	71.0	9000	CIS	9/16/1993
15	1813	19,650	7	SL-16 R/B	848	831	71	9000	CIS	11/23/1988
16	1771	24,298	8	SL-16 R/B	863	839	70.8	9000	CIS	April 9, 1996
17	1650	28,353	7	SL-16 R/B	848	842	71.0	9000	CIS	October 6, 2004
18	1617	17,590	8	SL-16 R/B	841	831	71.0	9000	CIS	3/18/1987
19	1547	19,120	7	SL-16 R/B	842	814	71.0	9000	CIS	5/15/1988
20	1477	25,400	7	SL-16 R/B	813	801	98.6	9000	CIS	October 7, 1998
21	1320	27,386	5	ENVISAT	766	764	98.1	7800	ESA	January 3, 2002
22	1182	27,001	6	METEOR 3 M	1013	994	99.6	2500	CIS	October 12, 2001
23	805	24,277	4	ADEOS	794	793	98.9	3560	JPN	8/17/1996
24	600	27,601	4	H-2A R/B	836	734	98.2	3000	JPN	12/14/2002
25	564	15,334	4	SL 12 R/B(2)	847	838	71.0	2440	CIS	9/28/1984
26	512	37,932	4	CZ-2D R/B	846	791	98.7	4000	PRC	11/20/2011
27	468	10,732	4	SL-8 R/B	995	966	82.9	1435	CIS	3/15/1978
28	416	24,279	5	H-2 R/B	1306	860	98.7	2700	JPN	8/17/1996
29	384	23,704	3	COSMOS 2322	854	842	71.0	3250	CIS	10/31/1995
30	324	21,090	3	SL-8 R/B	992	961	82.9	1435	CIS	May 2, 1991
31	316	28,352	3	COSMOS 2406	863	844	71.0	3250	CIS	October 6, 2004
32	309	23,087	2	COSMOS 2278	852	841	71.1	3250	CIS	4/23/1994
33	270	19,119	2	COSMOS 1943	851	833	71.0	3250	CIS	5/15/1988
34	261	27,597	2	ADEOS 2	801	800	98.5	3680	JPN	12/14/2002
35	240	25,861	4	SL-16 R/B	645	622	98.2	9000	CIS	7/17/1999
36	240	15,772	3	SL 12 R/B(2)	848	794	71.1	2440	CIS	5/30/1985
37	228	10,693	3	SL-8 R/B	989	957	83.0	1435	CIS	2/28/1978
38	228	17,973	2	COSMOS 1844	866	824	71.0	3250	CIS	5/13/1987
39	225	27,387	3	ARIANE 5 R/B	796	748	98.6	2575	FR	January 3, 2002
40	207	7594	3	SL-8 R/B	981	955	82.9	1435	CIS	12/26/1974
41	207	23,180	3	SL-8 R/B	992	950	82.9	1435	CIS	7/14/1994
42	204	10,138	3	SL-8 R/B	1001	970	82.9	1435	CIS	August 7, 1977
43	204	13,917	3	SL-8 R/B	996	954	82.9	1435	CIS	3/24/1983
44	198	13,719	3	SL-3 R/B	896	791	81.3	1100	CIS	12/14/1982
45	194	14,625	2	SL-8 R/B	999	969	82.9	1435	CIS	November 1, 1984
46	183	20,624	2	COSMOS 2082	856	833	71.0	3250	CIS	5/22/1990
47	164	12,092	2	SL-8 R/B	996	953	82.9	1435	CIS	October 12, 1980
48	153	9044	3	SL-8 R/B	988	966	83.0	1435	CIS	7/21/1976
49	146	12,504	2	COSMOS 1275	1014	954	83.0	800	CIS	April 6, 1981
50	144	16,292	3	SL-8 R/B	996	953	82.9	1435	CIS	11/28/1985

McKnight, Darren, et al. "Identifying the 50 statistically-most-concerning derelict objects in LEO." Acta Astronautica 181 (2021): 282-291.

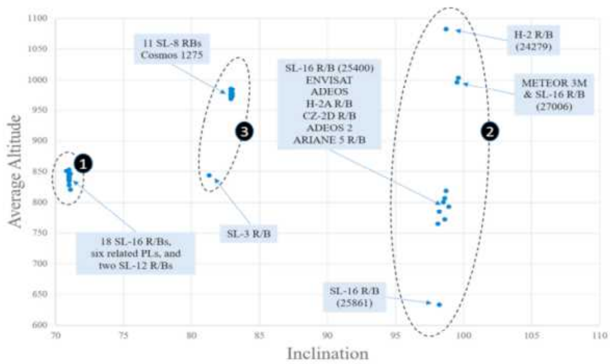
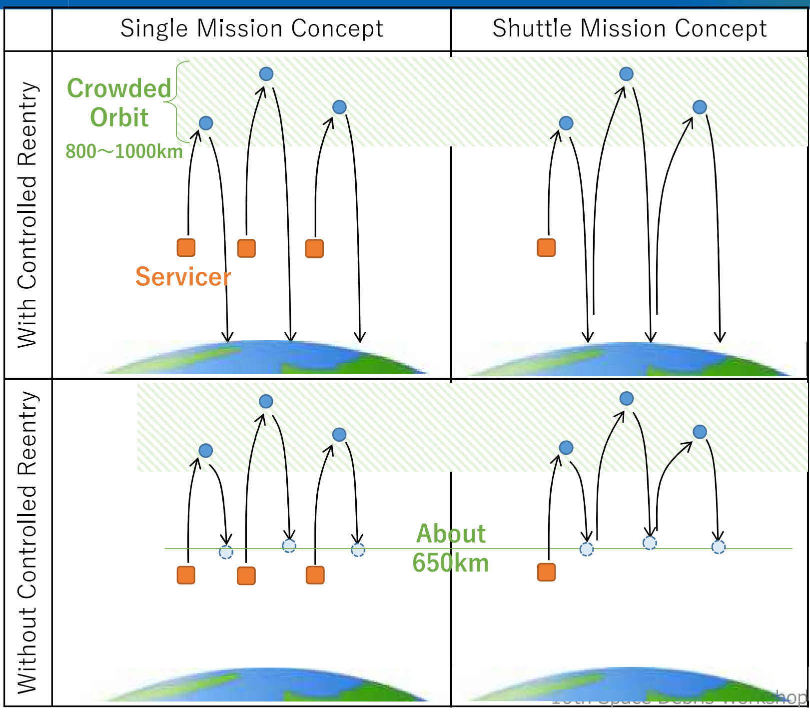


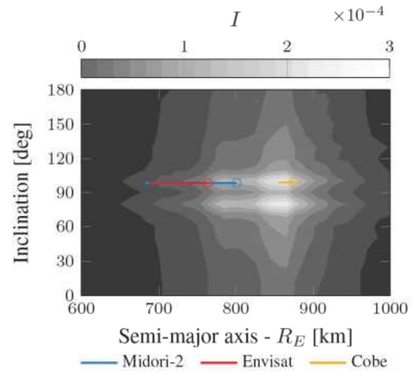
Fig. 6. Top 50 SMC objects are located in clumps that might aid in the efficient removal of them from orbit.

Target debris of this study are debris in near-sun-synchronous orbits at altitudes of approximately 800 km to 1000 km

Future ADR architecture and operational concept



- Controlled reentry is performed to reduce the Expected Casualty Ec of the debris upon reentry.
- To improve the orbital environment, it is important to shift the debris that remains in the orbit for a long period of time to a short lifetime orbit.



Letizia, Francesca, et al. "Extending the ECOB space debris index with fragmentation risk estimation.", European space debris conference, 2017

Simple evaluation

- Targets are debris at an altitude of 900 km(Weight:3ton)
  - ➤To 350km：Electric propulsion
  - ➤To 200km：altitude decay due to atmospheric drag
  - ➤Reentry：continuous thrusting with chemical propulsion at 40 m/s
  - ➤If controlled reentry is not performed, the debris is released after descending to an altitude of 650 km.
- Electric propulsion is used for large orbit changes except controlled reentry, and the specific impulse is assumed to be 1600 s.
- Change in orbit altitude is assumed to be a transition from a circular to a circular orbit

$$\Delta v = \sqrt{\frac{\mu}{r_2}} - \sqrt{\frac{\mu}{r_1}}$$

- Rendezvous and nearby operations are performed by chemical propulsion. The specific impulse is assumed to be the worst-case value of 100 s, assuming pulse injection. The required ΔV is uniformly 100 m/s.

Example of Estimated Required Propellant

■ **Estimated propellant (2-debris removal Shuttle concept, with controlled re-entry)**

Operation	⊿V[m/s]		Mass[kg]		Propellant[kg]		Electric Prop. Total impulse	Note
	RCS	EP	Before	after	N2H4	Xe		
#1 rendezvous		262	**1540**	1514		26	4.0.E+05 [Ns]	500km→900km Rocket Injection Error Correction : 50m/s
#1 Prox. Operation	100		1514	1368	147			
#1 deorbit		297	4368	4199		82	1.3.E+06 [Ns]	900km→350km
#1 reentry	40		4286	4199	87			
Return to orbit	200		1199	1083	116			
#2 rendezvous		297	1083	1063		20	3.2.E+05 [Ns]	350km→900km
#2 Prox. Operation	100		1063	959	103			
#2 deorbit		297	3959	3885		74	1.2.E+06 [Ns]	900km→350km
#2 reentry	40		3885	3807	78			
Total	**480**	**1152**			**531**	**202**	**3.2.E+06 [Ns]**	
			Dry Mass		N2H4 Mass	Xe Mass		
			800kg		535kg	205kg		

Satellite mass and cost estimates for each concept

Concept	Single	Sigle	Shuttle	Shuttle	Shuttle	Note*1
Number of removal debris	1	1	2	2	3	
Controlled Reentry	w/o	W	w/o	W	w/o	
Base Mass [kg] *2	200	250	250	643	405	Dry Mass without capture mechanism, electric propulsion, and tanks
Chemical propellant[kg]	35	120	90	535	210	
Electrical propellant[kg]	35	75	70	205	120	
Chemical Prop. Tank [kg]	4	12	9	54	21	Chemical propellant*0.1
Electrical Prop. Tank[kg]	6	12	11	33	19	Electrical propellant*0.16
Electrical Propulsion[kg]	37	43	42	64	50	Electrical propulsion subsystem （31kg（approximation））＋tank
Capture Mech.[kg]	40	40	40	40	40	Set in reference to JAXA Research
Dry Mass[kg]	280	345	341	800	516	
Wet Mass[kg]	350	540	501	1540	846	
Satellite Cost[million dollar]	49	58	58	105	77	model-based estimation
Launch Cost[million dollar]	11	16	15	46	25	$30,000.／kg
Removal cost per one debris [million dollar]	**60**	**74**	**36**	**76**	**34**	No precision in absolute values due to model-based estimation, used for relative evaluation

＊1）W. J. Larson, et.al., "Space mission analysis and design, third edition". Microcosm, Inc.

＊2） The tank mass is about 10% of the Base Mass, but the lower limit of the Base Mass is 200 kg and the upper limit of the Dry Mass is 800 kg.

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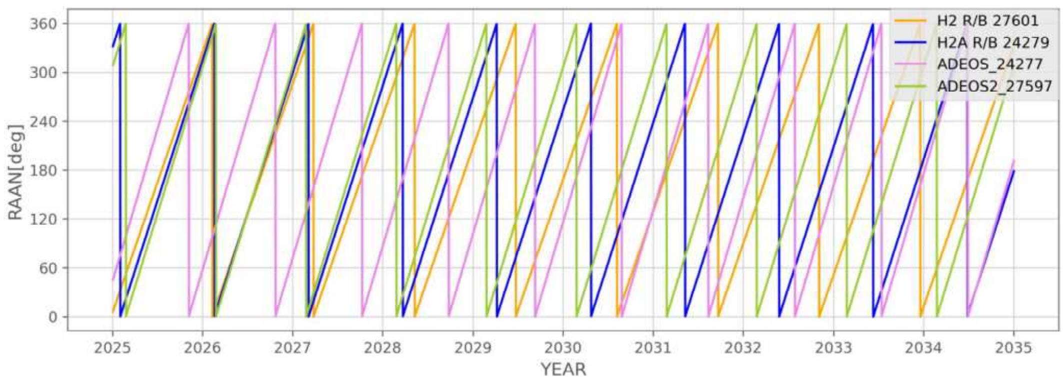
Example scenarios with specific targets

- Debris in near-sun-synchronous orbits at altitudes between 800 km and 1000 km have already lost their sun-synchronous nature.
- Example scenario of “Shuttle mission concept” with specific targets is illustrated by creating a simulated orbit with electric propulsion maneuvers taken into account.
  - Scenario 1 : Japanese debris（ADEOS，ADEOS2，Rockets that launched them）
  - Scenario 2 : ARIANE 40 R/B



Maneuver logic for electrical propulsion

- Control semi-major axis, inclination, and eccentricity vector simultaneously
- Thrust Direction $\vec{T}$: Linear sum of optimal thrust direction to change each orbit elements

$$\vec{T} = \sum_{COE} \left(1 - \delta_{COE_t, COE_s}\right) \frac{COE_t - COE_s}{\Delta COE_0} \vec{T}_{COE}$$

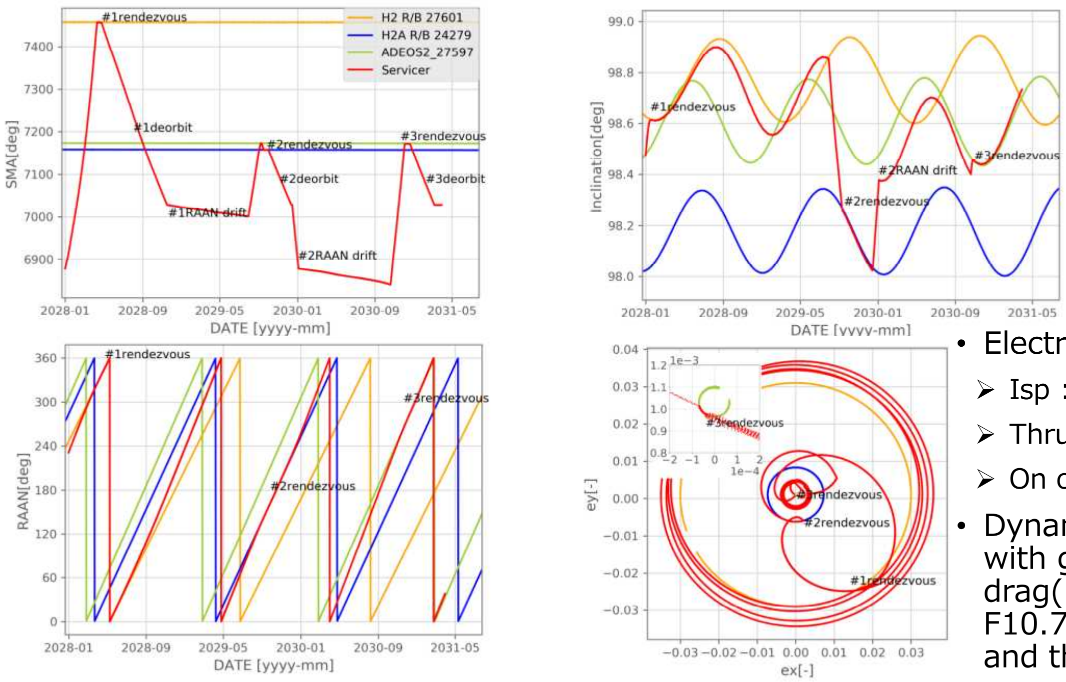
- ➢ Semi-major axis $\vec{T}_{SMA} = [\sin\alpha \quad \cos\alpha \quad 0]^T$, $\alpha = \tan^{-1}\left(\frac{e \sin\nu}{1 + e\cos\nu}\right)$
- ➢ Inclination $\vec{T}_{INC} = [0 \quad \cos\beta \quad \sin\beta]^T$, $\beta = \mathrm{sgn}(\cos(\omega + \nu))\frac{\pi}{2}$
- ➢ Eccentricity vector $\vec{T}_{EVEC} = (\vec{r} \times \vec{v}) \times \overrightarrow{\Delta_e} + (\overrightarrow{\Delta_e} \times \vec{v}) \times \vec{r}$

※$\overrightarrow{\Delta_e}$ is a vector that represents the difference between the target eccentricity vector and the current eccentricity vector considering only the orbit plane. $\|\overrightarrow{\Delta_e}\|$ is used for $COE_t - COE_s$ of eccentricity vector.

- ➢ The control of the RAAN is controlled using the difference in the orbit plane rotation speed (rate of change of the RAAN, $\Delta\dot{\Omega}$) due to perturbation, instead of orbit control by maneuvers.
  - ✓ The semi-major axis and inclination can be changed to increase the value of $\Delta\dot{\Omega}$, if necessary. But the expected $\Delta\dot{\Omega}$ is about several tens of degrees/year.
  - ✓ RAANs of debris to be targeted in the Shuttle mission concept should be close in value.

Scenario1 : Japanese debris

H2 R/B 27601→H2A R/B 24279→ADEOS2

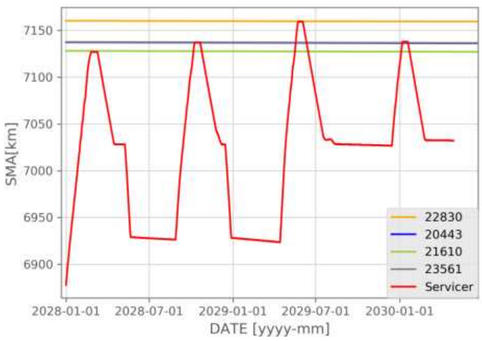


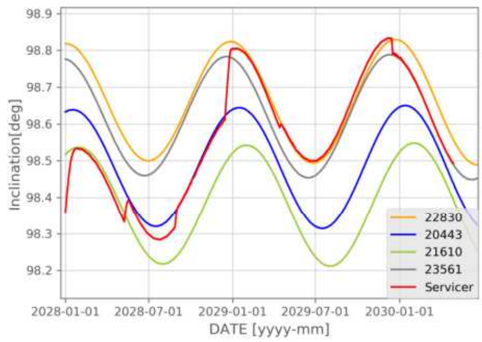
- Electric Propulsion
  - ➢ Isp : 1600seconds
  - ➢ Thrust : 60mN
  - ➢ On only during daytime
- Dynamic Simulation with gravity (J4), drag(NRLMSISE00, F10.7=100, Ap =15), and thrust acceleration.

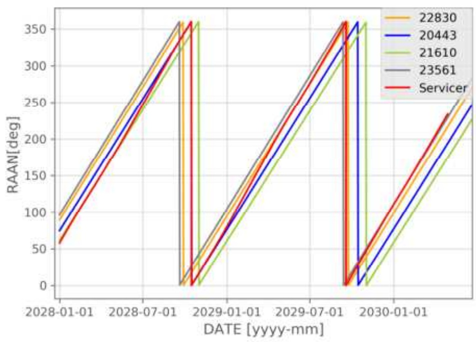
Scenario1 : Japanese debris

Operation	⊿V[m/s]		System Mass[kg]		Propellant[kg]		Electric Prop. Total impulse	Note
	RCS	EP	Before	after	N2H4	Xe		
#1 rendezvous		469.3	**800.0**	776.4		23.59	3.70.E+05 [Ns]	Rocket injection(500km)→ H-2_RB_24279
#1 Prox. Operation	100		776.4	701.1	75.3			
#1 deorbit		220.9	3701.1	3649.3		51.78	8.12.E+05 [Ns]	Descent to 650km
#1 RAAN drift			649.3					Wait at 650km
#2 rendezvous		362.5	649.3	634.5		14.84	2.33.E+05 [Ns]	Rendezvous to H-2A_RB_27601
#2 Prox. Operation	100		634.5	572.9	61.5			
#2 deorbit		68.4	3572.9	3557.4		15.56	2.44.E+05 [Ns]	Descent to 650km
#2 RAAN drift		118.7	557.4	553.2		4.20	6.59.E+04 [Ns]	Descent to 500km for RAAN drift, inclination change close to inclination of the ADEOS2
#3 rendezvous		279.9	553.2	543.4		9.79	1.53.E+05 [Ns]	Rendezvous to ADEOS2
#3 Prox. Operation	100		543.4	490.7	52.7			
#3 deorbit		75.8	3490.7	3473.8		16.84	2.64.E+05 [Ns]	Descent to 650km
Total	300	1595.5			**189.6**	**136.60**	2.14[MNs]	**Dry Mass : 473.8kg**

Scenario2 : ARIANE 40 R/B







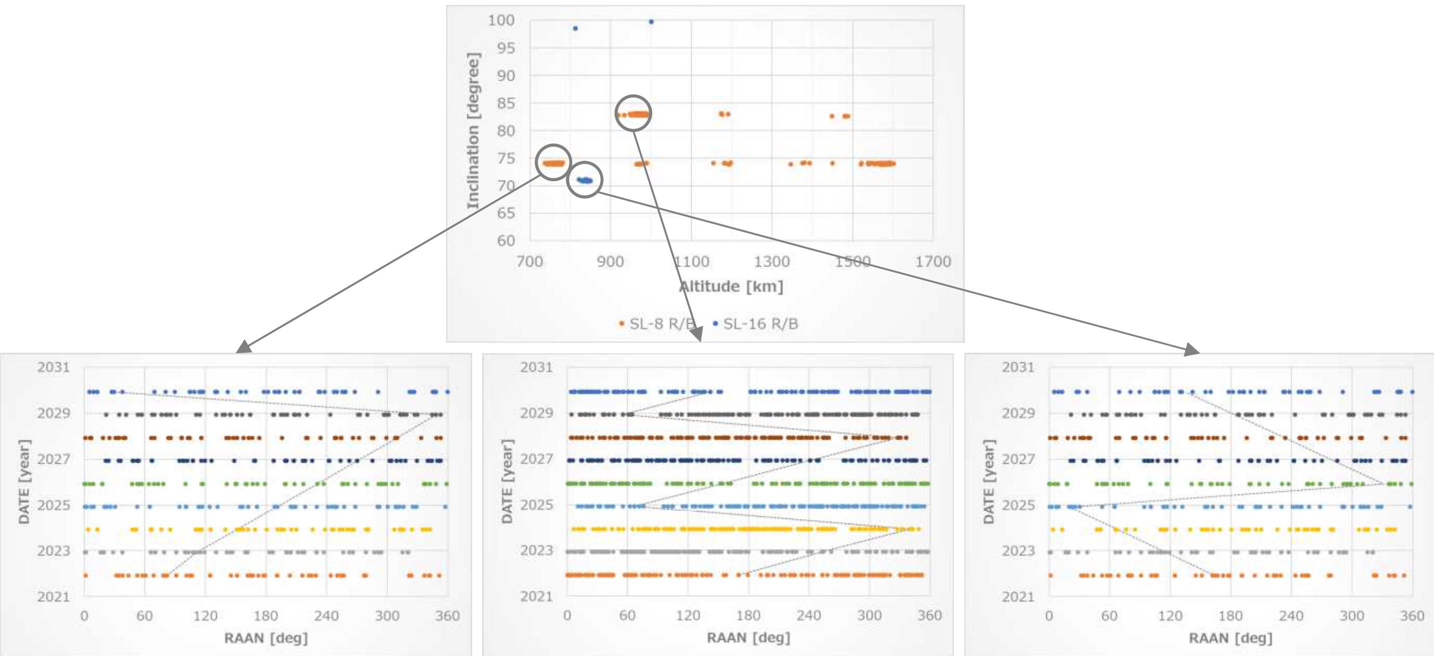
- Electric Propulsion
  - Isp：1600seconds
  - Thrust：60mN
  - On only during daytime
- Dynamic Simulation with gravity（J4）, drag(NRLMSISE00, F10.7=100, Ap =15), and thrust acceleration. Weight of ARIANE 40 R/B is 1780kg

Scenario2 : ARIANE 40 R/B

Operation	⊿V[m/s]		System Mass[kg]		Propellant[kg]		Electric Prop. Total impulse	Note
	RCS	EP	Before	after	N2H4	Xe		
#1 rendezvous		248.6	**800.0**	787.4		12.58	1.97.E+05 [Ns]	Rocket injection(500km)→ ARIANE_R/B_21610
#1 Prox. Operation	100		787.4	711.0	76.4			
#1 deorbit		54.7	2491.0	2482.4		8.67	1.36.E+05 [Ns]	Descent to 650km
#1 RAAN drift			702.4	699.6		2.78	4.36.E+04 [Ns]	Descent to 500km for RAAN drift, inclination change close to inclination of the 20433
#2 rendezvous		201.5	699.6	690.6		8.93	1.40.E+05 [Ns]	Rendezvous ARIANE_R/B_20443
#2 Prox. Operation	100		690.6	623.6	67.0			
#2 deorbit		68.1	2403.6	2393.2		10.42	1.63.E+05 [Ns]	Descent to 650km
#2 RAAN drift		77.2	613.2	610.2		3.01	4.72.E+04 [Ns]	Descent to 500km for RAAN drift, inclination change close to inclination of the 22830
#3 rendezvous		213.9	610.2	601.9		8.27	1.30.E+05 [Ns]	Rendezvous to ARIANE_R/B_22830
#3 Prox. Operation	100		601.9	543.6	58.4			
#3 deorbit		106.1	2323.6	2307.9		15.67	2.46.E+05 [Ns]	Descent to 650km
#3 RAAN drift		0.0	527.9	527.9		0.00	0.00.E+00 [Ns]	Wait at 650km
#4 rendezvous		145.5	527.9	523.0		4.88	7.65.E+04 [Ns]	Rendezvous to ARIANE_R/B_23561
#4 Prox. Operation	100		523.0	472.3	50.7			
#4 deorbit		59.2	2252.3	2243.8		8.49	1.33.E+05 [Ns]	Descent to 650km
Total	400	1174.9			**252.5**	**83.71**	1.31[MNs]	**Dry Mass : 464kg**

10th Space Debris Workshop 19

Discussion on Russian Rockets



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Summary

- One important requirement for the debris removal technology to be demonstrated in CRD2 is that it must be low-cost to the extent that it is sustainable.
- The architecture and operational concept of future ADR projects were studied from the perspective of debris removal cost per piece, and the **Shuttle mission concept**, which removes multiple pieces of debris with a single service satellite without controlled re-entry, was confirmed to be advantageous.
- The feasibility of this concept was confirmed for specific targets.
- For the CRD2 Phase II technical demonstration scenario, it is appropriate to set the service requirements based on the main technical items to be demonstrated, such as **capture and grasp, descent into orbit, and release (without controlled re-entry).**

Requirements	Contents
General Requirements	Acquisition and provision of position, velocity, attitude, angular velocity, and navigation sensor data of the satellite and target debris during the service period
Observation Service	Acquisition and provision of camera images when approaching target debris
Orbit Descent Service	Orbital descent of target debris (The target altitude is still under consideration.)
Termination Service	Safe release of debris after orbit descent

C14

低軌道における小型デブリを対象とした 安価で効果的な受動的デブリ除去衛星

Proposing a Low-cost and Effective Passive Debris Removal Satellite for Removing Small-sized Orbital Debris in Low Earth Orbit

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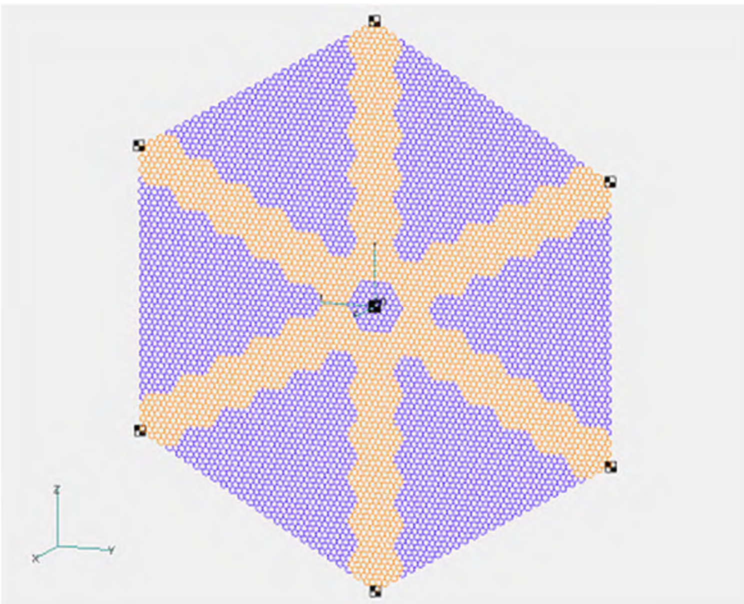
○SEKIKAWA Kenichi (Mitsubishi Electric Software Co. (former　Mitsubishi Space Software Co., Ltd.))

低軌道におけるデブリ環境の改善に貢献するため、受動的デブリ除去衛星を提案する。宇宙デブリの脅威が認識されてから半世紀程が経過しており、それを除去するための様々な方法が考案されている。比較的大型(廃棄衛星、ロケット上段等)のデブリの除去および今後打ち上げられる衛星のデブリ化を防ぐための方法は、有効と考えられる手法はある程度研究され、それらの技術検証が進んでいる状況である。一方で、混雑度の高い比較的小さい(10cm 程度以下)デブリは、その脅威の高いことにもかかわらず、除去する有効な手法は少ないのが現状のようである。著者は、これら比較的小さいデブリを除去するための受動的デブリ除去(Passive Debris Removal, PDR)システムをいくつかの既存の要素技術を応用し提案した。また、それを利用した安価で効果的な受動的デブリ除去衛星を設計し、除去できるデブリの数量と除去に要する時間を見積もった。その結果、低軌道における小型デブリ除去の実現性が示された。

It has been said for the last several decades that the chain reaction of the orbital debris collision, especially in the low Earth orbit (LEO), would occur in near future. Or has the debris population at present already exceeded the critical limit to cause so-called Kessler syndrome? The answer would probably be somewhat “yes”, but not “no” for sure. Some observation data implies the debris population level could have exceeded the critical limit by now, considering that the debris objects with diameter of 10 cm or less are not trackable by the observation system on the ground. The author focused on the small-sized debris objects with diameters approximately between 10 cm and 1 cm, that are to be removed for the remediation of the LEO. The author also proposes a low-cost passive ebris removal (PDR) satellite for removing small-sized orbital debris in LEO to provide a practical method, and to contribute to effective remediation of the Earth orbit for sustainable use of space environment.



10th Space Debris Workshop, Nov. 28th-30th, 2022

C14
低軌道における小型デブリを対象とした安価で効果的な受動的デブリ除去衛星
PROPOSING A LOW-COST AND EFFECTIVE PASSIVE DEBRIS REMOVAL SATELLITE FOR REMOVING SMALL-SIZED ORBITAL DEBRIS IN LOW EARTH ORBIT

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（旧社名： 三菱スペース･ソフトウエア（株）Former Mitsubishi Space Software Co., Ltd.）

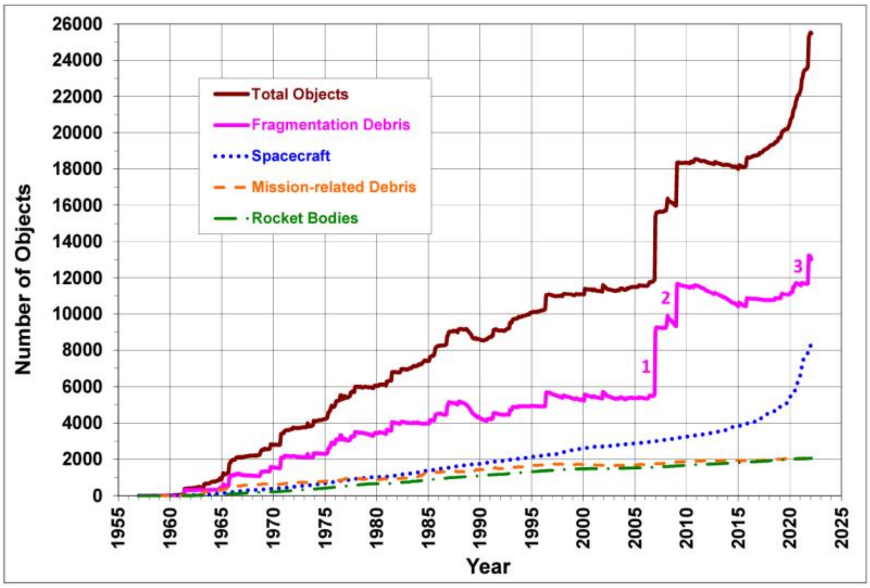
MITSUBISHI ELECTRIC Changes for the Better

Proposing a Low-cost and Effective Passive Debris Removal Satellite for Removing Small-sized Orbital Debris in Low Earth Orbit
低軌道における小型デブリを対象とした安価で効果的な受動的デブリ除去衛星

- ◆ 大型デブリはADRでの除去に任せる Large debris is subject to ADR.
- ◆ 小型デブリの除去が課題 Removal of small-sized debris is an issue.
- ◆ デブリ除去衛星システム(PDR方式)を提案 Proposed a PDR satellite for removing small debris in LEO.

MESW 2

1.1 Orbital Debris at Present



- # of debris in constant increase.
  デブリ数は増加の一途（カタログデブリ）
  1： the ASAT test conducted by China in 2007
  2： the accidental collision between Iridium 33 and Cosmos 2251 in 2009
  3： the ASAT test conducted by Russia in 2021
- Additional satellites expected due to “large constellation plan”.
  近年のメガコンステレーション計画でさらに増加する見込み

Citation;
NASA ODPO, Quarterly News, March 2022, Volume 26 – Issue 1

1.1 Orbital Debris at Present

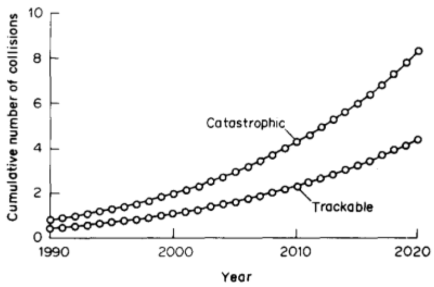


Fig. 6. Further evolution of the cumulative number of collisions in LEO if spaceflight activities are continued as in the past.

Up to 2020 there will be about 50 collisions among objects >1 cm in Earth orbit. 8–9 of these will be catastrophic and 4–5 will be between trackable objects. Hence, it can be predicted that we shall observe about one catastrophic collision up to the year 2000, another one up to 2010 and two others up to 2020. But remember that these are random events, which are not necessarily following the mean values of the collision probability.

Citation;
Peter Eichler, Analysis of the necessity and the effectiveness of countermeasures to prevent a chain reaction of collisions, Acta Astronautica Vol 26, No. 7, pp, 487-495, 1992

- Simulation by Dr. Eichler, 1992.
  Eichler氏のCHAINによる予測（1992年）
- 『catastrophic collisionを2000年までに1回、2010年までにさらに1回、2020年までにはさらに2回ほど観測できるだろう』と予測
- The accidental collision between Iridium 33 and Cosmos 2251 in 2009 may be relevant…?
  かのIridium 33とCosmos 2251の衝突（2009年2月）がそれに当たるのではないだろうか

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Changes for the Better

1.1 Orbital Debris at Present

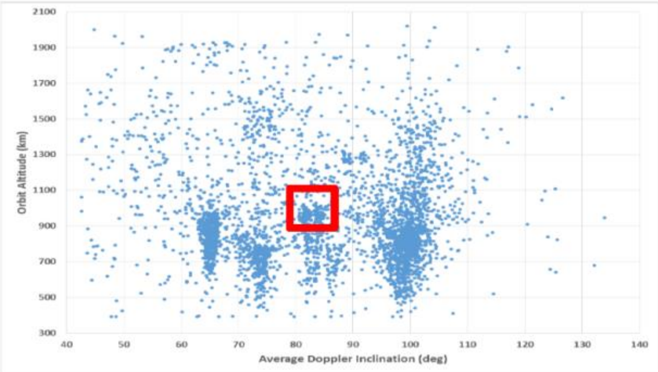

Fig 1. The CY2013–2015 composite HUSIR data. Of interest is the debris cloud at 900 km to 1100 km and 82° inclination with no known energetic breakup event.

Citation;
D. Gates and P. Anz-Meador, An 82-deg Inclination Debris Cloud Revealed by Radar, First Int'l. Orbital Debris Conf., Texas, USA, Dec. 2019

- ◆ Data obtained from HUSIR observation campaign, 2013 through 2015.
  HUSIRレーダ（旧Haystackレーダ）による5.5 [mm]から10 [cm]のデブリを対象とした観測（2013-2015年）
- ◆ A new debris cloud found.
  傾斜角約82度、高度900～1100 [km]の領域に新規のデブリ群を発見。
- ◆ Determined not collision between cataloged debris nor self-explosion.
  カタログデブリ同士の衝突あるいはバッテリや圧力容器の爆発によるものではないとされているため、1992年になされた予測の一つである可能性は否定できない。
- ◆ Chain reaction has already started…?
  一つの懸念は、自己増殖環境の既成

MESW 5

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Changes for the Better

1.2 Debris Sizes in LEO

Nomenclature	Size	Population	Trackability	Threat	Avoidable	Targeted by
Large	>10 [cm]	Approx. 13,000	Tracked (Intact debris)	Fatal	Yes	ADR
			In operation (Spacecraft)	Fatal	Yes	ADR
Small	>1 [cm]	Approx. 300,000	Detected but untracked	Often crucial	No	PDR
Micro	<1 [cm]	Several millions	Detected down to 5.5 [mm] but untracked	Some hazardous	No	PDR

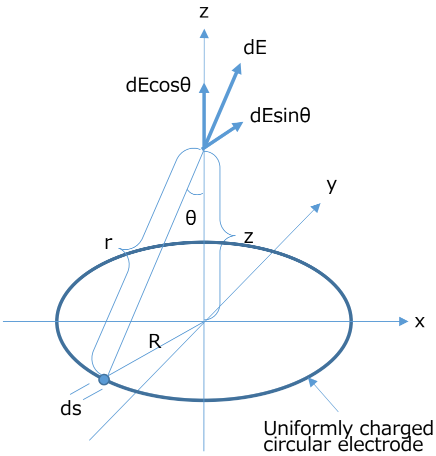
- ◆ Largeデブリの脅威は致命的
  ⇒監視・追跡されているため宇宙機は回避することが可能
  ⇒ADRの対象として除去されることが期待される
  ⇒新規打上げ衛星のPMDは必須（デブリ化は成功率による）
- ◆ Microデブリに対しては防護設計が施されている
  ⇒致命的な損傷の確率は一般的に低い
- ◆ Smallデブリは追跡が困難かつその脅威は依然致命的
  ⇒自己増殖を抑制する必要
  ⇒Proposed a PDR satellite for remediation

ADR: Active Debris Removal
PDR: Passive Debris Removal
PMD: Post-Mission Deorbit

MESW 6

MITSUBISHI ELECTRIC Changes for the Better

2. Principle of Debris Removal

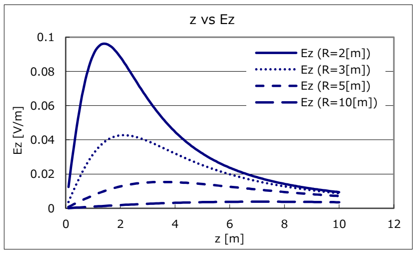


$$E_z = \int d\,E_z = \int \frac{\cos\theta dQ}{4\pi\epsilon_0 r^2} \qquad (1)$$

- Decelerate charged debris by electrostatic force acted by a circular electrode.
  負電荷化したデブリに円環電極の電界による静電気力を作用させ、デブリの速度を減じる。
- Electric field forms normal to the plane at the center.
  円環電極の中心を通る面外法線上（z軸）には、式1で示される電界Ezが生じる。
- 式1は円環の半径Rおよび円環からの距離zを用いて、式2で表すことができる。
- 電子シースにより負電荷化されるデブリの電荷量qは式3により求められる 。

$$E_z = \frac{Q\,\mathbf{z}}{4\pi\epsilon_0(R^2+z^2)^{3/2}} \qquad (2)$$

$$q = 4\pi\varepsilon_0\,\mathbf{r}\,V \qquad (3)$$

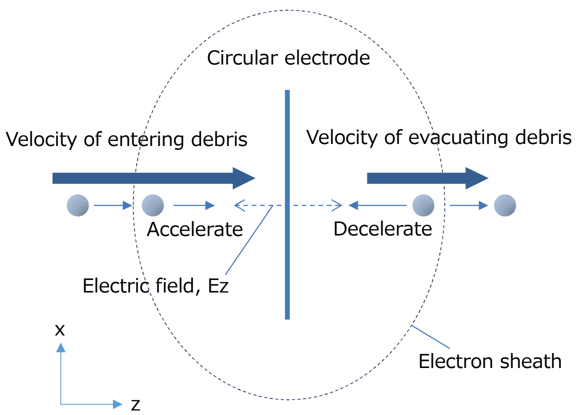


極大値 : (z, Ez) = $(R/\sqrt{2},\ 1/(6\sqrt{3}\pi\varepsilon_0 R^2))$

MESW 7

MITSUBISHI ELECTRIC Changes for the Better

2. Principle of Debris Removal



- Electron sheath is formed when positive-biased voltage is applied to the electrode.
  電極を正バイアスさせると、プラズマ環境に存在する電子が電極の周辺に電子シースを形成する。
- Debris is charged by electron sheath and electrostatic force is induced by electric field.
  デブリが電子シースにより負電荷化され、電極により形成される電界との相互作用により静電気力を受ける。
- Entering debris is accelerated less than evacuating debris decelerated because entering debris requires more time to be charged.
  進入時は負電荷化に時間を要するため、加速が減速を下回り、電極を通過したデブリは減速される。
- Decelerated debris gradually descends towards atmosphere and finally evaporates.
  電極を通過する度にデブリは高度を下げ、最終的に大気圏で焼失する。

MESW 8

3.1 Passive Debris Removal Satellite

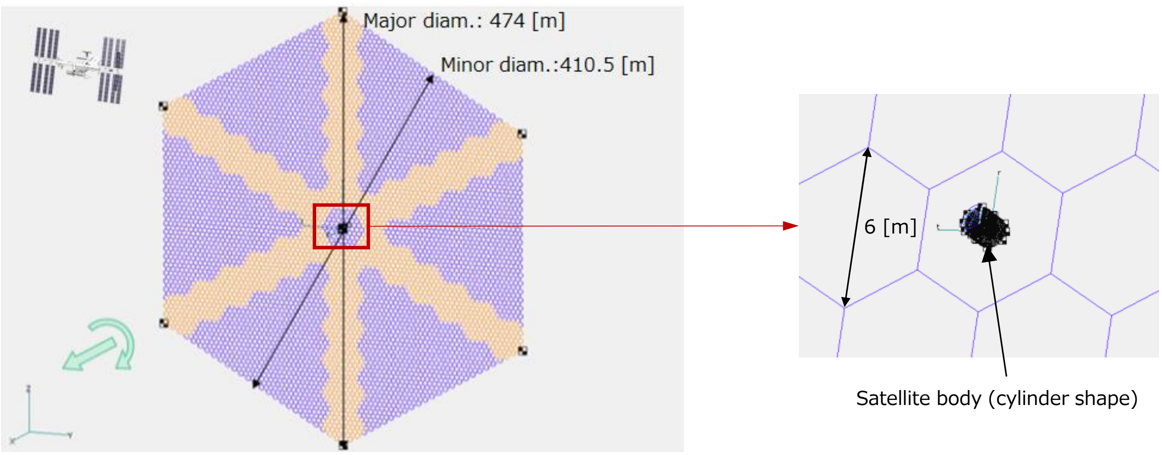
Feature	Benefit
Honeycomb-mesh electrode	・Effective for large number of small-sized debris. 小型デブリを多数同時に除去する場合に有効
Passive removal	・Information of debris not required. デブリの位置・姿勢などの情報が不要
Non-contact	・Rendez-vous not required. ランデブーが不要 ・No ejecta generated. 2次デブリの発生がない
In-situ measurement	・In-situ measurement possible. 軌道上でデブリ環境を計測できる
Ops duration	・Long ops duration possible. 長期の運用が可能

◆ Development risk is considered low because existing technology is applied.
要素技術は既存の技術を応用しており、開発リスクは低いと考えられる。

◆ Possible candidate to compensate the missing region of small-sized debris removal.
現在までに考案されていないsmallサイズのデブリを除去する手法となり得る。

MESW 9

3.1 Passive Debris Removal Satellite

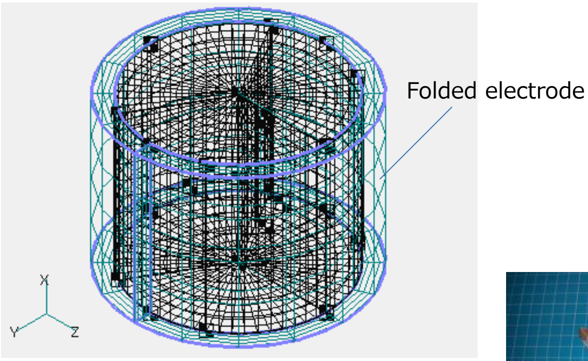


◆ Electrode is made honeycomb shape to form a complete mesh in a plane.
単位電極を同一面内に効率よく配置するため、電極を正六角形のハニカム形状とした。
◆ Very thin membrane capacitor is selected for effective weight and packageability.
電極には薄膜コンデンサを用い、軽量化と収納性を高めた。
◆ A simple bus system design is feasible to reduce costs of manufacture and operations.
姿勢安定はスピン安定方式を採用し、バス系の各機器を簡素にすることにより、安価な製造および運用が可能。

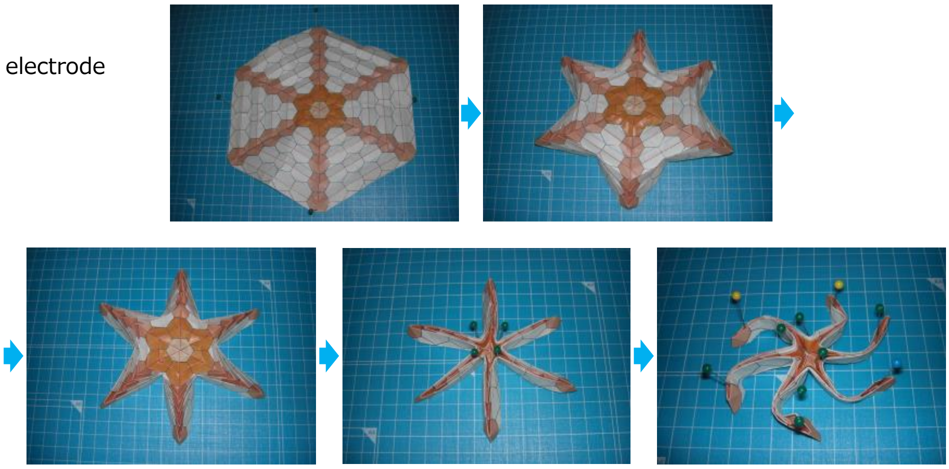
MESW 10

MITSUBISHI ELECTRIC Changes for the Better

3.1 Passive Debris Removal Satellite



Size (height, diameter) [m]	1.0, 1.2
Mass [kg]	70 (max.)
Moment of inertia [kg*m^2]	13.3 (Ixx) 12.8 (Iyy) 12.8 (Izz)
Eigenfrequency [Hz]	198 (x) 63 (y) 56 (z)



- ◆ “IKAROS” folding is selected for storing honeycomb mesh into satellite body.
  ハニカム電極の衛星本体への収納はいわゆる『イカロス折り』による。
- ◆ 周端部から周方向と平行に山折りと谷折りを繰り返していくと、正六角形の中心から対角線上を放射状に折り畳まれる。
- ◆ 折り畳まれた6本の腕を衛星本体の側面に巻き付ける。

MITSUBISHI ELECTRIC Changes for the Better

3.2 Effectiveness

Case ID		89_208	89_624	45_206	45_624	22_126
Area-to-mass ratio (AMR)		0.0208	0.0624	0.0206	0.0624	0.126
Diameter [m]		0.089	0.089	0.045	0.045	0.022
Mass [kg]		0.299	0.100	0.077	0.026	0.003
Orbital lifetime [year]	King-Hele	163.5	54.5	165	54.5	27.0
	STK	99.6	32.4	103.3	31.7	15.6
Time for removal [year]		72.0	22.4	60.4	18.3	5.9

- ◆ Time required to remove debris is simulated by STK (System Tool Kit).
  デブリ除去衛星(PDR方式)による**除去に必要な時間**をSTKを用いて解析。
- ◆ Inclination: 89 [deg], initial altitude: 800 [km], eccentricity: 0.0
- ◆ Debris model uses aluminum alloy and shape of solid sphere for the minimum area-to-mass ratio.
  最も小さい面積質量比を設定するため、密度の最も高いアルミニウム合金を適用し、デブリを中実球体としてモデル化。

MITSUBISHI ELECTRIC Changes for the Better

3.2 Effectiveness

Size [cm]	@700[km]	@800[km]	@900[km]	@1000[km]
1.1	131.34	280.19	131.34	113.83
2.2	74.43	113.83	65.67	56.91
4.5	19.26	56.91	39.40	10.51
8.9	9.63	19.26	9.63	6.13
Total of 6-year ops	234.66	470.20	246.04	187.38
Total # of debris captured	1138.28			

◆ Estimated number of debris captured during 6-year operations at representative altitude.
デブリ除去衛星を６年間運用した場合の代表的な高度における**デブリ捕獲数**を試算。

◆ 8.9 [cm] debris with AMR of 0.126 requires 5 to 6 years to descent altitude by 100 [km].
8.9 [cm]のデブリ（AMR: 0.126）の高度を100 [km]降下させるのに5～6年を要する。

◆ For example, deploy 4 satellites at each altitude bin and sweep them down within the bin for 6 years.
例えば、4機の衛星を各高度に配置し、6年かけて100 [km]降下させる運用。

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4. Conclusions

◆ Some observation data implies that chain reaction may have already started in the LEO.
低軌道におけるchain reaction環境の既成が懸念される。

◆ A PDR satellite was proposed for a remediation.
その対処として、PDR技術とそれを利用したデブリ除去衛星を提案した。

◆ It is shown this PDR satellite is feasible using the existing technology.
デブリ除去衛星は既存技術の応用により実現できる可能性が示された。

◆ On the other hand, international law enactment is an urgent issue.
一方で、国際法令の整備が課題。

MESW 14

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ご清聴ありがとうございました！
Thank you for your attention!

C14
低軌道における小型デブリを対象とした安価で効果的な受動的デブリ除去衛星
PROPOSING A LOW-COST AND EFFECTIVE
PASSIVE DEBRIS REMOVAL SATELLITE FOR REMOVING
SMALL-SIZED ORBITAL DEBRIS IN LOW EARTH ORBIT

MESW 15

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C15

レーザ衛星を用いたADRミッションにおける軌道設計
Orbit Design for ADR Mission Using Laser Satellite

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五十部 駿、吉村 康広、花田 俊也（九州大学）
○ITAYA Yuki, FUKUSHIMA Tadanori, Aditya Baraskar, FUJIHARA Tomoaki,
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HANADA Toshiya (Kyushu University)

宇宙機やデブリの急激な増加に伴い、能動的デブリ除去（ADR）の必要性も一層高まりつつある。スカパーJSATと理化学研究所は、レーザアブレーションによって得られる推力に着目し、レーザを搭載した衛星をによるADR手法を提案している。本手法の特徴の一つとして、ターゲット物体に対して、物理的な接触が不要という点があげられる。レーザ衛星は、レーザの射程距離内に接近できれば、ターゲット物体のデタンブリングやデオービットを行うことが可能である。そのため、接触型ADRで必要となるターゲット衛星へのドッキングは不要となるが、一方で、レーザ衛星とターゲット物体との相対位置の保持がより重要なタスクとなる。レーザ衛星によるADRミッションは、幾つかのフェーズに分割されるため、それぞれの目的に沿った相対軌道設計が必要となる。本発表では、各フェーズごとの相対軌道について、Hill座標系やROEsを用いて設計し評価した結果を紹介する。

As the number of spacecraft and orbital debris is rapidly increasing, Active Debris Removal is becoming an essential technology to maintain a sustainable space environment. SKY Perfect JSAT and RIKEN are developing a laser equipped ADR satellite which adopts laser ablation technology to generate thrusting force on the target object. This ADR method does not require any physical contact to the target object, which is the remarkable characteristics compared to the widely proposed methods. The laser satellite can perform detumbling and deorbiting of the target object as long as their relative distance is within the laser range. For that reason, docking or capturing is no longer needed for this ADR method. On the other hand, proximity operations need to be considered over the entire mission period. ADR mission provided by Laser satellite can be divided into several phases, such as detumbling phase and deorbiting phase, and each phase requires individual orbit design. This presentation will show the concept of the orbital design for each mission phase and provides the validation results by using Hill coordinate systems and relative orbital elements.

The 10th Space Debris Workshop

C15. Orbit Design for ADR Mission Using Laser Satellite
レーザ衛星を用いたADRミッションにおける軌道設計

November 30th, 2022

●Yuki Itaya[1)], Tadanori Fukushima[1)], Aditya Baraskar[1)], Tomoaki Fujihara[1)], Kenshin Nagamine[1)]
Shun Isobe[2)], Yasuhiro Yoshimura[2)], Toshiya Hanada[2)]
●板谷 優輝[1)]、福島 忠徳[1)]、Aditya Baraskar[1)]、藤原智章[1)]、長峯 健心[1)]、五十部駿、吉村康広、花田俊也
（1) スカパーJSAT株式会社, 2) 九州大学 ）

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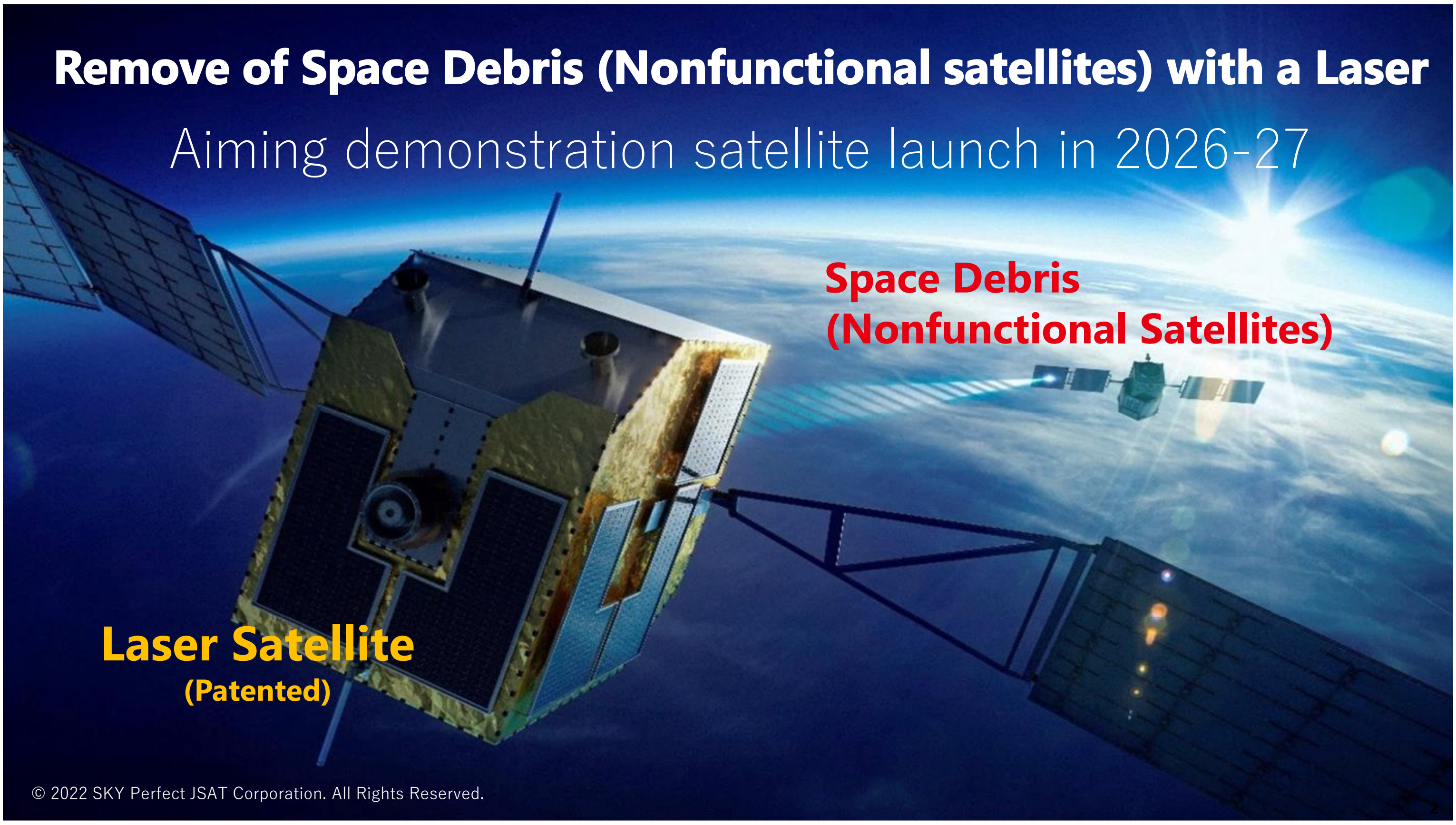
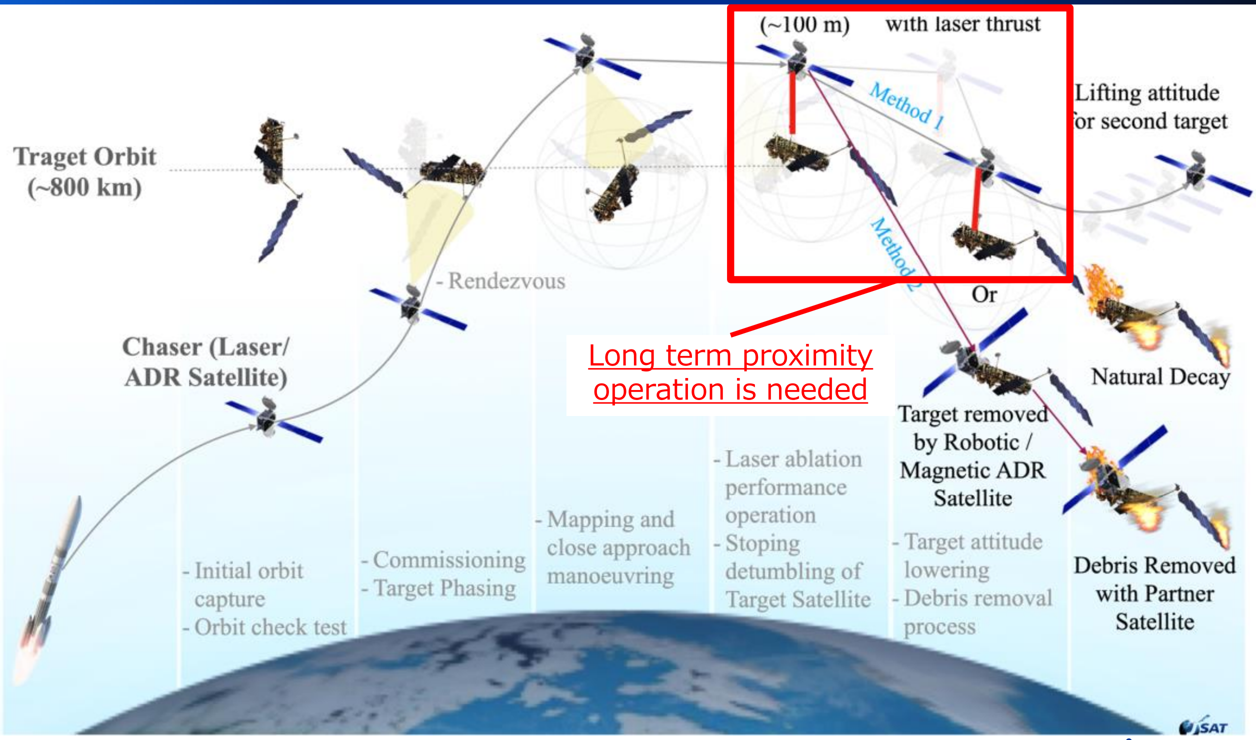


Mission Scenario for ENVISAT case (IAC 2022)



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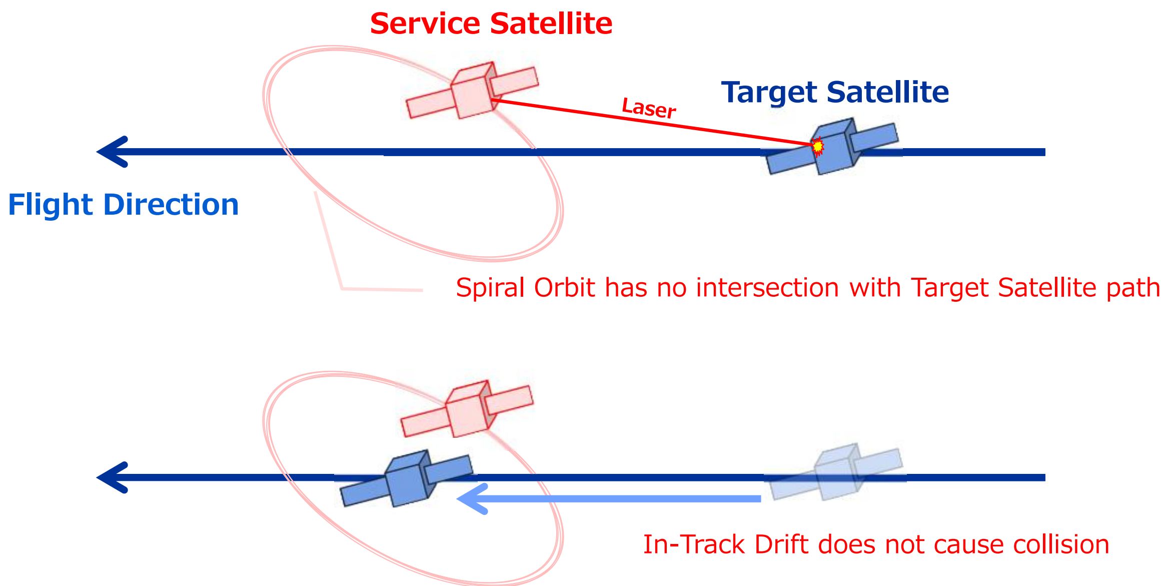
Proximity Operation by Spiral Orbit

Safer operation can be provided by Spiral Orbit strategy



This presentation provides the progress on the Spiral Orbit Designing for Laser ADR mission

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Spiral Orbit Design

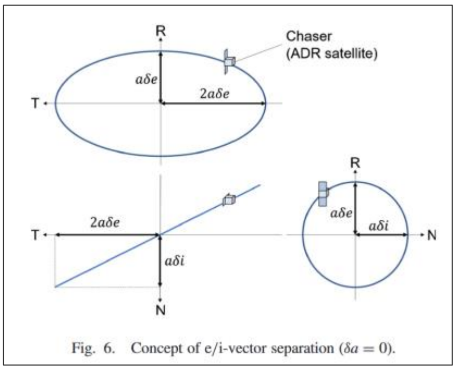
Relative Orbital Elements (ROEs) can be used for spiral orbit designing

ROEs: Delta between two orbital elements of Target and Service satellites

$$\delta\boldsymbol{\alpha} = \begin{bmatrix} \delta a \\ \delta\lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{bmatrix} = \begin{bmatrix} \Delta a/a \\ \Delta u + \Delta\Omega\cos i \\ \Delta e_x \\ \Delta e_y \\ \Delta i \\ \Delta\Omega\sin i \end{bmatrix}$$

Specific ROEs combination gives a specific relative elliptical orbit on Hill coordinate system (see right figure).

By adjusting (aδe, aδi, aδλ)[m], the desired relative orbit can be obtained



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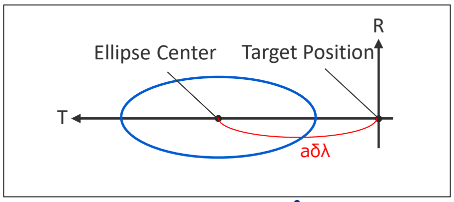

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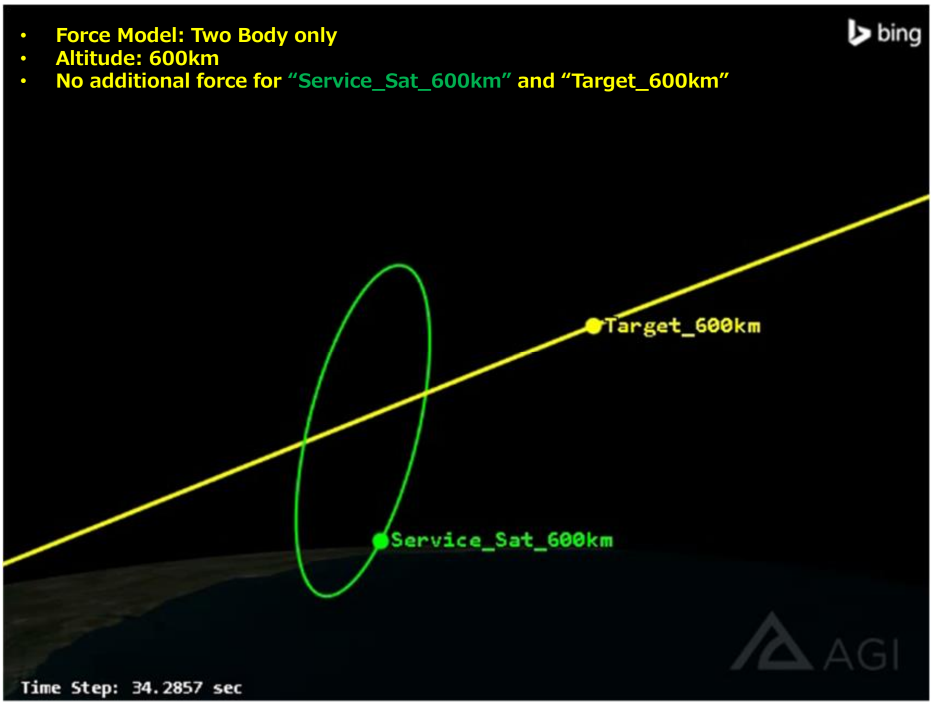
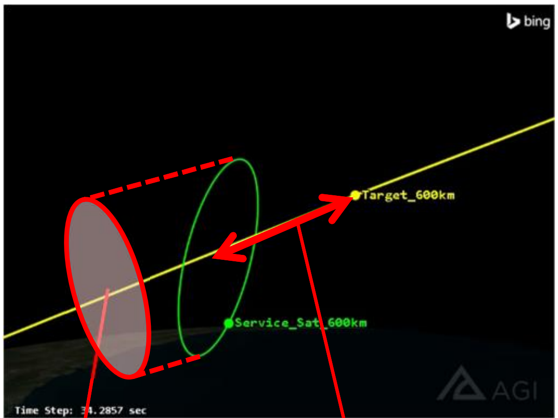
Example of Spiral Orbit Design





Distance between Target and Center of ellipse = 100m

R-N plane radius = 30m

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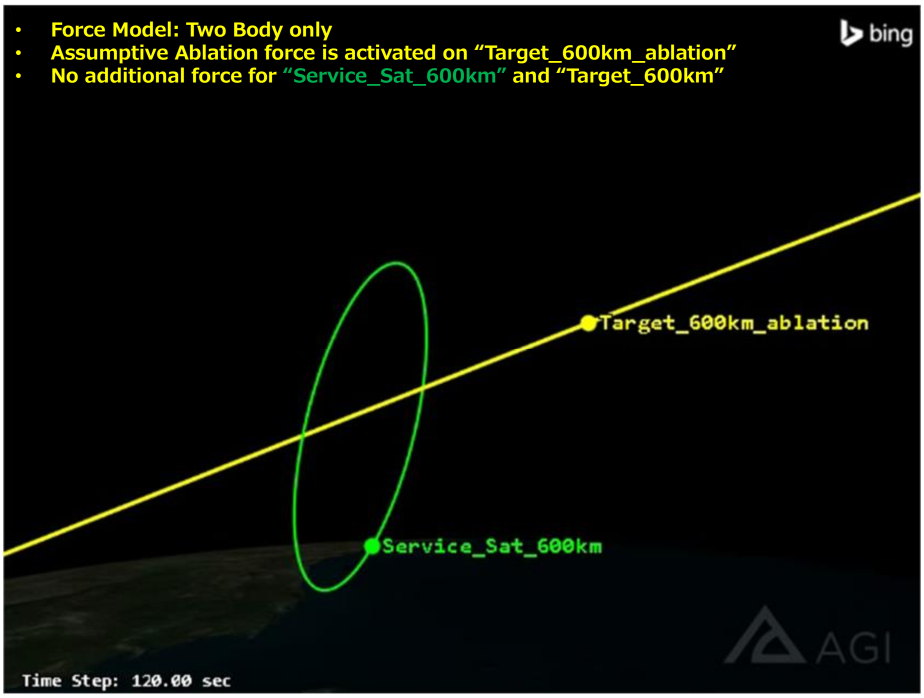
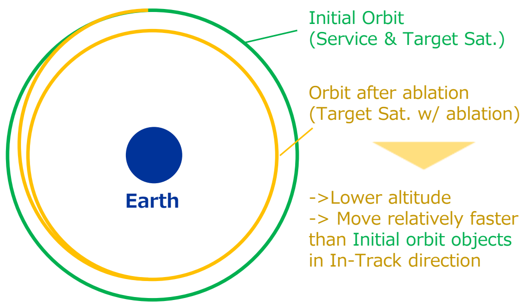
Orbit Change Caused by Ablation Force





Ablation Force gradually changes the target object orbit.

Service satellite needs to perform thrusting to keep the relative position.

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Follow-up Maneuver during Detumbling & Deorbiting

Previous research* found the **Equation for Ablation & Maneuver Planning**
-> Which contributes to defining finite propulsion and Laser ablation planning to keep relative orbit.

*Isobe, S., Yoshimura, Y., Hanada, T., Itaya, Y., Fukushima, T., Formation keeping control for simultaneous deorbit using laser ablation,73 rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.

$$\Delta\boldsymbol{\alpha}_{\mathrm{des}} = \delta\boldsymbol{\alpha}_{\mathrm{des}} - \boldsymbol{\Phi}(t_m, t_{\mathrm{ini}})\delta\boldsymbol{\alpha}_{\mathrm{ini}}$$

$$\Delta\boldsymbol{\alpha}_{\mathrm{des}} = \sum_{j=1}^{N} \boldsymbol{\Phi}(t_m, t_{j,f})\boldsymbol{\Psi}_d(t_{j,f}, t_{j,0})\boldsymbol{F}_{\mathrm{ab}} + \sum_{j=1}^{N} \boldsymbol{\Phi}(t_m, t_{j+1,0})\boldsymbol{\Psi}_c(t_{j+1,0}, t_{j,f})\boldsymbol{F}_{\mathrm{el}}$$

$\delta\boldsymbol{\alpha}_{des}$: *Desired ROEs*
$\delta\boldsymbol{\alpha}_{ini}$: *Initial ROEs*
$\boldsymbol{F}_{el}$: *Electric Propultion Force*
$\boldsymbol{F}_{ab}$: *Ablation Force*

Details & Analysis of Equation

- Gaussian Equation is combined with ROEs representations
- Ablation Force is assumed to always act in In-Track direction
- 4 Non-Linear Equations are obtained (= 4 parameters can be designed)
- According to the analysis, uncertainty of ablation direction and orbital perturbation (geopotential) can be compensated.

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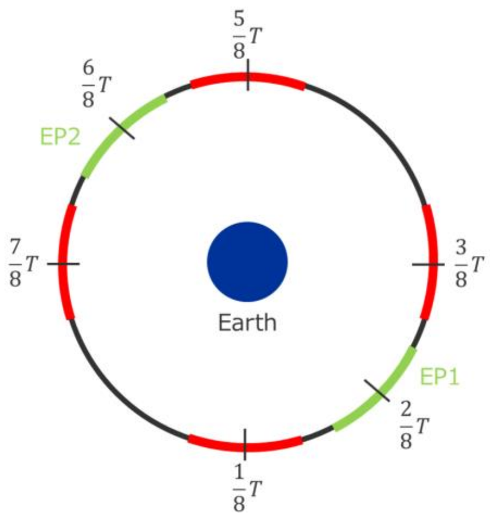
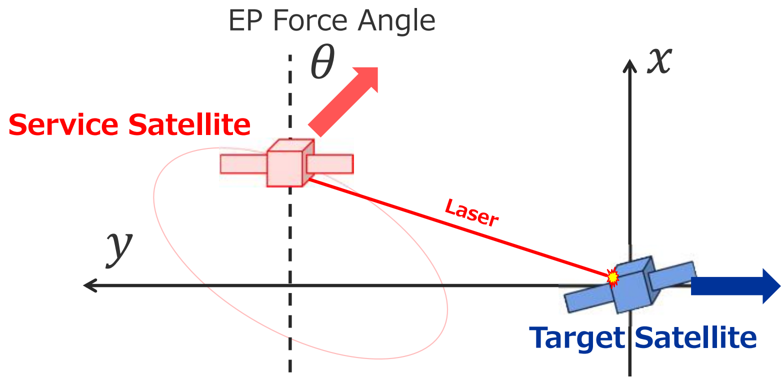
Follow-up Maneuver during Detumbling & Deorbiting

T: Orbital Period
Ablation Arc
Electric Propulsion(EP) Arc

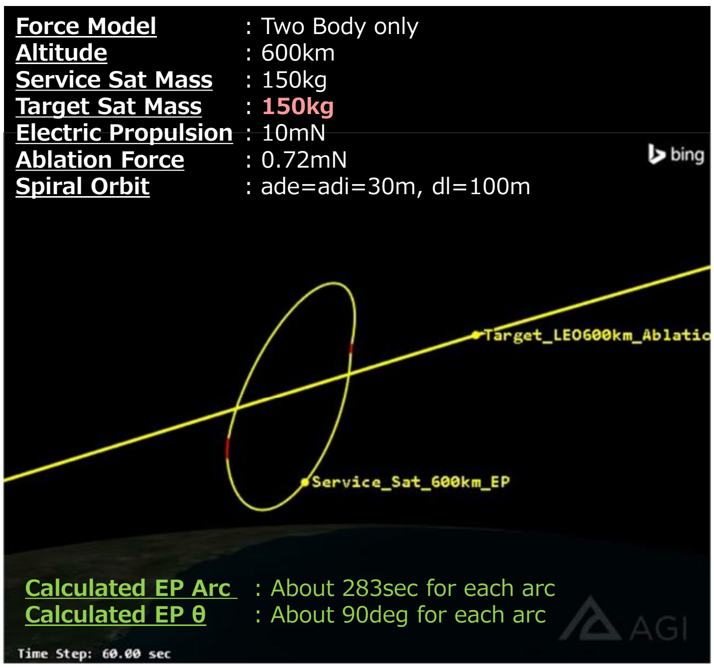


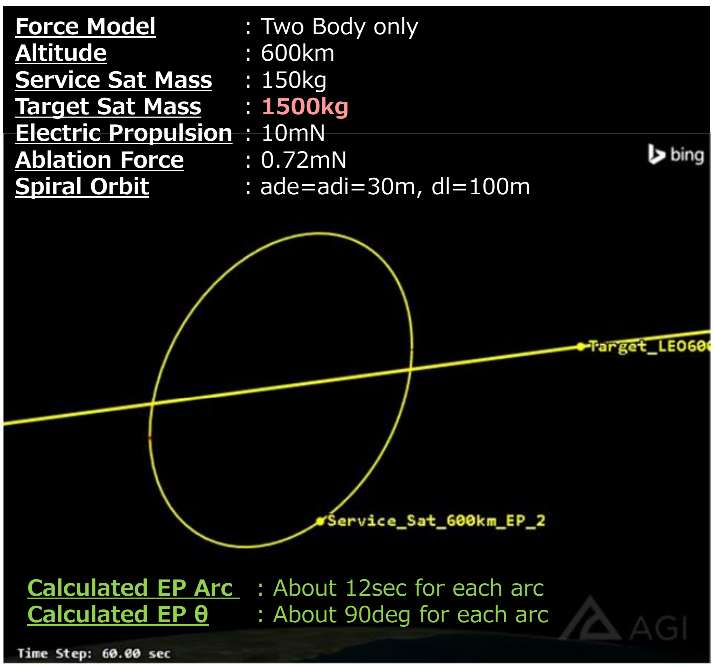


Constraints
- Total Ablation Arc = 0.6T
- Ablation Force Direction = In-Track
- Arc Centers are fixed

Parameters
- EP1 Duration
- EP2 Duration
- EP1 Angle
- EP2 Angle

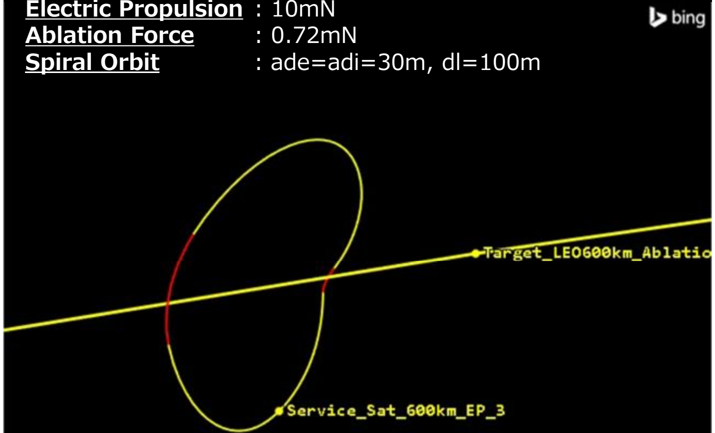
Examples of Orbit Design





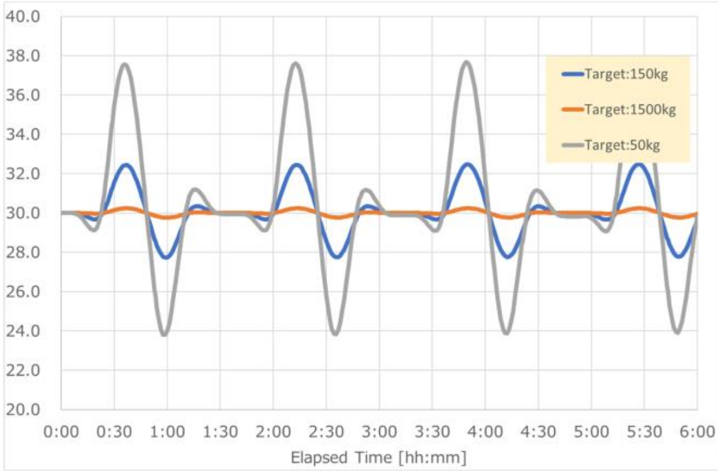
Examples of Orbit Design

Force Model : Two Body only
Altitude : 600km
Service Sat Mass : 150kg
Target Sat Mass : 50kg
Electric Propulsion : 10mN
Ablation Force : 0.72mN
Spiral Orbit : ade=adi=30m, dl=100m



Calculated EP Arc : About 375sec for each arc
Calculated EP θ : About 90deg for each arc
AGI
Time Step: 60.00 sec

$\sqrt{y^2+z^2}$ [m] (Distance from In-Track axis(=x axis))



As EP duration becomes longer,
the spiral orbit becomes more distorted.

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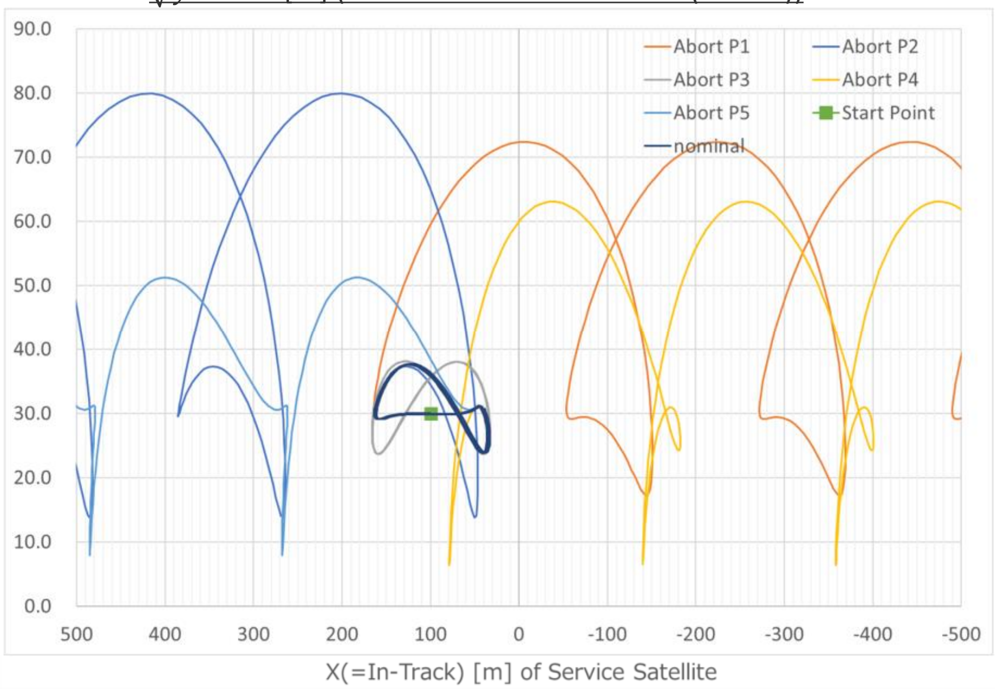
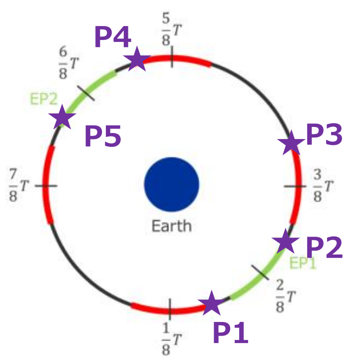
Orbital Safety after Abort

$\sqrt{y^2+z^2}$ [m] (Distance from In-Track axis(=x axis))



Abort Point Definition



In some case, spike-like approach to x-axis is observed

To ensure orbital safety, design should be done not to cause the spike around Target (=coordinate origin)

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Summary & Future Works

Summary

- The research shows the examples of orbit design for Laser ADR mission.
- Relative elliptic orbit can be maintained by following the maneuver plan provided by a specific equation, but sometimes the ellipse partially collapses depending on the initial conditions.
- The degree of collapse and abort timing determine the safety of the orbit (possibility for colliding target satellite).

Future Works

- Further evaluation of Abort Safety (Analytical & Numerical)
- Mission safety evaluation by taking into account the orbit determination error.

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C16

レーザアブレーションにより剥離する MLI の解析

Simulation of MLI Detached by Laser Ablation

○長峯 健心、福島 忠徳、Aditya Baraskar、板谷 優輝、藤原 智章（スカパーJSAT）、
中村 友祐、佐宗 章弘（名古屋大学）
○NAGAMINE Kenshin, FUKUSHIMA Tadanori, Aditya Baraskar, ITAYA Yuki, HUJIHARA Tomoaki
(SKY perfect JSAT Corporation),
NAKAMURA Yusuke, SASOH Akihiro (Nagoya University)

昨今の衛星打ち上げ数増加に伴う低軌道混雑化は著しく、宇宙環境保全のため、スペースデブリの能動的除去(ADR)が注目されている。スカパーJSAT・理化学研究所・名古屋大学は、レーザーアブレーションにより発生した推力を利用する ADR 手法を提案している。デブリに発生する推力はアブレーションされる部材（アブレータ）に依存するため、効率良い ADR を実現するには適切なアブレータを選択する必要がある。これまでの研究より、比推力の観点から、アルミニウムがアブレータとして有用であることが明らかになっている。一方、多くの衛星筐体は多層断熱材(MLI)で覆われており、筐体部材のアルミニウムをアブレータとするためには、先に MLI をアブレーションして除去する必要がある。実運用において、レーザー照射には誤差が含まれるため、MLI 自体が剥離しデブリとなる可能性が考えられる。
本発表では、レーザー照射に伴う誤差を考慮し、デブリ化した MLI の数の解析結果、および MLI がデブリ化しない照射精度・方法について報告する。

The recent increase in the number of satellite launches has significantly increased low orbit congestion, and hence, active debris removal of space debris (ADR) is attracting attention in order to protect the space environment. SKY Perfect JSAT, RIKEN, and Nagoya University have proposed an ADR method that uses the thrust generated by laser ablation. Since the thrust generated in debris depends on the ablated material (ablator), it is necessary to select an appropriate ablator to realize efficient ADR.
Previous studies have shown that aluminum is a useful ablator from the viewpoint of specific impulse. On the other hand, many satellite surface are covered with multi-layer insulation (MLI), and in order to use aluminum as an ablator, the MLI must first be ablated to remove it. In actual operation, the MLI itself may detach and become debris due to errors in laser irradiation.
In this presentation, considering the error of laser irradiation, we report the analysis results of the number of detached MLIs that become debris and the irradiation accuracy and methods for MLIs without debris generation.

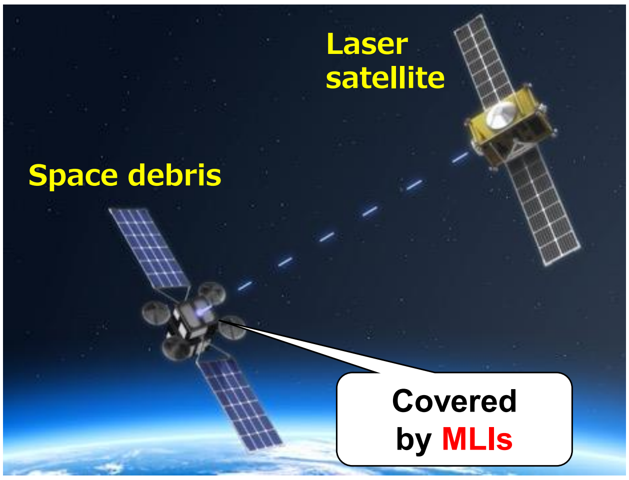
The 10th Space Debris Workshop, November 30th, 2022.
SKY Perfect JSAT corporation.

Simulation of MLI detached by laser ablation

Kenshin Nagamine, Tadanori Fukushima, Aditya Baraskar,
Yuki Itaya, Tomoaki Hujihara (SKY perfect JSAT Corporation),
Yusuke Nakamura, and Akihiro Sasoh (Nagoya University)

Background (1/2)

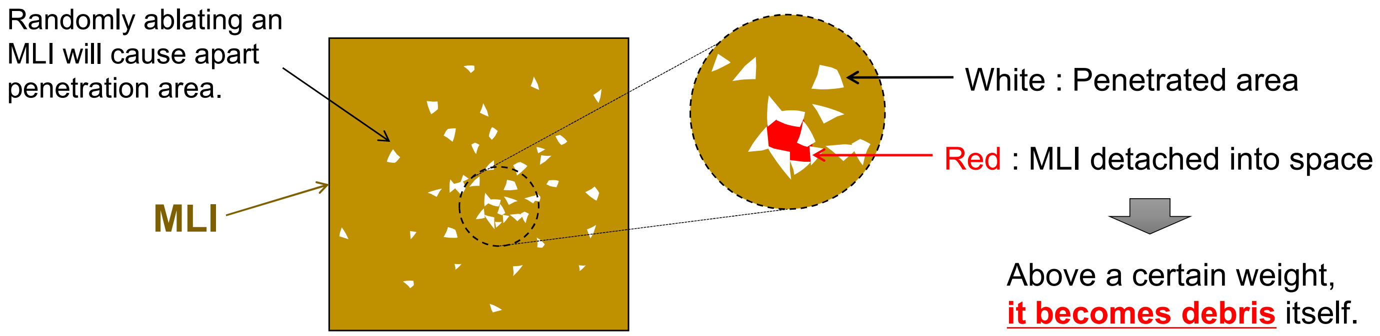
- Possible to remove debris remotely using laser ablation.
- Thrust depends on the component to be ablated (ablator).
- Most satellite bodies are covered by MLI (Multi-layer insulator).



Necessary to investigate characteristics of MLI ablation.

Background (2/2)

- From the viewpoint of thrust and specific impulse, it is **more efficient to use aluminum as an ablator** than MLI, which covers the surface of the satellite.
- However, when MLI is ablated and removed with **a certain degree of error**, there is a possibility that MLI will be **detached into space**.



MLI in the process of ablation

Objectives

① Determine required **irradiation accuracy** by simulating the irradiation error with a two-dimensional Gaussian distribution.

② Investigate an **optimal irradiation method**.

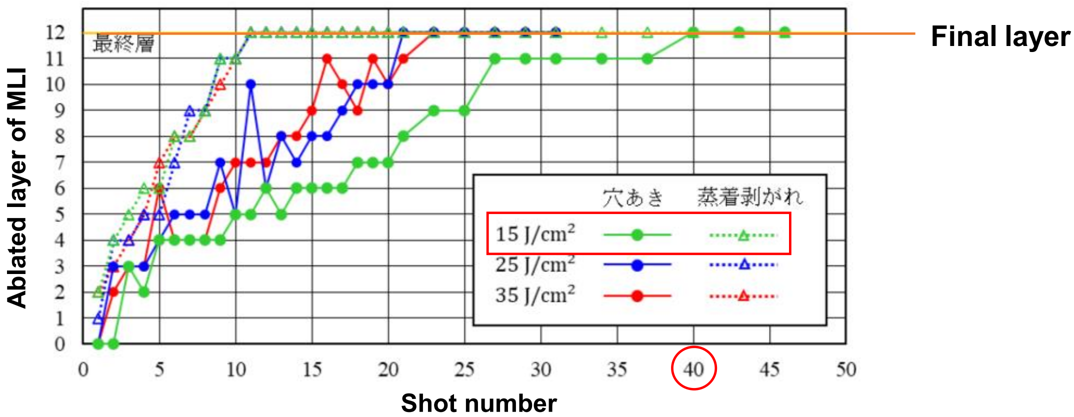
③ Investigate **the amount of debris generation**.

Results of MLI ablation (Nagoya Univ.)

Total shot number to penetrate MLI

Fluence, J/cm²	1	3	5	15	25	35
Total shot number	-	-	-	40	21	23

- It is impossible to penetrate MLI below 5 J/cm² → In this study, apply the fluence of **15 J/cm²**.



Shot number vs ablated layer of MLI

Simulation condition

☐ Diameter of laser spot : 2.9 mm

Assuming laser power of 1 J, then the fluence is 15 J/cm² apart 200 m from a target satellite

☐ Threshold of debris : 1.41 mg

In the LEO protected region and GEO region,
slags emitted by solid rocket motor **larger than 1 mm** is restricted.[1)]

⇩

Some of the **aluminum particles** in the solid rocket motor do not burn to completion and may remain in the motor case as residue (slag). [2)]

- Aluminum density : 2.70 g/cm³
- Assuming 1 mm diameter aluminum sphere, threshold weight of a debri is defined as follows:

$$(4/3)*\pi*0.5^3*2.7 = 1.4137 \text{ mg.}$$

1) First International Orbital Debris Conference, held 9-12 December, 2019 in Sugar Land, Texas. LPI Contribution No. 2109. Houston, TX: Lunar and Planetary Institute, 2019, id.6053
2) マグナリウムの固体ロケット推進薬への適用

Simulation condition

- **MLI weight : 315 g/m²**

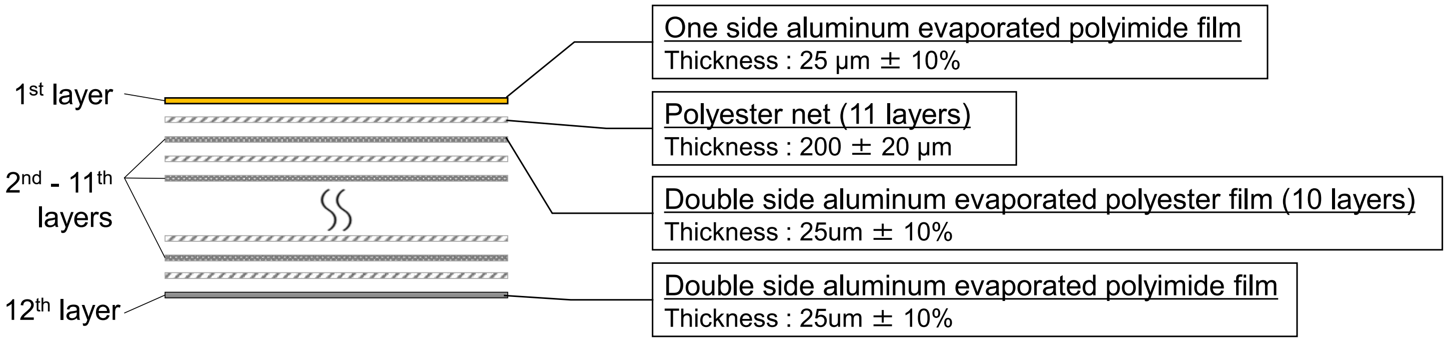


Diagram of MLI (product of KANEKA)

Given that 40 times irradiations are required to penetrate the MLI, we assumed the MLI as 40 layers and 7.875 g/m² for each layer.

Simulation method

- **Mesh analysis**

  Calculate number of irradiation for each element, and it reaches 40, the element is penetrated.

- **Irradiation error**

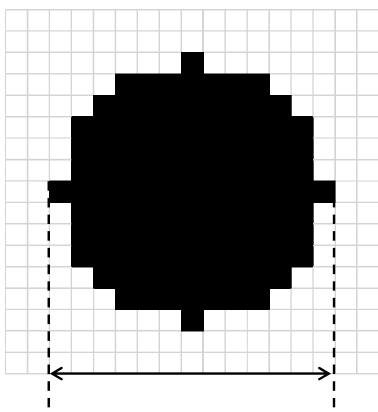
  Assume an irradiation error as two-dimension Gaussian distribution

$$G(\boldsymbol{x}, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\boldsymbol{x}^2}{2\sigma^2}\right)$$

→ set standard deviation σ as a parameter.

σ = 10 – 50 mm (10 mm step)

Mesh analysis



Resolution of spot
(In this case, Res = 13)

Confirm that the results do not change when changing the resolution of the spot.

Results

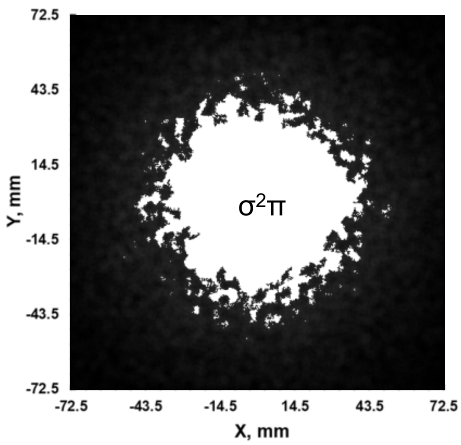
Effects of irradiation accuracy

Results - Effects of irradiation accuracy

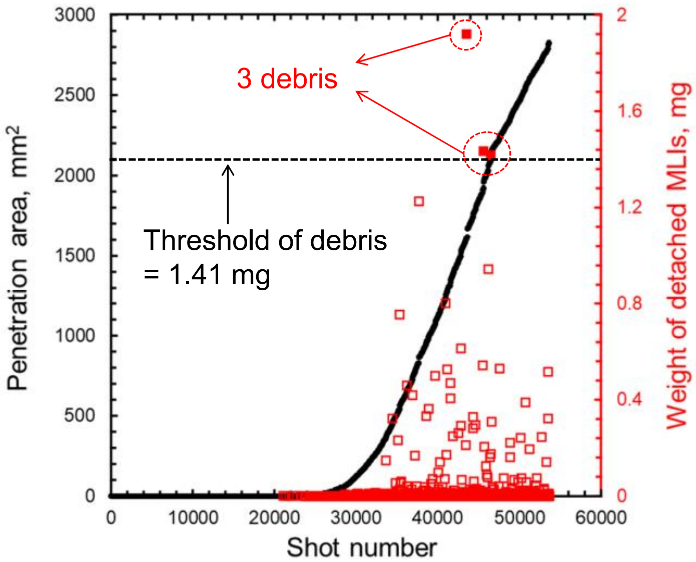
☐ Simulation condition

σ = 10 - 50 mm (10 mm step)
End condition is when penetration area over $\sigma^2\pi$.

ex) Result of σ = 30 mm

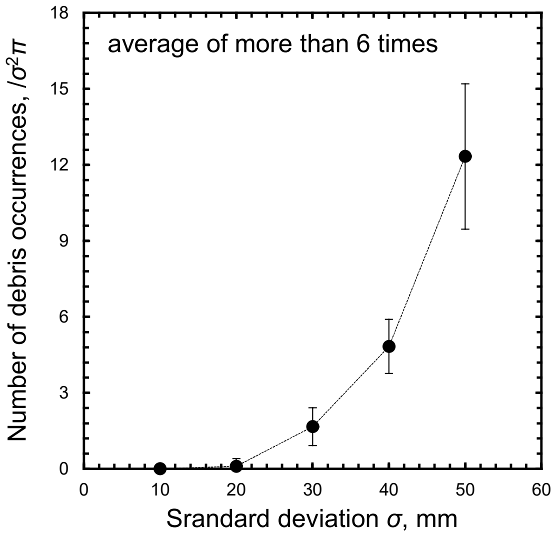


Penetration area of σ = 30 mm



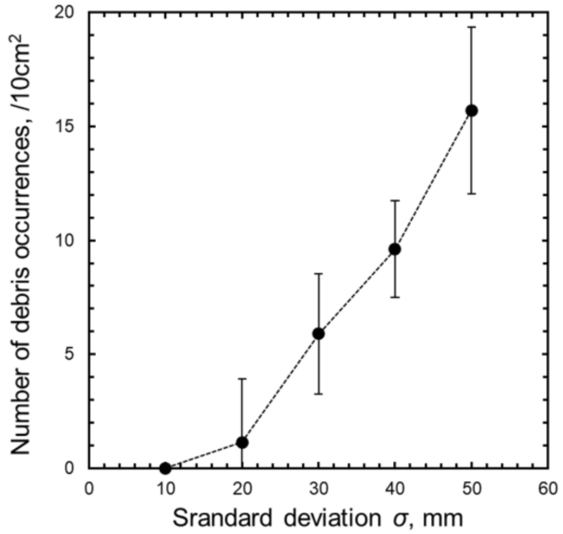
Penetration area and detached MLIs weight

Results - Effects of irradiation accuracy



Number of debris until $\sigma^2\pi$ is penetrated

× (10cm^2 / $\sigma^2\pi$)



Number of debris until 10cm^2 is penetrated

The rougher the accuracy, the higher the number of debris.

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Results

Effects of sweeping irradiation point linearly

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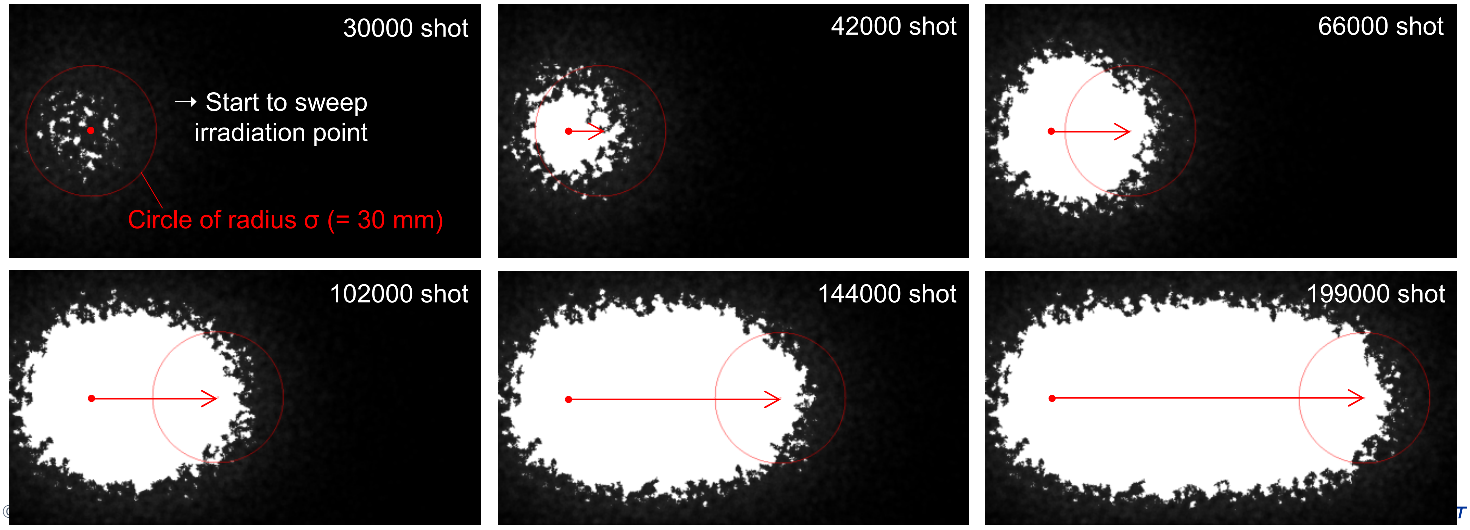
Sweep irradiation point linearly

☐ Simulation condition

- σ = 30, 40, 50 mm
- Sweep speed = 200 – 500 shot/mesh (100 step)
  ≃ 800 – 2000 shot/mm (200 step)

※ After MLI is penetrated by $\sigma^2\pi$ in the condition of fixed irradiation center, the irradiation center starts to be swept at a constant speed.

ex) Penetration trace of 1200 shot/mm for σ = 30 mm.



Results - linear sweep

☐ Example of results

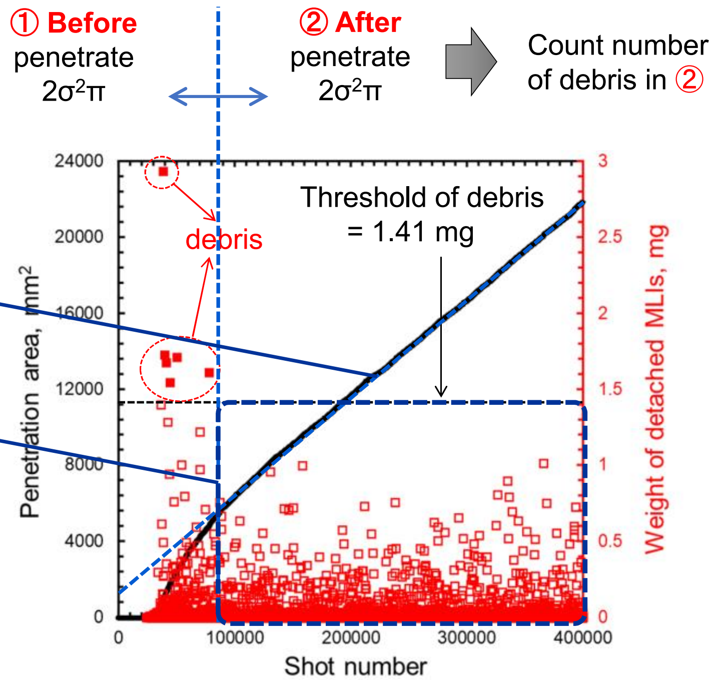
(σ = 30 mm for 2000 shot/mm)

Penetration speed (slope) becomes almost constant after $2\sigma^2\pi$ is penetrated.

When penetration speed becomes constant, the number of debris generation becomes very low.

In ① region, the number of debris can be estimated using the results obtained by irradiating fixed point.

As for σ = 30 mm, 3 debris are generated.



Penetration area and detached MLIs weight

Results - linear sweep

☐ Number of debris

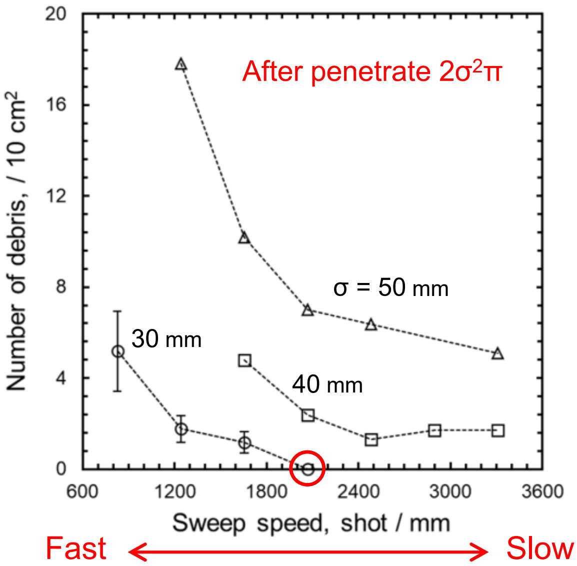
- The slower the sweep speed,
  the smaller the number of debris for all σ.

- Only for σ = 30 mm, debris are not generated
  when the sweep speed is 2000 shot/mm.

Appropriate conditions are considered as bellow;

- accuracy : less than σ = 30 mm
- sweep speed : slower than 2000 shot/mm

σ = 30 mm → average of 5 times
σ = 40, 50 mm → only 1 trial



Number of debris vs Sweep speed

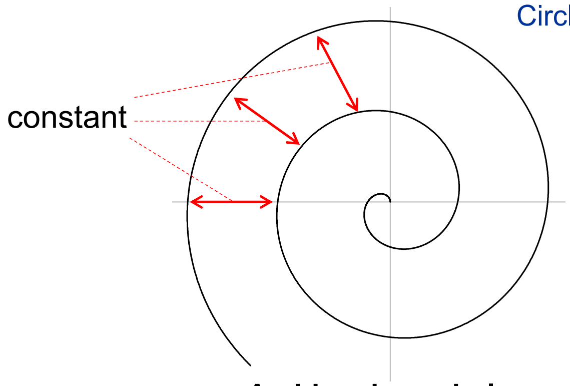
Results

Effect of sweeping irradiation point along to the Archimedes spiral

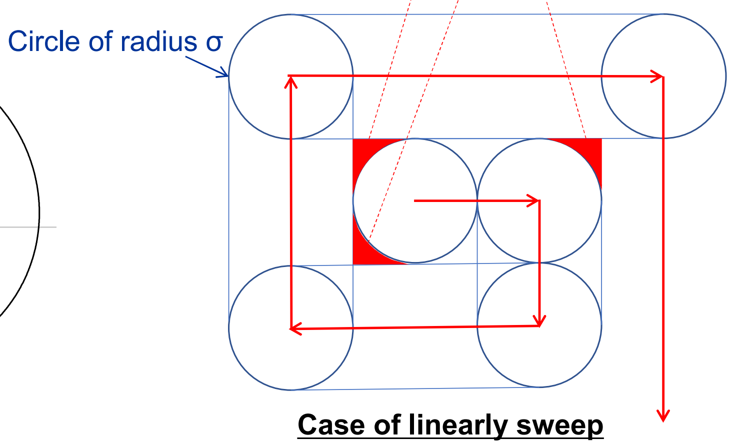
Optimal trajectory to penetrate MLI

1. **Start point of irradiation**
   Considering torques applied to a target satellite, it's better to irradiate the center of surface.

2. **Trajectory**
   The radial spans are constant for the Archimedes spiral.
   → It's better to chose the Archimedes spiral.



Archimedes spiral



Case of linearly sweep

Archimedes spiral

◻ Equation of Archimedes spiral

$r = a\theta$
$(x = r\cos\theta = a\theta\cos\theta)$
$(y = r\sin\theta = a\theta\sin\theta)$

◻ Simulation conditions

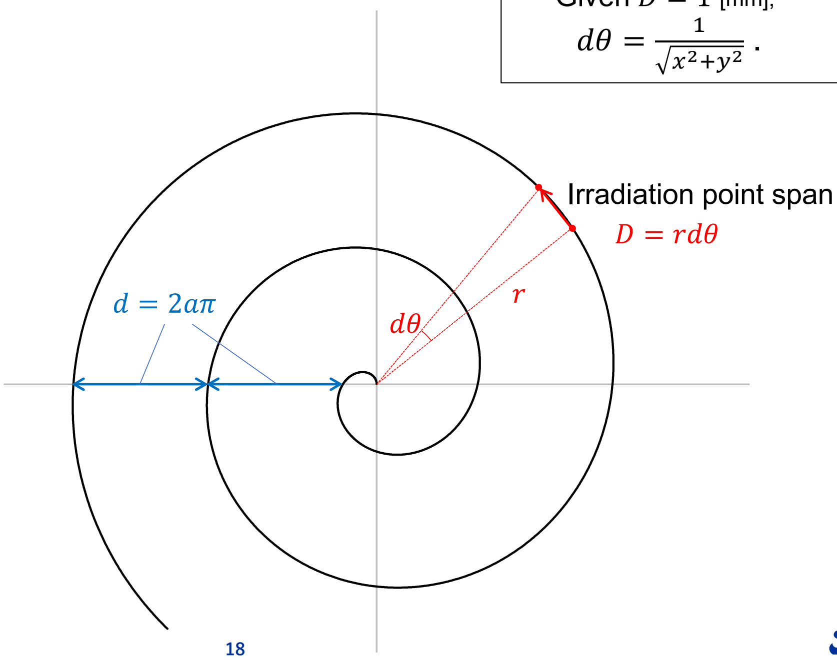
σ = 30 mm
Sweep sped : 2000 shot/mm
(500 shot/mesh)

◻ Parameter

a = 7 – 15 (1 step)
→ d : radial direction span
$d = 2a\pi$

◻ Irradiation point span

Span D is shown as below:
$D = rd\theta = \sqrt{x^2 + y^2}d\theta.$
Given $D = 1$ [mm],
$d\theta = \frac{1}{\sqrt{x^2+y^2}}.$

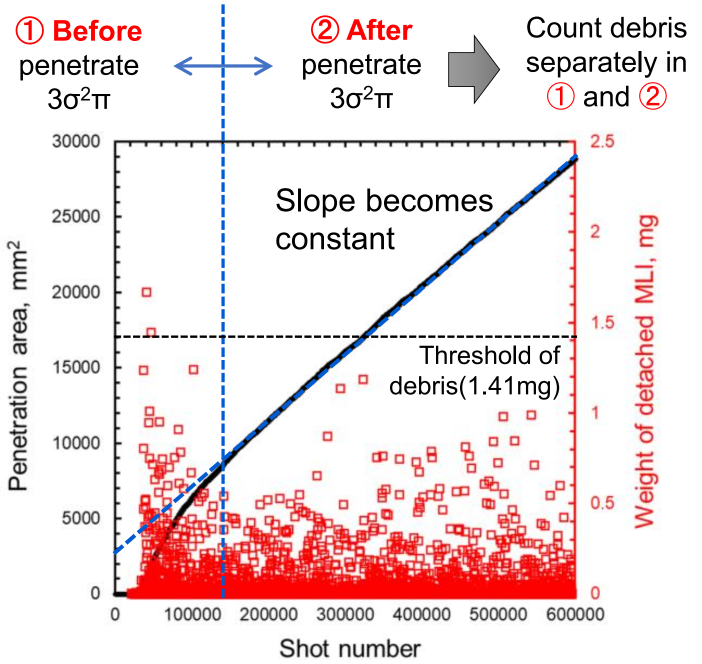


Results - sweep with Archimedes spiral

☐ Example of results

(σ = 30 mm for 2000 shot/mm)

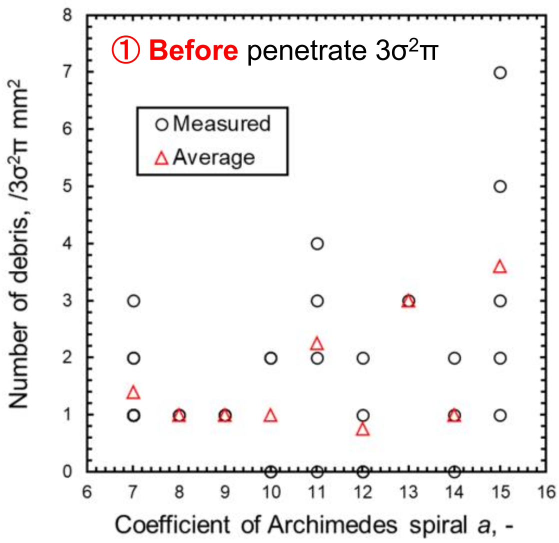
Penetration speed (slope) becomes almost constant after $3\sigma^2\pi$ is penetrated



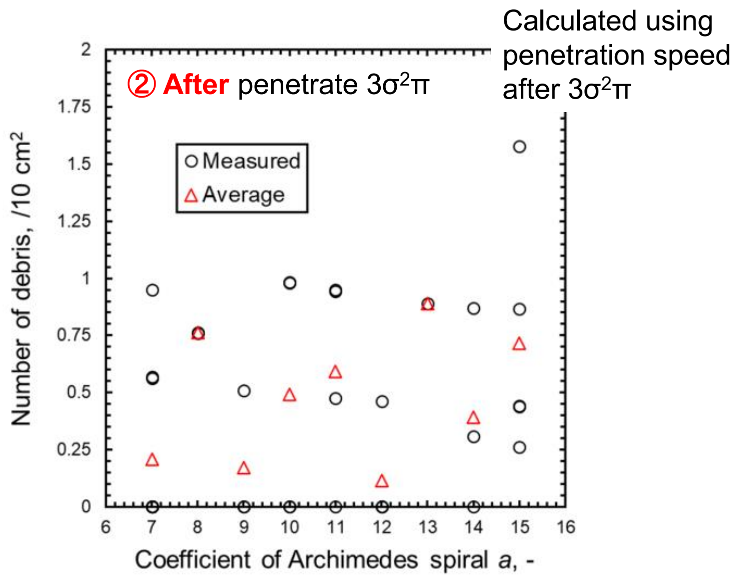
Penetration area and detached MLIs weight

Results - sweep with Archimedes spiral

- When 10 cm^2 of MLI is penetrated, number of detached debris is **about 3**.



Number of debris vs a ($r = a\theta$)



Number of debris vs a ($r = a\theta$)

Conclusion

- **Required irradiation accuracy**

  less than σ = 30 mm

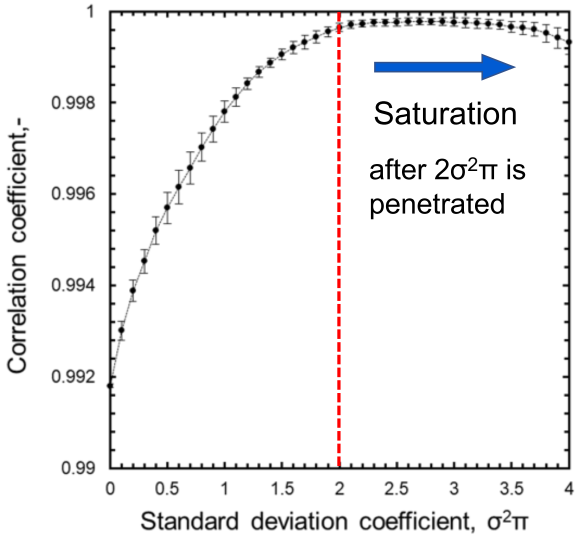
- **Optimal irradiation method**

  Archimedes spiral
  (the trajectory is along $r = a\theta$, a is constant)

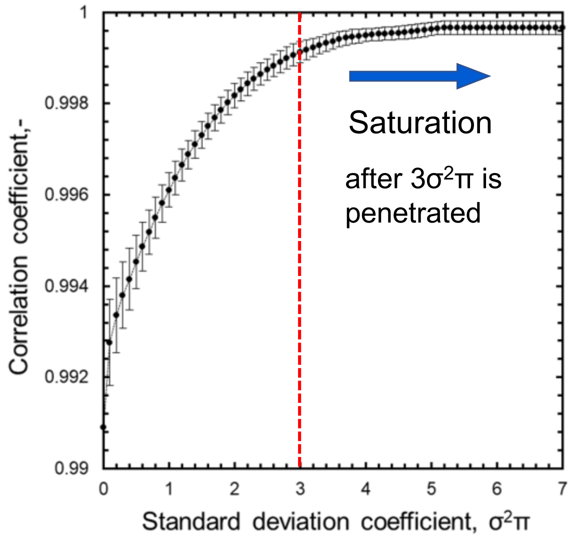
- **Number of debris**

  about 3 debris are generated to penetrate 10 cm^2 MLI

Saturation of penetration speed



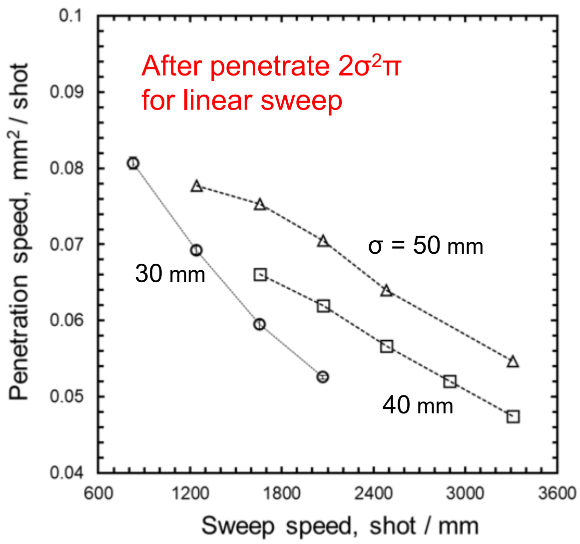
Linear sweep



Archimedes spiral

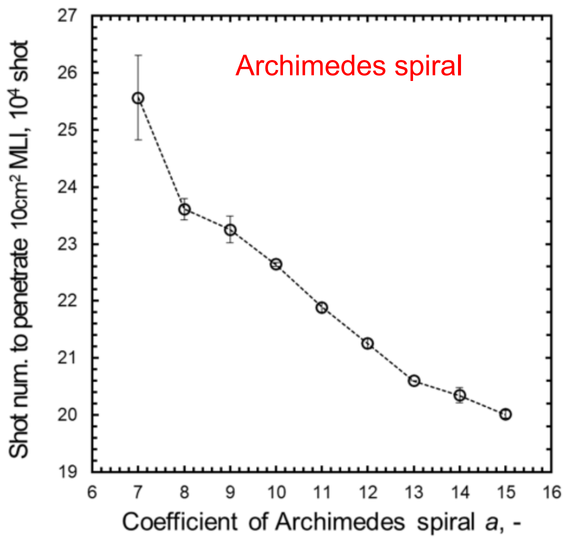
Penetration speed and required number of shots

"Penetration speed" and "Sweep speed" are a trade-off relationship.



Penetration speed vs Sweep speed

More than 200 thousands shots are required to penetrate 10 cm^2 MLI.



Required shot number to penetrate 10 cm^2 MLI

Determine resolution of spot

Simulate with different resolutions and compare follows:

1. Total shot number to penetrate certain area of MLI;
2. Weight of detached MLIs.

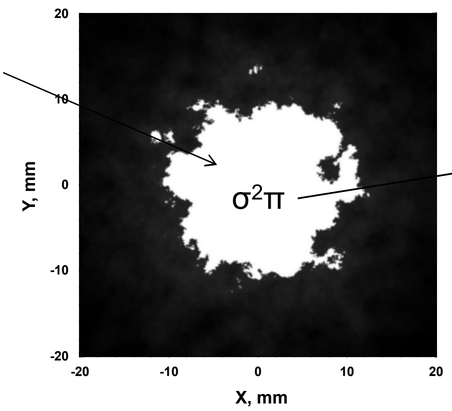
Determine resolution of spot

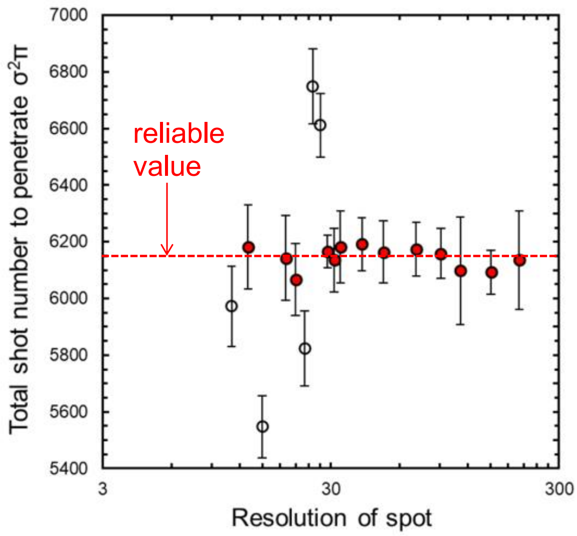
1. Comparison of total shot number

Simulation condition : σ = 10 mm

This simulation is stopped when the penetration area over $\sigma^2\pi$ as shown in below figure.

White area is penetrated by laser irradiation.

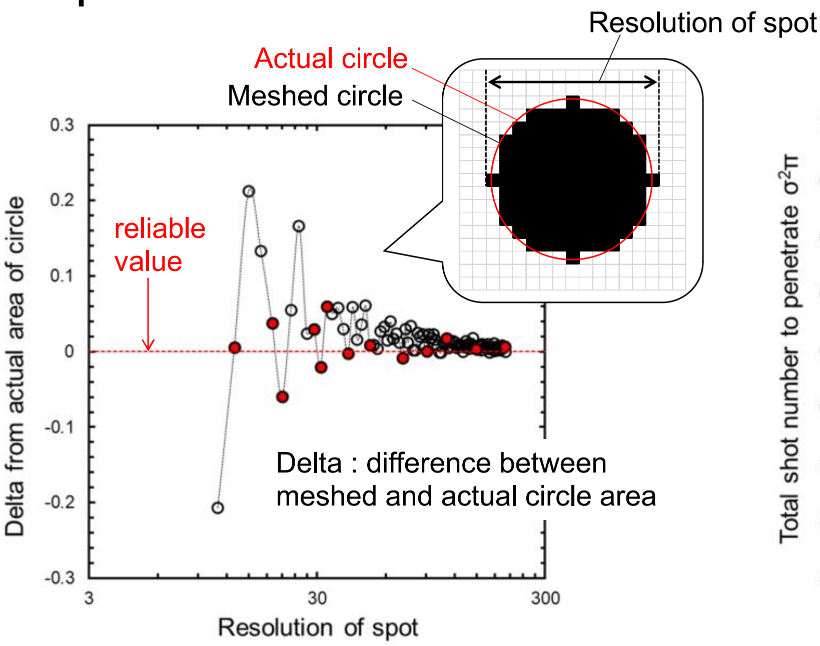




Total shot number vs Res

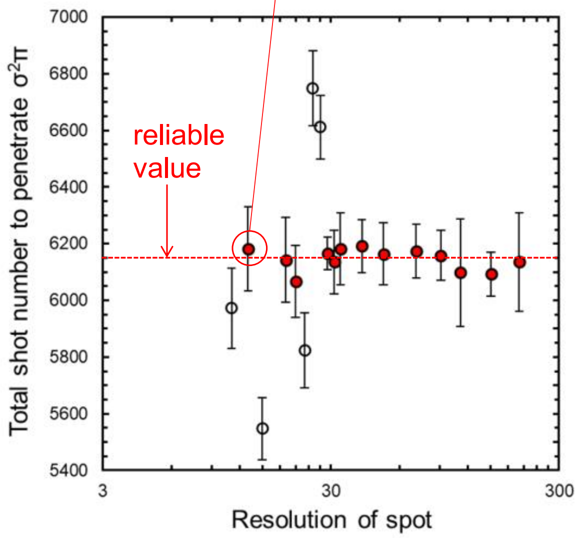
Determine resolution of spot

1. Comparison of total shot number



Delta of meshed and actual circle vs Res

Considering a calculation cost, **Res = 13** is the best.

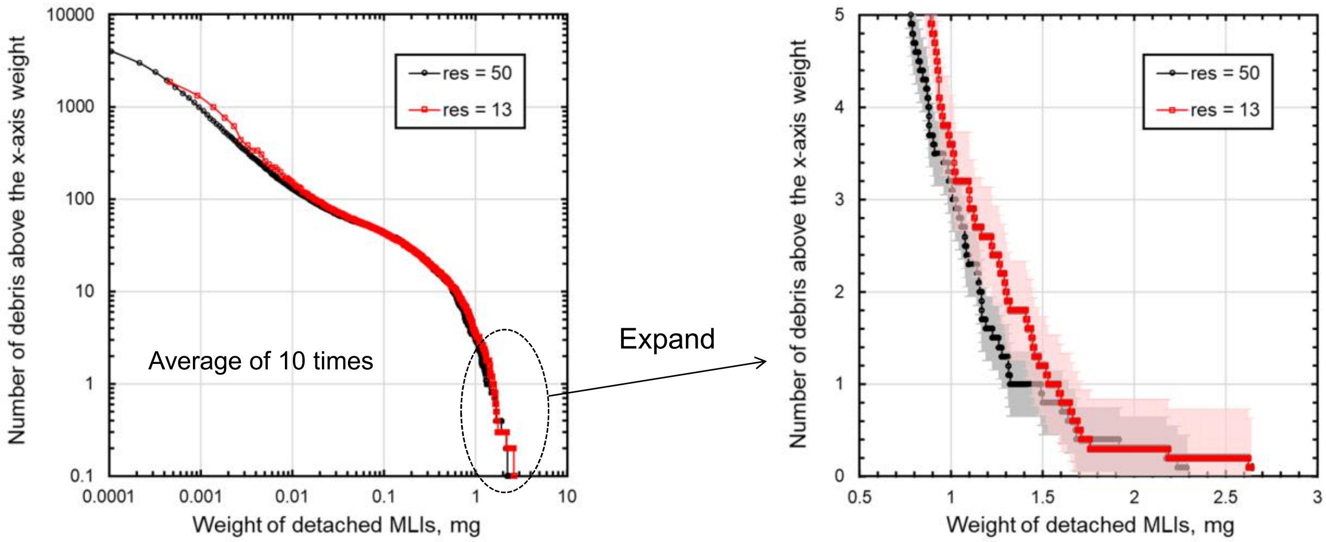


Total shot number vs Res

Determine resolution of spot

2. Comparison of detached MLIs weight

Compared with res = 13 and 50 for σ = 30 mm, number of debris are almost same.
Hence, even with res = 13, it seems certain.



QA

- Size of debris
- Spot diameter
- Required shot number
- How difference in thrust and Isp between aluminum and MLI
- Is there any problem for generating few debris to penetrate MLIs?

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C17

パルスレーザを用いたスペースデブリの回転静止解析

Analysis for Detumbling of Space Debris with Pulsed Laser

○藤原 智章、福島 忠徳、Aditya Baraskar、板谷 優輝、長峯 健心、酒井 大輔（スカパーJSAT）
○FUJIHARA Tomoaki, FUKUSHIMA Tadanori, Aditya Baraskar, ITAYA Yuki,
NAGAMINE Kenshin, SAKAI Daisuke (SKY Perfect JSAT Corporation)

近年、100機以上の衛星を使ってサービスを提供する事業者が多数出現している。この環境下で軌道の安全を保つために、不機能衛星を定期的に撤去することが必要であり、宇宙研究機関や複数の企業から様々な除去方法が提案されている。ほとんどの方法では、サービス衛星が何らかの方法により不機能宇宙物体と一体化し、一緒に軌道降下する。
しかし、不機能宇宙物体は非協力物体であることから、初期の回転と重力傾斜トルク等による外力の影響による振動がミックスされた姿勢になっていると考えられる。回転や振動が大きくなってくると物理接触が非常に困難となる。そのような物体に対しても対応できるように、スカパーJSATと理化学研究所は、非接触の方式であるパルスレーザーによるインパルス生成により、デブリ除去（ADR）を行うこととした。
本発表では、ターゲット衛星の回転を静止するためのレーザー照射方法と解析の結果について紹介する。解析の結果から、本ミッションへの影響を評価する。

Recently, a number of service companies have emerged to provide a single service using more than 100 satellites named as Mega-Constellation. In order to keep the orbit safe in this environment, there is a need to periodically remove non-functional satellites and various removal methods have been proposed from space research institute and several companies.
In most methods, the service satellite is somehow integrated with the non-functional space object and deorbit together. However, since the non-functional space object is a non-cooperative object, its attitude is never stable and is likely to be a mix of initial rotation and vibration caused by external forces such as gravitational gradient torque. Therefore, physical contact becomes very difficult as the rotation and vibration increase. To be able to deal with such objects, SKY Perfect JSAT and RIKEN decided to perform active debris removal (ADR) by generating impulses with a pulsed laser, a non-contact method. And we are now designing a payload system using pulsed lasers.
This presentation will provide an overview of the laser irradiation method and simulation results for stopping the rotation of the target satellite. From the results of the simulations, the effects on this mission will be evaluated.

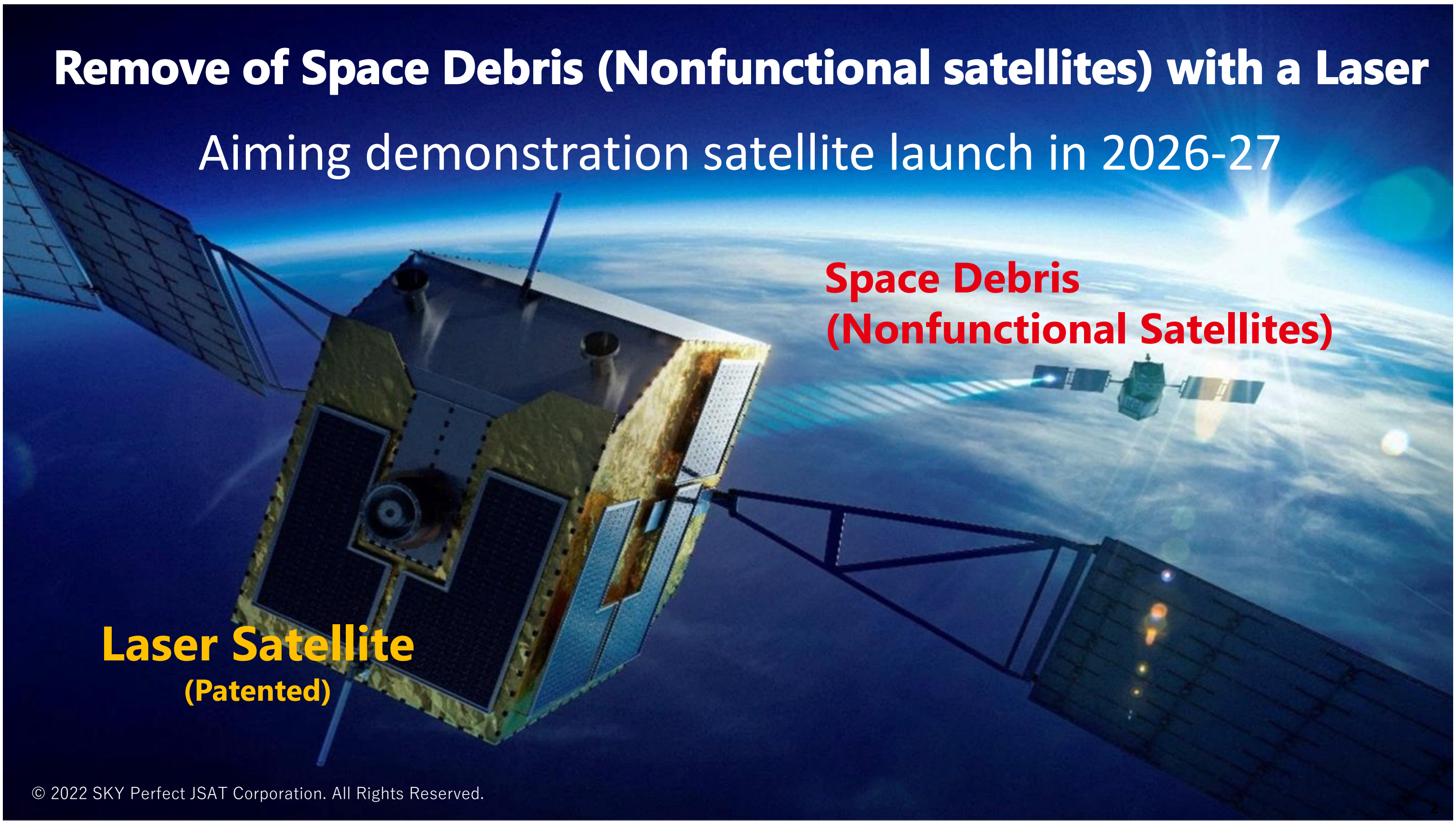
The 10th Space Debris Workshop

C17. Analysis for Detumbling of Space Debris with Pulsed Laser
パルスレーザを用いたスペースデブリの回転静止解析

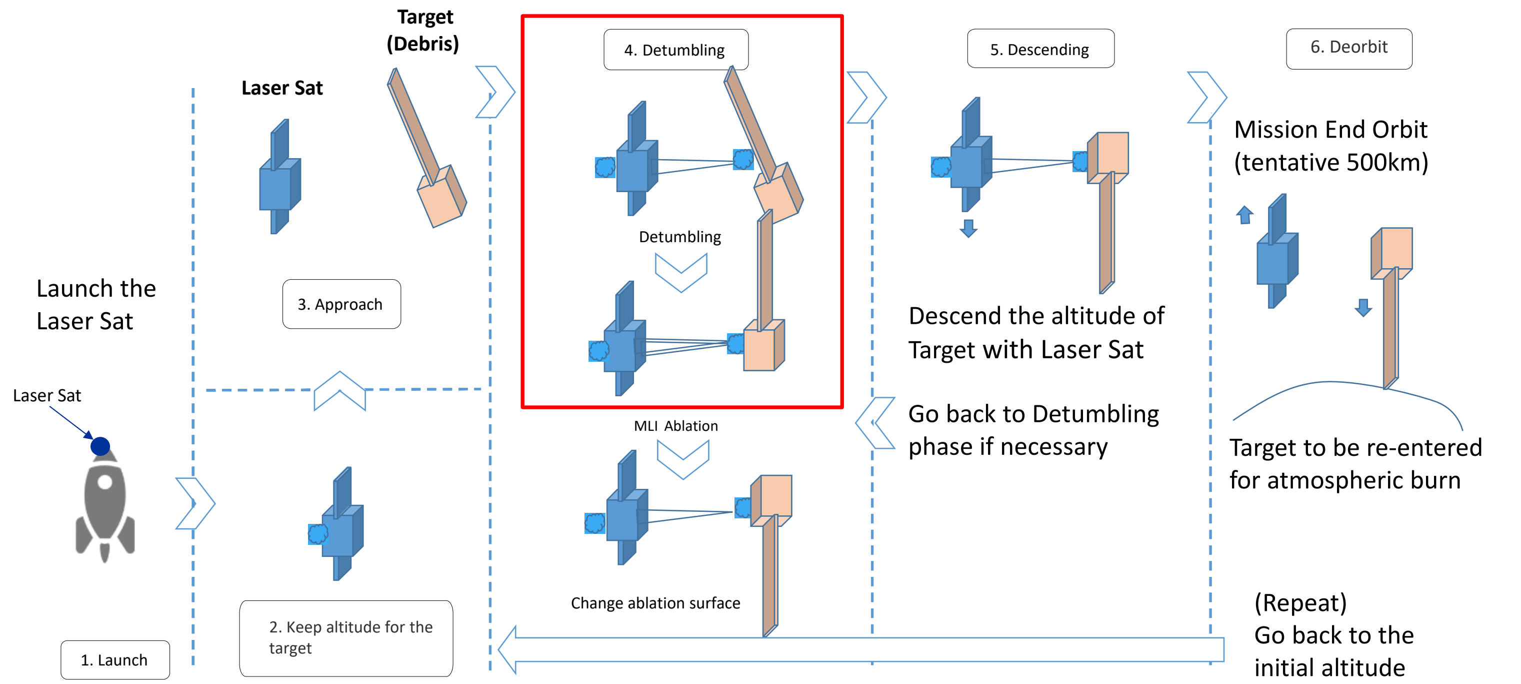
November 30th, 2022

Tomoaki Fujihara, Tadanori Fukushima, Aditya Baraskar
Yuki Itaya, Kenshin Nagamine, Daisuke Sakai
SKY Perfect JSAT Corporation

スカパーJSAT 未知を、価値に。

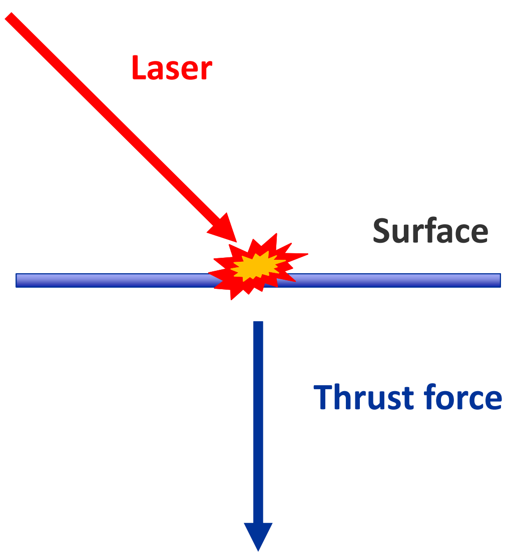


Mission Scenarios



  スカパーJSAT 未知を、価値に。

Constraint

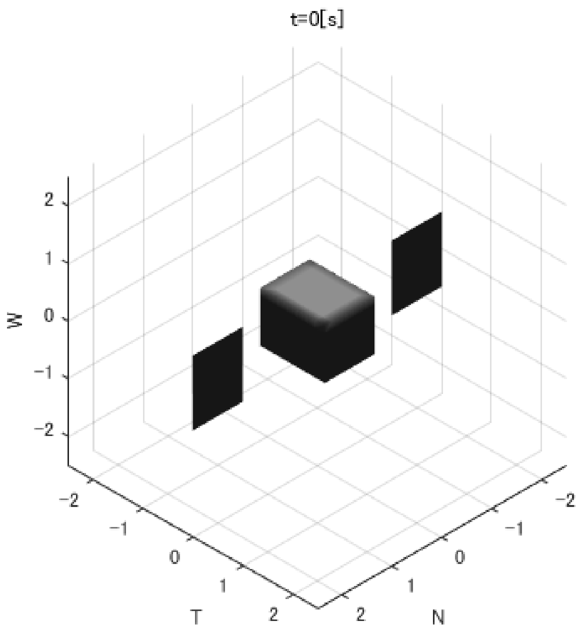


- ✓ Thrust has the property of occurring in the normal direction to the surface of the irradiation.
- ✓ The surface that can be irradiated depends on the attitude angle of the target satellite.

The rotation of the target satellite must be stopped in order to move to the Descending Phase.

  スカパーJSAT 未知を、価値に。

Conditions of simulation



Size	1 x 1.3 x 1	m^3
Mass	150	kg
Moment of inertia	$\begin{bmatrix} 32.6 & 0 & 0 \\ 0 & 73.7 & 0 \\ 0 & 0 & 79.9 \end{bmatrix}$	kgm^2
Initial angular velocity in body frame	[1, 0.5, 0]	deg/s
Nominal angular velocity in orbital frame	$[0, 0, 0.0548]$	deg/s
Laser Ablation Thrust	0.72	mN

*Assume that the laser is always available. In other words, it is assumed that there are no restrictions on the time the laser can be irradiated.

*Only gravity gradient torque is taken into account.

* Define that the rotation stopped when the norm of the error from the nominal value reaches 0.05 and is maintained for 10 minutes.

Simulation pattern

1. Laser steering or controlling the attitude of the laser satellite to irradiate the laser to an arbitrary location

→Assumed to efficiently deter rotation of target satellites

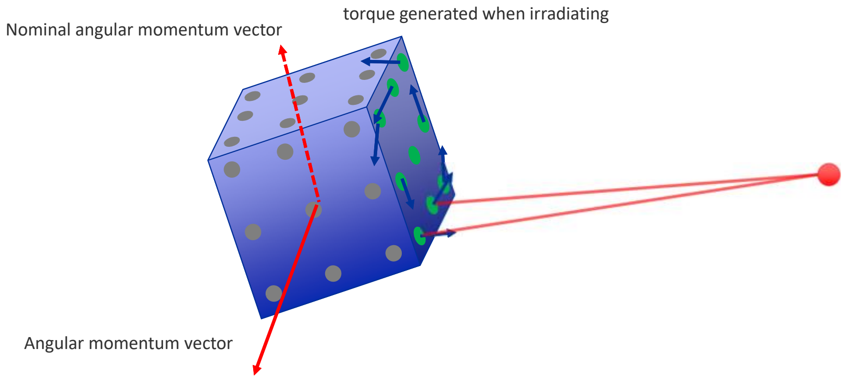
2. Laser irradiation is always directed at the center of the target satellite.

→ Assumed operation when steering mechanism cannot be installed or in case of steering mechanism failure

Irradiating Algorism

Simulation 1

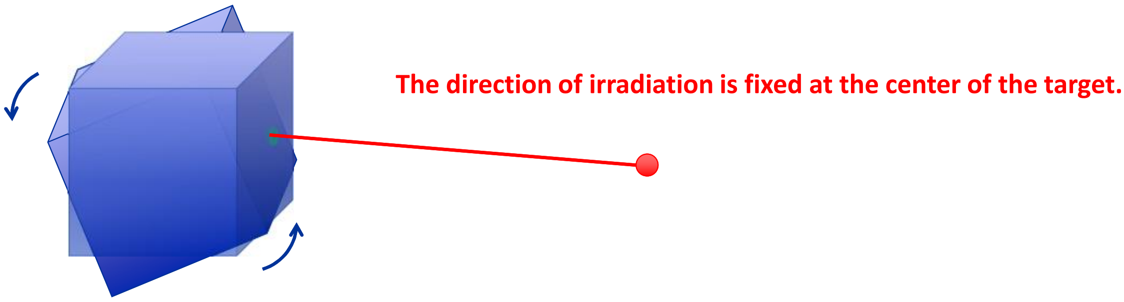
1. Determine points that can be irradiated from laser satellite
2. Calculate the difference between the nominal angular momentum vector and the current angular momentum vector
3. Set the irradiation position that generates torque close to the vector obtained in step 2 or the inner product with the irradiation direction of one step ago as an evaluation function, and calculate the optimum irradiation point from step 1.



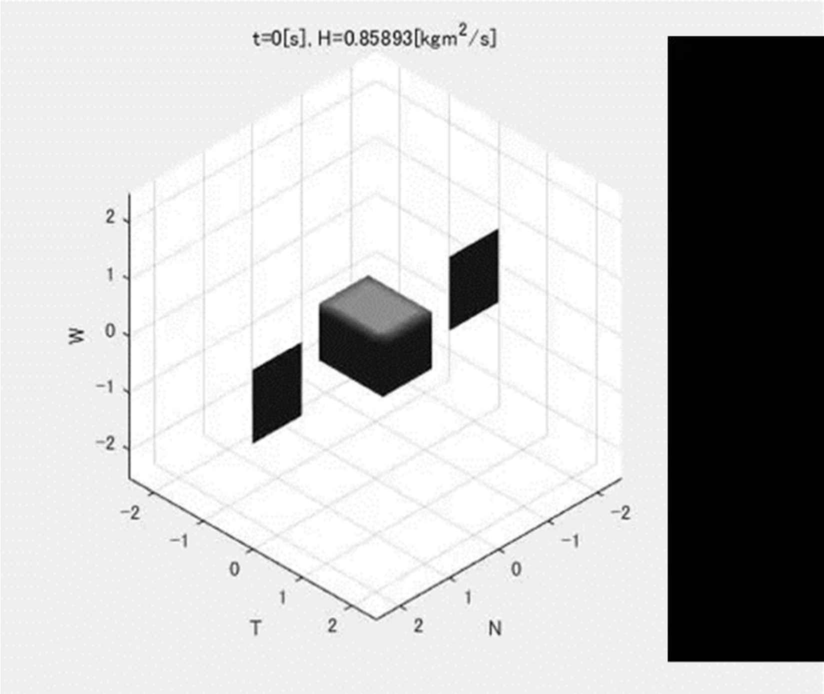
Irradiating Algorism

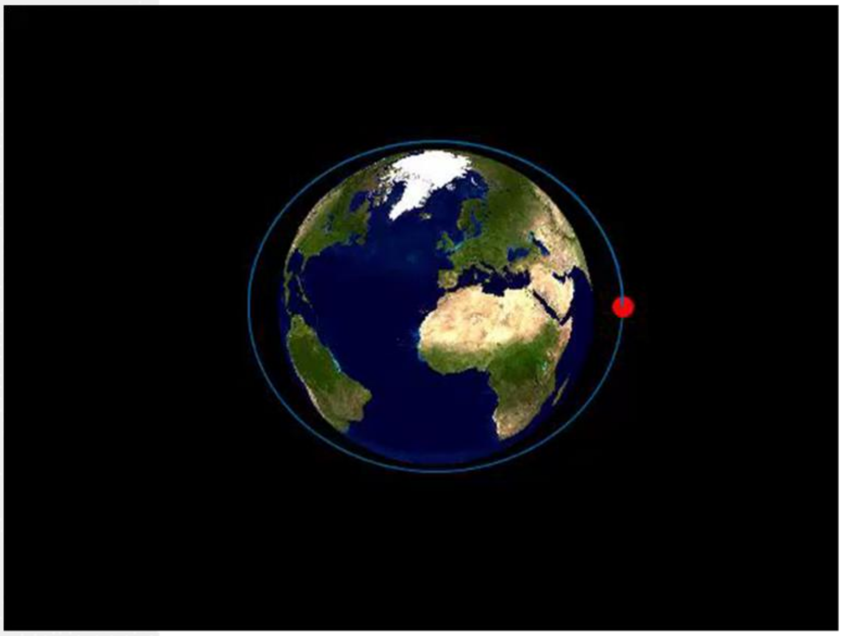
Simulation 2

1. Determines the irradiation point when the laser is attempted at the center of the target satellite
2. Calculate the difference between the nominal angular momentum vector and the current angular momentum vector
3. Judges whether the torque generated at the irradiation point determined in step 1 generates a torque close to the vector determined in step 2, and if it is close, irradiates it.

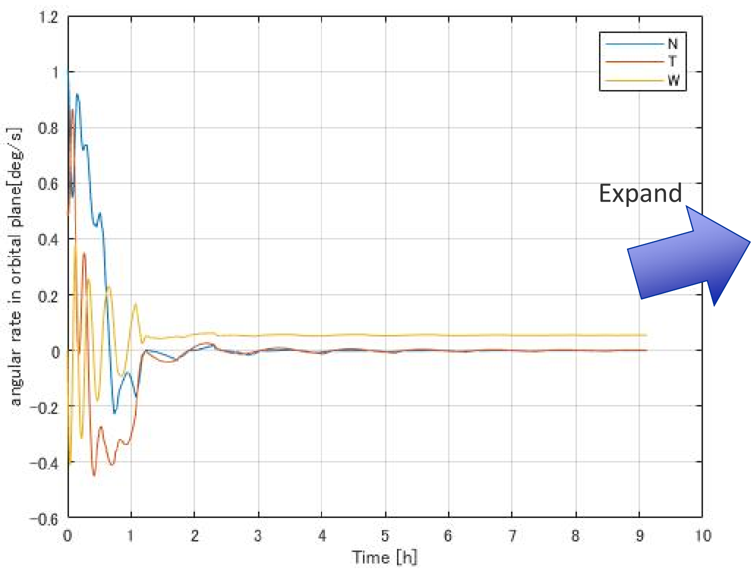


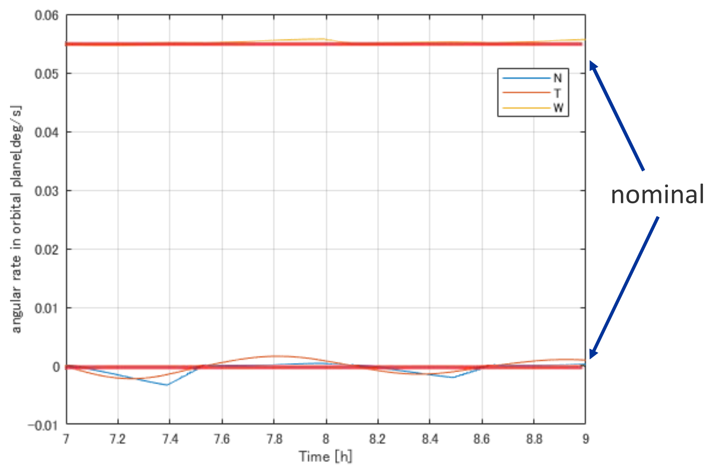
Simulation Results 1





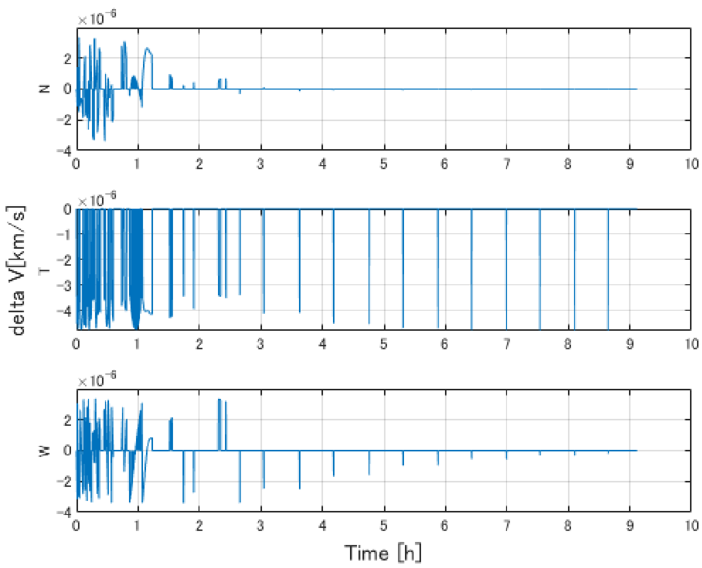
Simulation Results 1

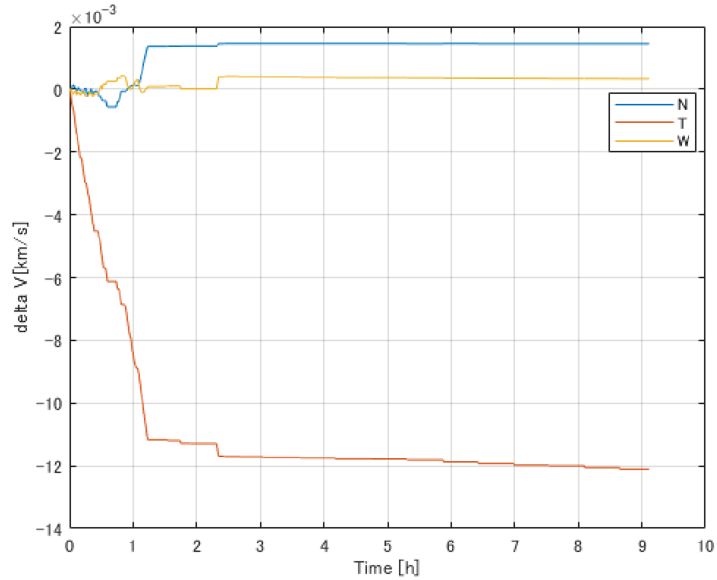




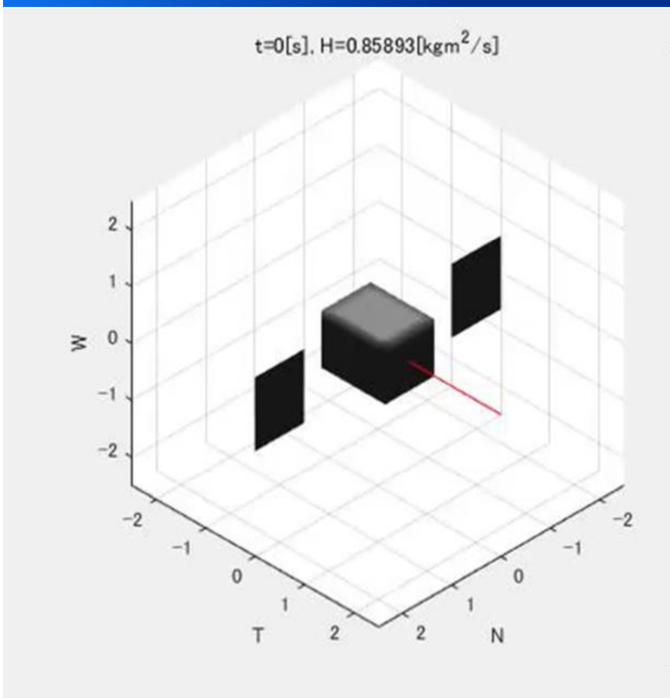
It took 1.22 hours to stop the rotation.

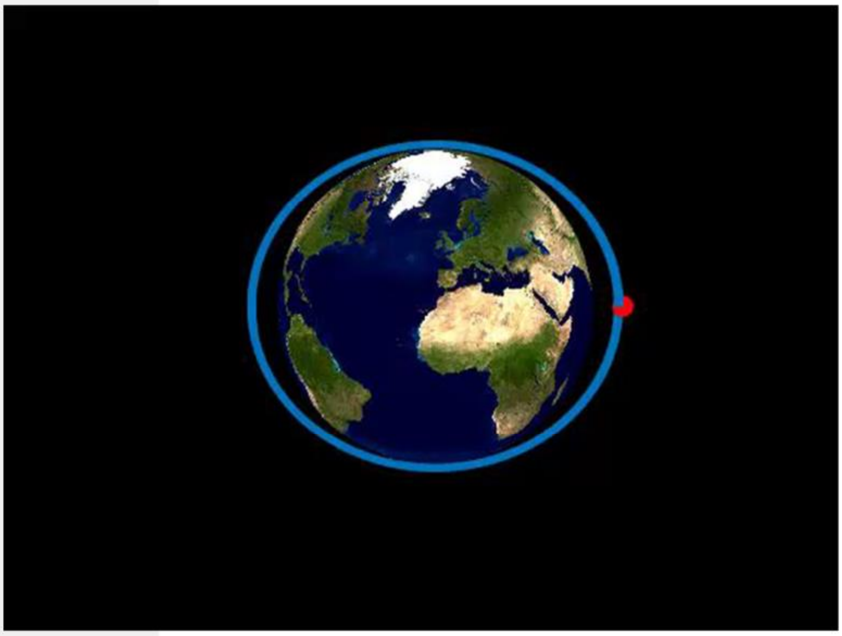
Simulation Results 1



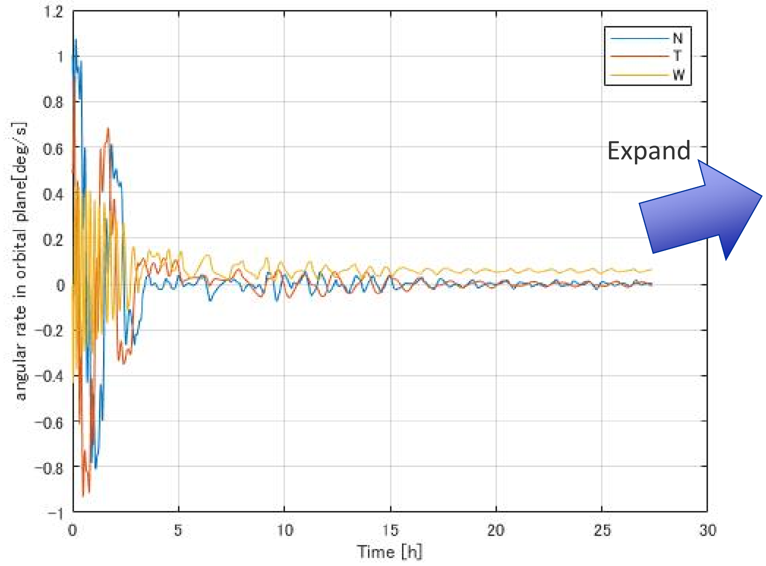


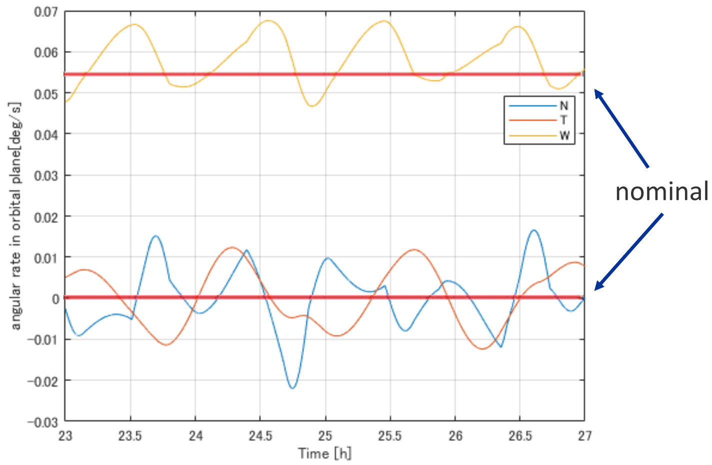
Simulation Results 2





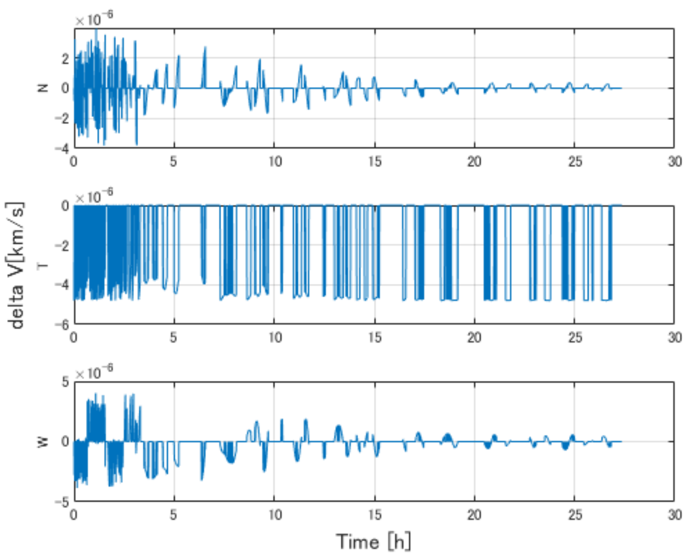
Simulation Results 2

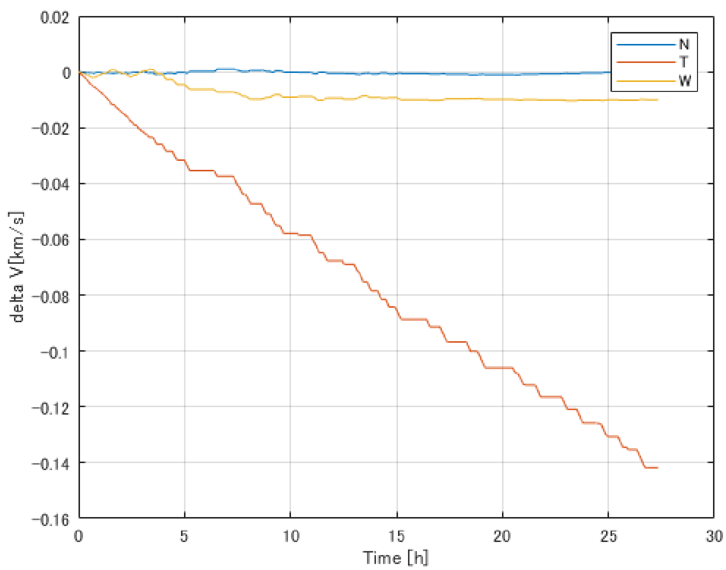




It took 5.38 hours to stop the rotation.

Simulation Results 2





Summary

- If a steering mechanism is available under the conditions of this simulation, the rotation can be stopped in about 1.2 hours.
- On the other hand, even without a steering mechanism, most of the rotation can be stopped in 5.4 hours.
- The robustness of the mission was confirmed by the ability of multiple irradiation algorithms to reduce rotation.
- The effect of ΔV, which also occurs in the out-of-plane and earth directions, needs to be examined in the future.

C18

レーザアブレーションを用いたマルチデオービットの相対軌道設計
Formation Flying Design for Multi-deorbit Using Laser Ablation

〇五十部駿，正木翔，吹井柊太，吉村康広，花田俊也（九州大学），
板谷優輝，藤原智章，福島忠徳（スカパーJSAT 株式会社）
〇ISOBE Shun, MASAKI Kakeru, FUKII Shuta, YOSHIMURA Yasuhiro, HANADA Toshiya (Kyushu University),
ITAYA Yuki, FUJIHARA Tomoaki, FUKUSHIMA Tadanori (SKY Perfect JSAT Corporation)

能動的デブリ除去の一つに，レーザ照射により表面から放出する物質の反作用を利用する手法がある．このレーザアブレーションを用いたデブリ除去ミッションでは，デブリに非接触であるため安全性が高い．さらに取付デバイスや燃料を必要としないため，単一のターゲットを軌道離脱するだけでなく，複数のターゲットを同時に軌道離脱するマルチデオービットへの拡張が見込まれる．本発表では，ターゲットの近傍軌道へランデブー後の軌道離脱フェーズにおける，サービス衛星と複数ターゲットのフォーメーションを提案する．レーザ照射時間，衝突回避性能を評価指標とし，レーザシステムの制約を満たす２つのフォーメーションを設計する．またサービス衛星の姿勢変更を伴うフォーメーションを含む２つの案について検討を行う．

To remediate the orbital environment, active debris removal (ADR) from low Earth orbit is required. Laser ablation is a vital technology for contactless active debris removal, where a service satellite irradiates laser pulses to a target satellite to generate the ablation force for deorbiting. Since the ADR method using a laser requires no deorbiting device to attach, the ADR by laser enables simultaneously deorbiting multi-targets, which is a promising ADR technology. As a preliminary study of multi-deorbit, this paper designs the formation with respect to multi targets to maximize the laser duration or minimize collision probability. Furthermore, the laser system has significant constraints such as laser focal length, laser irradiating angle, and camera angle. Thus, the designed formations must satisfy the constraints of the laser system. To this end, two formations that require attitude control or no attitude control are proposed. Their performances are compared in terms of safety and deorbit efficiency.

Nov. 30, 2022

C18. Formation Flying Design For Multi-Deorbit Using Laser Ablation

レーザアブレーションを用いたマルチデオービットの相対軌道設計

Shun Isobe[1)], Kakeru Masaki[1)], Shuta Fukii[1)], Yasuhiro Yoshimura[1)], Toshiya Hanada[1)]
Yuki Itaya[1) 2)], Tomoaki Fujihara[2)] and Tadanori Fukushima[2)]
([(1)] Kyushu University, [(2)] SKY Perfect JSAT Corporation)

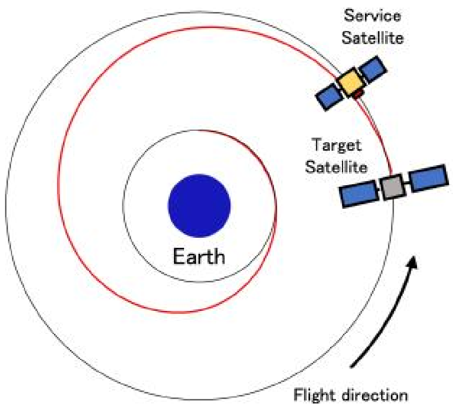
五十部駿[1)]，正木翔[1)]，吹井柊太[1)]，吉村康広[1)]，花田俊也[1)]
板谷優輝[1) 2)]，藤原智章[2)]，福島忠徳[2)]
([(1)] 九州大学, [(2)]スカパーJSAT株式会社)

Wednesday, November 30th, 2022
10th Space Debris Workshop

KYUSHU UNIVERSITY　Formation flying design for multi-deorbit using laser ablation　1

1. Background　2. Preliminaries　3. Design　4. Evaluation and Conclusion

Deorbit service using laser ablation



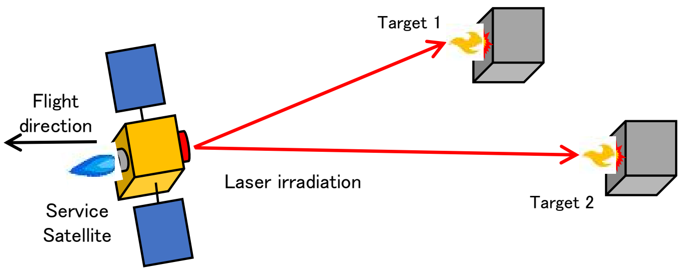
Mission Scenario

Descent altitude using force generated by laser ablation

Advantages [1,2]

- Contactless debris removal
- Adaptability to Tumbling Objects
- No need to carry deorbit fuel

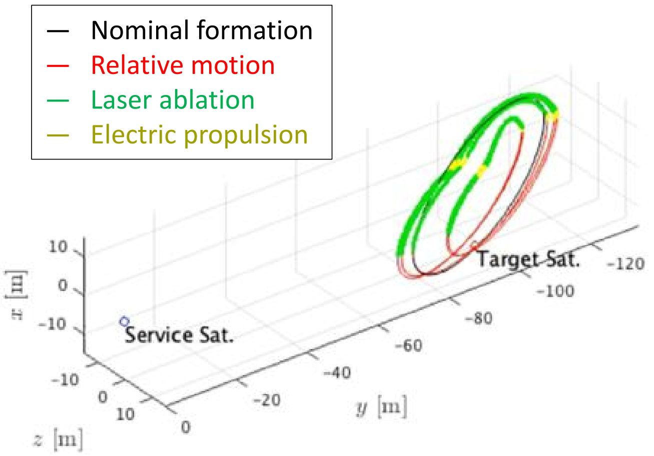
➡ Extending to multi-target deorbit by a single service satellite



KYUSHU UNIVERSITY Formation flying design for multi-deorbit using laser ablation 2

1. Background 2. Preliminaries 3. Design 4. Evaluation and Conclusion

Deorbit Phase



Relative motion respect to the service satellite

Nominal formation

- The relative motion periodically returns to the nominal formation.
- Forming the nominal formation when not irradiating the laser.

Outcome of this research

Nominal formation design and evaluation for multi-deorbit using laser ablation

KYUSHU UNIVERSITY Formation flying design for multi-deorbit using laser ablation 3

1. Background 2. Preliminaries 3. Design 4. Evaluation and Conclusion

Relative motion [3,4]

Relative Orbital Elements (ROE)

$$\begin{bmatrix} \delta a \\ \delta\lambda \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \end{bmatrix} = \begin{bmatrix} (a_d - a)/a \\ (u_d - u) + (\Omega_d - \Omega)\cos i \\ e_{xd} - e_x \\ e_{yd} - e_y \\ i_d - i \\ (\Omega_d - \Omega)\sin i \end{bmatrix}$$

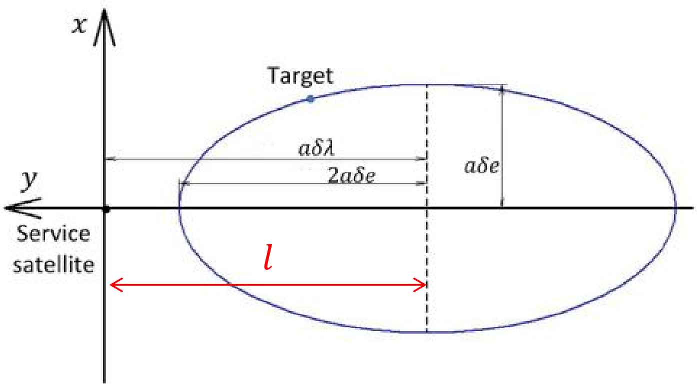
Safety Ellipses

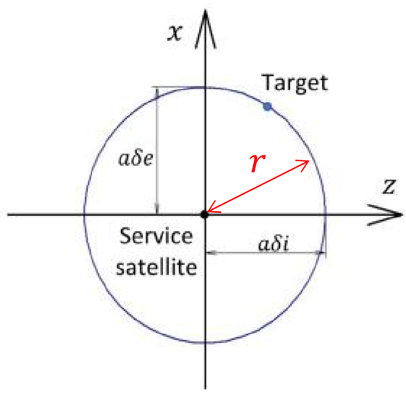
- Bounded in-plane motion
- Target doesn't intersect the tangential axis.

In this research

$a\delta a = 0 \quad \delta\boldsymbol{e} \parallel \delta\boldsymbol{i} \quad a\delta\lambda = l \quad a\delta e = a\delta i = r$

Formation parameters = l , r

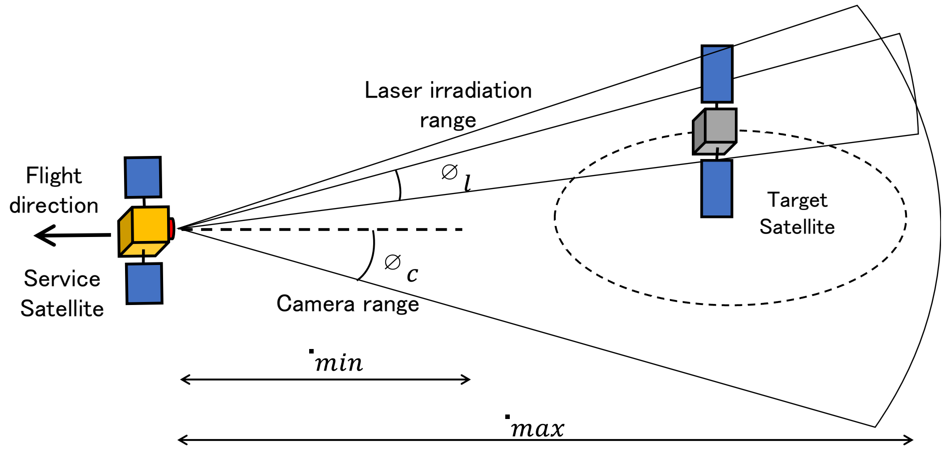




KYUSHU UNIVERSITY — Formation flying design for multi-deorbit using laser ablation — 4

1. Background 2. Preliminaries 3. Design 4. Evaluation and Conclusion

Constraint



Laser system
$\emptyset_l$=5 [deg]
l_{max} = 200 [m]
$\emptyset_c$=10 [deg]
l_{min} = 50 [m]

- Always capturing the targets by the camera
- Limited laser and camera range

➡ Evaluate the closest distance and laser irradiation time

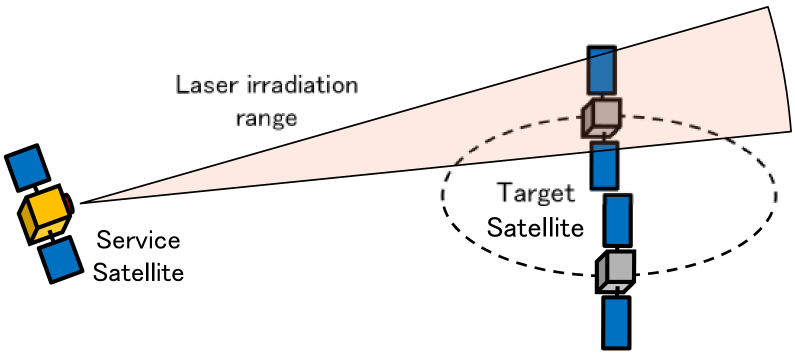
KYUSHU UNIVERSITY — Formation flying design for multi-deorbit using laser ablation — 5

1. Background 2. Preliminaries 3. Design 4. Evaluation and Conclusion

Design Policy

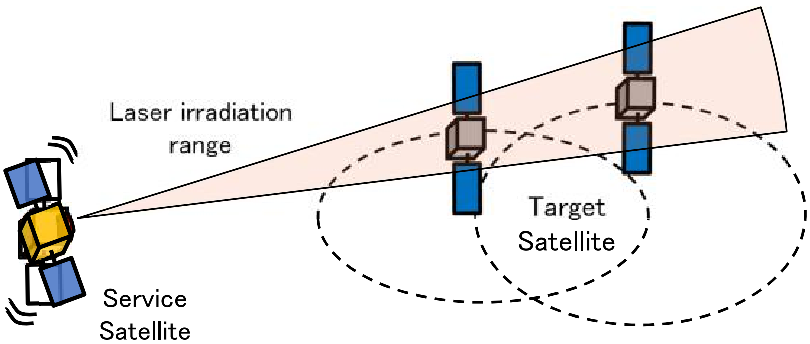
Formation 1

- Same relative orbit
- One by one irradiating laser
- No attitude control



Formation 2

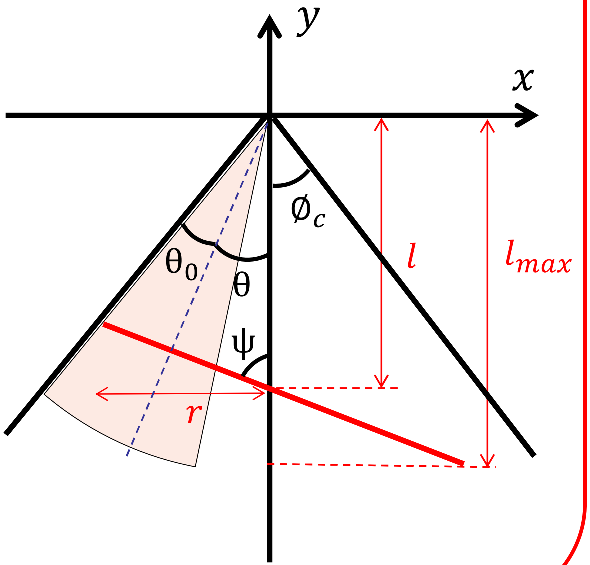
- Different relative orbit
- Always irradiating laser
- Need attitude control



Formation 1

Input

$\phi_l, \phi_c, l_{max}, r$



output

l, θ

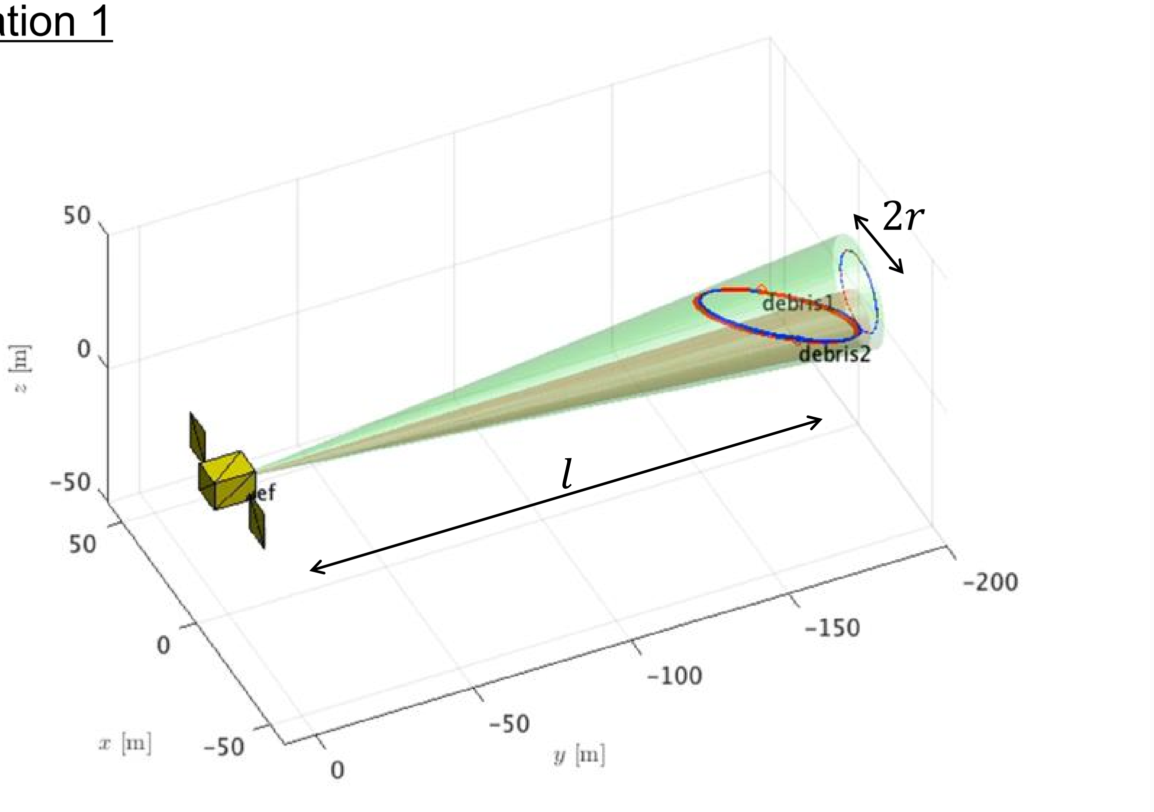
$$r_{max} = \frac{\tan\phi_c}{1 + 4\tan\phi_c} l_{max} \qquad l = l_{max} - 2r$$

$$\theta = \begin{pmatrix} -\mathrm{atan}\left(\frac{l\sqrt{-l^2\tan(\theta_0)^2+4r^2\tan(\theta_0)^2+r^2}+2r^2}{l^2-4r^2}\right) \\ \mathrm{atan}\left(\frac{l\sqrt{-l^2\tan(\theta_0)^2+4r^2\tan(\theta_0)^2+r^2}-2r^2}{l^2-4r^2}\right) \end{pmatrix} \qquad \theta_0 = \frac{\phi_l}{2}$$

Result

r [m]	12.0
l [m]	176.0
θ [deg]	2.53
laser irradiation time [%]	27.2
closest distance [m] (in RN plane)	24.0 (24.0)

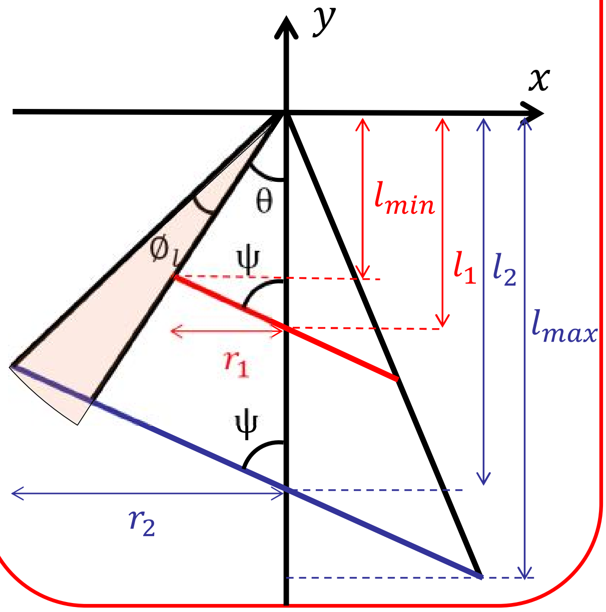
Formation 1



Formation 2

Input

$\phi_l, \phi_c, l_{max}, l_{min}, r_1$



output

r_2, l_1, l_2

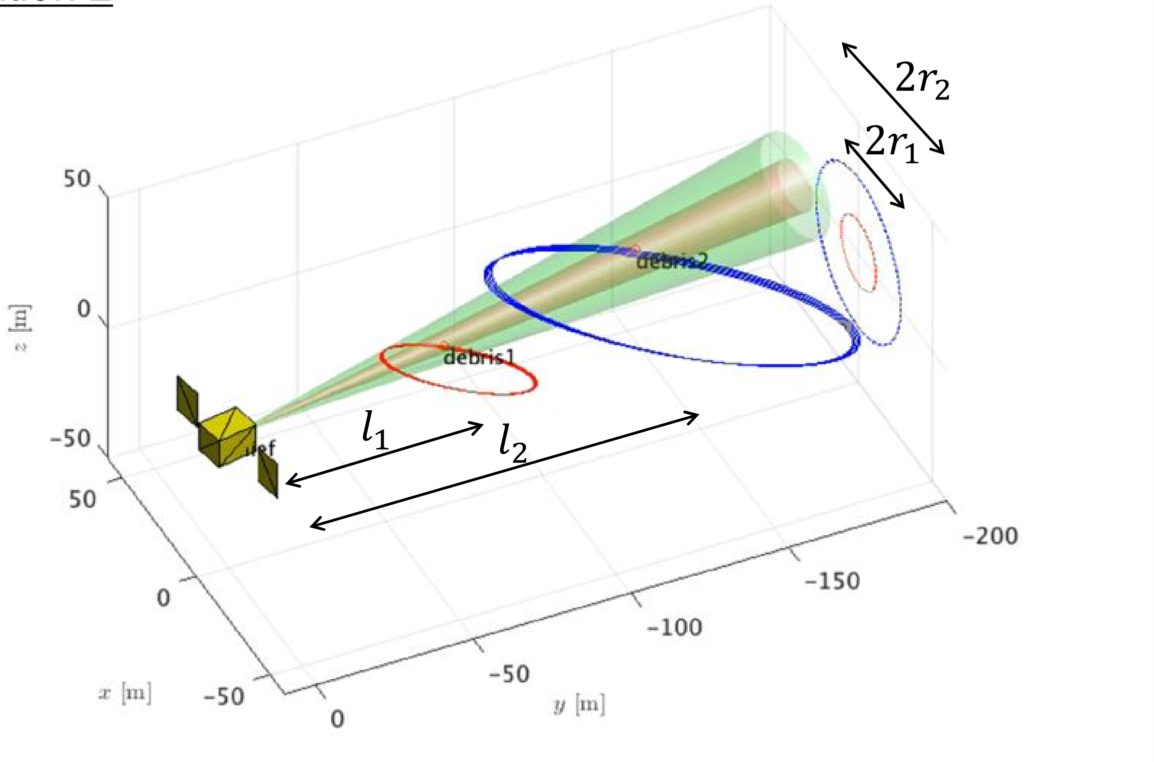
$$r_2 = \frac{\frac{l_{max}}{l_{min}+2r_1}(1+W)}{1+\frac{2r_1}{l_{min}+2r_1}(1+W)} r_1 \quad \begin{cases} W = \frac{\sin\phi_l \sin\psi}{\sin\theta \sin(\phi_l+\theta+\psi)} \\ \theta = arctan\frac{r_1}{l_{min}} \\ \psi = arctan\frac{1}{2} \end{cases}$$

$$l_1 = l_{min} + 2r_1 \qquad l_2 = l_{max} - 2r_2$$

Result

r_1 [m]	12.0
l_1 [m]	74.0
r_2 [m]	28.6
l_2 [m]	142.8
laser irradiation time[%]	100.0
closest distance [m] (in RN plane)	39.2 (16.6)

Formation 2



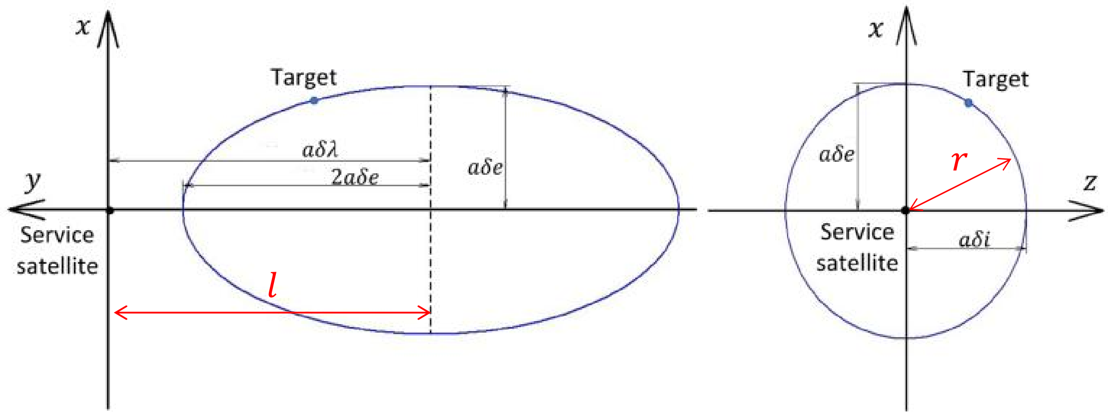
KYUSHU UNIVERSITY Formation flying design for multi-deorbit using laser ablation 10

1. Background 2. Preliminaries 3. Design 4. Evaluation and Conclusion

Evaluation

Result

	Formation 1	Formation 2
r_1 [m]	9.0 – 12.9	5.0 – 21.0
laser irradiation time [%]	40.5 – 25.0	100
closest distance [m] (in RN plane)	18.0 – 26.0 (18.0 – 25.8)	70.0 – 19.3 (16.5 – 12.9)



KYUSHU UNIVERSITY Formation flying design for multi-deorbit using laser ablation 11

1. Background 2. Preliminaries 3. Design 4. Evaluation and Conclusion

Conclusion

- As the first step of multi-deorbit, this research designed two nominal formations.
  Formation 1 → No attitude control
  Formation 2 → Need attitude control
- Formation 2 has longer laser irradiation time and better collision avoidance performance.
- The user should select the formation based on whether or not attitude control.

Future works

- Orbit Control for configuration of the formation
- Analysis of safety between non-cooperating objects

References

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C19

スペースデブリ除去ミッションを目指した電気推進ホールスラスタの開発状況と事業展開
Hall Thruster Development and Business Plan for Mission of Space Debris Removal at NETS Co.,Ltd.

○中村 秀一(株式会社 ネッツ)
○NAKAMURA Shuichi (Nakamura Engineering and Trading Service)

株式会社ネッツは、CRD2 ミッションに適した電気推進ホールスラスタ(スラスタヘッド及び流量調整器)の事業化を目論み、研究開発を行っている。その取組・開発状況について報告するとともに、電源メーカーとのアライアンスによるシステム化、そこから派生する多くの潜在的なユーザーに対する事業展開に関して説明する。
①会社概要並びに電気推進(ホールスラスタ)開発事業化に向けた経緯
②ホールスラスタコンポーネント開発への取組(開発)状況と課題
③ホールスラスタシステム化に向けた取り組み
④ホールスラスタ事業展開及び企業間アライアンスについて

Electric propulsion are now studied and developed now. Condition of developing situation, organized system, company alliance to potential users and business plan for CRD2* mission will be reported.
In the near future, more needs will take place on these business.
Main activity items are as follows:
(1) Business plan of NETS Co., Ltd. with the Hall thruster.
(2) The hall thruster system and component development situation.
(3) Systematized the Hall thruster.
(4) The hall thruster business plan and corporate alliance.
*CRD2（COMMERCIAL REMOVAL OF DEBRIS DEMONSTRATION PhaseII)

C-19 第10回スペースデブリワークショップ講演資料
(10th Space Debris Workshop)

スペースデブリ除去ミッションを目指した電気推進ホールスラスタの開発状況と事業展開

Hall Thruster Development and Business Plan for Mission of Space Debris Removal at NETS Co., Ltd

株式会社ネッツ　中村　秀一

Shuichi Nakamura / Nakamura Engineering and Trading Service

November 30, 2022

1

講演目次 / Contents

NETS(Nakamura Engineering & Trading Service)

2

1. 会社概要及びホールスラスタ開発事業化に向けた経緯
Business Plan(Our Activities) of NETS Co. ,Ltd

株式会社ネッツは、宇宙・航空分野において
推進系を中心に研究・開発支援業務を20年に渡り行ってきました。
Propulsion Systems are studied and developed for over 20 years at NETS Co.,Ltd

現在NETSが特に注力している３大テーマ
Recently Main Business Plan at NETS Co.,Ltd

1. 衛星電気推進(ホールスラスタ)
   Hall Thruster Systems
2. 極超音速飛翔体関連(吸熱反応応用)
   Hypersonic Flight Propulsion
3. ローテ―ティングデトネーションエンジン
   Rotating Detonation Jet Engine Systems

NETS Nakamura Engineering and Trading Service

構成する事業形態と実績

▶ 研究開発事業
Study and Development Business

研究開発に重きをおいた活動

研究開発
・デトネーションエンジンシステム関連
Rotating Detonation Engine System
・触媒点火システム
・電気推進システム関連
研究開発支援
・RDE推進関連
・極超音速飛翔体フライト実証支援
・ホールスラスタ研究開発支援

NETSは
宇宙航空分野
特に推進系を中心に
事業展開しています。

▶ 受託製造
Product Field With Chemical Propulsion System

幅広い対応範囲
Wide Business Field

化学推進系
・触媒点火システム
・1kw級ホールスラスタ　燃焼器　試験スタンド等
・GG-ATR　GG製造・燃焼設備
・固体ロケット多分力推力スタンド

▶ 製品開発
Commercial　Filed

研究を活かしたビジネスモデルの構築

1kw級ホールスラスタ推進システムの
商品化と事業展開
Hall Thruster Systems

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◆ JAXA殿との研究

RESEARCH AND DEVELOPMENT OF A 1-KW CLASS LONG-LIFE HALL THRUSTER SYSTEM FOR JAXA MISSIONS
SPACE PROPULSION 2022
ESTORIL, PORTUGAL | 09 – 13 MAY 2022
Shinatora

◆ 名古屋大学殿との共同研究
Nagoya University

2015-2016 新エネルギー・産業技術総合開発機構

自発予圧縮機構付き回転デトネーションエンジン

特願申請　特願2016-29761(名古屋大学他)
「回転デトネーションエンジン」

◆民間からの受託研究開発
Commercial Development

エンジン系関連
Engine
高温・高圧航空宇宙機器
Space Propulsion
ロケット/衛星推進系システム

◆ 防衛装備庁殿より受託開発
Acquisition Technology & Logistics Agency

2022-2025 安全保障技術推進制度（採択）

極超音速飛行における可変機構の
耐熱性・気密性向上に関する研究

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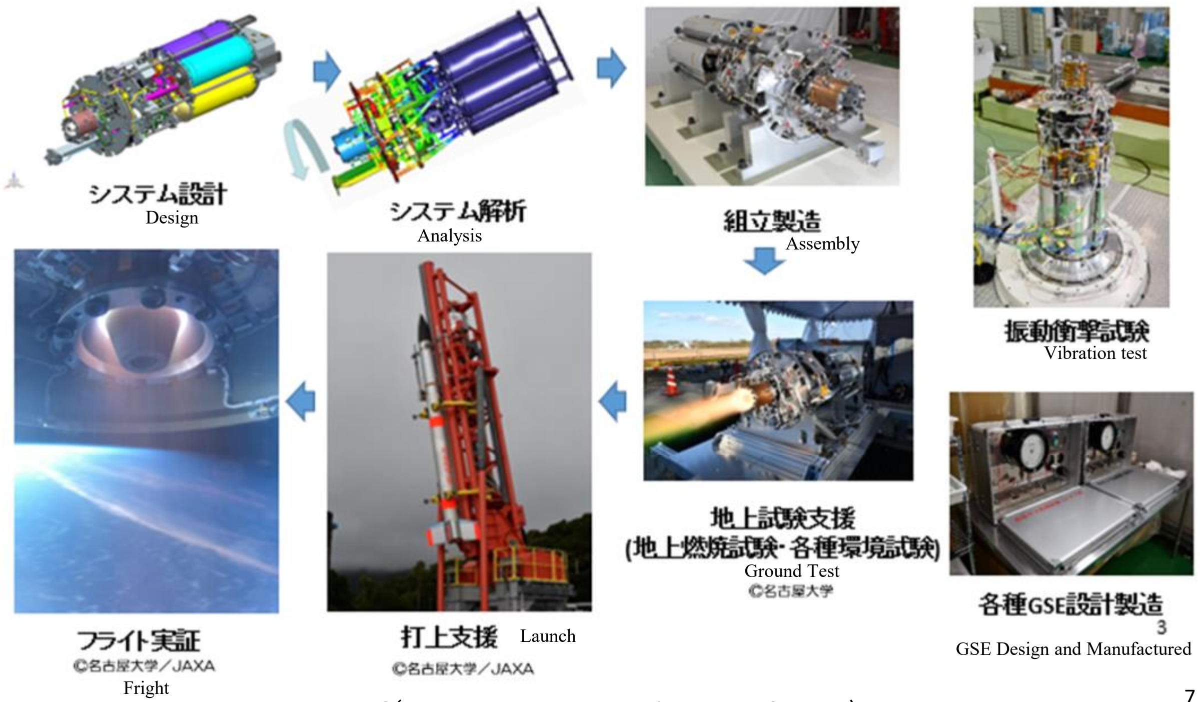
名古屋大学殿DES（Detonation Engine System)の観測ロケット S520-31号機（2020年打上）による飛翔実証まで一連の工程をサポートしました。

Detonation Engine System Launched by S520-31,NETS Design ,Analyzed



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名古屋大学未来材料・システム研究所ホ－ムページ（一部抜粋）

Topics:RDE Space Test Result was successful

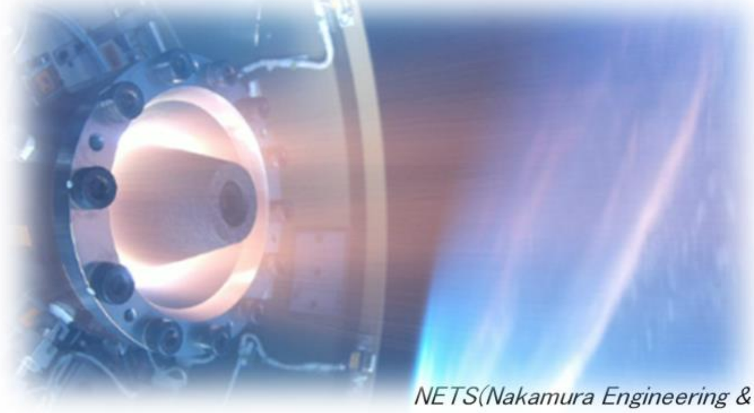
2021.08.19　プレスリリース

世界初！深宇宙探査用デトネーションエンジンの宇宙飛行実証に成功

本研究の成果は、飛行データの詳細解析後、学術論文誌にて公開予定です。

本研究は、2014～2021年度JAXA宇宙科学研究所宇宙工学委員会戦略的開発研究（工学）、2014～2016年度NEDOエネルギー・環境新技術先導研究プログラム、2019～2023年度日本学術振興会科学研究費補助金特別推進研究の支援のもとで行われ、デトネーションエンジンシステムの開発は、株式会社ネッツ（中村 秀一 社長、畳永 慎治氏、原田 修氏、河野 秀文氏、山本 文孝氏、川本 昌司氏、東野 和幸氏）、明治電機工業株式会社（味田 直也氏、神藤 博実氏、堂山 一郎氏、加藤 辰哉氏）の協力のもと実施され、また、制御・計測システムには日本ナショナルインスツルメンツ株式会社の製品（CompactRIO・LabVIEW）が使用されました。

Ⓒ 名古屋大学未来材料・システム研究所



S520-31で打上、
宇宙空間で燃焼するRDE
（Rotating　Detonation　Engine）
©名古屋大学/JAXA

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電気推進事業参入の経緯
Hall Propulsion System Business Plan History

NETS社は、JAXA殿研究「1kw級ホールスラスタ推進システムｖ800」の研究支援を

数年に渡りサポートさせていただく中で、JAXA殿研究成果とNETS社の長年にわたる、

システム開発・生産技術ほか、様々な推進系開発に係る関連技術の融合により、

電気推進システム事業者として、市場参入する決断！

1kw Class Hall Thruster System In JAXA ,Take Part In The Development For Several years

NETS社製 1kW級ホールスラスタ推進システム「NH-1K」の開発スタート
JAXA殿より技術提供・ライセンス申請中

・2025年度に打上予定の　商業デブリ除去実証(CRD2) 用推進システム受注をターゲットとして、開発を進めている。
2025 Year, CDR2 will be Launched, System

・現在EMフェーズで、2022年下期より QT試験・耐久試験・機器嚙合 試験実施予定
2022 Year, QT Endurance Test and Assembly System Test will be done

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2. コンポーネント開発の状況と課題
The Hall Thruster System and Component Development Situation

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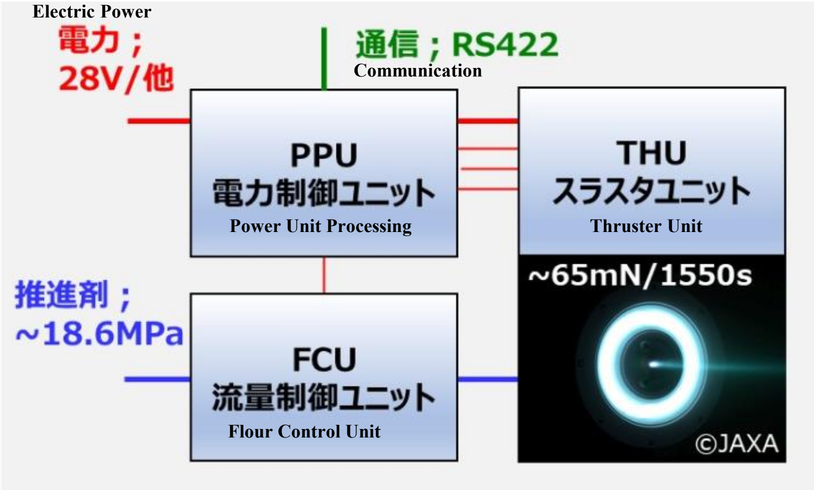
高信頼性・長寿命の電気推進ホールスラスタシステム
Reliability , Long Life Hall Thruster Systems

・20,000時間／20,000サイクル　・トータルインパルス4MNs
20,00hours/20,000cycle Total Impulse



NH-1Kは、JAXA研究「ν800ホールスラスタシステム」のライセンス供与により実現しています。
NH-K is Realized with JAXA License

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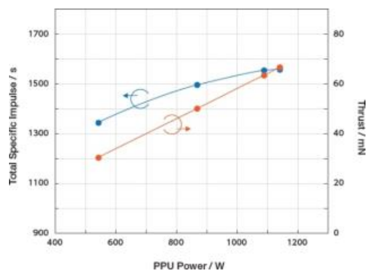
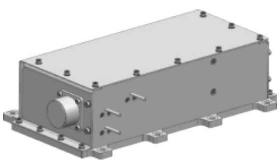
THU スラスタユニット

センターカソードで、コンパクトかつ長寿命

サイズ	Φ150×H135 mm
質量	2.7 kg
推力, 比推力, 電力	グラフ参照
総インパルス	≧4.4 MNs
ON回数	≧20,000回



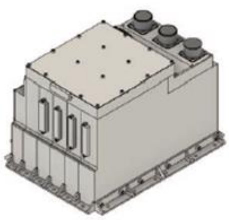
FCU 流量制御ユニット



高圧対応でロバスト

サイズ	300×190×90 mm
質量	2.5 kg
作動圧力範囲	0.4~18.6MPa
内部漏洩量	≦1×10^{-4} Pa・m^3/s
外部漏洩量	≦1×10^{-6} Pa・m^3/s

PPU 電力制御ユニット



小型衛星標準の28非安定バス対応, 自動シーケンス

サイズ	300×200×200 mm
質量	8.0 kg
入力電圧	DC 28V (非安定), 他
通信インターフェース	RS422
トータル効率	≧92%

**株式会社
高橋電機製作所製**

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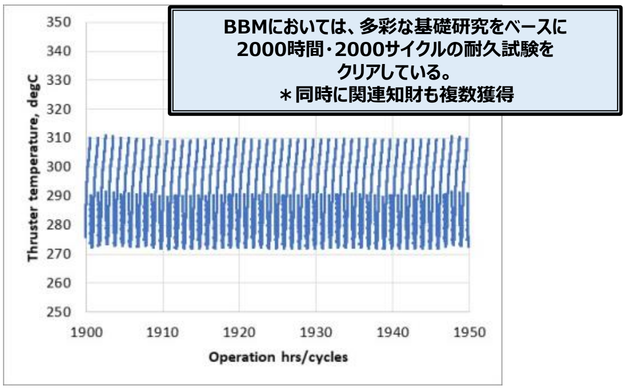
■現在の技術成熟度レベル(Technology Readiness level)

□各ユニットは、エンジニアリングモデル製造を行っており、今年度中には、システム試験・耐久試験などを行いTRL7段階を目指す TRL8(Flight Test) Target Level , EMC Test will be done

□販売展開には、飛翔実証（TRL8）の獲得は必須項目であり、実現を目指す



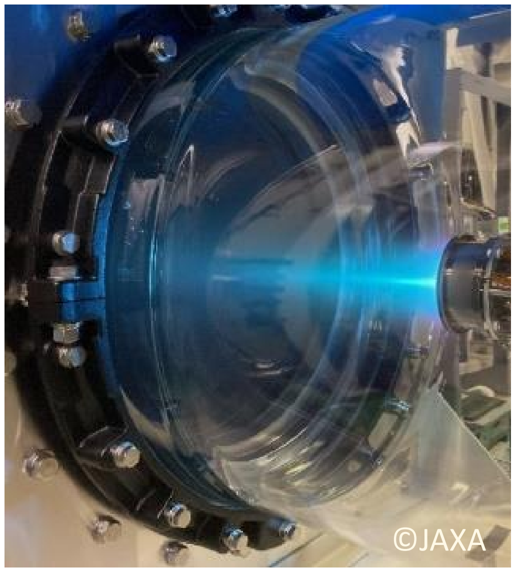
□ 実運用を模擬した（1時間作動+30分停止）×2000セットの耐久試験

RESEARCH AND DEVELOPMENT OF A 1-KW CLASS LONG-LIFE HALL THRUSTER SYSTEM FOR JAXA MISSIONS

SPACE PROPULSION 2022
ESTORIL, PORTUGAL | 09 – 13 MAY 2022

Shinatora CHO[1], Hiroki WATANABE[1], Yoshiki MATSUNAGA[1], Hiroaki KUSAWAKE[1], Yasushi OHKAWA[1], Ryudo TSUKIZAKI[1], Shuichi NAKAMURA[2], Kazuyuki HIGASHINO[2], Toru TAKAHASHI[3]

[1]Research and Development Directorate, Japan Aerospace Exploration Agency, Kanagawa, Japan, Email: choh.shinatora@jaxa.jp
[2]NETS, Saitama, Japan, Email: s-nakamura@nets-co.jp
[3]TDS, Fukushima, Japan, Email: toru_takahashi@tds-i.co.jp



□ ガラスチャンバを用いたEMC試験

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3. ホールスラスタシステム化に向けた取組

Systematized the Hall Thruster

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NH-1Kをベースとした、幅広い拡張性 (様々なサイズの衛星・運用方法をカバー)

Wide Extension Use Field with NH-1K

□コンポーネントの共通化により、開発コストを抑え、低価格化を目指す。
□THU･FCUはオールレンジをカバー可能
（1kW級PPU開発ノウハウをベースに、PPUを開発することにより対応可能）

衛星サイズ	50kg級	100-200kg級	500kg級	1ton級	2-3ton級
スラスタシステム	NH-400(TBD)		NH-1K	NH-1.5K(TBD)	
THU(スラスタヘッド)	オールレンジ対応可能				
FCU(流量制御器)	オールレンジ対応可能				
PPU(電源ユニット)	300-500W級(TBD)	600-1050W級		1500W級(TBD)	
システム質量（推進剤タンク除外）	9kg(TBD)	12kg		15kg(TBD)	
推進性能（寿命平均）	Isp ~1100秒/推力~30mN	Isp ~1550秒/推力~65mN		Isp ~1800秒/推力~85mN	
推進剤	Xe, Kr他(TBD)				
システム	単独システム		単独システム	クラスタ化	
運用方法	軌道投入, 軌道制御		軌道投入, 軌道制御	軌道投入, 軌道制御	
	デブリ回避		デブリ回避	デブリ回避	
	ディオービット		ディオービット	ディオービット	
	超低高度軌道維持		超低高度軌道維持	姿勢制御	
	フォーメーションフライト		デブリ除去, SSAなど軌道上サービス	寿命延長など軌道上サービス全般	

NETS Nakamura Engineering and Trading Service

4. 事業展開及び企業間アライアンスについて

The Hall Thruster Business plan and Corporate Alliance

NETS Nakamura Engineering and Trading Service

古河電気工業㈱殿とのアライアンス

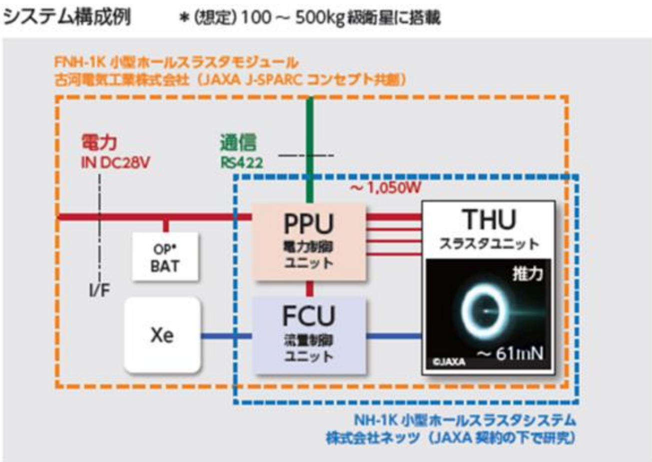
Alliance Furukawa electric Co.,Ltd

企業間アライアンスにより、ビジネスモデルを模索

① 国内衛星メーカーへの売り込み
② ニュースペース企業との新しい衛星利用への協力関係構築
③ 化学推進系との水平統合
④ 宇宙輸送系との垂直統合

多様なシステム構成で
潜在的な顧客・パートナーにアプローチ

この企業間アライアンスの中で、
革新的衛星技術実証４号機に対して
エントリーを行い、飛翔実証機会獲得への
模索も積極的に行っている。



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C20

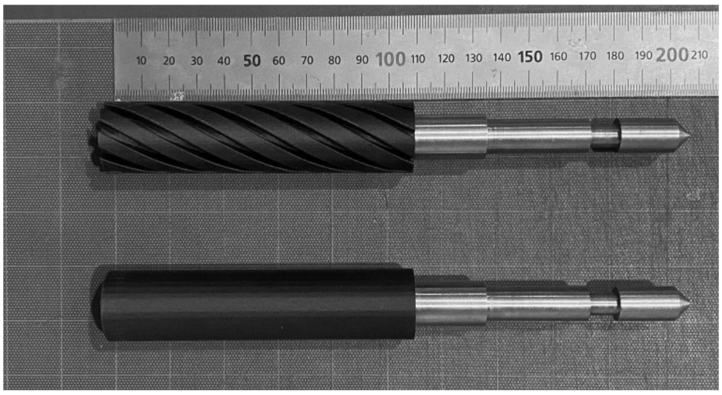
スペースデブリ模擬構造への金属製銛撃ち込みにおける銛回転の影響評価

Effects of Rotation of a Metal Harpoon on Penetration Behavior for Capturing Space Debris

〇玉置悠人，田中宏明（防衛大学校）
〇TAMAKI Yuto, TANAKA Hiroaki (National Defense Academy of Japan)

この研究では回転する銛をデブリ模擬構造へ撃ち込み，その貫入挙動を調べた．対象の傾きと先端形状が貫入挙動に大きな影響を与え，場合によっては貫入が難しくなることがあるため，銛自身に回転を加えることで安定した貫入の実現を目指した．
地上での試験のため，溝を有する銛後端部を炭素粉末入りのナイロン素材で作成し，銛に取り付け，その溝を空気が通ることで銛を回転させた．銛の回転により生じるジャイロ剛性により，銛の直進性を増加させる．回転する銛の影響評価のために，比較用として溝のない銛も用意し，0°，30°，45°で傾いた対象に対する銛の撃ち込みを行った．
実験結果から銛の回転数と撃ち込み速度にはおよそ正の相関があることが分かった．傾き角 0°，30° における銛の撃ち込みでは貫入挙動に大きな差異は見られなかったが，傾き角 45° における銛の撃ち込みでは貫入速度及び貫入孔の大きさが回転しない銛に比べて小さくなった．

In this study, we shot a rotating harpoon into a structure simulating space debris and investigated its penetration behavior. The penetration behavior greatly depends on the harpoon tip shape and an oblique angle of a target. Hence, we make a harpoon rotate to stabilize the harpoon during the penetration. We installed the special part with grooves made of nylon material with carbon powder to the rear part of the harpoon to rotate the harpoon during the penetration experiments on the ground. The harpoon rotates by air passing through the grooves. The gyro effect is generated by the harpoon rotation, and it increases the stability of the harpoon. We also prepared a harpoon without the groove for comparison and shot the harpoon into the target at the oblique angle of 0, 30 and 45 degrees to evaluate the effect of the rotation of the harpoon. It was observed that there was an approximate positive correlation between the rotation speeds and the injection velocity from the experimental results. There is no difference in the penetration behavior of the harpoon at the oblique angle of 0 and 30 degrees. However, the penetration velocity and the size of the penetration hole by the rotating harpoon were smaller than those of the non-rotation harpoon at the oblique angle of 45 degrees.



Harpoon with grooves and harpoon without grooves

10 th Space Debris Workshop
14 December 2022

Effects of Rotation of a Metal Harpoon on Penetration Behavior for Capturing Space Debris

National Defense Academy of Japan

Department of Equipment and Structural Engineering

Yuto Tamaki and Hiroaki Tanaka

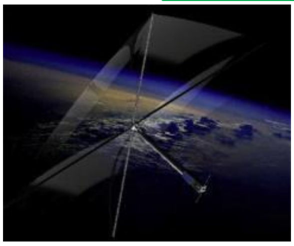
C20
16:45-17:00

1

Active Debris Removal (ADR)

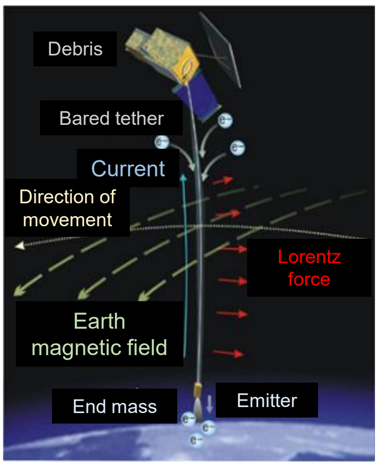
- ADR is a method in which a spacecraft equipped debris removal system actively approaches space debris, captures it, and deorbits it. So, orbital environment is gradually improved.

Debris removal system



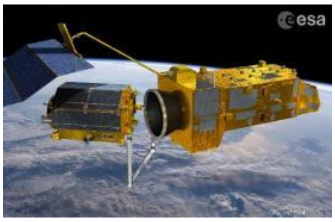
De-orbit sail ©SSC

Propulsion system ©ESA

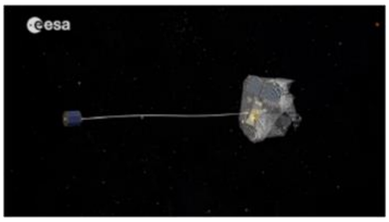


Electrodynamic tether (EDT) ©JAXA

Capturing system

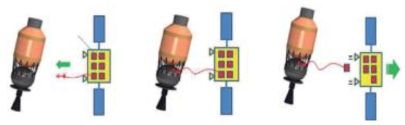


Robotic arm ©ESA

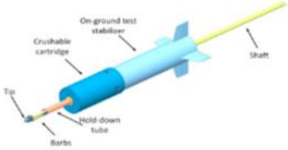


Net ©ESA

Research object



Capture concepts by JAXA

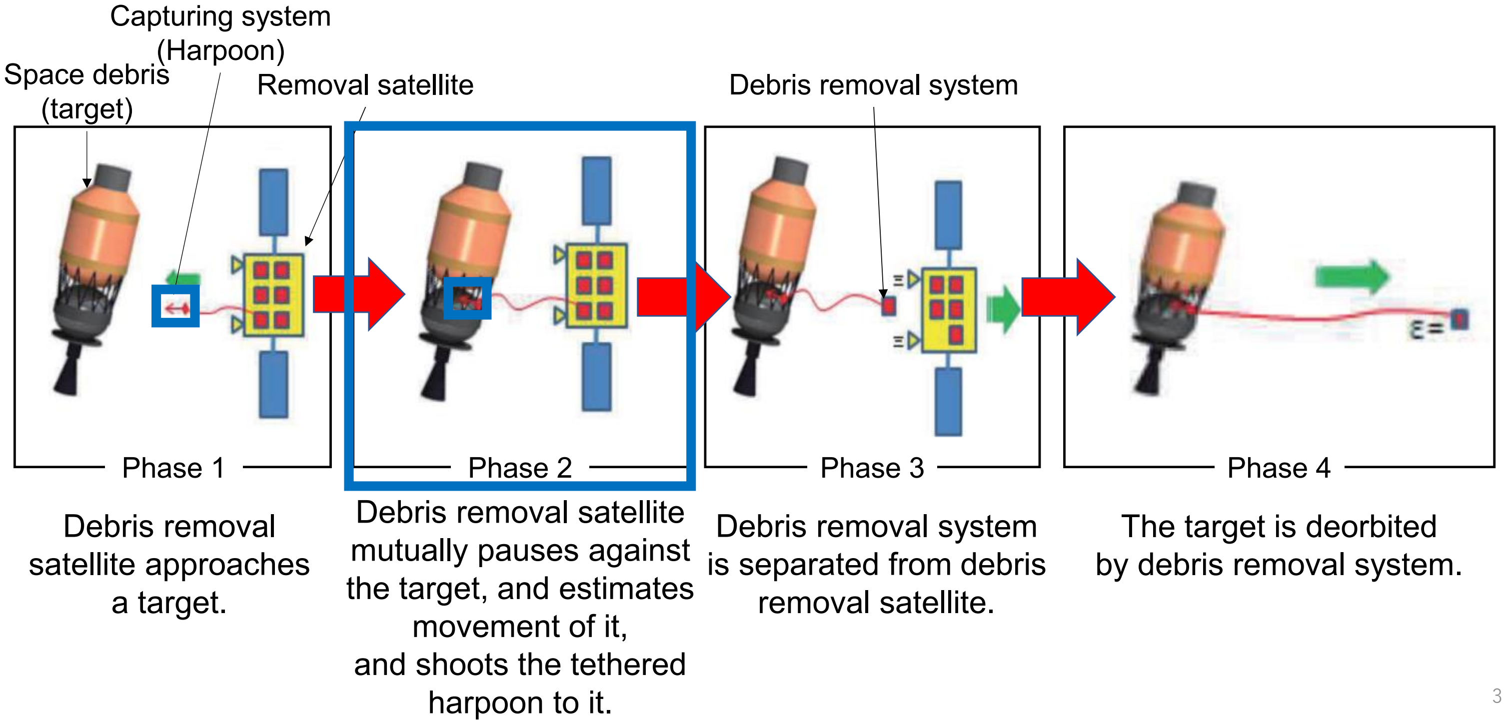


Capture concepts by ESA

Capturing space debris by shooting metal harpoon.

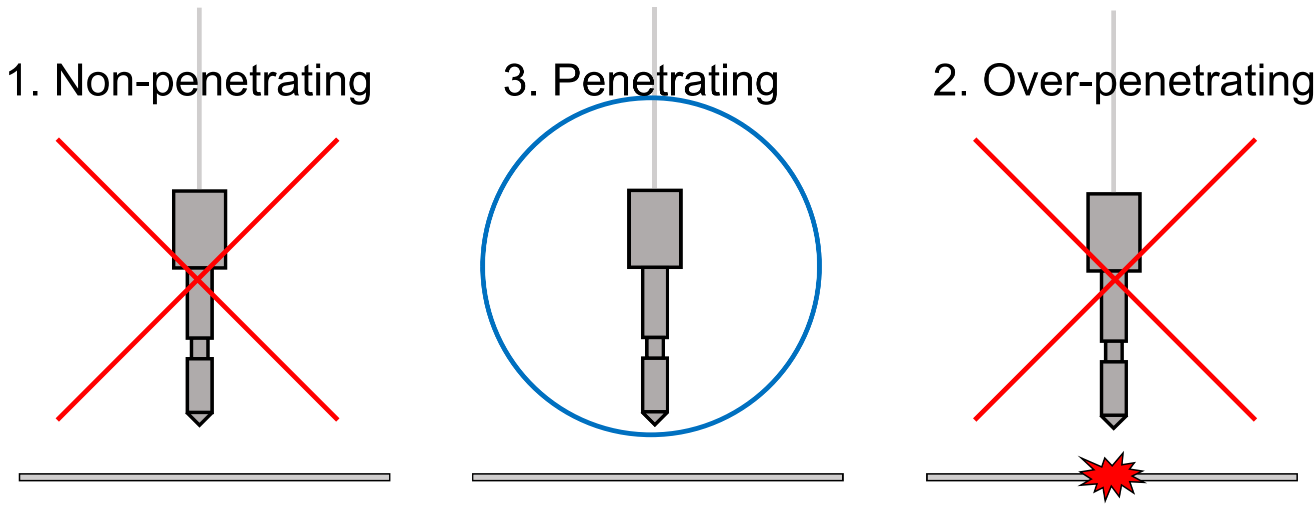
2

Capturing space debris by shooting a metal harpoon



Difference in the penetration states at injection speed

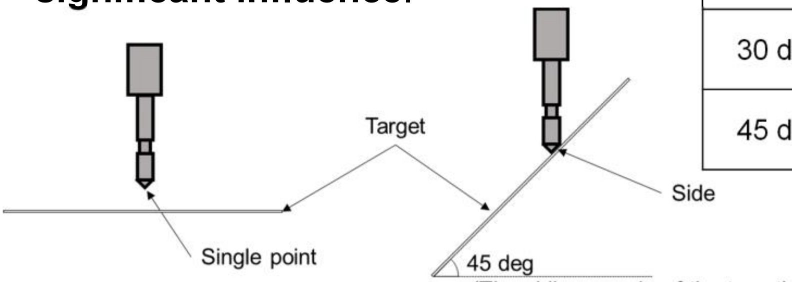
Penetrating state is suitable for capturing space debris because of generating holding force by hooking a narrow section of the harpoon on penetration hole.



The shooting test of a metal harpoon with various tip shapes in previous study

・The penetration velocity of conical harpoon tip is comparably smaller than that of the other tips but it **increases sharply** at an oblique angle of 45 deg.

⇒The relation the tip shape and the oblique angle of the specimen has a **significant influence**.



The collision of the harpoon with conical tip shape

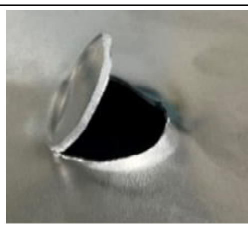
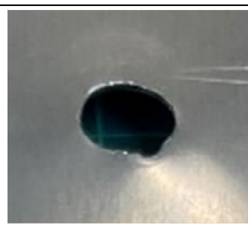
The minimum penetration velocity of each harpoon (m/s)

Angle	Conical 	Spherical 	Flat 	Double-bladed 
0 deg	16.8	22.7	23.6	15.6 (15.0)
30 deg	17.5	23.3 (22.5)	13.9	15.4
45 deg	**35.2**	44.6*	30.9	17.3

* : Velocity of passing through

※ The velocity in parentheses is the average velocity of the difference between the maximum non-penetration velocity and minimum penetration velocity when the difference is greater than 1m/s.

Penetration hole by various tip shapes

Tip shapes	**Conical**	**Spherical**	**Flat**	**Double-bladed**
Penetration hole				
Characteristics	The penetration hole is petaling and pullout resistance is big after penetrating.	The penetration hole is round hole and pullout resistance is not expected after penetrating.	The penetration hole is round hole and pullout resistance is not expected after penetrating.	The penetration hole is round hole and new additional debris is generated.  New additional debris

Research objective about rotation of the harpoon

The problem of the previous study

The conical harpoon tip shape is suitable for capturing space debris.

However, its penetration behavior was greatly changed at the oblique angle of 45 deg.

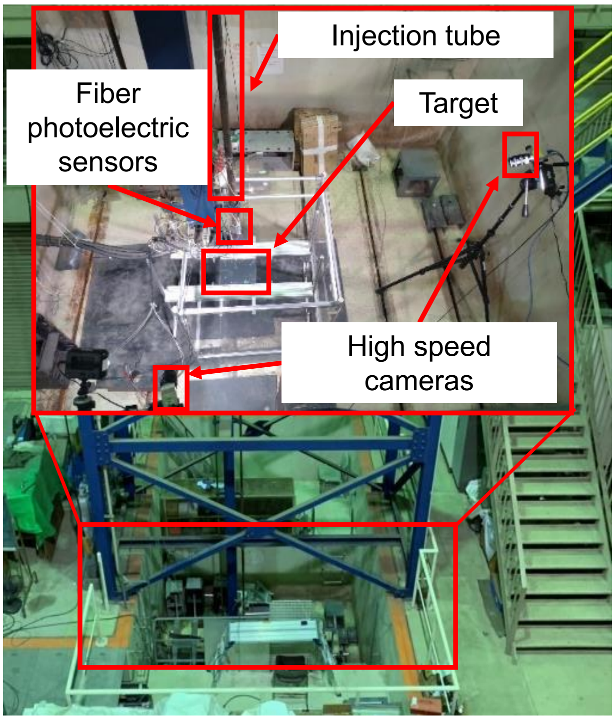
Rotating the harpoon increases its straightness, which is thought to be effective when shooting the target with the oblique angle.

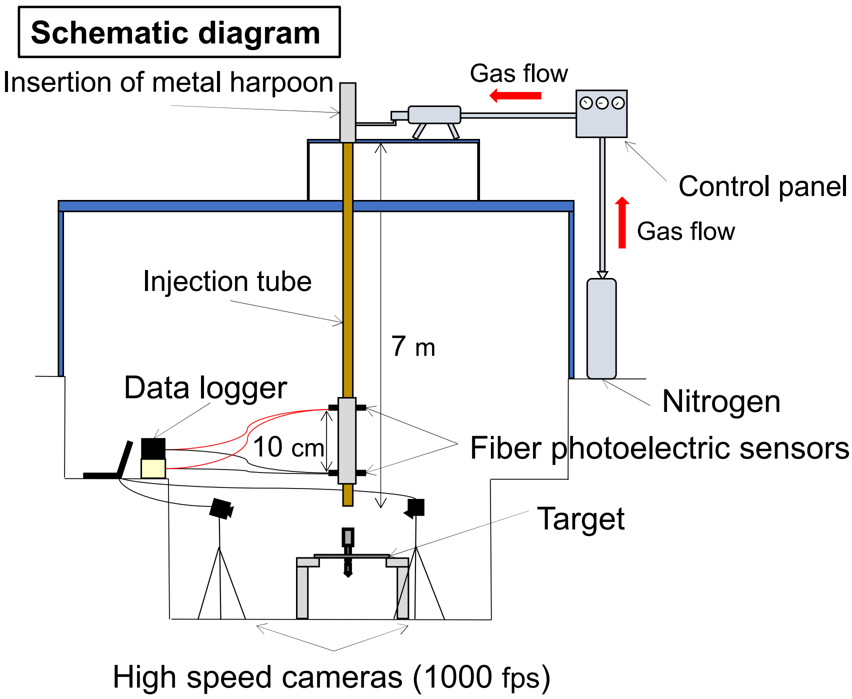
Research objective

- We develop the system for rotating harpoon for ground test.
- We evaluate the effects during shooting the harpoon by rotating it.

7

Experimental equipment in National Defense Academy of Japan



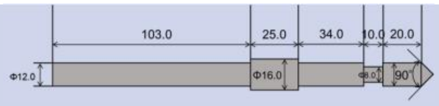


8

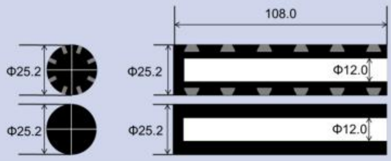
The appearance of a metal harpoon and the structure of the rear part

		Rotation harpoon	Non-rotation harpoon
Material	Core part	Made from SS400	
	Outer part	Made from Onyx (Carbon fiber)	
Appearance			
Mass		200 g	213 g
Inertia momentum		7071.5 $g \cdot mm^2$	8520.9 $g \cdot mm^2$

The size of each component

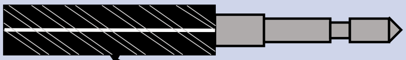


Core part

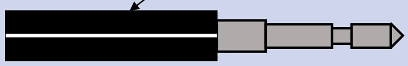


Outer part

Schematic diagram after configuration



We drew white lines on the rear section of the harpoon to make it easier to observe penetration behavior with high-speed camera.



※ Basic study as ground tests

The harpoon rotates by the air flowing through the grooves.

In the experiment, rotation speed is between approximately 700 and 2000 rpm.

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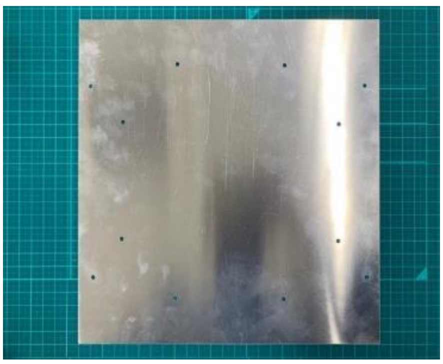
Specification of a target and experimental method

Specification of the target

Material	Al2024-T3
Size (mm)	250 × 250 × 1
Density (kg/m^3)	2770

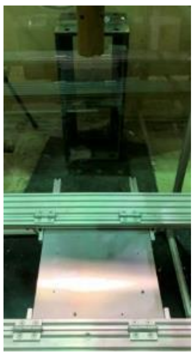


Al2024-T3

Material of space debris is various, but aluminium alloy is commonly used for satellite.

(The target shape is simple because of basic study about shooting the metal harpoon.)

Experimental equipment

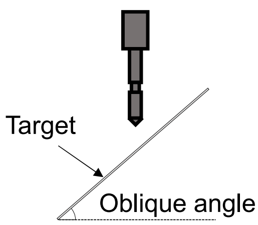


0 deg

30 deg

45 deg

We evaluate penetration characteristics of the harpoon while oblique angle of fixed target was changed.



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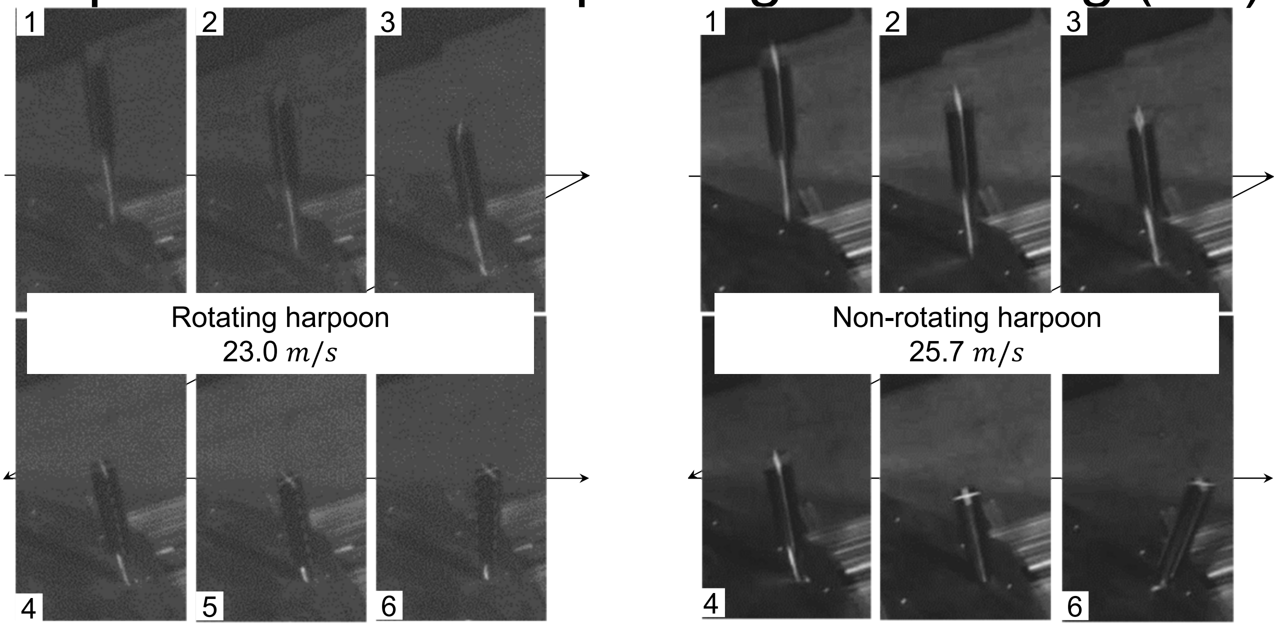
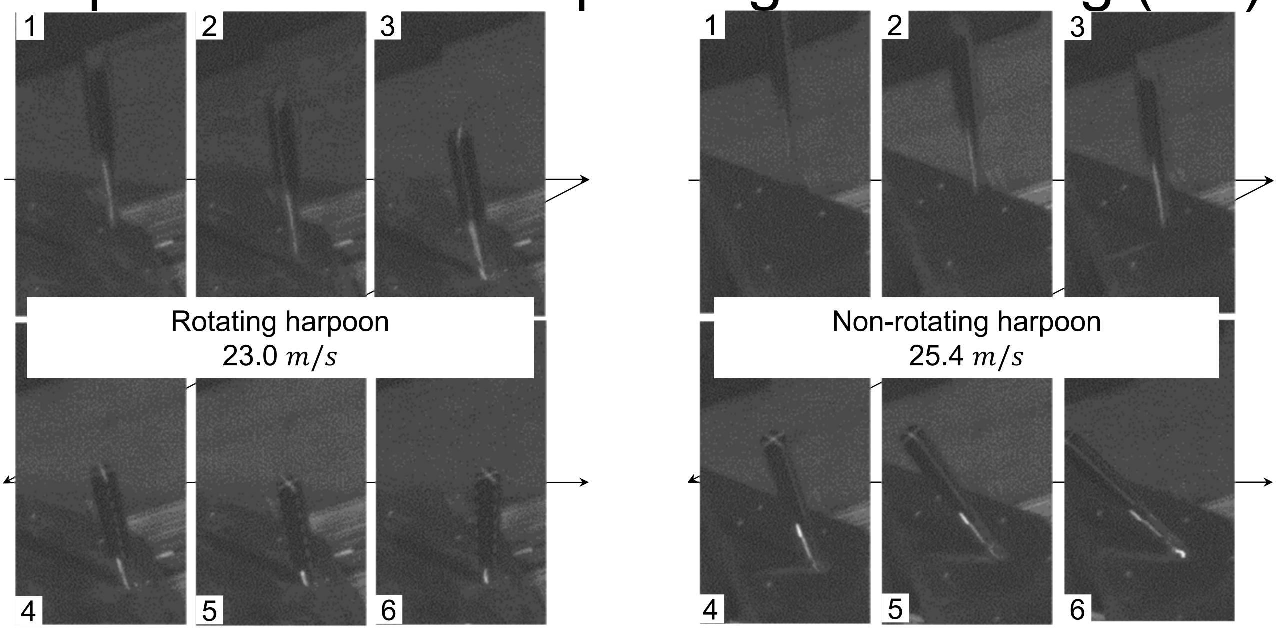
Shooting tests of rotating and non-rotating harpoons at the oblique angle of 45 deg (1/2)



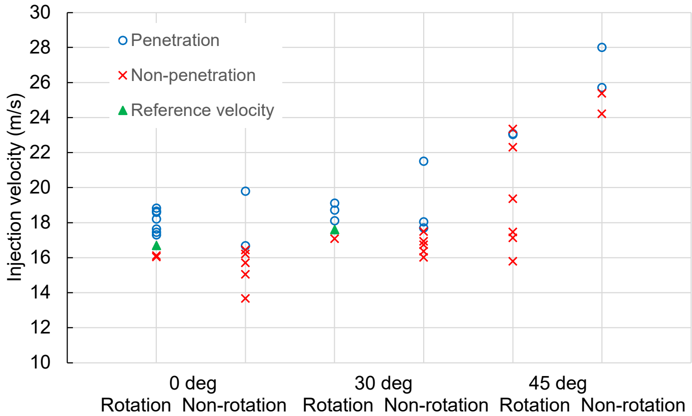
Rotation of the harpoon generates gyro effect and rotating harpoon penetrates the target stably.
On the other hand, non-rotating harpoon is not stable.

Shooting tests of rotating and non-rotating harpoons at the oblique angle of 45 deg (2/2)



The fact that the non-rotating harpoon is non-penetrating despite its high injection velocity means that the rotation of the harpoon has a significant effect on penetration.

The injection velocity and penetration behavior of each harpoon



The minimum penetration velocity of each harpoon type (m/s)

Angle	Rotating harpoon	Non-rotating harpoon
0 deg	17.3 (16.7)	16.7
30 deg	18.1 (17.6)	17.7
45 deg	23.0	25.7

※ The velocity in parentheses is the average velocity of the difference between the maximum non-penetration velocity and minimum penetration velocity when the difference is greater than 1m/s.

Oblique angle of 0 deg → No difference in the penetration behavior is observed regardless of whether rotation exists.

Oblique angle of 30 deg → Little slippage of the harpoon with the grooves was observed.

Oblique angle of 45 deg → The difference of the penetration velocity is 2 m/s and harpoon rotation has effects on the penetration behavior.

The effect of penetrating was improved by using harpoon rotation.

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Size of penetration hole for each harpoon type

Penetration hole by **rotating harpoon**

Penetration hole by **non-rotating harpoon**

→ We think penetration hole of non-rotating harpoon is **bigger** than that of rotating harpoon because the posture of non-rotating harpoon is not stable after penetrating.

The narrow section of the harpoon hooks on the penetration hole during pulling out the harpoon. Therefore, rotating harpoon is expected to increase pullout resistance.

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Conclusion

・We developed the system for rotating the harpoon for ground test.

・The rotating harpoon penetrates stably due to the gyro effect.
⇒The penetration hole and penetration velocity of the rotating harpoon are smaller than that of the non-rotating harpoon.

The rotation of the harpoon is effective for improving penetration behavior.

Thank you for your kind attention.
Please let me know if you have any question.

Mail: ed22003@nda.ac.jp

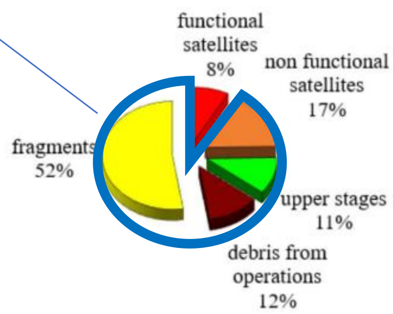
Artificial objects in earth orbits

- Since space development has been rapidly progressed, there are many problems of space debris because the objects orbiting the earth have not been properly disposed of in the past.

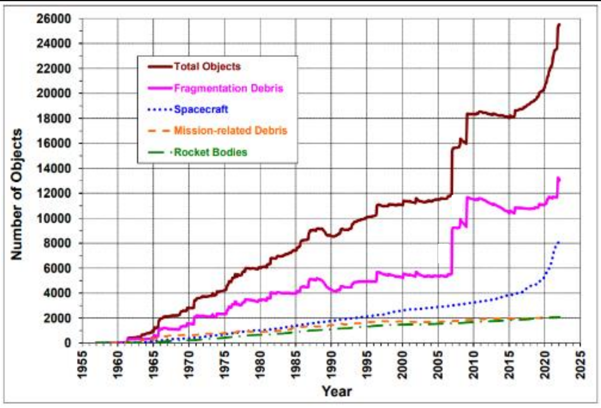
Space debris is mainly

① Fragmentation	③ Mission-related Debris
② Spacecraft that have completed their mission	④ Rocket body

~~92 %~~ of the objects orbiting the earth is space debris.



Source：Committee on the Peaceful Uses of Outer Space, Scientific and Technical Subcommittee, February 2019

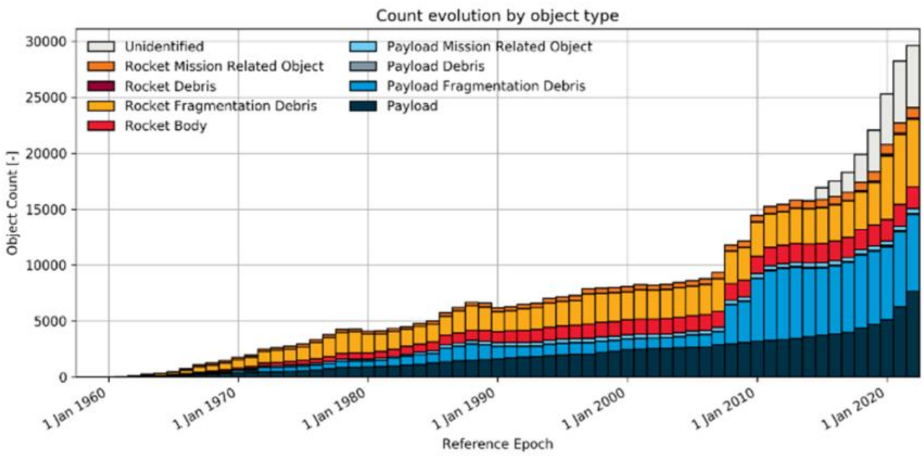


Catalogued debris (more than 10 cm)

Source : NASA Orbital Debris Quarterly News, Volume 26, Issue 1, March 2022

Space debris orbits at high speed. When it collides with spacecrafts, they will be greatly damaged.

The number of space debris



The number of observing objects
About 23,000 objects

Rocket Mission Related Object + Payload Mission Related Object + Rocket Debris + Payload Debris	6%
Rocket Fragmentation Debris + Payload Fragmentation Debris	56 %
Rocket Body	9%
Pay load	29 %

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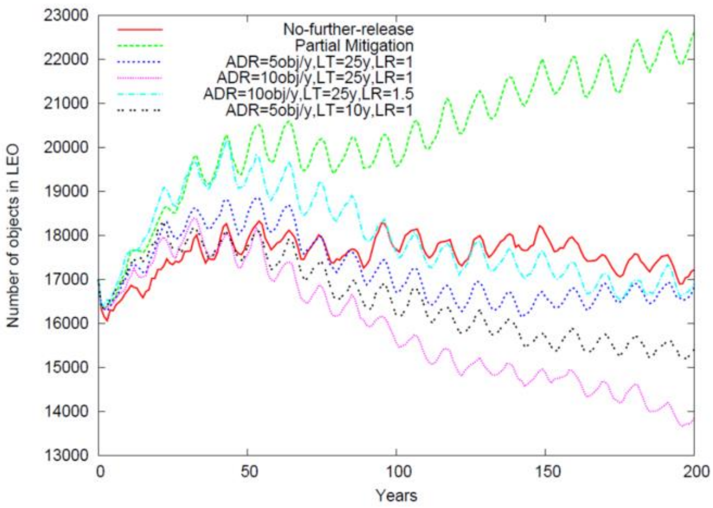
Projected change in total debris count due to debris removal



It is possible to be stable space environment by removing space debris from LEO per 5 or 10 objects.

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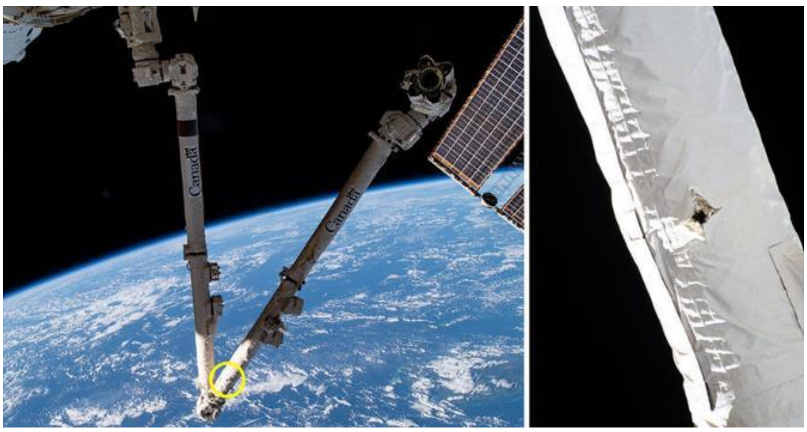
Space debris scar



Space debris scar found in the Canadaarm2 ©CSA

The function of the robotic arm was not affected.

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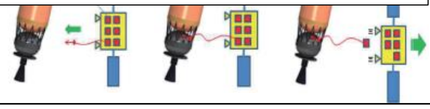
Risk reduction measure against a spacecraft

Removement of orbiting debris

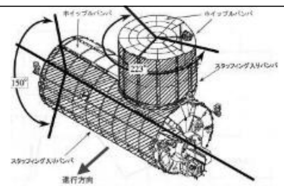


Reduction of debris

Avoidance operation of a spacecraft for preventing it from colliding with debris

There are four countermeasures

Protective measure by the debris bumper like a "KIBO"



No more debris

SSA system ©JAXA

Debris bumper of the Japanese experiment module "KIBO" ©JAXA

Prevention of occuring component with launching a satellite

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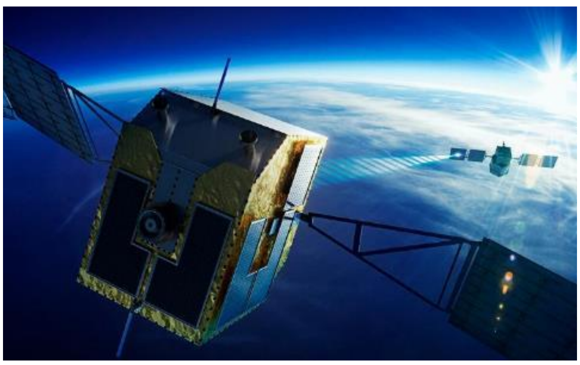
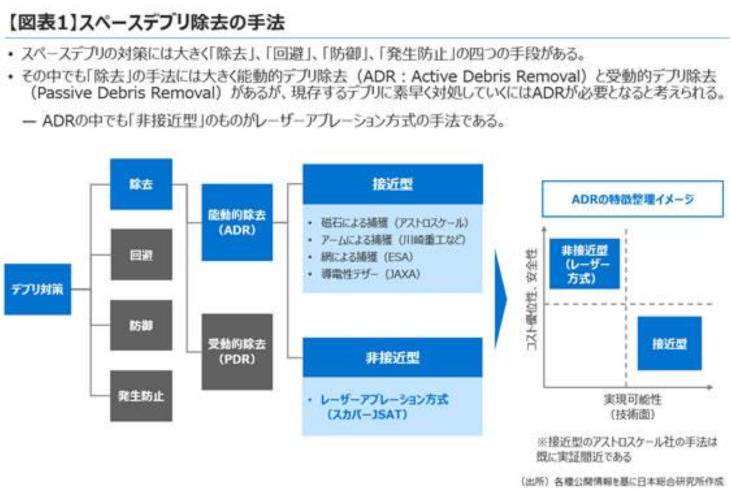
Space debris removal method





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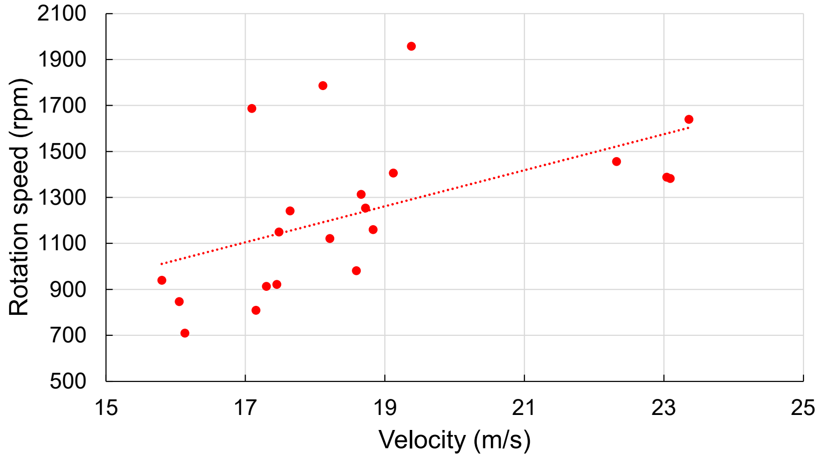
The relation between injection velocity and rotation speed of each harpoon

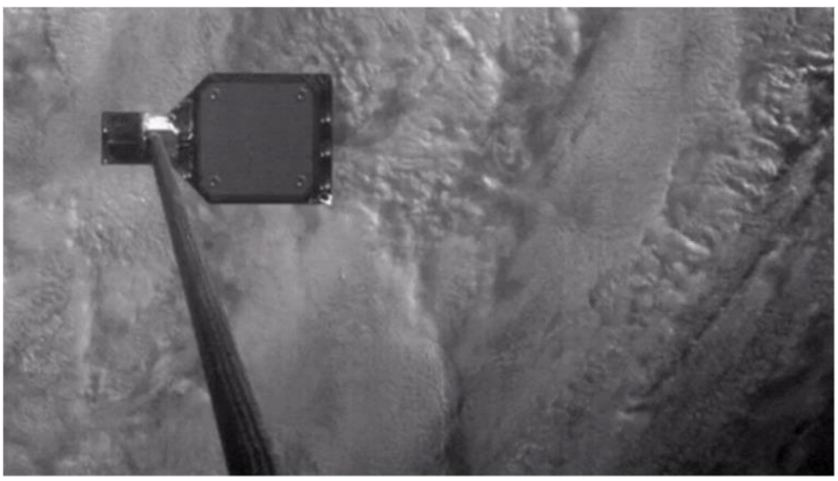


The relation between the velocity of each harpoon and rotation speed.

The relation between the velocity of each harpoon and rotation speed is positive correlation.

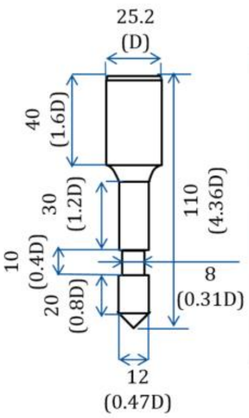
We guess injection velocity and rotation speed depends on air pressure.

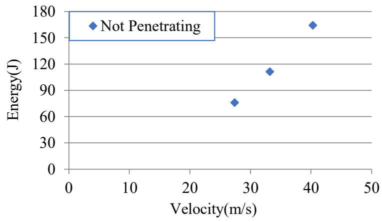
Demonstration of shooting the harpoon in the space

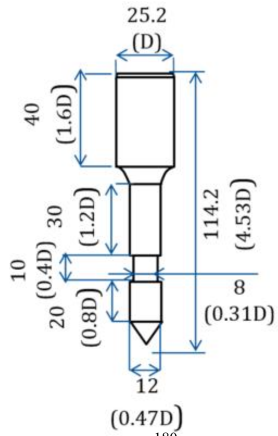


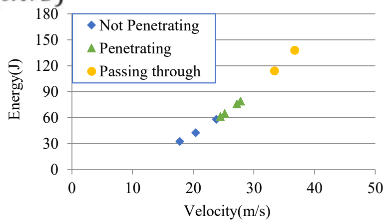
Shooting a deployable harpoon into a structure simulating space debris

The conical tip shape harpoon with various tip angle



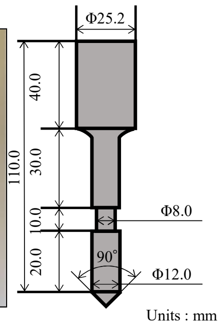




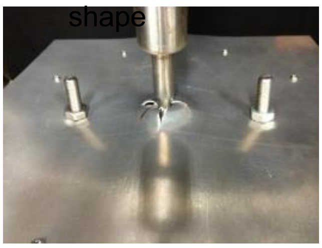


L. B. T. Nguyen, H. Tanaka and H. Hata,
"Evaluation of the effect of the point angle and angle of incidence of a metal anchor on its docking state in a satellite structure for space debris mitigation," 25
Mechanical Engineering Journal, Vol.5, Issue.1, pp.17-00087, 2018.

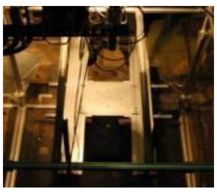
The shooting previous study of the metal harpoon in National Defense Academy of Japan

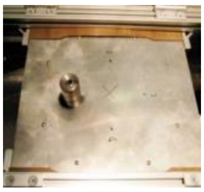


Conical tip shape

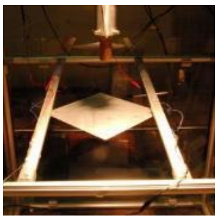


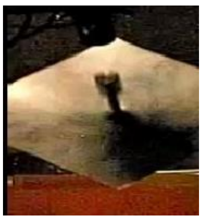
Pullout resistance test





Shooting the harpoon into fixed target





Shooting the harpoon into free fall target

Assumption

Citation：Thanh Long NGUYEN, Hiroaki TANAKA, Hidehiro HATA, Fundamental study on lodgeing an anchor on satellite structure for space debris mitigation system, Transaction of the JSME, 2017 (in Japanese).

26

Penetration velocity of the harpoon when gravity acceleration is taken into account

$v^2 - {v_0}^2 = 2gy$

$v = \sqrt{{v_0}^2 + 2gy}$

$= \sqrt{15^2 + 2 * 9.8 * 0.59}$

$= 15.38 \ldots \ [m/s]$ ← About 2% increase

Penetration velocity of the harpoon when gravity acceleration is taken into account (m/s)

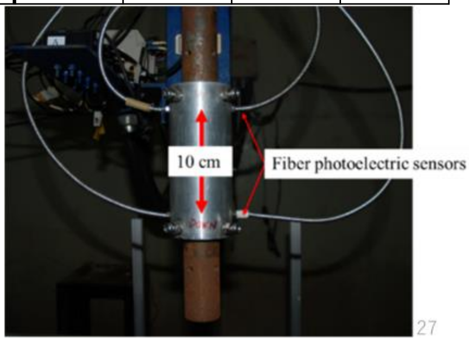
Angle	Conical	Spherical	Flat	Double-bladed
0 deg	17.3	22.9	23.9	16.0 (15.3)
30 deg	17.9	23.5 (22.7)	14.3	15.7
45 deg	35.4	44.8*	31.0	17.7

v: The harpoon velocity before impact $[m/s]$

v_0: The harpoon speed when passing lower sensor (Assume 15 $[m/s]$)

g: Gravity acceleration $[m/s^2]$

y: The distance from lower sensor to the specimen $[m]$



計測誤差

$$V_m = V + V_e = \frac{L + L_e}{T + T_e} = \frac{L}{T}\left(\frac{1 + \frac{L_e}{L}}{1 + \frac{T_e}{T}}\right) \fallingdotseq \frac{L}{T}\left(1 + \frac{L_e}{L}\right)\left(1 - \frac{T_e}{T}\right)$$

$$\fallingdotseq \frac{L}{T}\left(1 + \frac{L_e}{L} - \frac{T_e}{T}\right) = V\left(1 + \frac{L_e}{L} - \frac{T_e}{L/V}\right)$$

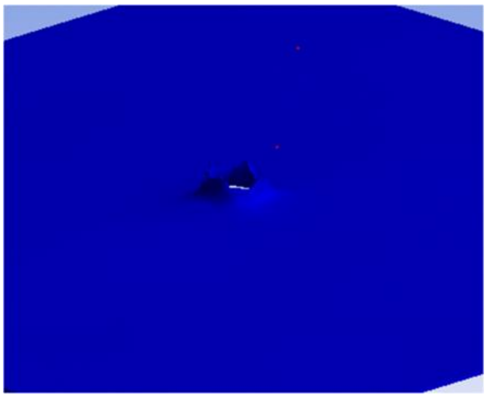
$$V_e = V\left|\frac{L_e}{L}\right| + V^2\left|\frac{T_e}{L}\right| \fallingdotseq V_m\left|\frac{L_e}{L}\right| + {V_m}^2\left|\frac{T_e}{L}\right|$$

V_m：計測された銛の速度 $[m/s]$
V: 銛の真の速度 $[m/s]$
V_e：銛の真の速度との誤差 $[m/s]$
L：光スイッチの間隔 $[m]$ (10 cm =0.1 m)
L_e：光スイッチ間隔の誤差 $[m]$ (機械加工誤差が支配的)
T：計測時間 $[s]$
T_e：光スイッチによる計測時間誤差$[s]$

銛の速度を10 m/s とすると(機械加工誤差：1.0×10^{-4} m,
サンプリング周期10 μs及び人為的計測誤差も含めて30 μsとする．)

$$V_e = 10 \times \left|\frac{1.0\times10^{-4}}{0.1}\right| + 10^2\left|\frac{30\times10^{-6}}{0.1}\right| = 4.0 \times 10^{-2}[m/s]$$

The shape of the penetration hole(Conical tip shape harpoon)



Numerical simulation indicates similar shape.

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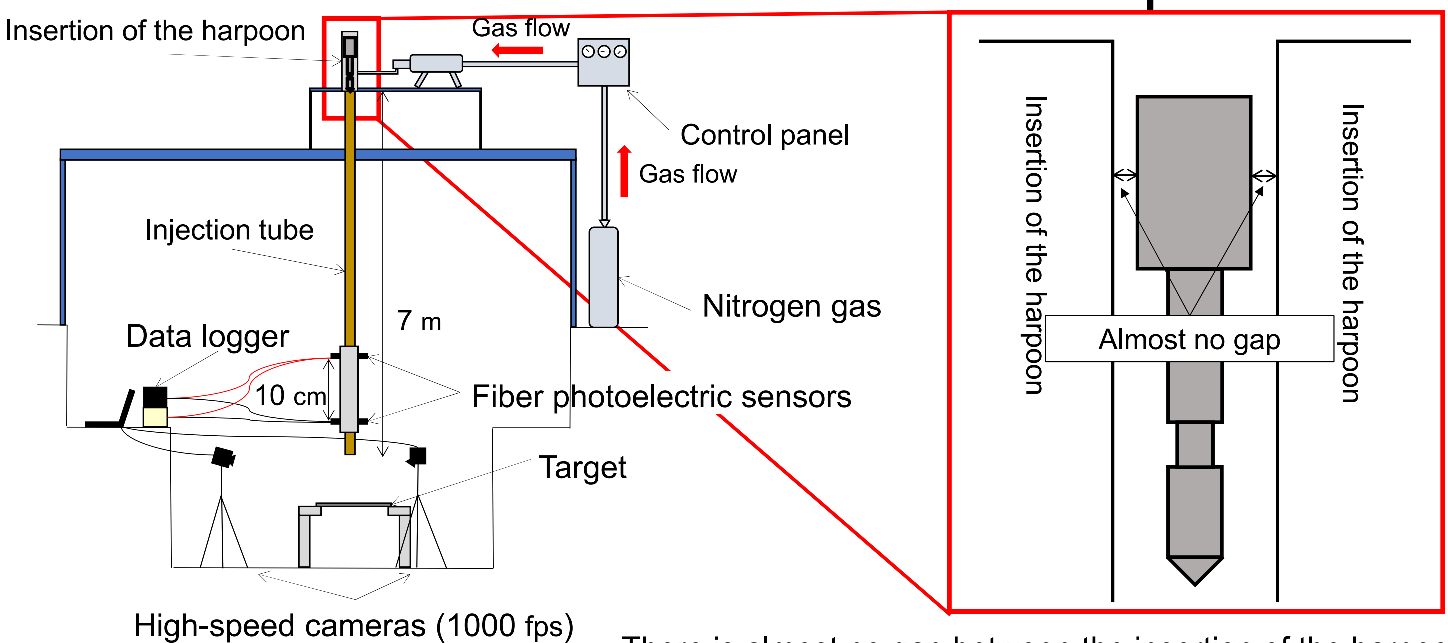
The width of insertion of the harpoon



There is almost no gap between the insertion of the harpoon and the harpoon. We consider the harpoon itself is not tilted.

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Precision error of the fixed stand

Oblique angle of 0°

Oblique angle of 30°

Oblique angle of 45°

Mechanical accuracy error is less than 1 deg in the fixed target.

質 問

1. 球先端形状は45° 以上で貫通するのか.
→実際には実験していないが，傾き角が大きくなるにつれ貫入速度が必要になる.
　貫入速度が上がると運動エネルギーも上がるため
　貫入することなく，貫通すると思われる.
　銛が供試板と衝突し，滑ったとしても捕獲には適さない.

2. 解析上でも貫入孔の形状は同じか.
→同じである.

質問

1. 銛の回転はしているのか.
→回転していない.
　現在の研究は銛に回転機構を取り付けて回転させている．摩擦のみが実験とシミュレーションの誤差ではないと思うが，今後定量的な誤差についても追求する.

質問

1. 固定台の計測精度について

2. なぜ15°をしなかったのか.
→銛の先端形状にもよるが，平以外の先端形状に関しては傾き角が大きくなるにつれ貫入速度も上がる．15°も0°に比べて貫入速度は大きくなると予想される.
傾き角45°の時，円錐先端形状や球先端形状について特異な挙動を示した．円錐先端形状については先端形状の側面で衝突し，滑った.
球先端形状は貫入することなく，貫通した.
したがって，傾き角45°よりも例えば傾き角40°等滑りの影響や先端形状に影響がない角度については今後考察の余地がある.

3. 銛自体の傾きはないのか.
→挿入口と銛の隙間はほとんどない．銛挿入時には銛自体の傾きはないものと考えられる.

C21

デブリ除去捕獲機構 HKK によるデブリのソフトリリースに関する研究

Study on Soft-Release of Debris by Debris Capturing Mechanism HKK

○谷嶋信貴，岡本博之，奥村哲平，渡邊恵佑，中村涼(JAXA 研開部門)
○TANISHIMA Nobutaka, OKAMOTO Hiroyuki , OKUMURA Teppei, WATANABE Keisuke,
NAKAMURA Ryo (JAXA Research and Development Directorate)

JAXA では、大型デブリ除去を目的とした非協力対象の捕獲エンドエフェクタとして、デブリ除去捕獲機構（HKK）を開発した。HKK はケージング手法により大きな許容誘導制御誤差かつ弾き飛ばしを発生させないという要求を可能としたエンドエフェクタ技術である。
しかし、従来の HKK 技術は ADR 衛星が対象デブリとともにリエントリを行うというミッションコンセプトを前提に開発されてきた。そのため、捕獲把持に特化しており、単純なリリースを行うという機能は有しているものの、将来的な需要が見込まれる複数対象への軌道上サービスやデブリ除去サービスで必要とされる安全なソフトリリースに関しては仕様化されていない。
本発表では、HKK の強みである捕獲把持コンセプトを維持したまま、ソフトリリースへの対応も可能とする捕獲機構技術に関する紹介および開発状況を説明する。

JAXA has developed HKK as a capturing and grasping end-effector for ADR mission. This technology satisfies the requirements of capturing the target even large position/attitude errors are existing, and does not push away the target, by caging-based capturing method.
However, conventional HKK technology has been developed based on the mission concept that the ADR satellite performs reentry with the target debris.
Therefore, HKK is specialized for capturing and grasping. Although it has the function of releasing the debris, but not has been specified for the safe soft releases that would be required for on-orbit services or ADR mission of multiple targets, which are expected to be in demand in the future.
In this presentation, the concept model of HKK that realizes the soft release is proposed.

10th Space Debris Workshop, Presentation C21

デブリ除去捕獲機構HKKによるデブリの ソフトリリースに関する研究

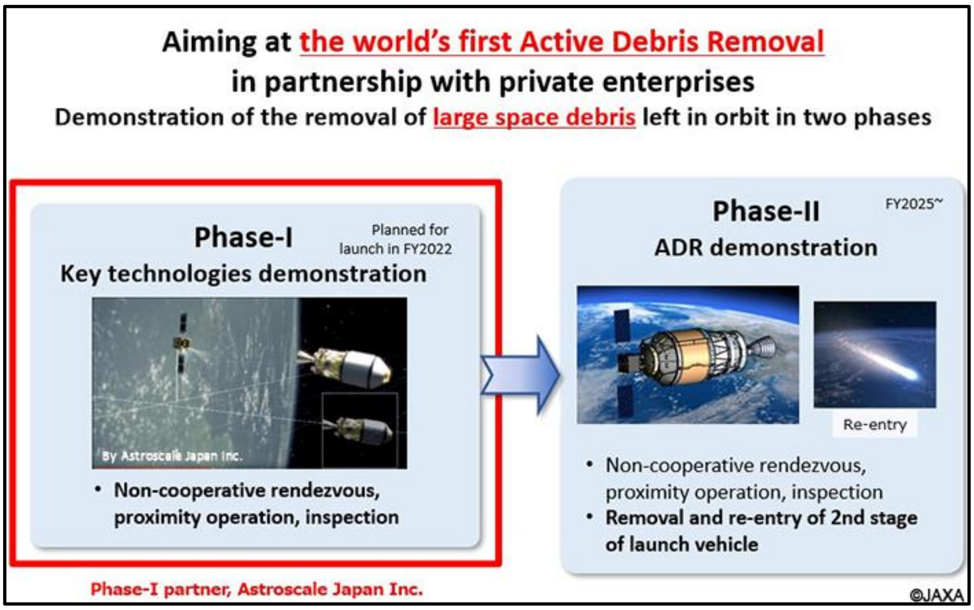
Study on Soft-Release of Debris by Debris Capturing Mechanism HKK

Tanishima, Okamoto, Okumura, Watanabe and Nakamura. (JAXA)

Agenda

- Brief introduction of conventional HKK
- Background of the study
- Proposal and status of Soft-Releasing methods
  - Wrist Rotational Release
  - Robotic Arm Release
- Summary and future works

Assumptions for HKK study and development



from "*https://www.kenkai.jaxa.jp/eng/research/crd2/crd2.html*"

HKK is being studied and developed to realize the CRD2 mission.

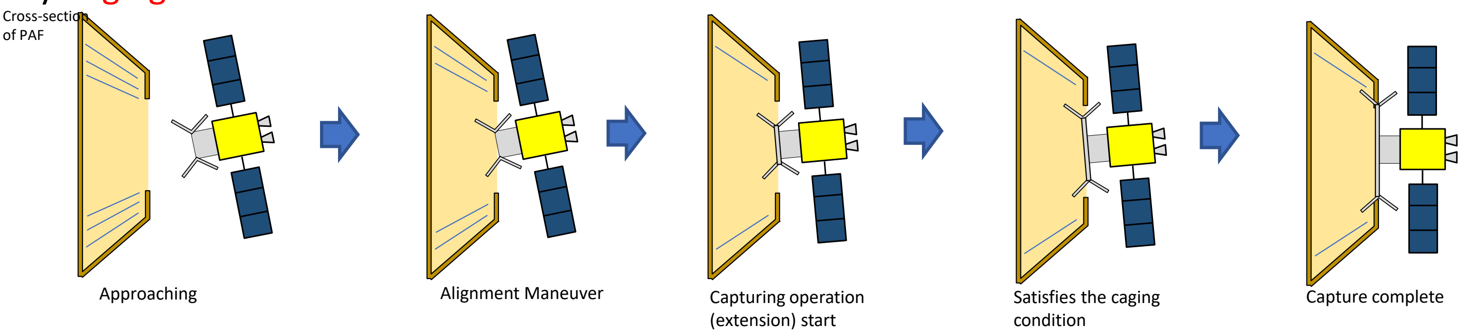
Conventional HKK: Specialized in capturing and grasping

Requirements to HKK:

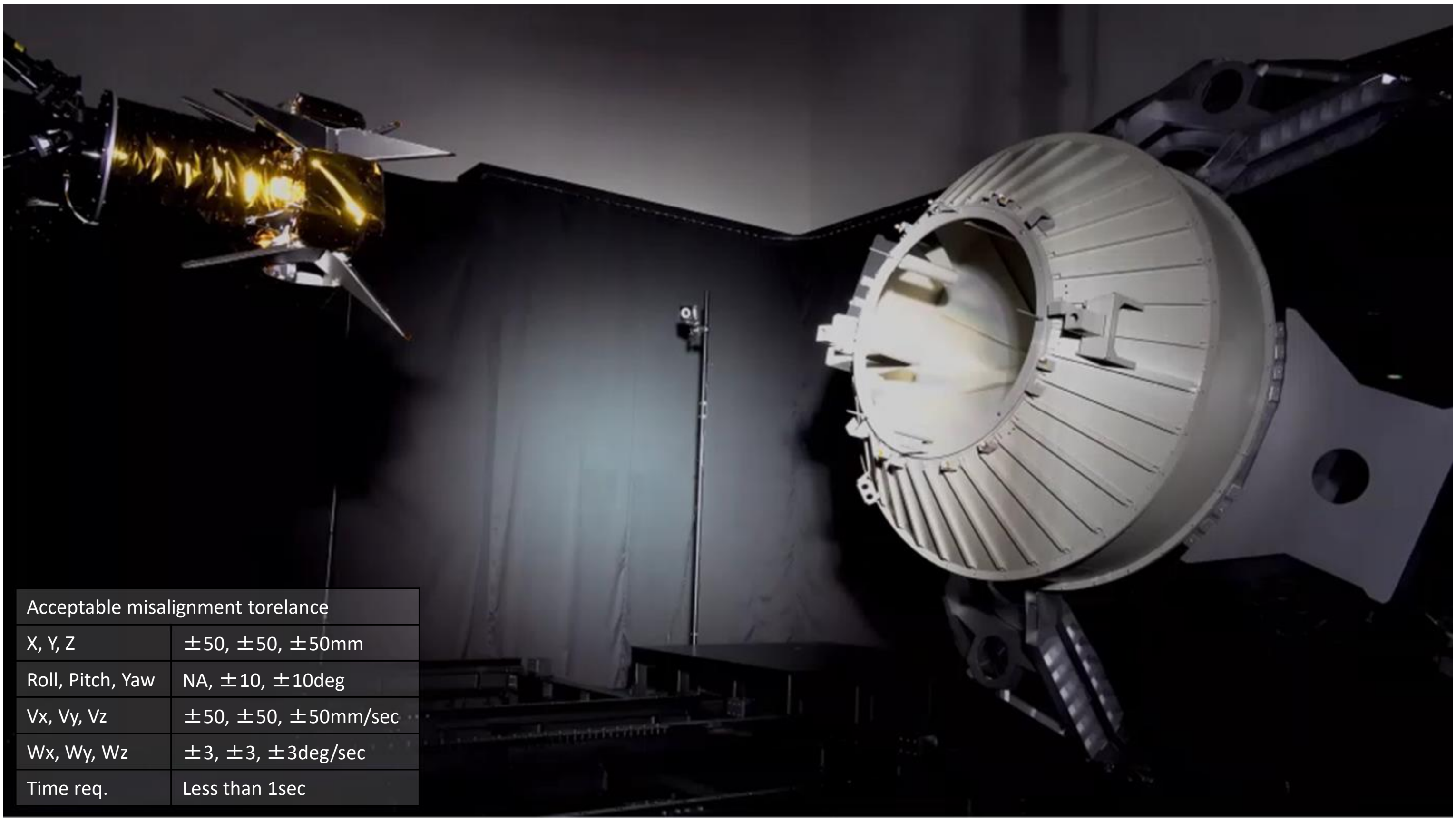
MUST be reliable of capturing the target (debris), which is non-cooperative object, without pushing away.

- Not designed to be captured and grasped.
- Unknown contact dynamics.
- Alignment accuracy is poor.

Devised a capturing mechanism that enables the capture of target debris (HII-A upper body) by Caging method.



Caging is satisfied by extension the boom with V-shaped structure inside the PAF.
This ensures reliable capture even in the presence of the issues.



Acceptable misalignment torelance	
X, Y, Z	±50, ±50, ±50mm
Roll, Pitch, Yaw	NA, ±10, ±10deg
Vx, Vy, Vz	±50, ±50, ±50mm/sec
Wx, Wy, Wz	±3, ±3, ±3deg/sec
Time req.	Less than 1sec

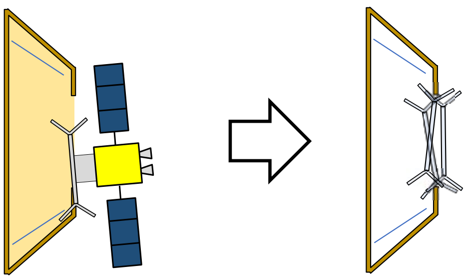
Background of the study: Requirement to the releasing function

	End of ADR mission	Release requirement to HKK
Conventional mission plan	ADR satellite re-enter with the debris.	NOT REQUIRED
Updated mission plan	Release safety and move to the next mission.	**REQUIRED**

Since HKK is specialized for capturing and grasping, releasing should be considered.

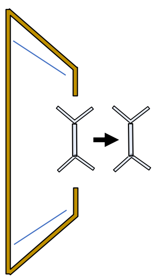
Characteristics of the Caging capture
- Because of geometric constraints, highly effective in capturing un-cooperative target, such as space debris.
- Because of geometric constraints, caging configuration ***should be disengaged to release*** the target.

Major assumption of the release



Satisfies the caging condition

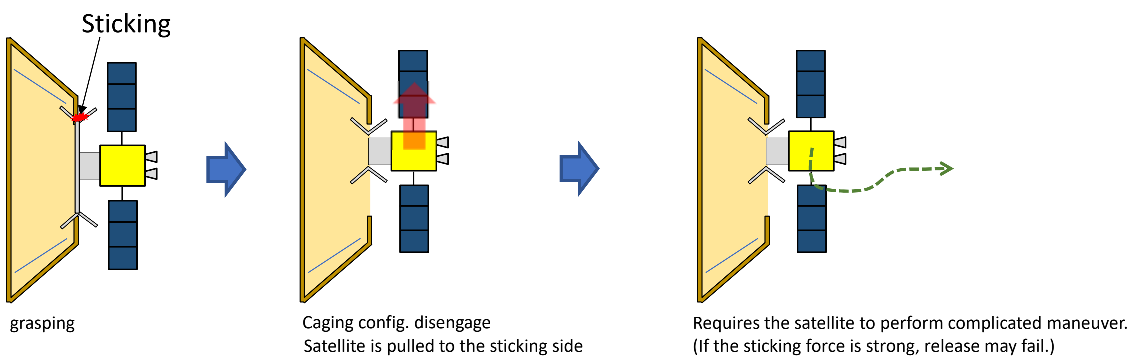
Cannot move away from PAF because of geometric constraints.



Caging configuration should be disengaged to move away from PAF (= release)

Technical problem and requirement

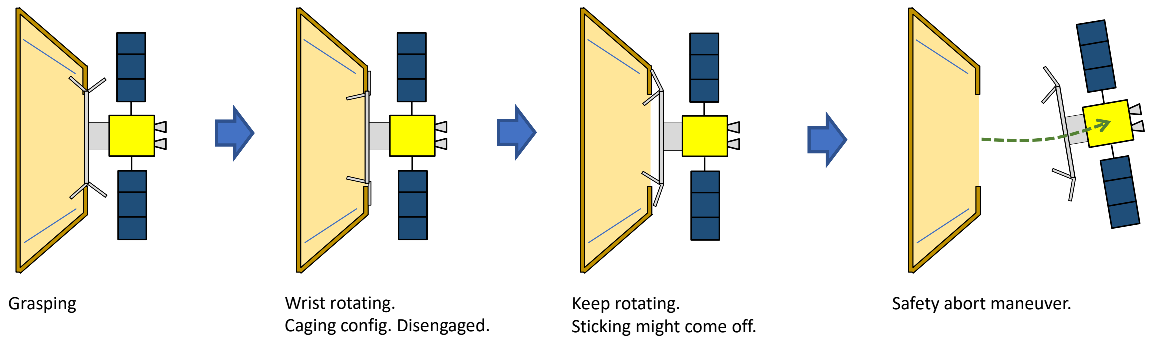
Since the release phase is the last phase of the mission, contacting point might be stick on environmental conditions.



Soft releasing (= Safe releasing) method and functions should be considered and added to HKK.

Proposal: Wrist Rotational Release

Add a mechanism of rotating the wrist (base of the V-shaped structure).

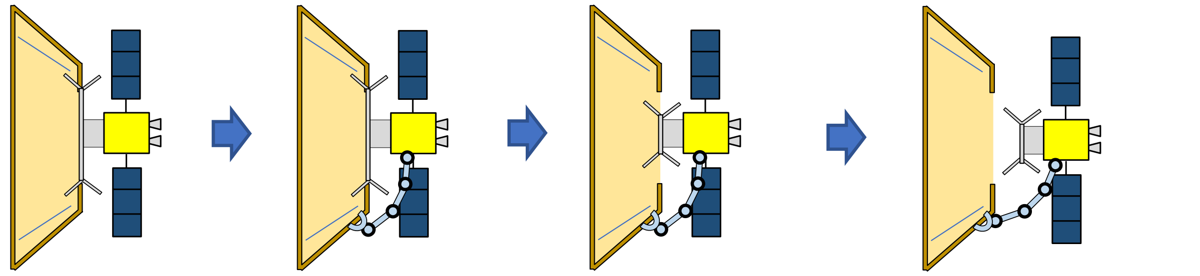


- Realizes the safety release function without losing the advantage of HKK capturing function.
- Sticking might come off during the sequence of wrist rotating.
- Mechanism has been confirmed feasible by scale model.

Tanishima, Nobutaka, et al. "Concept and mechanism of the tendon actuated versatile debris gripper." *2017 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, 2017.

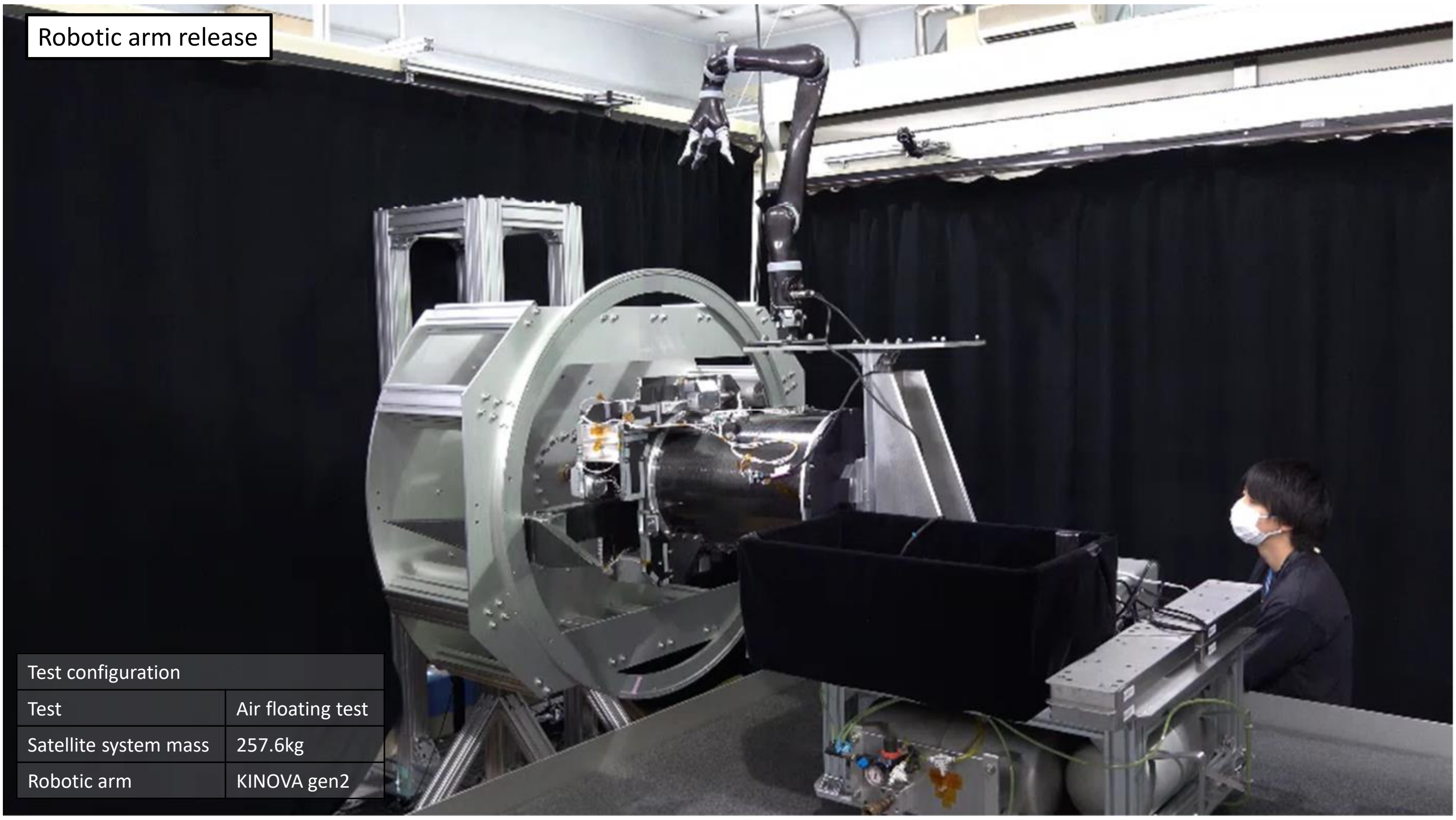
Proposal: Robotic Arm Release

Add a robotic arm for the release.

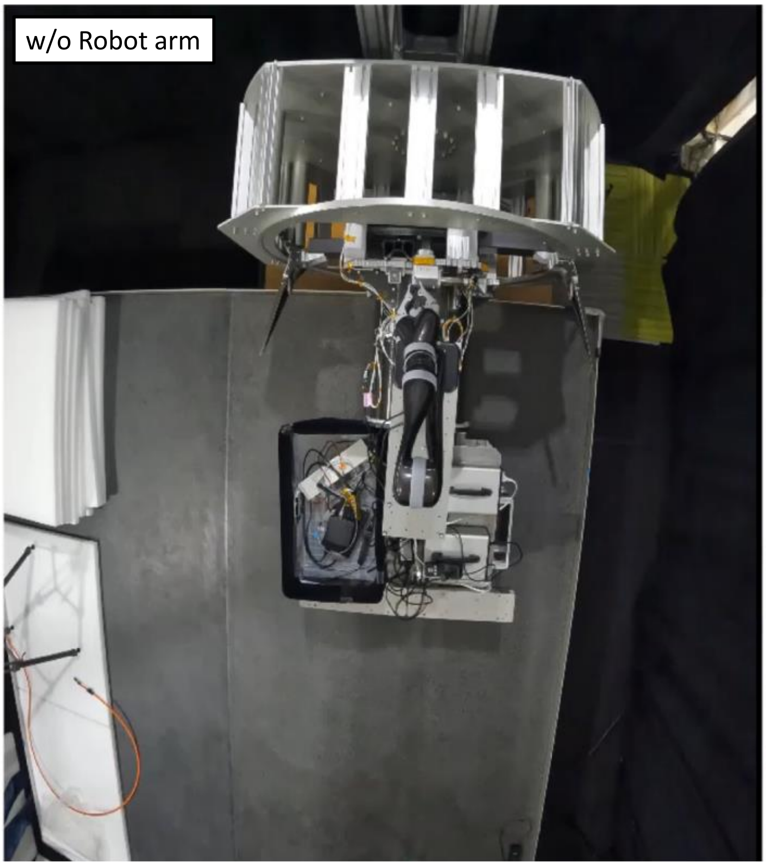


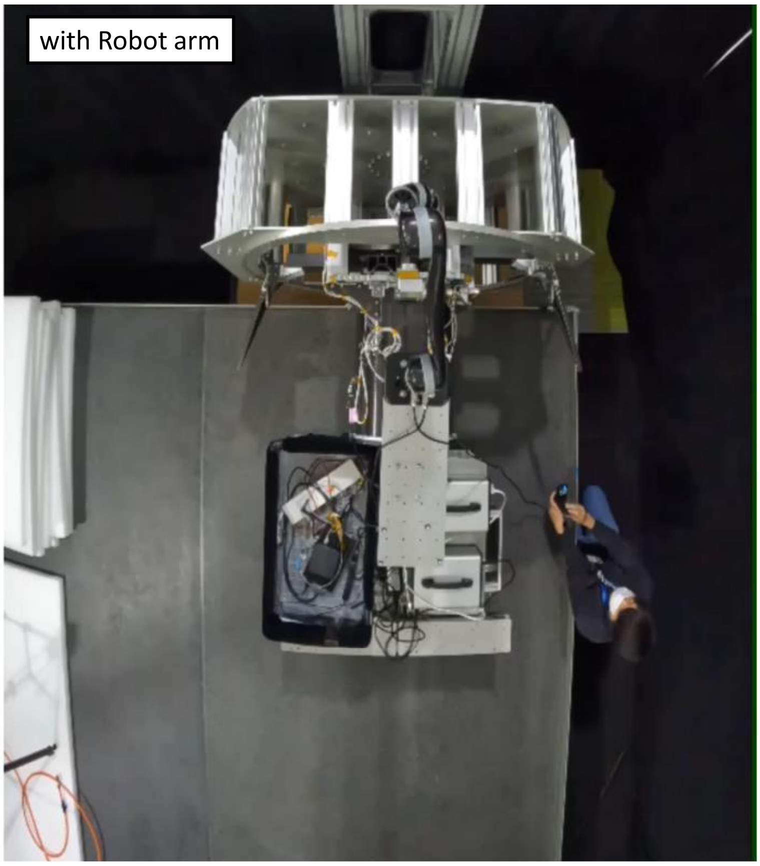
Grasping by HKK → Grasping with robotic arm → Constrict the boom. Caging config. disengaged. → Safety release using the robotic arm.

- Realizes the safety release function without losing the advantage of HKK capturing function.
- Capturing + Grasping End effector with robotic arm is one of the ideal configuration for on-orbit service.
- Robot arm does not to be rigid because it is only used for the release.



Test configuration	
Test	Air floating test
Satellite system mass	257.6kg
Robotic arm	KINOVA gen2





Summary and future work

- Soft releasing function is required to HKK.
- Proposed two method
  - ➢Wrist rotation release
  - ➢Robotic arm release
- Feasibility of Robotic arm release is confirmed by air-floating testbed.

Future works

- Develop the full-scale model of wrist rotational HKK to verify by air-floating testbed.
- Consider the proposed method (including the combination of wrist rotational and robotic arm release) by comparing the performance of air-floating testbed and SATdyn test.

Thank you for your attention!!

C22

非協力的ターゲット捕獲・把持機構の検討
A Study of Capture Devices for Non-Cooperative Target

〇中西洋喜，高橋健一郎，川口直毅，橋本拓哉，德安彰大（東京工業大学）
〇NAKANISHI Hiroki, TAKAHASHI Kenichiro, KAWAGUCHI Naoki, HASHIMOTO Takuya, TOKUYASU Akihiro (Tokyo Institute of Technology)

能動的スペースデブリ除去（ADR）作業において，ターゲットの把持および，スラスタや EDT，デオービット膜といったデオービットデバイスの取付は重要なキーテクノロジーの一つである．これまでに確立されている軌道上サービス技術は全て，専用の被把持機構を備え，姿勢が安定化している「協力的」な作業ターゲットを前提している．一方 ADR の対象は「非協力的」なターゲットとなるため，これに対応できる捕獲・把持をできるだけ簡易な機構・制御で実現することが必要である．筆者らは，衛星やロケット上段の構造を利用する・または全体を包み込むことにより把持をした後，直ちにサービス衛星から切り離されることによりデオービットデバイス固定機構としても機能するデブリ把持機構について様々な方式について検討を進めている．本発表では，これまでの取り組みおよび最新の成果について報告する．

In active space debris removal (ADR) operations, target grasping and attachment of deorbit devices such as thrusters, EDTs, and deorbit membranes is one of the key technologies. All on-orbit service technologies established so far assume a "cooperative" working target with a dedicated grasping mechanism and stabilized attitude. On the other hand, ADR targets are "non-cooperative" targets, so it is necessary to realize capture and grasping with simple mechanisms and control. The authors have been studying various methods of debris grasping mechanisms that can also function as a deorbit device fixation mechanism by being immediately detached from the service satellite after grasping by utilizing the structure of the satellite or rocket upper stage or by encasing the entire debris. In this presentation, we will report on our past efforts and latest results.

非協力的ターゲット捕獲・把持機構の検討
A Study of Capture Devices for Non-Cooperative Target

〇Hiroki Nakanishi, Kenichiro Takahashi, Naoki Kawaguchi,
Takuya Hashimoto, Akihiro Tokuyasu

Tokyo Institute of Techonology

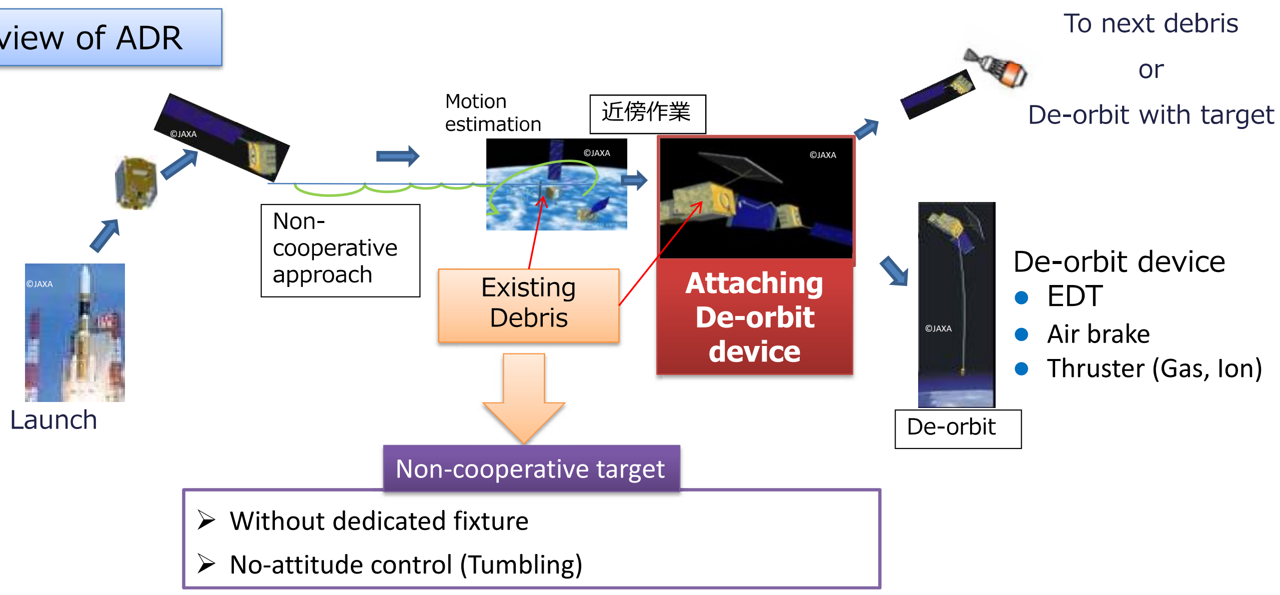
Space Debris WS (2022/Nov./30)

Contents

- Background
- Research of capture mechanism for non-cooperative target
  - Debris wrapping system using bi-stable convex spring
  - Twining mechanism that mimics a plant
  - Low contact force truss gripper
- Summary

Background

Overview of ADR

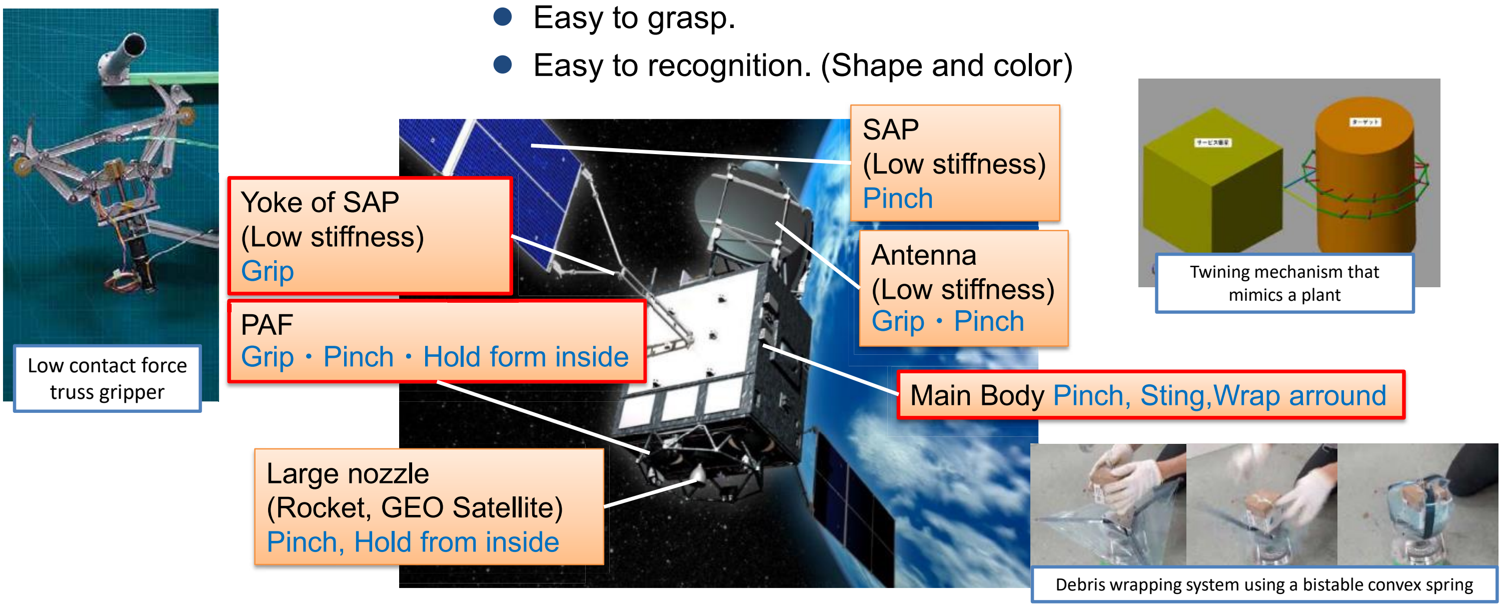


Purpose：
Establishment of a mechanism that enables secure grasping and fixing without causing destruction or ejection by contact force.

Candidate of alternative grapple-fixture on non-cooperative target

"Where" and "How" do we capture on debris?

- Easy to access.
- High stiffness enough to be applied force.
- Easy to grasp.
- Easy to recognition. (Shape and color)



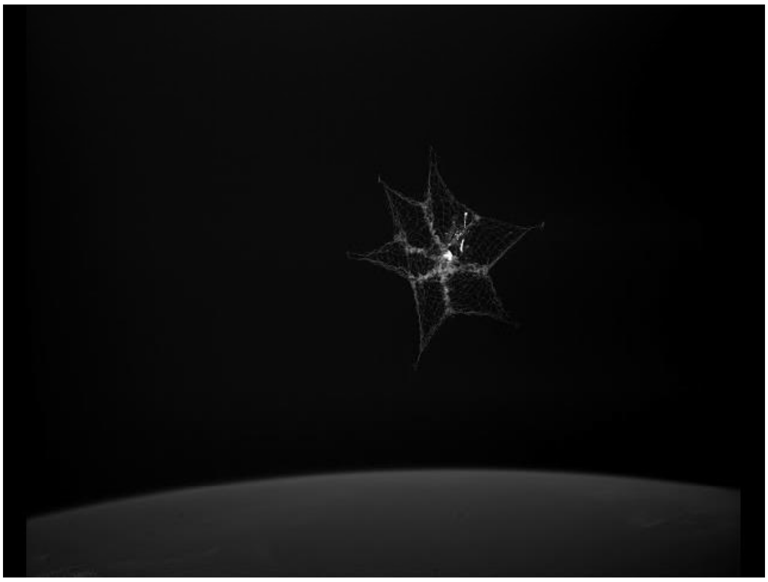
Debris wrapping system using bi-stable convex spring

Wrapping whole body of a target

Ex.) Casting net

Advantege:
No need for gripping I/F,
independent of shape

Disadvantage:
Uncertainty in shape maintenance and control



Net casting at RemoveDEBRIS mission ©SSTL

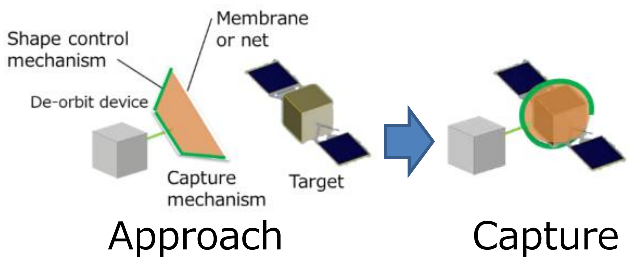
Debris wrapping system using bi-stable convex spring

Wrapping whole body of a target

Concept of the gripper

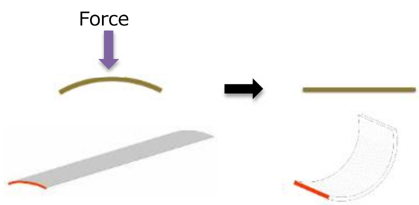
A mechanism that

- holds the shape until contact with the target maintains the grasping state.
- until the deorbit after the completion of grasping.

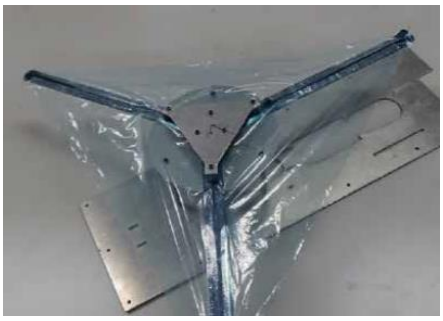


Bi-stable convex spring

- It is commercially available as a wristband.
- As the gutter-shaped cross section is deformed, it transitions between a straight state and a coiled state.
- The coiling force emerges from the point where the force to flatten the cross section is added.

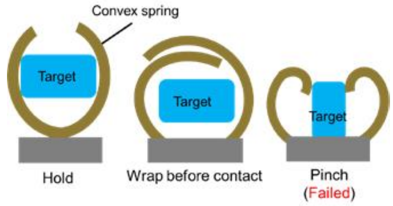


Cross-sectional change of convex spring before and after deformation



A prototype capture mechanism combined with a membrane.
The gripper is activated when the target contacts the center of the gripper.

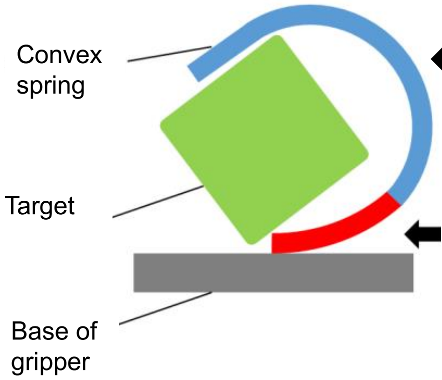
Design of convex spring for gripper



Ideal motion:

"Enclose the target before contact, then tighten it up"

➡ Different requirement is given to each part of spring



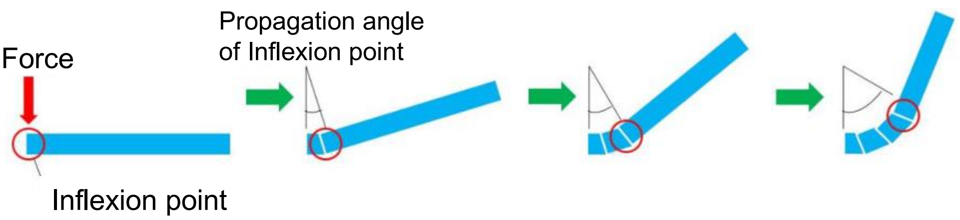
End tip side
Fast propagation of inflexion point
⇒Fast tightening up

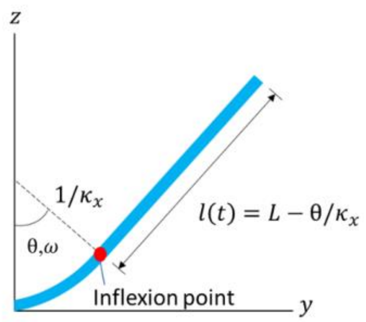
Root side
Slow propagation of inflexion point
⇒ Inhibiting end tip coiling before enclosing

This is achieved by changing the curvature of the cross-sectional shape.

Dynamics modeling

Propagation of coiling torque ⇒ Coiling motion of spring



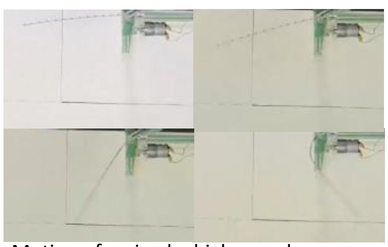


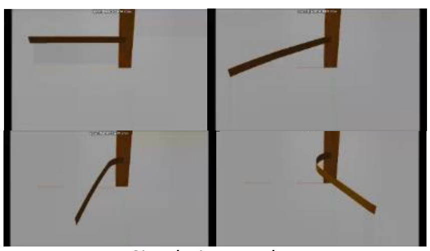
Equation of rotational motion around an inflection point

$$I\frac{d^2\theta}{dt^2}=\tau_0 \quad \begin{cases}\tau_0 = \dfrac{Ewh^3}{12(1-\nu^2)}(\kappa_{x_0}+\nu\kappa_{y_0}) \\ I \cong \dfrac{1}{3}\rho w h\left(L-\dfrac{\theta}{\kappa_{x_0}}\right)^3\end{cases}, \quad l(t)=\frac{\theta}{\kappa_{x_0}}$$

κ	Curvature
ν	Poisson's ratio
I	Inertia moment around inflexion point
τ_0	Coiling torque

E	Young's modulus
ρ	Density
w	Width
h	Thickness
L	Length


Motion of spring by high speed camera

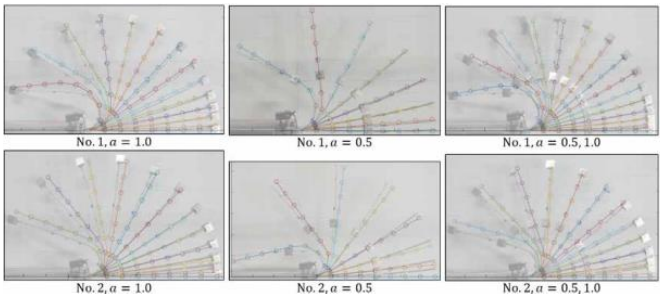

Simulation result

Motion control method by adding mass

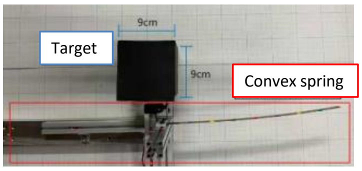
By changing the mass distribution of the spring, the ideal spring motion was achieved.

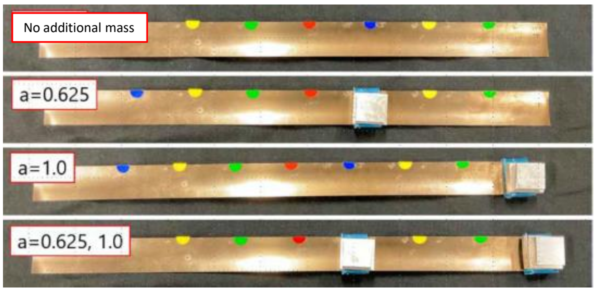
$$I = \frac{1}{3}\rho w h(\mathrm{L} - \theta/\kappa_x)^3 + \Sigma m_i (a_i L - \theta/\kappa_x)^2$$

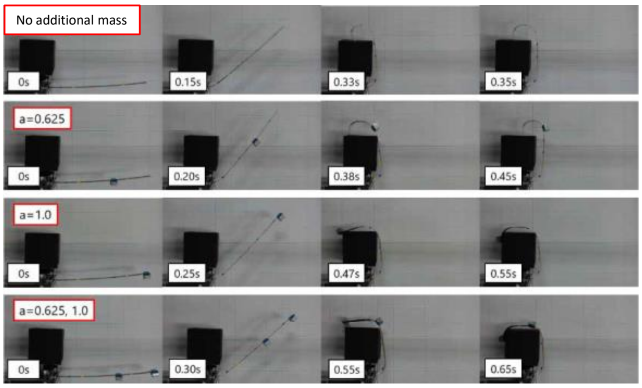
Inertia of spring — Additional mass



Comparison of experimental results and simulations





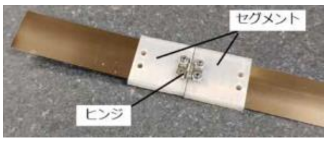


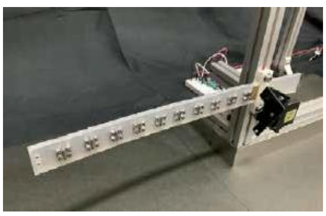
Failed to capture

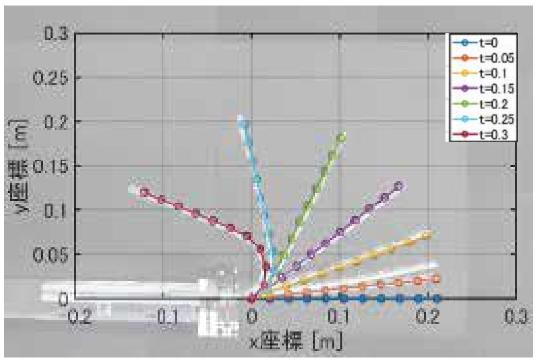
Successful capture

Exoskeleton-based functional enhancement methods

- An exoskeleton was used to prevent twisting of the spring.
- The influence of the exoskeleton can be represented by the addition of inertia.
- Re-deployment was achieved by passing a string through the exoskeleton.







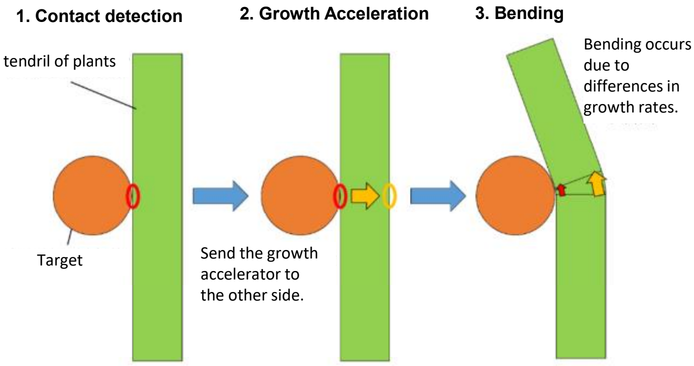
Twining characteristics of plants

Acknowledgement
This work was supported by JSPS KAKENHI Grant Number 20K04396

Thigmotropism of tendril of plants
(つる植物の接触屈性)

The main control system (the brain) is not responsible for the movement, but the reflex response of each cell group to contact achieves the coiling movement as a whole.

Tendril of plants



Repeat steps 1 to 3 to achieve winding.

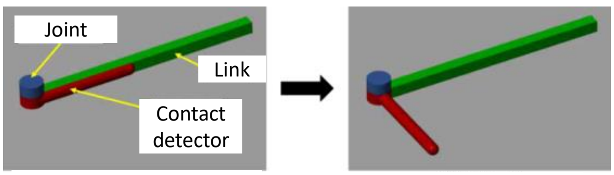
- Applying this property to a multi-link arm enables adaptive wrapping around a target.
- Each link is controlled independently by its own contact detection, so each link has the characteristics of a swarm robot.
  - **Easy to modularize.**
  - **Various configurations can be taken according to the target.**

Purpose

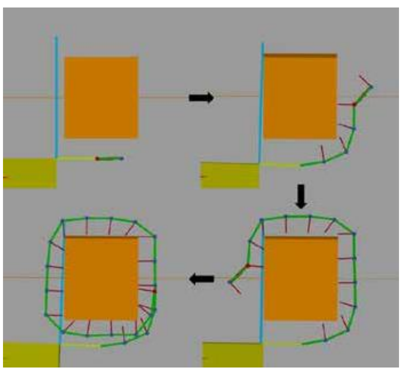
Design and algorithm of an adaptive winding mechanism based on a thigmotropism of tendril is discussed.

Concept design of twining mechanism

Module unit



Stored state Deployed state



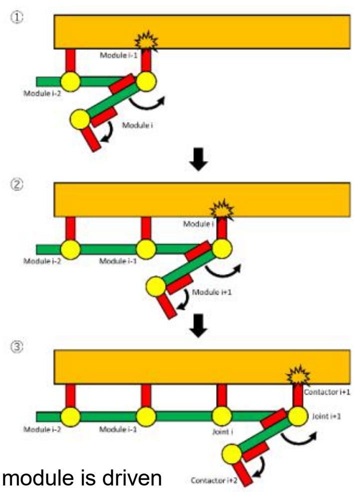
Target capture simulation

Algorithm for target caging

① Contactor i-1 contacts to the target
- Module i-2 stops Joint i-2 motion
- Module i-1 starts Joint i-1 motion
- Module i deploys Contactor i

② Contactor i contacts to the target
- Module i-1 stops Joint i-1 motion
- Module i starts Joint i motion
- Module i+1 deploys Contactor i+1

③ Contactor i+1 contacts the target
- Module i stops Joint i motion
- Module i+1 starts Joint i+1 motion
- Module i+2 deploys Contactor i+2



Caging operation is achieved when each module is driven based on its own and neighboring modules' contact history.

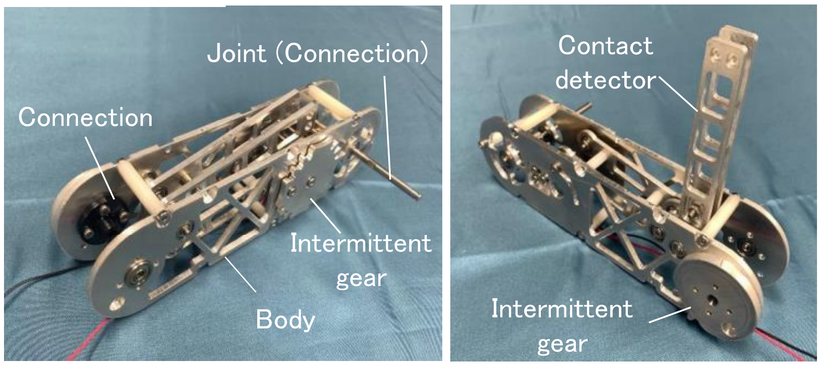
Algorithm for target tightening

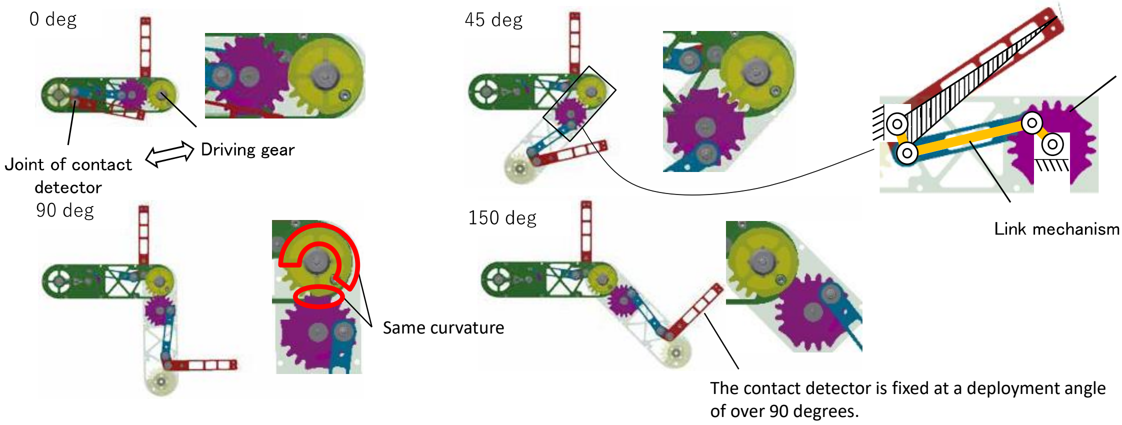
- ✓ It does not drive when two or more of them are not in contact continuously.
- ✓ When the front and rear of the motor are in contact and the motor itself is not in contact, it drives in the opposite direction of the winding direction.
- ✓ Otherwise, it is driven in the winding direction.

Design of actual devices

A single motor is used to achieve the winding motion and contact detector deployment using intermittent gears and a link mechanism.

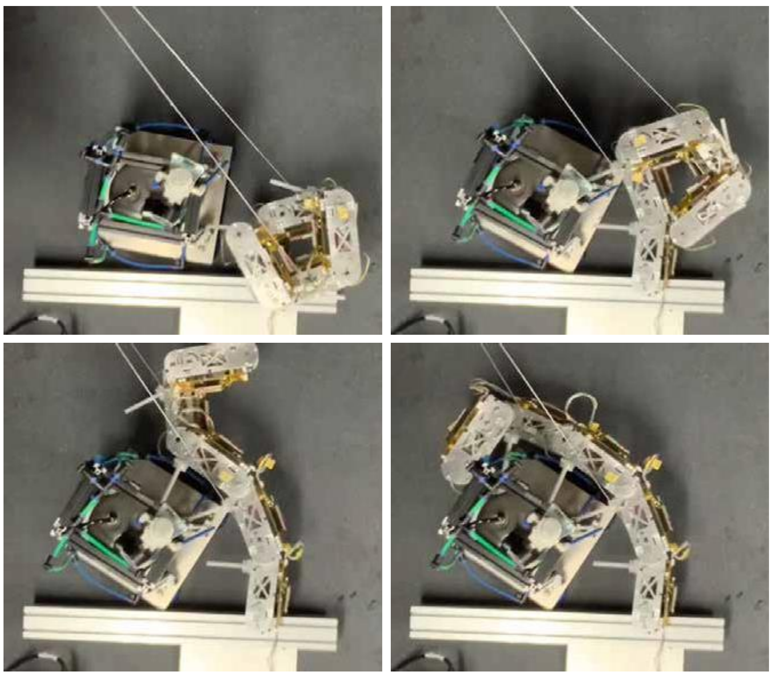
Retraction state   Deployment state





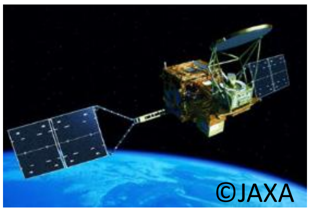
Capture demonstration

The capture mechanism successfully captures the floating target while adapting to its shape.



Low contact force truss gripper

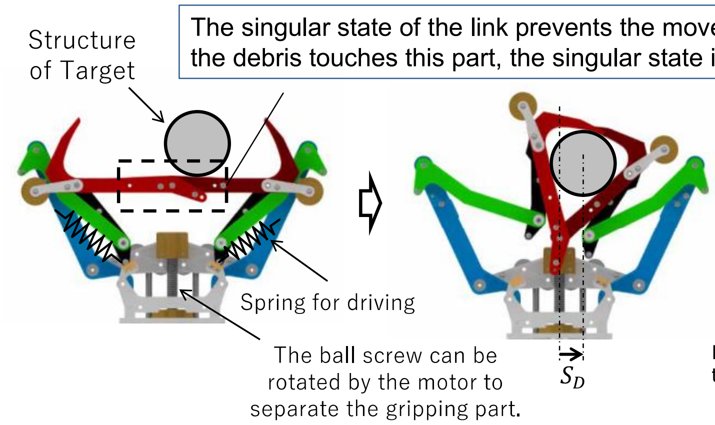
Assumed target :
Rockets and satellites with rod-like structures such as truss-type PAF (e.g. Cosmos 3M)

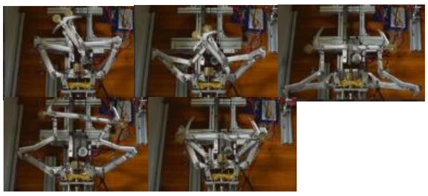


Concept :
Hand and mounting mechanism for attaching a device by simply pressing down.

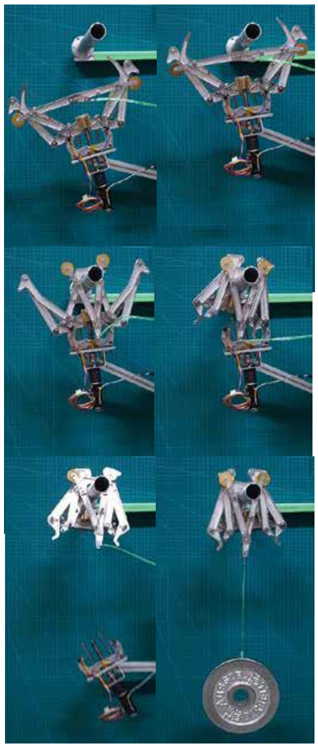
Model 2018 (2017-2019 Joint research of JAXA-Tokyo Tech)

The singular state of the link prevents the movement by the spring forces. When the debris touches this part, the singular state is released and the grasping starts.





Reversing the disconnection motor restores the initial state.



Capture and separation motion

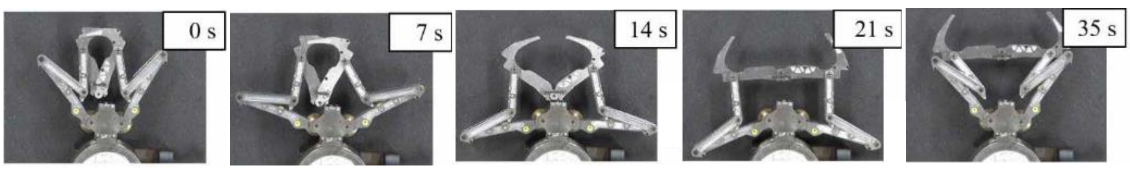
Low contact force truss gripper (Model 2020)

Modification of gripper

- Suitable for debris removal devices that require higher restraint forces than tether attachment.
- Self-locking fixation by worm gear.
- Improved operational stability by changing the contact link shape.

Grasping a free-floating target

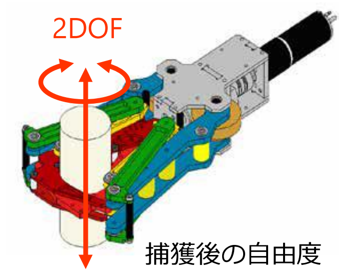
Recovery motion



Low contact force truss gripper

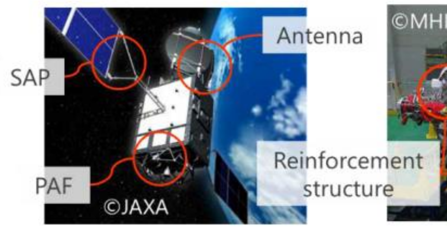
Extension to 6DOF constraints

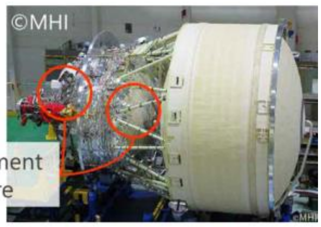
- When using a thruster as a deorbit device (when a controlled deorbit is required, such as for large debris), it is necessary to ensure that all six degrees of freedom are constrained.
- Fixation by friction is difficult to guarantee because it depends on surface conditions.

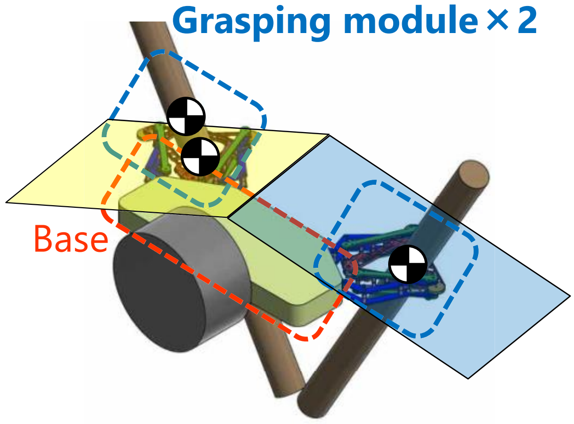


- Proposed grasping method:

  2 cylinders of the truss are fixed by symmetrically placed fingers.





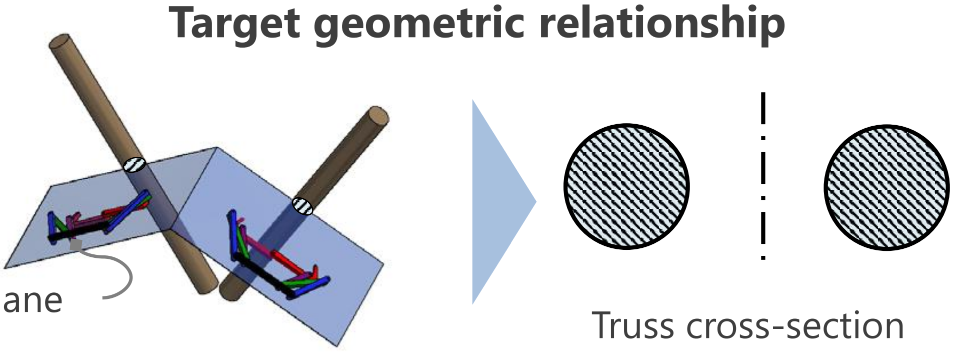


Low contact force truss gripper

- Problem：Position and attitude error results in different Truss cross-section of Grasping plane

Target geometric relationship

Grasping plane



Truss cross-section

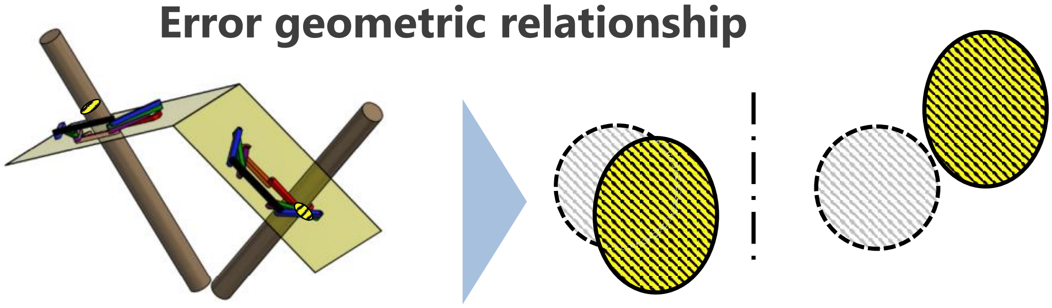
- Fixing motion of LCFH-1,2 causes relative motion to the truss.
- Fixation must be adapted to the **position and shape** of cross section

Underactuated grasping is needed to match the position and shape of the Truss cross-section

Low contact force truss gripper

- **Problem**：Position and attitude error results in different Truss cross-section of Grasping plane

Error geometric relationship



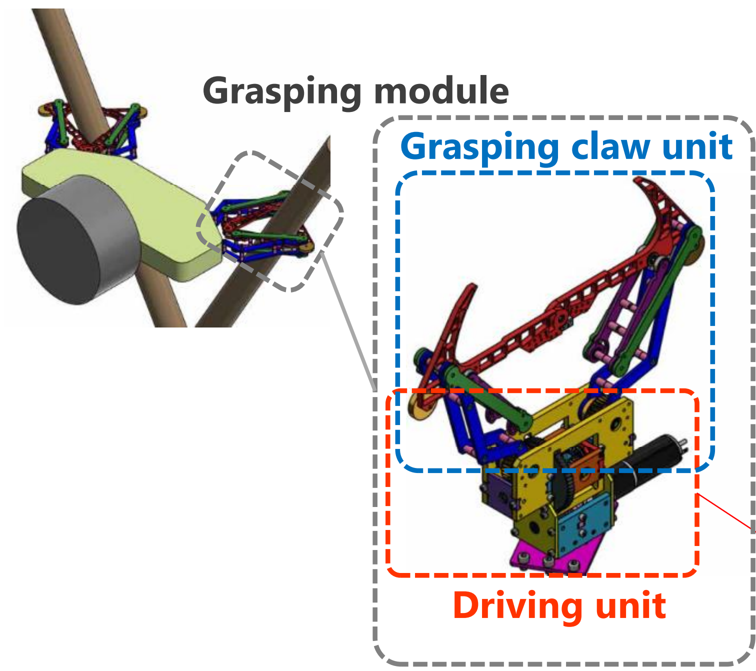
Truss cross-section

- Fixing motion of LCFH-1,2 causes relative motion to the truss.
- Fixation must be adapted to the **position and shape** of cross section

Adaptive grasping is needed to match the position and shape of the Truss cross-section

Low contact force truss gripper

Grasping module consists of **Grasping claw unit** and **Driving unit**

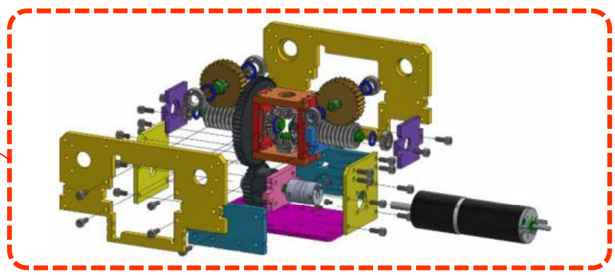


Grasping claw unit

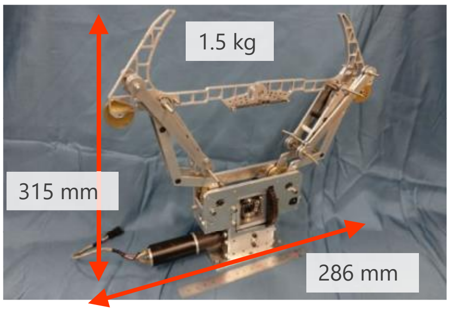
- Design based on LCFH

Driving unit

- Adaptive grasping by differential gears
- High gripping force
  (Self-locking of Worm gear)

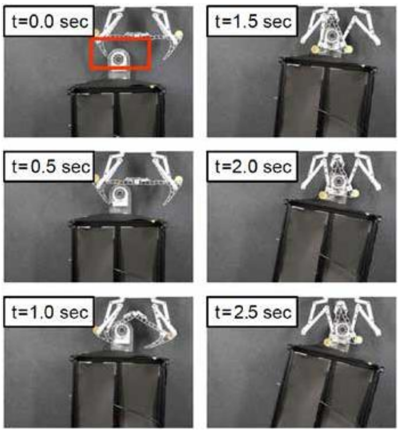


Capture Experiment

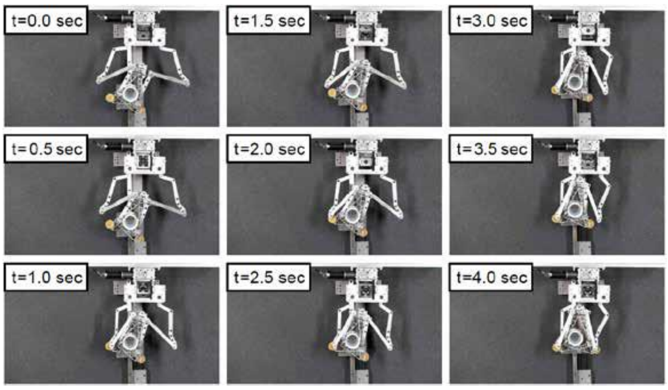


Prototype Gripper

Even if the captured position is offset, the fixation is completed at that position.

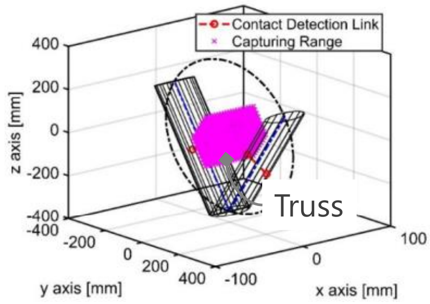


Caging motion

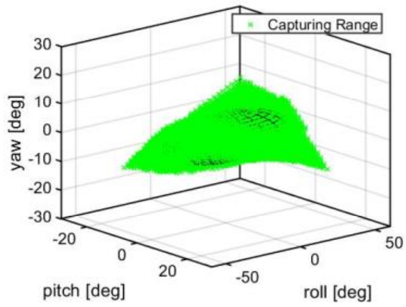


Fixation motion (Target is fixed)

Capture Experiment



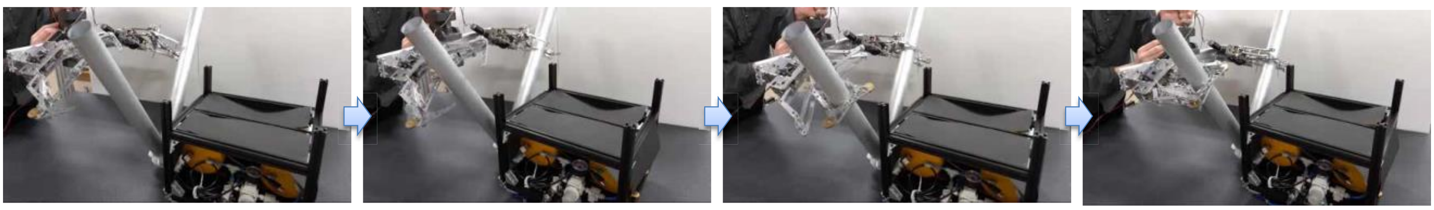
Position error area



Attitude error area

Axis	Maximum permissible error
X [mm]	±27.5
Y [mm]	±51.5
Z [mm]	±89.2
Roll [deg]	±42.5
Pitch [deg]	±8.5
Yaw [deg]	±8.5

Truss capture demonstration



Summary

- The purpose of this study is to establish debris grasping strategies and methods, and non-cooperative grasping mechanisms (end-effector and arm).
- The mechanical analysis and design of a debris wrapping mechanism using a bi-stable convex were clarified.
- A mechanism that mimics the twining motion of plants is investigated.
- The mechanical analysis and design of a hand that can grasp a truss structure by simply pushing on it are clarified.

パネルディスカッション

Panel Discussion

Panel Discussion

新しい世界潮流の見極め ～5年ルールに対する民間企業の視点～

Perspective from private sectors toward global trends on debris environment: Possible five-year rule for deorbiting

モデレーター：上野浩史（JAXA）
パネリスト：蔵本順（ALE)、岩本彩（アストロスケール)、泉山卓（IHI)、後藤眞理（MELCO)、八田真児（MUSCAT スペース・エンジニアリング)、福島忠徳（スカパーJSAT）
Moderator: UENO Hiroshi (JAXA)
Panelist: KURAMOTO Jun (ALE), IWAMOTO Aya (Astroscale), IZUMIYAMA Taku (IHI), GOTO Mari (MELCO), HATTA Shinji (MUSCAT Space Engineering), FUKUSHIMA Tadanori (SKY Perfect JSAT)

メガコンステレーションの軌道上への実装が本格化し、衛星による観測・通信サービス提供等の実利用も開始された。今後も、打ち上げ衛星数は増加傾向にあり、宇宙デブリの環境も次第に深刻化しつつある。特に影響を受ける地球低軌道の環境においては、これまでに、宇宙デブリ低減への主要な対策として、IADC ガイドラインや ISO 標準等が制定され、25 年以内の軌道離脱が求められてきた。さらに、今年 9 月には米国通信連邦委員会（FCC）は軌道離脱期間を 5 年以内に短縮化するルールへと変更した。本ルールは、米国民間企業が今後 2 年後以降に打ち上げる衛星に対して義務化が適用される見込みであるが、これまでのルールとは一線を画するものであり、世界からも注目されている。
本パネルでは、昨年度に引き続き、国内の宇宙デブリに関係する民間企業の方がパネリストとして一堂に会し、企業の視点から本ルールの意義・効果や賛否、またルールが与える企業への影響・課題について議論する。さらに、様々な国内ルールが国際ルールに発展するこれまでのルール化の流れも踏まえ、国際ルール化の調整にむけての日本の対応について、民間企業の意見・期待について議論する。

With the rapid increase of space utilization and the appearance of large constellations; space debris is a growing threat to space sustainability in the future. Due to the high impact on low earth orbit (LEO) environment, space debris mitigation guidelines have been established under IADC (Inter-agency Debris Coordination Committee) and ISO (International Organization for Standard), notably deorbiting within 25 years after the end of the mission. Recently FCC (Federal Communication Commission) adopted a new rule to deorbit within 5 years which makes significant difference from the current 25 years periods.
In this panel, the private companies which cares space debris in Japan will discuss values, impacts and challenges of the new rule, and explore the coordination of the international rule making from the viewpoints of Japanese private sectors.

新しい世界潮流の見極め　～５年ルールに対する民間企業の視点～

Perspective from private sectors toward global trends on debris environment: Possible five-year rule for deorbiting

パネリスト：蔵本順（ALE）、岩本彩（アストロスケール）、泉山卓（IHI）、後藤眞理（MELCO）、八田真児（MUSCATスペース・エンジニアリング）、福島忠徳（スカパーJSAT）
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Moderator: UENO Hiroshi (JAXA)

■ メガコンステレーションの軌道上への実装が本格化、衛星による観測・通信サービス提供等の実利用も開始
　打ち上げ衛星数は増加傾向、宇宙デブリの環境も次第に深刻化
　Due to rapid increase of launched satellites, space debris is a growing threat

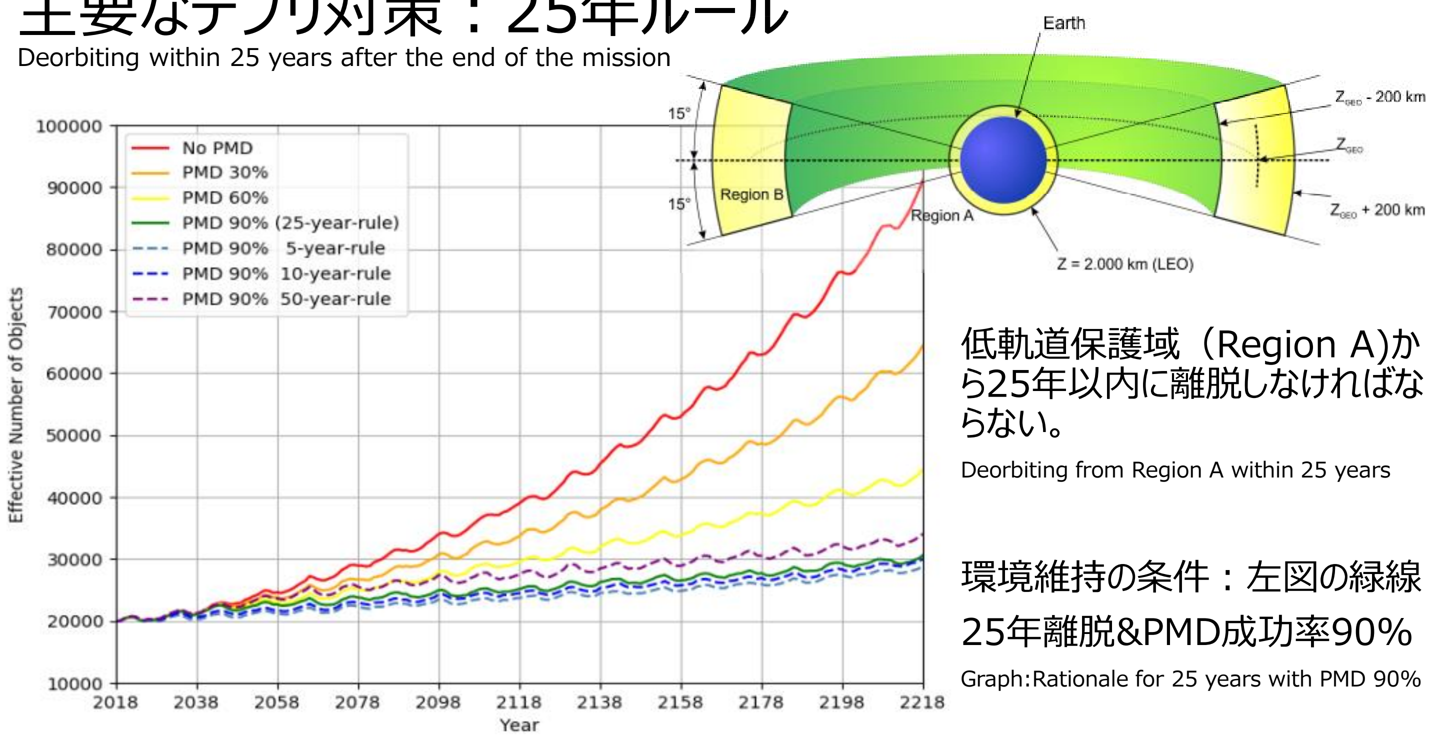
■ 宇宙デブリ低減への主要な対策：25年以内の軌道離脱
　IADCガイドラインやISO標準等が制定された国際ルール
　Deorbiting within 25 years after the end of the mission have been established by IADC and ISO

■ 今年9月、米国通信連邦委員会（FCC）は軌道離脱期間を５年以内に短縮化するルールへと変更
　これまでのルールとは一線を画するものであり、世界からも注目されている。
　Last September, FCC adopted a new rule to deorbit within 5 years

■ 民間企業の視点からパネルディスカッション: discuss a new rule and international rule making perspective from private sectors
　宇宙デブリ環境の現状、５年ルールの意義・効果・業界への影響: orbital debris status, impact of the rule
　イノベーション機会、衛星の信頼性、宇宙のガバナンス、国際ルール化への日本の対応
　opportunity of innovation, satellite reliability, space governance, possible Japan’s action to international rule making

主要なデブリ対策：25年ルール

Deorbiting within 25 years after the end of the mission



低軌道保護域（Region A)から25年以内に離脱しなければならない。

Deorbiting from Region A within 25 years

環境維持の条件：左図の緑線
25年離脱&PMD成功率90%

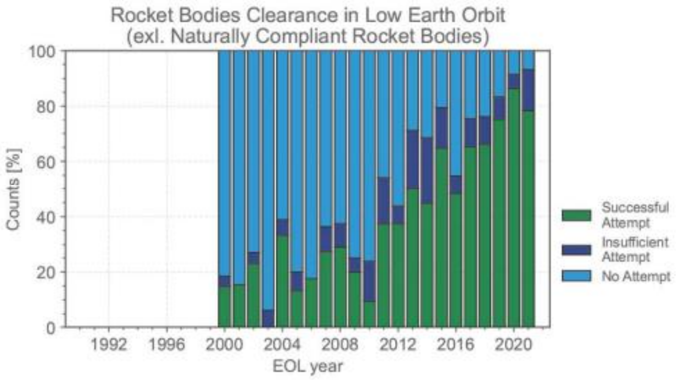
Graph:Rationale for 25 years with PMD 90%

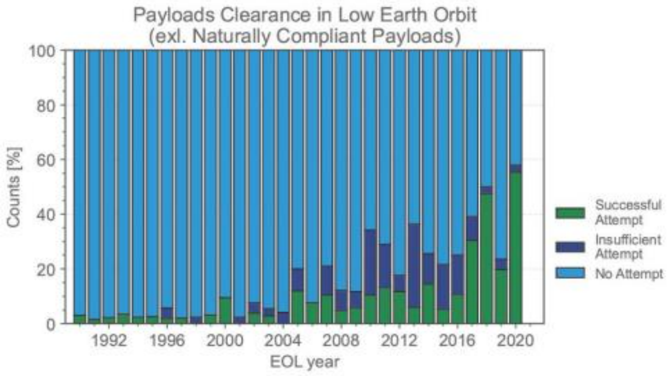
PMD期間の影響　　PMD:ミッション終了後の軌道離脱
Impact of PMD (post mission disposal) duration

Kawamoto, et al., 9th debris WS, 2021

25年ルールに適合するPMD遵守率

Compliance status with PMD of 25 years deorbiting





ESA's Space Environment Report 2022によると、自然に25年ルールに適合する軌道に存在するもの除いて、

- ロケット上段のPMD遵守率は改善を続け80%近くになっている。
  Rocket bodies PMD are getting better to reach 80%.
- 宇宙機については、PMD遵守率は改善傾向にあるが、依然として低水準（60%以下）。
  Payloads PMD are also getting better but still lower performance close to 60%.

ESA's Space Environment Report 2022

FCC NEWS from the Federal Communications Commission

Media Contact:
Will Wiquist
will.wiquist@fcc.gov

For Immediate Release

FCC ADOPTS NEW '5-YEAR RULE' FOR DEORBITING SATELLITES TO ADDRESS GROWING RISK OF ORBITAL DEBRIS

WASHINGTON, September 29, 2022—The Federal Communications Commission today adopted new rules requiring satellite operators in low-Earth orbit to dispose of their satellites within 5 years of completing their missions. The new rules shorten the decades-old 25-year guideline for deorbiting satellites post-mission, taking an important step in a new era for space safety and orbital debris policy.

The FCC takes seriously the short- and long-term challenges of orbital debris. Defunct satellites, discarded rocket cores, and other debris now fill the space environment, creating challenges for current and future missions. There are more than 4,800 satellites operating in orbit as of the end of last year, and the vast majority of those are commercial low-Earth orbit (LEO) satellites. The new 5-year rule for deorbiting satellites will mean more accountability and less risk of costly collisions that increase debris.

The Report and Order adopted today requires satellites ending their mission in or passing through the low-Earth orbit region (below 2,000 kilometers altitude) to deorbit as soon as practicable but no later than five years after mission completion. This is the first concrete rule on this topic, replacing a long-standing guideline. These new rules will also afford satellite companies a transition period of two years. The mission length and deorbit timeline for any given satellite are established through its application process with the FCC's International Bureau.

The FCC's Space Innovation docket is addressing the new space age with modernized regulations to match the new realities, support for technological innovation in this burgeoning economic sector, and taking seriously the space sustainability questions that come with rapidly growing and changing public and private space endeavors. The FCC recently launched a new proceeding for in-space servicing, assembly, and manufacturing (ISAM) capabilities. The agency is making more spectrum available to fuel the nation's space ambitions, including identifying spectrum for the first time to support commercial launches and proposing new spectrum sharing rules to increase competition. The satellite and launch industry is now an estimated $279 billion-a-year sector.

Action by the Commission September 29, 2022 by Second Report and Order (FCC 22-74). Chairwoman Rosenworcel, Commissioners Carr, Starks, and Simington approving. Chairwoman Rosenworcel, Commissioners Starks and Simington issuing separate statements.

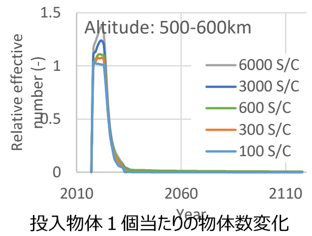
IB Docket Nos. 22-271, 18-313

https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites

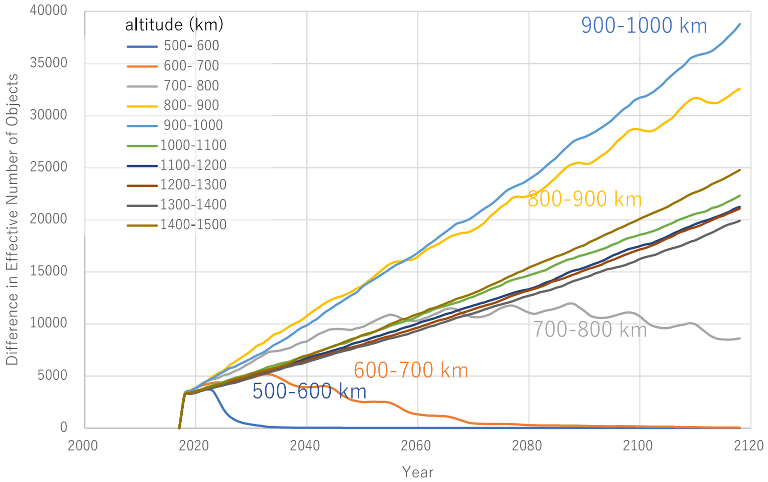
FCCは**民間衛星**の運用許可を出している。政府系のNASA、DoD、NOAAについてはこのルールの対象外。
FCC license are valid to U.S. commercial operators. The government satellites such as NASA, DoD, NOAA are out of scope of 5 years rule.

米国議会からは反対意見の書簡がFCCに対して出されるなど、米国全体としてはまだ意見が統一されていない。
Congress sent the letter to FCC regarding to the concerns of 5 year rule.

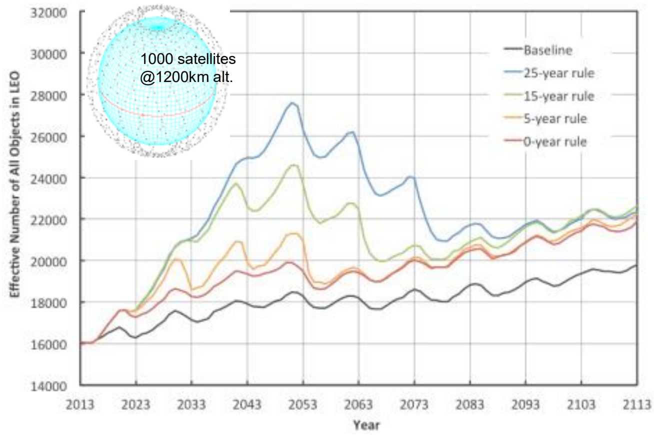
- ５年ルールに関するJAXAのこれまでの検討結果では: JAXA study of 5 years deorbiting
  - 短期的に高度600km付近の衝突率・接近回数低減には効果がある：左
    For short term, collision rates will be reduced around 600km altitude (See at bottom left)
  - LCの場合、短期的に軌道上物体数は減るが、長期的にはあまり変わらない：右下
    For long term with LC cases, there are no big difference among deorbiting period（bottom right)
  - 高度500km付近、ISS軌道などの衝突率はかえって上がる可能性
    Around 500km altitude and ISS orbit, collision rates will potentially be higher



投入物体１個当たりの物体数変化



各高度に**3000**機のデブリを投入した場合の、そのデブリ起源物体数の変化: 3000 debris inserted at specified altitude
低高度だと短期的に影響はなくなるが、高高度だと影響拡大
Kawamoto, et al., 8th ECSD, 2021



LCのPMD期間の影響
Kawamoto, et al., ISTS, 2017

IADC　2022年年次総会での主な議論

Primary discussion of FCC five years deorbiting rules at IADC annual meeting on November 2022

- 米連邦通信委員会（FCC）が低軌道寿命5年ルールを採用したことに関して、IADCとして何かアクションを起こすか議論した。
  IADC members are discussed at annual meeting about FCC five years rules whether actions are needed.
- **400-500kmが墓場軌道になることによるトラフィックの影響、CubeSat等大学ミッションへの影響が大きいこと、ロケット／宇宙機のシステム設計にも影響が大きいこと、等、IADCとして5年ルールを採用することについては慎重論が多数**であった。
  Due to the traffic effect of potential grave orbit of 400-500km altitude, the large impact of academic missions by cube sat, the design influence of launch vehicle and satellites and so on, prudent comments are major part of IADC members for adoption of five years rules
- 議論を先に進めるために、まずは5年ルールを採用した場合の影響を「環境シミュレーション」と「宇宙機システム設計（推薬搭載量等）」の両面から影響を確認していくこととなった。
  Promoting the discussion, impact of five years rules will be evaluated from the viewpoints of “debris environment trend simulation” and “spacecraft system design such as volume of propellant required”

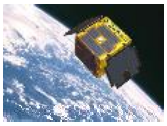
Ave. Satellite Life Span ≒ 7 years

- 25 years (magenta)
- 5 years (yellow)
- 32 years（25＋7）(blue line)
- 12 years（5 ＋7）(green line)

Nano/CUBE

File:Ncube2.jpg - Wikimedia Commons

Small/Micro



©JAXA

Large/Middle

©JAXA

IKAROS

©JAXA

Uneasy to decay　　A/M [m²/kg]　　Easy to decay

Altitude [km]	0.005	0.006	0.007	0.008	0.009	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
750	180.00	149.00	128.00	115.00	103.00	92.70	48.00	30.70	23.40	19.50	18.20	16.30	11.50	10.10	9.53
700	96.60	82.80	71.70	62.00	53.80	50.70	27.60	18.70	14.00	9.98	9.16	8.67	8.30	8.01	7.80
650	51.50	42.10	38.90	31.60	29.80	28.30	15.24	9.28	8.38	7.84	7.43	7.10	6.82	6.53	6.28
600	28.20	21.20	19.50	18.40	17.30	15.10	8.38	7.39	6.74	6.16	5.59	4.93	4.27	3.57	3.00
550	13.34	10.39	9.49	8.95	8.58	8.25	6.49	5.13	3.61	2.46	1.81	1.44	1.19	1.03	0.90
500	8.01	7.52	7.10	6.74	6.41	6.04	2.79	1.47	1.03	0.78	0.62	0.53	0.45	0.41	0.37

* Calculated by DEMIST

Space Debris WS　2022/11/28
MUSCAT Space Engineering Co., Ltd.

米FCC：5年ルールの経緯と概要

経緯 Background

- 2004年 FCCデブリ低減ガイドライン作成
- 2018年のSPD-3（大統領令第３号）、軌道環境の変化を踏まえ、**同年11月より見直し開始**
- 2020年４月　改訂版のR&O公表（2021年10月より効力発生
- 一部の論点については、継続協議（Further Notice of Proposed Rulemaking (FNPRM) ）
- **継続協議となっていた論点のうち、今般25年ルールの見直し部分について新たな決定が発出**。

今回のFCC決定の内容/ outline of the new rule

- 2022年９月、LEO上で運用する衛星について、運用終了から大気圏突入までの期間を５年に短縮
  - すでに運用中の衛星については適用されない
  - 2022年9月29日からの祖父条項（猶予期間）
  - 米国市場にアクセスする外国企業の衛星にも適用
  - 大学等の研究用のミッションについては、適用除外も検討可能。

(参考)
継続協議となっている事項
- 偶発的な破砕の確率、複数の衛星システムの衝突確率、マヌーバビリティの要求、損害リスク、免責、パフォーマンス・ボンド（保証金）
- FCCは、宇宙空間でのサービス、組立及び製造（ISAM)に関するミッションを促進するための政策見直しのための意見募集の公告発出（2022年8月）しており、本件はNew Spaceに対応するための一連の規制見直しの第一弾との位置付け。

Astroscale Proprietary　8

FCC's new five years rule

Background

- 2004 FCC's Space debris mitigation guideline
- Nov 2018 Review based on SPD-3
- April 2020 R&O (effective from Oct 2021)
- Further Notice of Proposed Rulemaking (FNPRM) for some issues
- **This decision on adopting Five Years rule was among the remaining issues in FNRPM.**

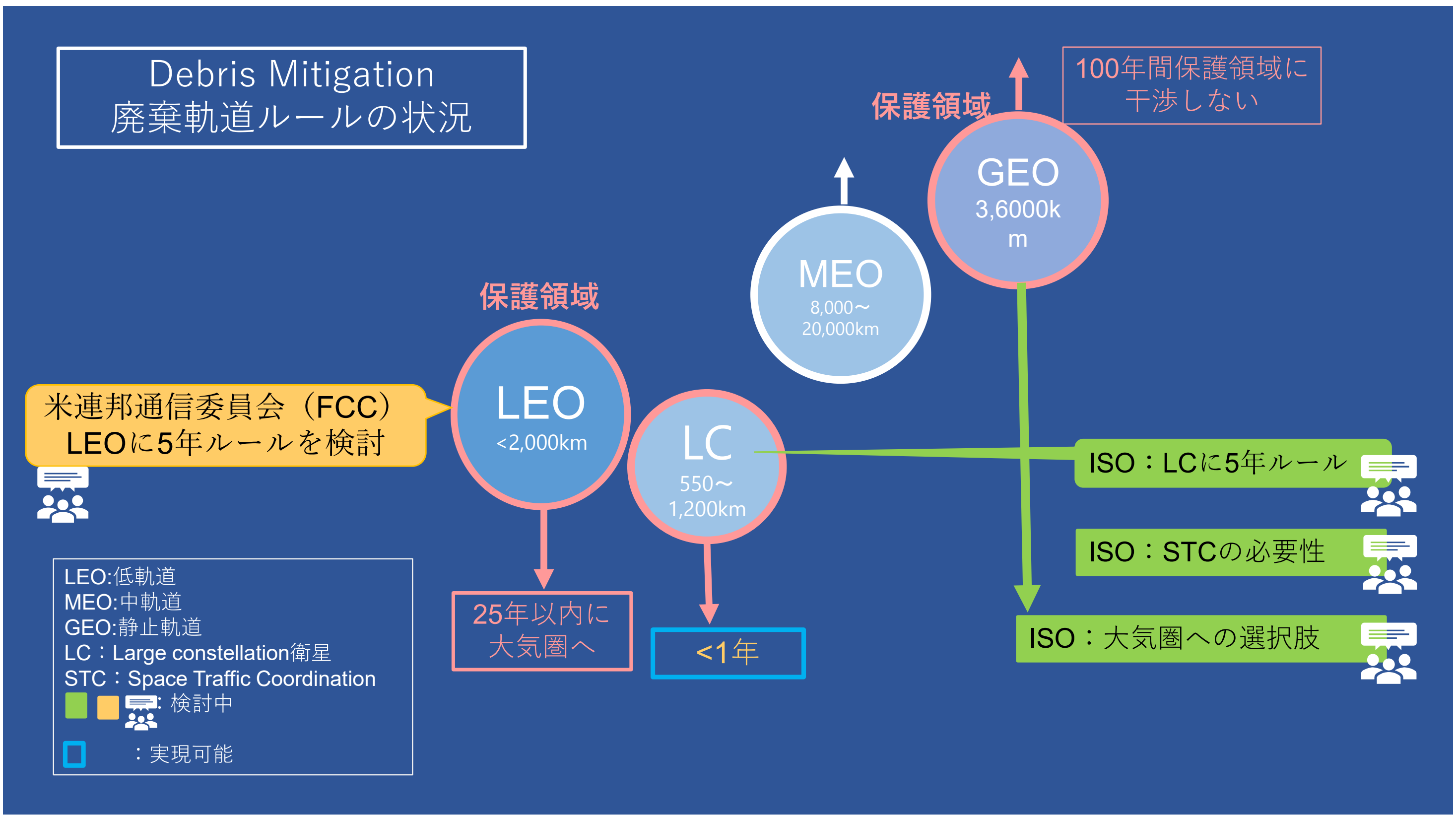
outline of the new rule

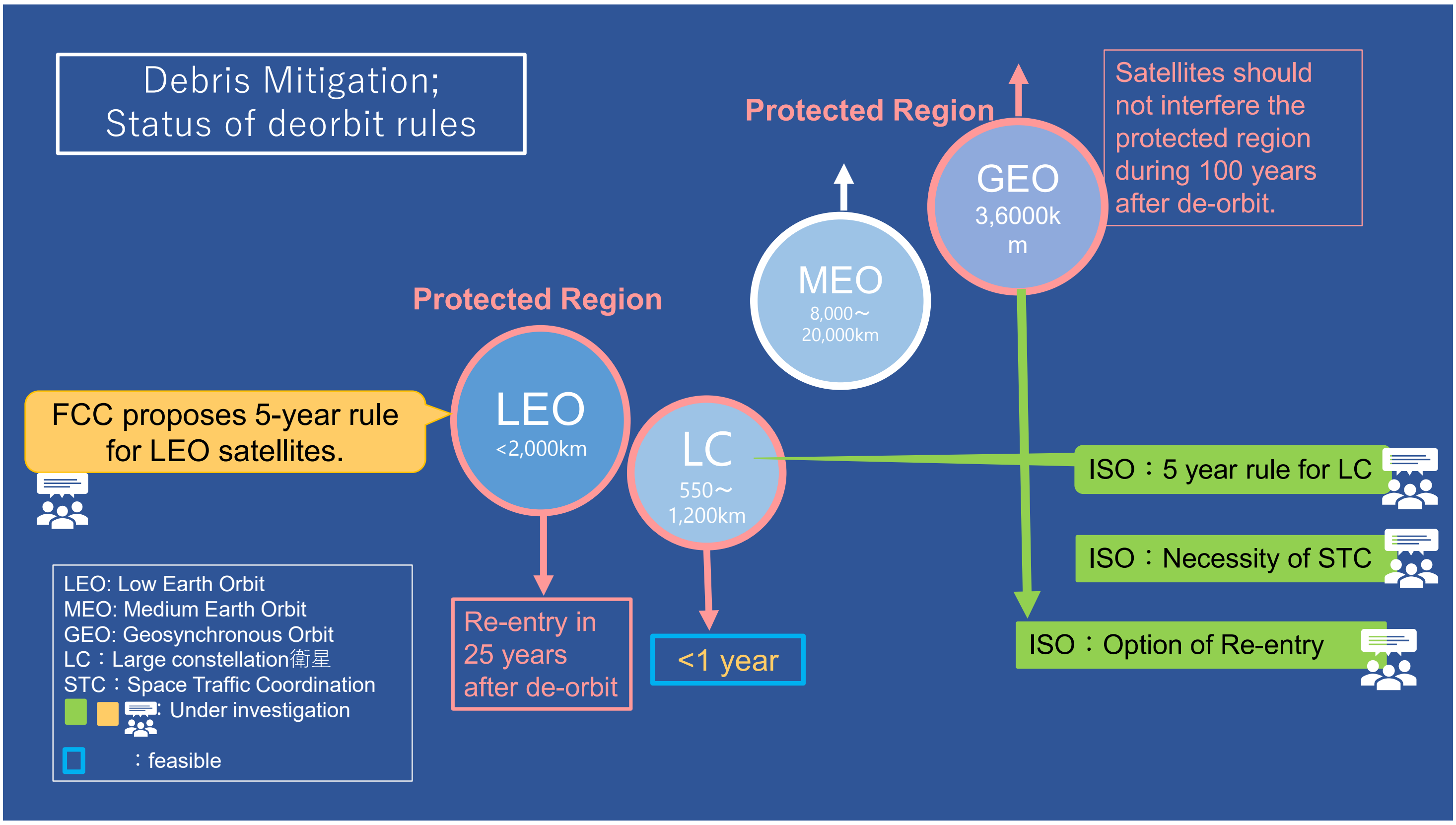
- Sep 2022 FCC adopted he new five years rules to shorten the decades-old 25-year guideline for deorbiting satellites post-mission.
  - Operational satellite are not applied
  - Grandfathering for two years
  - It will be applied for US market access
  - Additional flexibilities for Academic and Research Missions

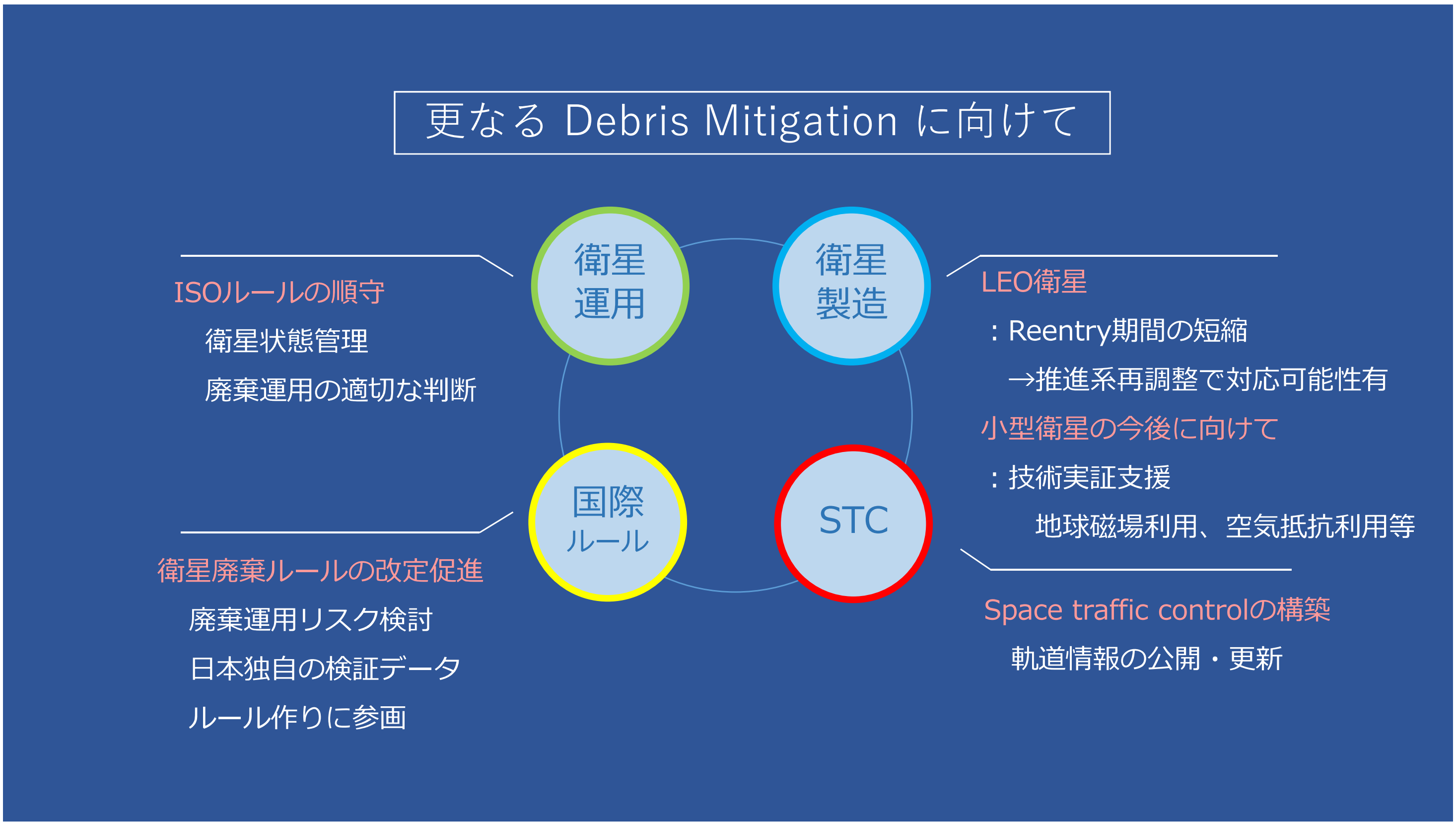
(参考)

- Other issues in FNRPM (probabilities of accidental explosions, collision risk for multi-satellite systems, maneuverability requirements for, causality risks, indemnification and performance bond)
- FCC also opens a new proceeding called Space Innovation and a Notice of Inquiry on the nascent In-Space Servicing, Assembly and Manufacturing industry as the first step.

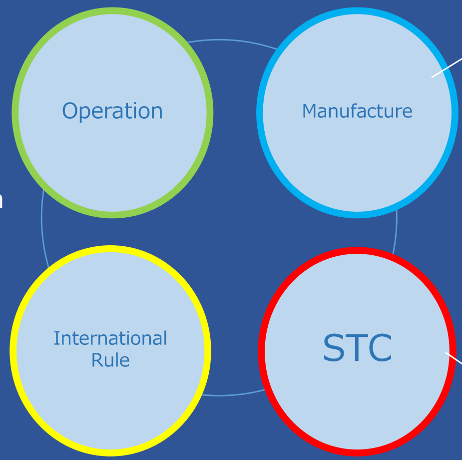
Astroscale Proprietary 9




Debris Mitigation;
Status of deorbit rules
Protected Region
Satellites should not interfere the protected region during 100 years after de-orbit.
GEO
3,6000km
MEO
8,000～20,000km
Protected Region
LEO
<2,000km
FCC proposes 5-year rule for LEO satellites.
LC
550～1,200km
ISO：5 year rule for LC
ISO：Necessity of STC
ISO：Option of Re-entry
Re-entry in 25 years after de-orbit
<1 year
LEO: Low Earth Orbit
MEO: Medium Earth Orbit
GEO: Geosynchronous Orbit
LC：Large constellation衛星
STC：Space Traffic Coordination
: Under investigation
：feasible


更なる Debris Mitigation に向けて
衛星運用
衛星製造
国際ルール
STC
ISOルールの順守
衛星状態管理
廃棄運用の適切な判断
衛星廃棄ルールの改定促進
廃棄運用リスク検討
日本独自の検証データ
ルール作りに参画
LEO衛星
：Reentry期間の短縮
→推進系再調整で対応可能性有
小型衛星の今後に向けて
：技術実証支援
地球磁場利用、空気抵抗利用等
Space traffic controlの構築
軌道情報の公開・更新

Further Debris Mitigation



Observance of ISO Rules
:Monitoring of satellite status
:Politic decision of de-orbit operation

Update of de-orbit rules
:Risk analysis of de-orbit operation
:Japanese original verification data
:Participation in the regulation discussion

LEO satellites
: Shortening the reentry period
→ feasible without re-design

Next level of small satellites
: Supporting for technical verifications using geomagnetic field, air drug etc.

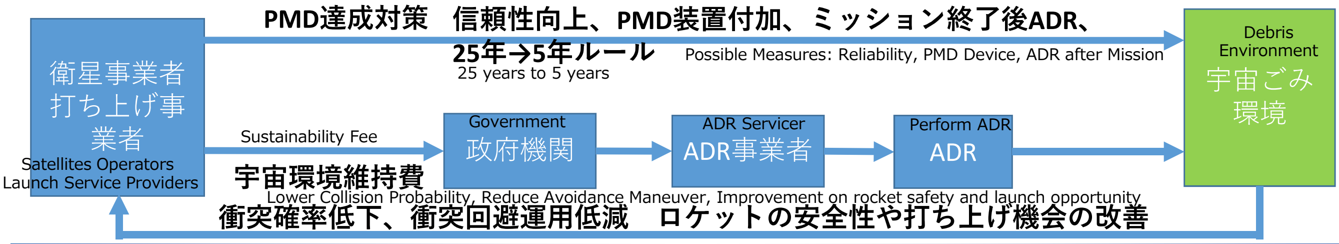
Space traffic control
: Transparency and update of orbit information

5年ルールに対する衛星事業者の視点 Perspective from private sectors for five-year rule for deorbiting

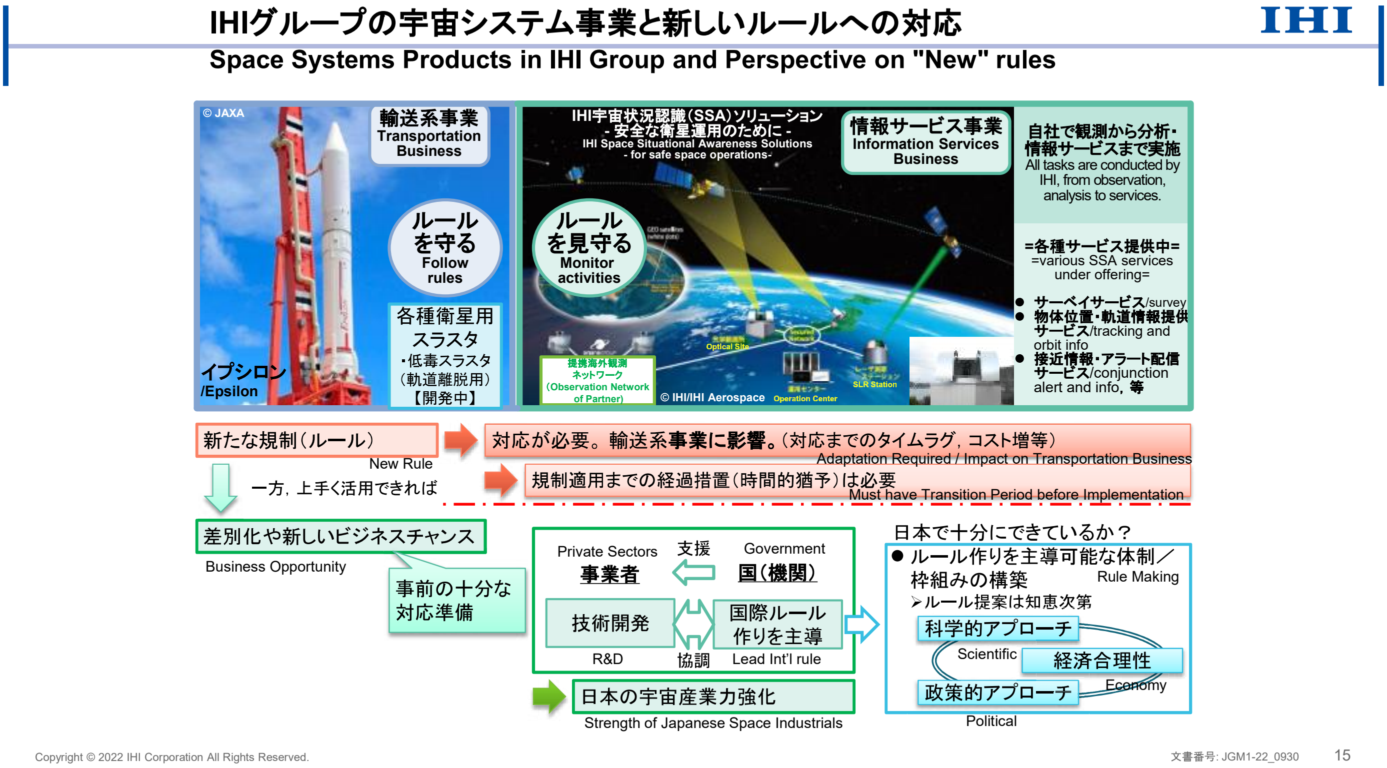
スカパーJSAT

ロケット全体のコスト増になるため、宇宙事業全般のコストを上げることに繋がり、デメリットの方が見えやすい。25年から5年にしたときのメリットとデメリットを定量的な議論が必要か。 Quantitative Comparison may be required between 25 years vs 5 years

- ロケット [Launcher] Cons: Lower Launcher Performance, Cost Increase Pros: Improvement on rocket safety and launch opportunity
  - デメリット：ミッション終了後軌道高度低下量の増加→打ち上げ能力低下→コスト増
  - メリット：ロケットの安全性や打ち上げ機会の改善？
- 静止衛星：影響なし（ロケットの打ち上げ能力低下以外） [GEO sat] No effect
- 低軌道衛星 [LEO sat] Cons: Propellant Increase, add thruster, Cost Increase Pros: lower collision probability, reduce avoidance maneuver
  - デメリット：ミッション終了後軌道高度低下量の増加→必要積算推進力増、スラスタ追加→コスト増。
  - メリット：将来的（長期的視点での）な衝突確率低下、衝突回避運用数の低減？



第10回スペースデブリワークショップ SKY Perfect JSAT Group 14



新しい世界潮流の見極め　～５年ルールに対する民間企業の視点～

＜５年ルール：業界への影響＞

〇衛星製造：質量特性、ロケットIF等の再調整は必要だが、現在の設計から大きな変更は不要。（搭載推薬の増量は必要ながら、推薬タンク容量増等のHW変更は不要の見込み。）

〇衛星運用：衝突回避数の低減。

〇輸送サービス：能力低下、高コスト化。

〇小型衛星：ライドシェア選択に制約、推進系の追加必須。

＜５年ルール：議論の観点＞

〇デブリ数量（宇宙環境）だけでなく、衝突回避負担軽減など経済性、ESG企業評価にも関連。

〇イノベーション機会を具体的に創出可能。猶予期間で官民協力での技術開発を推進し、競争力強化。

〇デブリ排出取引・資金徴収によりゴミ問題の国際的な仕組みが作れるかも。但し、排出権取引が成立するためには軌道空間に関する「権利の確定」が必要で、実現は困難との見解もあり。

〇信頼性の担保はNewSpaceにとっては課題。基準も不明確。

<国際ルール化>

〇国際ルール作りでは、データ・根拠が重要。データは、保険・SSRでも使われる。民間企業もルール作りに積極的に関与したい。事例作りも重要。日本の強み（かつては衛星試験のISO化で貢献）を生かせるはず。現在もISOデブリ低減に関する規格では、日本が他国の協力を得て進めている。これに上記の根拠データを加えることで、日本の強みになる。

〇国連のLTSでは、キャパビルも柱。ミドルパワーの日本からの発信は途上国にも響くはず。

〇日本（日本という人間のコミュニティ、日本企業、日本企業の集団など）がデブリ対策に携わることに関する、コア・バリューやパーパスについて考えておくことが重要。

Perspective from private sectors toward global trends on debris environment: Possible five-year rule for deorbiting

< Impact of five years rule to private sectors>

〇Satellite manufacturer: no major changes of current spacecraft design. propellant increase.

〇Satellite operator: reduction of collision warning detection.

〇Launch provider: lowering performance. higher launch service cost.

〇Small satellite sector: restriction of ride-share on orbit selection. propulsion equipped on satellites.

<Discussion subjects to five years rule>

〇Not only debris volume (space environment), but also economy effect based on lower burden of collision avoidance maneuver and reputation related on ESG investments.

〇Possibility to create opportunity for innovation. Reinforcement of international competitiveness by promoting technology development under PPP during transition periods.

〇International framework of debris problems by providing debris emission trade and/or resource collection required. But trade may require “certification of rights” regarding to orbital space.

〇Reliability securement of satellites and their components will be difficult to solve new space sectors only. Definition of reliability is unclear including GO/NOGO criteria.

<International rule making>

〇Data and its rationales are important under international rule making process. The data could be used for insurance as well as SSR (space sustainable rating). The private sectors want to be actively involved in rule making process. Best practices are welcome.

〇Japan and other countries are cooperatively discussing ISO standardization of the debris mitigation. By providing rationale data for standardization, it will become Japanese strength for rule making.

〇Capacity buildings are one of objectives of UN LTS. Japan as middle power may hold position to exert influences to developing countries.

〇Japanese entities might be considered on core-value and/or purpose regarding to debris mitigation.

付録　第 10 回スペースデブリワークショッププログラム

Appendix: 10th Space Debris Workshop Program

※開催時に配布、講演申込をもとに作成

主催　　国立研究開発法人 宇宙航空研究開発機構
　　　　研究開発部門

後援　　内閣府宇宙開発戦略推進事務局
　　　　一般社団法人 日本航空宇宙学会

2022年11月28日(月), 29日(火), 30日(水)

November 28-30, 2022

宇宙航空研究開発機構 調布航空宇宙センター 事務棟 1 号館 2 階講堂

オンライン

宇宙航空研究開発機構

研究開発部門

Japan Aerospace Exploration Agency

Research and Development Directorate

第 10 回スペースデブリワークショップ　プログラム

11 月 28 日（月）10:00 ～ 17:45

10:00 **Opening Remarks** SANO Hisashi (JAXA)

<u>*司会: Vincent Morand (CNES)*</u> *English Session*

10:05 A01. Invited Lecture: **Highlights of Recent ODPO Measurements and Modeling Activities**
〇J.-C. Liou (NASA)

10:35 A02. Invited Lecture: **Essential Elements of the STCM Enterprise**
〇Dan Oltrogge (COMSPOC)

10:55～11:00 換気休憩

<u>*司会: Christophe Bonnal (CNES)*</u> *English Session*

11:00 A03. **Preventive Measure to Mitigate Debris by Using ElectroDynamic Tether System for Space Debris Prevention, Considering Sustainable Space Development**
OKAJIMA Lena, 〇UTO Yasuhito, ISHII Munehiro, KAMACHI Koh (ALE), KAWAMOTO Satomi, OHKAWA Yasushi (JAXA), SATO Tsuyoshi (KAIT)

11:15 A04. **Activities in Japan to Reduce Slag Generated from Solid Rocket Motors**
〇KINOSHITA Masahiro, UI Kyoichi, SATO Kenichi, NITTA Kumi, IKEDA Hirohide, MORISHITA Naoki, OKUDOME Shinichiro, HORI Keiichi (JAXA), MATSUURA Yoshiki (IHI Aerospace)

11:30 A05. **Active Debris Removal by Electric Propulsion: Charging Mitigation on Target Debris in Debris Capture Sequence**
〇MURANAKA Takanobu (Chukyo Univ.), CHO Shinatora, OKUMURA Teppei, OHKAWA Yasushi (JAXA)

11:45 A06. **Monocular Image Measurement of Space Debris Attitude and Motion**
〇NISHIDA Shin-Ichiro, NAKAMURA Shunsuke (Tottori University)

12:00～13:20 昼休み

13:20 パネルディスカッション
「新しい世界潮流の見極め　～５年ルールに対する民間企業の視点～」
モデレーター：上野浩史（JAXA）

パネリスト：
蔵本順（ALE）
岩本彩（アストロスケール）
泉山卓（IHI）
後藤眞理（MELCO）
八田真児（MUSCAT スペース・エンジニアリング）
福島忠徳（スカパーJSAT）

14:50～15:00 休憩

<u>*司会: 秋山祐貴（JAXA）*</u>

15:00 A07. 人工衛星の光学 CAD モデルと衛星材料 BRDF を用いたライトカーブの推定
〇遠藤貴雄，尾野仁深，辻秀伸（MELCO）

15:15 A08. スタートラッカを用いた宇宙状況監視による衛星衝突回避運用の改善
〇岩城陽大，秋山恭平，柳沢俊史，日南川英明（JAXA）

15:30 A09. 低軌道分析評価ツールについて
〇藤本浩平, Darren McKnight, Erin Dale, Rachit Bhatia (LeoLabs), Chris Kunstadter (AXA XL), Matthew Stevenson, Mohin Patel (LeoLabs)

15:45～15:50 換気休憩

司会: 中道達也（IHI エアロスペース）

15:50　A10.　初期軌道誤差及び大気密度誤差がもたらす軌道予測誤差の解析解とその応用
〇日南川英明（JAXA）

16:05　A11.　スターシグナルソリューションズが取り組む接近情報の改良方法に関する概要
〇日南川英明，岩城陽大，秋山恭平，柳沢俊史（JAXA）

16:20　A12.　UMA の利用で SSA 解析の向上
〇ティモシー・グリンスキー（LSAS Tec）

16:35〜16:45　休憩

司会: Daniel Ceperley (Leolabs)　English Session

16:45　A13.　Invited Lecture: **Space Traffic Management-Coordination as a Necessity for Future Orbital Operations　A French Perspective**
〇Christophe Bonnal (CNES)

17:15　A14.　Invited Lecture: **Update on CNES Space Debris Activities**
〇Vincent Morand (CNES)

11月29日（火）10:00 ～ 17:45

司会: Dan Oltrogge (COMSPOC)　English Session

10:00　B01.　Invited Lecture: **Space Sustainability Rating: Incentivising Long-term Sustainability in Orbit**
○Minoo Rathnasabapathy , Danielle Wood (MIT), Adrien Saadaa, Emmanuelle David, Florian Micco, Jean-Paul Kneib (eSpace), Dennis Weber, Francesca Letizia, Stijn Lemmens (ESA), Moriba Jah (University of Texas at Austin), Simon Potter (BryceTech), Nikolai Khlystov (World Economic Forum)

10:30　B02.　**How to Make Spaceflight Safer**
○Siamak Hesar (Kayhan space)

10:45　B03.　**Would the Introduction of a Space Environment Tax Be Effective in Balancing Space Activities and the Space Environment?**
○MINATO Nobuaki (Ritsumeikan University), KOHTAKE Naohiko, OTSUKA Akiko (Keio University), FUSE Testuhito (Kyushu Institute of Technology)

11:00～11:05　換気休憩

司会: J.-C. Liou (NASA)　English Session

11:05　B04.　**Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory**
○Manuel Cegarra Polo, YANAGISAWA Toshifumi, KUROSAKI Hirohisa (JAXA), OHSAWA Ryou, SAKO Shigeyuki (The University of Tokyo)

11:20　B05.　**China's Role in the International Framework for SDM**
○Tao Yangzi (Keio Univ.)

11:35　B06.　**Current Status for S&MA Leadership on Sustainable Space Activities and Mission Security TF Under the Trilateral Safety and Mission Assurance Meeting**
○NITTA Kumi, KITAZAWA Yukihito, TAURA Shinichiro (JAXA)

11:50～13:10　昼休み

司会: 日南川英明（JAXA）

13:10　B07.　**大型 CMOS センサを利用した低軌道デブリ観測**
○柳沢俊史, セガーラポロマヌエル, 黒崎裕久（JAXA）

13:25　B08.　**日豪 2 地点からの低軌道物体光学観測実証（追加検証結果の報告）**
○中道達也（IHI エアロスペース), 篠原流, 泉山卓（IHI), 柳沢俊史, 黒崎裕久（JAXA）

13:40　B09.　**EISCAT レーダー観測データを用いた既知デブリとの相関解析**
○藤田浩輝, 有吉雄哉（日本文理大学), 吉村康広（九州大学), 小川泰信（国立極地研),
花田俊也（九州大学）

13:55～14:00　換気休憩

司会: 藤田浩輝（日本文理大学）

14:00　B10.　**東京大学「トモエゴゼン」の科学観測データを活用した民間宇宙状況監視データプラットフォームの取り組みについて -**
○満田和真, 服部邦洋 (デロイトトーマツリスクアドバイザリー), 谷本浩隆, 脇本拓哉,
益田哲也 (デロイトトーマツコンサルティング), 酒向重行（東京大学), Tomo-e Gozen プロジェクト

14:15　B11.　**光・赤外大学間連携による Starlink Visorsat の等級評価**
○堀内貴史（東京大学）, 花山秀和, 大石雅寿（国立天文台), OISER collaboration

14:30　B12.　**自己位置推定と自律制御を用いた軌道上微小デブリ衝突痕観測ロボットの開発**
○八木宗一郎, 中山元晴, 平山寛（秋田大学）

14:45～14:55　休憩

司会: 吉村康広（九州大学）

14:55　B13.　**SLR 反射器（Mt.FUJI）の開発と SLR データによる PSO を用いた姿勢推定手法の提案**
○秋山祐貴, 日南川英明（JAXA）

15:10 B14. **H-2A R/B のライトカーブ観測と光学シミュレーション**
○黒崎裕久，柳沢俊史，林正人，原田隆佑，河本聡美（JAXA）

15:25 B15. **静止衛星のライトカーブと数値シミュレーション**
○藤原智子，奥村真一郎，西山広太(JSGA)

15:40～15:50 休憩

司会：佐藤健一（JAXA）

15:50 B16. **ロケット上段モニタ装置と飛行中ロケットの衝突回避**
○高木友士，小早川豊範，竹中健一朗，木村友久（MHI）

16:05 B17. **ISO における大規模衛星コンステレーションに関する規格化の状況**
○加藤明（加藤技術士事務所）

16:20 B18. **H-2A 断熱材の軌道上剥離・飛散について**
○加藤明（加藤技術士事務所）

16:35～16:45 休憩

司会：竹内悠（JAXA）

16:45 B19. **宇宙の持続可能性をめぐる政策動向について**
○岩本彩（アストロスケール）

17:00 B20. **STM をめぐる米欧関係と日本への示唆**
○岩城陽大（JAXA）

17:15 B21. **新たな宇宙活動のルール作りに関する軌道上サービスガイドラインの含意**
○菊地耕一（JAXA）

17:30 B22. **宇宙活動における国家の責任ある行動の法的根拠とその展開**
○竹内悠（JAXA）

11月30日（水）10:00 ～ 17:35

司会: 原田隆佑（JAXA）

10:00　C01.　**微小デブリ観測衛星を用いた破砕起源の推定**
棚橋茉拓，吉村康広（九州大学），藤田浩輝（日本文理大学），○花田俊也（九州大学）

10:15　C02.　**模擬衛星を用いた爆発源位置による影響評価と実例による考察**
○波多英寛，井ノ口凪紗（熊本大学），仁田工美，佐藤健一（JAXA），花田俊也（九州大学）

10:30　C03.　**軌道上デブリ推移モデルを用いた軌道上破砕片の推移解析**
○長岡信明，河本聡美，原田隆佑，北川康弘（JAXA），花田俊也（九州大学）

10:45～10:55　換気休憩

司会: 花田俊也（九州大学）

10:55　C04.　**軌道上デブリデータベースの更新状況　―PMDおよび異常検知への応用―**
○上田裕子，中原雄樹，八田真児（MUSE），小林泰三（秋枌），河本聡美，長岡信明，
原田隆佑（JAXA）

11:10　C05.　**大気上層の長期変動を考慮した宇宙開発の持続可能性評価**
○清水貴裕，吉村康広（九州大学），河本聡美，原田隆佑（JAXA），花田俊也（九州大学）

11:25　C06.　**スペースデブリインデックスの活用及び定式化に関する検討**
○原田隆佑，河本聡美，長岡信明（JAXA），花田俊也（九州大学）

11:40～13:00　昼休み

司会: 北澤幸人（日本大学/JAXA）

13:00　C07.　**静止軌道太陽光発電衛星実現に向けたデブリ衝突時のイジェクタ評価**
○大保颯野，赤星保浩，内田岳志，北黒裕麻，藤井理紀，高良隆男（九州工業大学），河本聡美，
上土井大助，木本雄吾，長岡信明，原田隆佑（JAXA），泉山卓，福重進也（IHI），北澤幸人

13:15　C08.　**耐AO コーティング／ポリイミドCFRP からのイジェクタに与える電子線・原子状酸素の影響**
○西田政弘，木村大地（名古屋工業大学），古田尚正，岩瀬賢明（東亜合成），東出真澄，
石田雄一（JAXA）

13:30　C09.　**MLI用耐AO性材料に対するデブリ衝突の影響評価の取り組み**
○久保優子，木本雄吾（JAXA），梅田花織（エイ・イー・エス），長谷川直（JAXA）

13:45～13:55　休憩

司会: 中西洋喜（東京工業大学）

13:55　C10.　**ELSA-d 軌道上実証成果について**
小林裕亮，瀬戸裕基，○飯塚清太（アストロスケール）

14:10　C11.　**ADRAS-J プロジェクトステータス - 世界初大型デブリ除去実証プロジェクトの開発進捗 -**
○新栄次朗（アストロスケール）

14:25　C12.　**当社のデブリ除去の取り組みとデブリ捕獲システム超小型実証衛星（DRUMS）の運用状況**
○菅原靖敬，松下悠里，山崎裕司，森田大地，町野泰章，丸山辰也，田中稔久(KHI)

14:40　C13.　**持続可能なデブリ除去運用コンセプトと商業デブリ除去実証フェーズⅡの技術実証シナリオの検討**
○中村涼，岡本博之，山元透（JAXA）

14:55　C14.　**低軌道における小型デブリを対象とした安価で効果的な受動的デブリ除去衛星**
○関川賢一（三菱電機ソフトウエア）

15:10～15:20　休憩

司会: 中村涼（JAXA）

15:20　C15.　**レーザ衛星を用いたADRミッションにおける軌道設計**
○板谷優輝，福島忠徳, Aditya Baraskar，藤原智章，長峯健心（スカパーJSAT），
五十部駿，吉村康広，花田俊也（九州大学）

15:35 C16. **レーザアブレーションにより剥離するMLIの解析**
○長峯健心, 福島忠徳, Aditya Baraskar, 板谷優輝, 藤原智章（スカパーJSAT),
中村友祐, 佐宗章弘（名古屋大学)

15:50 C17. **パルスレーザを用いたスペースデブリの回転静止解析**
○藤原智章, 福島忠徳, Aditya Baraskar, 板谷優輝, 長峯健心, 酒井大輔（スカパーJSAT)

16:05 C18. **レーザアブレーションを用いたマルチデオービットの相対軌道設計**
○五十部駿, 正木翔, 吹井柊太, 吉村康広, 花田俊也（九州大学), 板谷優輝, 藤原智章,
福島忠徳（スカパーJSAT)

16:20～16:30 休憩

司会: 西田政弘（名古屋工業大学）

16:30 C19. **スペースデブリ除去ミッションを目指した電気推進(ホールスラスタ)の 開発状況と事業展開**
○中村秀一（ネッツ)

16:45 C20. **スペースデブリ模擬構造への金属製銛撃ち込みにおける銛回転の影響評価**
○玉置悠人, 田中宏明（防衛大学校)

17:00 C21. **デブリ除去捕獲機構HKKによるデブリのソフトリリースに関する研究**
○谷嶋信貴, 岡本博之, 奥村哲平, 渡邊恵佑, 中村涼（JAXA)

17:15 C22. **非協力的ターゲット捕獲・把持機構の検討**
○中西洋喜, 高橋健一郎, 川口直毅, 石渡美里, 德安彰大（東京工業大学)

17:30 **閉会挨拶** 第10回スペースデブリワークショップ実行委員会

10th Space Debris Workshop Program

November 28 (Monday) 10：00 ～ 17：45

10:00 **Opening Remarks** SANO Hisashi（JAXA）

Chairperson: Vincent Morand (CNES) *English Session*

10:05 A01. Invited Lecture: **Highlights of Recent ODPO Measurements and Modeling Activities**
○J.-C. Liou (NASA)

10:35 A02. Invited Lecture: **Essential Elements of the STCM Enterprise**
○Dan Oltrogge (COMSPOC)

10:55～11:00 **Break**

Chairperson: Christophe Bonnal (CNES) *English Session*

11:00 A03. **Preventive Measure to Mitigate Debris by Using ElectroDynamic Tether System for Space Debris Prevention, Considering Sustainable Space Development**
OKAJIMA Lena, ○UTO Yasuhito, ISHII Munehiro, KAMACHI Koh (ALE), KAWAMOTO Satomi, OHKAWA Yasushi (JAXA), SATO Tsuyoshi (KAIT)

11:15 A04. **Activities in Japan to Reduce Slag Generated from Solid Rocket Motors**
○KINOSHITA Masahiro, UI Kyoichi, SATO Kenichi, NITTA Kumi, IKEDA Hirohide, MORISHITA Naoki, OKUDOME Shinichiro, HORI Keiichi (JAXA), MATSUURA Yoshiki (IHI)

11:30 A05. **Active Debris Removal by Electric Propulsion: Charging Mitigation on Target Debris in Debris Capture Sequence**
○MURANAKA Takanobu (Chukyo Univ.), CHO Shinatora, OKUMURA Teppei, OHKAWA Yasushi (JAXA)

11:45 A06. **Monocular Image Measurement of Space Debris Attitude and Motion**
○NISHIDA Shin-Ichiro, NAKAMURA Shunsuke (Tottori University)

12:00～13:20 **Luncheon**

13:20 **Panel Discussion**
Perspective from Private Sectors Toward Global Trends on Debris Environment: Possible Five-year Rule for Deorbiting
Moderator: UENO Hiroshi (JAXA)

Panelist: KURAMOTO Jun (ALE)
IWAMOTO Aya (Astroscale Japan)
IZUMIYAMA Taku (IHI)
GOTO Mari (MELCO)
HATTA Shinji (MUSCAT Space Engineering)
FUKUSHIMA Tadanori (SKY Perfect JSAT)

14:50～15:00 **Break**

Chairperson: AKIYAMA Yuki（JAXA）

15:00 A07. **Photometric Light Curve Estimation Using GEO Satellite CAD Models and Material BRDFs**
○ENDO Takao, ONO Hitomi, TSUJI Hidenobu (MELCO)

15:15 A08. **Improving Collision Avoidance Operations of Satellites by Space Situation Monitoring Using Star Tracker**
○IWAKI Akihiro, AKIYAMA Kyohei, YANAGISAWA Toshifumi, HINAGAWA Hideaki (JAXA)

15:30 A09. **LEO Analytic Assessment Tools**
○FUJIMOTO Kohei, Darren McKnight, Erin Dale, Rachit Bhatia (LeoLabs), Chris Kunstadter (AXA XL), Matthew Stevenson, Mohin Patel (LeoLabs)

15:45～15:50 **Break**

Chairperson: NAKAMICHI Tatsuya (IHI AEROSPACE)

15:50 A10. **Analytical Solution and Application for Orbit Prediction Error Due to Initial Orbit and Atmospheric Density Errors**
○HINAGAWA Hideaki (JAXA)

16:05 A11. **Overview of Conjunction Data Enhancement by Star Signal Solutions**
○HINAGAWA Hideaki, IWAKI Akihiro, AKIYAMA Kyohei, YANAGISAWA Toshifumi (JAXA)

16:20 A12. **UMA and its Application for SSA**
○Timothy Glinski (LSAS Tec)

16:35～16:45 **Break**

Chairperson: Daniel Ceperley (Leolabs) *English Session*

16:45 A13. Invited Lecture: **Space Traffic Management-Coordination as a Necessity for Future Orbital Operations A French Perspective**
○Christophe Bonnal (CNES)

17:15 A14. Invited Lecture: **Update on CNES Space Debris Activities**
○Vincent Morand (CNES)

November 29 (Tuesday) 10：00 ～ 17：45

Chairperson: Dan Oltrogge (COMSPOC) *English Session*

10:00 B01. Invited Lecture: **Space Sustainability Rating: Incentivising Long-term Sustainability in Orbit**
○Minoo Rathnasabapathy , Danielle Wood (MIT), Adrien Saadaa, Emmanuelle David, Florian Micco, Jean-Paul Kneib (eSpace), Dennis Weber, Francesca Letizia, Stijn Lemmens (ESA), Moriba Jah (University of Texas at Austin), Simon Potter (BryceTech), Nikolai Khlystov (World Economic Forum)

10:30 B02. **How to Make Spaceflight Safer**
○Siamak Hesar (Kayhan space)

10:45 B03. **Would the Introduction of a Space Environment Tax Be Effective in Balancing Space Activities and the Space Environment?**
○MINATO Nobuaki (Ritsumeikan University), KOHTAKE Naohiko, OTSUKA Akiko (Keio University), FUSE Testuhito (Kyushu Institute of Technology)

11:00～11:05 **Break**

Chairperson: J.-C. Liou (NASA) *English Session*

11:05 B04. **Real-time Streaks Detection in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory**
○Manuel Cegarra Polo, YANAGISAWA Toshifumi, KUROSAKI Hirohisa (JAXA), OHSAWA Ryou, SAKO Shigeyuki (The University of Tokyo)

11:20 B05. **China's Role in the International Framework for SDM**
○Tao Yangzi (Keio Univ.)

11:35 B06. **Current Status for S&MA Leadership on Sustainable Space Activities and Mission Security TF Under the Trilateral Safety and Mission Assurance Meeting**
○NITTA Kumi, KITAZAWA Yukihito, TAURA Shinichiro (JAXA)

11:50～13:10 **Luncheon**

Chairperson: HINAGAWA Hideaki（JAXA）

13:10 B07. **LEO Debris Observation Using Large CMOS Sensors**
○YANAGISAWA Toshifumi , CegarraPolo Manuel, KUROSAKI Hirohisa(JAXA)

13:25 B08. **Optical Observation Demonstration of LEO Objects from Japan and Australia (The Report of Additional Verification)**
○NAKAMICHI Tatsuya (IHI AEROSPACE), SHINOHARA Ryu, IZUMIYAMA Taku (IHI), YANAGISAWA Toshifumi, KUROSAKI Hirohisa (JAXA)

13:40 B09. **A Correlation Analysis Between Space Debris Detected by an EISCAT Radar and Cataloged Ones**
○FUJITA Koki, ARIYOSHI Yuya (Nippon Bunri Univ.), YOSHIMURA Yasuhiro (Kyushu Univ.), OGAWA Yasunobu (National Institute of Polar Research), HANADA Toshiya (Kyushu Univ.)

13:55～14:00 **Break**

Chairperson: FUJITA Koki (Nippon Bunri Univ.)

14:00 B10. **Leveraging Scientific Observational Data Taken by Tomo-e Gozen to a Commercial SSA Data Platform**
○MITSUDA Kazuma, HATTORI Kunihiro (Deloitte Tohmatsu Risk Advisory Co., Ltd.), TANIMOTO Hirotaka, WAKIMOTO Takuya, MASUDA Tetsuta (Deloitte Tohmatsu Consulting Co., Ltd.), SAKO Shigeyuki (The University of Tokyo), Tomo-e Gozen Project

14:15 B11. **Magnitude Estimation of Starlink's Visorsat with the OISTER Collaboration**
○HORIUCHI Takashi (The University of Tokyo), HANAYAMA Hidekazu, OHISHI Masatoshi (NAOJ), OISER collaboration

14:30 B12. **Development of In-situ Observation Robot for Micro Space Debris Impact Marks Using Localization and Autonomous Control**
○YAGI Soichiro, NAKAYAMA Motoharu, HIRAYAMA Hiroshi (Akita Univ.)

14:45～14:55 **Break**

Chairperson: YOSHIMURA Yasuhiro (Kyushu Univ.)

14:55 B13. **Development of SLR Reflector (Mt.FUJI) and Attitude Motion Estimation Based on Particle Swarm Optimization by SLR Data**
○AKIYAMA Yuki, HINAGAWA Hideaki (JAXA)

15:10 B14. **Light Curve Observation and Simulation of H-2A R/B**
○KUROSAKI Hirohisa, YANAGISAWA Toshifumi, HAYASHI Masato, HARADA Ryusuke, KAWAMOTO Satomi (JAXA)

15:25 B15. **Observations and Numerical Simulations of Light Curves for GEO Satellites**
○FUJIWARA Tomoko, OKUMURA Shin-ichiro, NISHIYAMA Kota (JSGA)

15:40～15:50 **Break**

Chairperson: SATO Kenichi (JAXA)

15:50 B16. **Launch Vehicle Upper Stage Monitor and Collision Avoidance for Ascending Rocket**
○TAKAKI Yuji, KOBAYAKAWA Toyonori, TAKENAKA Kenichiro, KIMURA Tomohisa (MHI)

16:05 B17. **Status of Standardization for Large Constellation of Spacecraft in ISO**
○KATO Akira (Kato Professional Engineer's Office)

16:20 B18. **Orbital Fragmentation of Insulator from H-2A Launch Vehicles**
○KATO Akira (Kato Professional Engineer's Office)

16:35～16:45 **Break**

Chairperson: TAKEUCHI Yu (JAXA)

16:45 B19. **Recent Global Policy Trend on Space Sustainability**
○IWAMOTO Aya (Astroscale Japan)

17:00 B20. **U.S.-European Relations Regarding STM and Implications for Japan**
○IWAKI Akihiro (JAXA)

17:15 B21. **Implication of On-Orbit Servicing Guidelines on Rule Making for Emerging Space Activities**
○KIKUCHI Koichi (JAXA)

17:30 B22. **Legal Basis and Developments of Responsible Behavior of States in Space Activities**
○TAKEUCHI Yu (JAXA)

November 30 (Wednesday) 10:00 ～ 17:35

Chairperson: HARADA Ryusuke (JAXA)

10:00 C01. **Origin Identification of Breakup Event from In-situ Debris Measurements**
TANAHASHI Mahiro, YOSHIMURA Yasuhiro (Kyushu Univ.), FUJITA Koki (Nippon Bunri Univ.), ○HANADA Toshiya (Kyushu Univ.)

10:15 C02. **Effect of Source Location on Mock-up Satellite Fragmentation**
○HATA Hidehiro, INOKUCHI Nagisa (Kumamoto Univ.), NITTA Kumi, SATO Kenichi (JAXA), HANADA Toshiya (Kyushu Univ.)

10:30 C03. **Analysis of Orbital Debris Environment Using Debris Evolutionary Model**
○NAGAOKA Nobuaki, KAWAMOTO Satomi, HARADA Ryusuke, KITAGAWA Yasuhiro (JAXA), HANADA Toshiya (Kyushu Univ.)

10:45～10:55 **Break**

Chairperson: HANADA Toshiya (Kyushu Univ.)

10:55 C04. **Update Status of the On-orbit Objects Database --Application for Detecting PMDs and Anomalies of Orbit--**
○UEDA O. Hiroko, NAKAHARA Yuki, HATTA Shinji (MUSCAT Space Engineering), KOBAYASHI Taizo (AcisomA), KAWAMOTO Satomi, NAGAOKA Nobuaki, HARADA Ryusuke (JAXA)

11:10 C05. **Evaluation of Sustainable Space Development with Considering the Long-term Change in the Upper Atmosphere**
○SHIMIZU Takahiro, YOSHIMURA Yasuhiro (Kyushu Univ.), KAWAMOTO Satomi, HARADA Ryusuke (JAXA), HANADA Toshiya (Kyushu Univ.)

11:25 C06. **A Study of Utilization and Formulation of Space Debris Index**
○HARADA Ryusuke, KAWAMOTO Satomi, NAGAOKA Nobuaki (JAXA), HANADA Toshiya (Kyushu University)

11:40～13:00 **Luncheon**

Chairperson: KITAZAWA Yukihito (Nihon Univ./JAXA)

13:00 C07. **Evaluation of Ejecta Generated at Hypervelocity Impact on Space Components in Realization of Space Solar Power Satellite in GEO**
○DAIBO Soya, AKAHOSHI Yasuhiro, UCHIDA Takeshi, KITAGURO Yuma, FUJII Masanori, KOURA Takao (Kyutech), KAWAMOTO Satomi, JOUDOI Daisuke, KIMOTO Yugo, NAGAOKA Nobuaki, HARADA Ryusuke (JAXA), IZUMIYAMA Taku, FUKUSHIGE Shinya (IHI), KITAZAWA Yukihito

13:15 C08. **Effect of Electron Beam and Atomic Oxygen Irradiation on Ejecta from Anti-AO Coating Polyimide CFRP**
○NISHIDA Masahiro, KIMURA Daichi (Nagoya Institute of Technology), FURUTA Naomasa (Toagosei Co., Ltd.), IWASE Yoshiaki (Toagosei Co., Ltd.), HIGASHIDE Masumi (JAXA), ISHIDA Yuichi (JAXA)

13:30 C09. **Initiative for Evaluation of Space Debris Impact on Atomic Oxygen Resistant Materials for MLI**
○KUBO Yuko, KIMOTO Yugo (JAXA), UMEDA Kaori (AES), HASEGAWA Sunao (JAXA)

13:45～13:55 **Break**

Chairperson: NAKANISHI Hiroki (Tokyo Institute of Technology)

13:55 C10. **ELSA-d Demonstration Achievement in Orbit**
KOBAYASHI Yusuke, SETO Yuki, ○IIZUKA Seita (Astroscale Japan)

14:10 C11. **Status of ADRAS-J project - Development Progress of ADR**
○ATARASHI Eijiro (Astroscale Japan)

14:25 C12. **Our Debris Removal Efforts and the Operational Status of the Debris Removal Unprecedented Micro-satellite (DRUMS)**
○SUGAWARA Yasutaka, MATSUSHITA Yuri, YAMASAKI Hiroshi, MORITA Daichi, MACHINO Yasuaki, MARUYAMA Tatsuya, TANAKA Toshihisa (KHI)

14:40 C13. **Study of Technology Demonstration Scenarios of CRD2 Phase2 Aiming Sustainable Debris Removal**
○NAKAMURA Ryo, OKAMOTO Hiroyuki, YAMAMOTO Toru (JAXA)

14:55 C14. **Proposing a Low-cost and Effective Passive Debris Removal Satellite for Removing Small-sized Orbital Debris in Low Earth Orbit**
○SEKIKAWA Kenichi (Mitsubishi Electric Software)

15:10～15:20 **Break**

Chairperson: NAKAMURA Ryo (JAXA)

15:20 C15. **Orbit Design for ADR Mission Using Laser Satellite**
○ITAYA Yuki, FUKUSHIMA Tadanori, Aditya Baraskar, FUJIHARA Tomoaki, NAGAMINE Kenshin (SKY Perfect JSAT), ISOBE Shun, YOSHIMURA Yasuhiro, HANADA Toshiya (Kyushu University)

15:35 C16. **Simulation of MLI Detached by Laser Ablation**
○NAGAMINE Kenshin, FUKUSHIMA Tadanori, Aditya Baraskar, ITAYA Yuki, HUJIHARA Tomoaki (SKY perfect JSAT), NAKAMURA Yusuke, SASOH Akihiro (Nagoya University)

15:50 C17. **Analysis for Detumbling of Space Debris with Pulsed Laser**
○FUJIHARA Tomoaki, FUKUSHIMA Tadanori, Aditya Baraskar, ITAYA Yuki, NAGAMINE Kenshin, SAKAI Daisuke (SKY Perfect JSAT)

16:05 C18. **Formation Design for Multi-deorbit Using Laser Ablation**
○ISOBE Shun, MASAKI Kakeru, FUKII Shuta, YOSHIMURA Yasuhiro, HANADA Toshiya (Kyushu University), ITAYA Yuki, FUJIHARA Tomoaki, FUKUSHIMA Tadanori (SKY Perfect JSAT)

16:20～16:30 **Break**

Chairperson: NISHIDA Masahiro (Nagoya Institute of Technology)

16:30 C19. **Hall Thruster Development and Business Plan for Mission of Space Debris Removal at NETS Co.,LTD.**
○NAKAMURA Shuichi (NETS)

16:45 C20. **Effects of a Rotation of a Metal Harpoon on Penetration Behavior for Capturing Space Debris**
○TAMAKI Yuto, TANAKA Hiroaki(National Defense Academy of Japan)

17:00 C21. **Study on Soft-release of Debris by Debris Capturing Mechanism HKK**
○TANISHIMA Nobutaka, OKAMOTO Hiroyuki, OKUMURA Teppei, WATANABE Keisuke, NAKAMURA Ryo (JAXA)

17:15 C22. **A Study of Capture Devices for Non-Cooperative Target**
○NAKANISHI Hiroki, TAKAHASHI Kenichiro, KAWAGUCHI Naoki, ISHIWATA Misato, TOKUYASU Akihiro (Tokyo Institute of Technology)

17:30 **Closing Address** 10th Space Debris Workshop Executive Committee

--- 第 10 回スペースデブリワークショップ実行委員 ---
河本聡美（実行委員長）、柳沢俊史（副委員長）、大川恭志、原田隆佑、長岡信明、山元透、竹内悠、大坊俊彰、黒崎裕久、西本裕子（以上研究開発部門）、上野浩史（新事業促進部）、佐藤健一、吉原徹、仁田工美（安全・信頼性推進部）、日南川英明（追跡ネットワーク技術センター）、花田俊也（九州大学）、赤星保浩（九州工業大学）

--10th Space Debris Workshop Program Committee--
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第10回「スペースデブリワークショップ」講演資料集

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