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第9回 「スペースデブリワークショップ」 講演資料集
Proceedings of the 9th Space Debris Workshop

2021年8月

宇宙航空研究開発機構
Japan Aerospace Exploration Agency

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Panel Discussion

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第 9 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 9th JAXA Space Debris Workshop Executive Committee
KAWAMOTO Satomi
Research Unit II, Research and Development Directorate
Japan Aerospace Exploration Agency

近年スペースデブリ（宇宙ゴミ）の増加に加え、大規模コンステレーションも出現しつつあり、軌道上環境は急激に変化している。スペースデブリ低減ガイドラインの見直し、STM（Space Traffic Management, 宇宙交通管理）や民間 SSA(Space Situational Awareness, 宇宙状況把握)、宇宙機のレーティング、デブリ除去技術実証など、新たな動きも次々に生まれており、現在の軌道上状況や世界の動向等に関する正しい情報を共有し、様々なステークホルダーとの連携を取ることが今まで以上に重要になっている。

本資料集は、2021 年 2 月 24~26 日にオンライン開催された第 9 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収集、意見交換のための国内最大規模の会合として、近年は JAXA 調布航空宇宙センター講堂にて隔年開催されてきたが、今回は新型コロナウィルスの感染拡大を受けて初めてのオンライン開催となった。会場での交流がかなわず残念ではあったが、過去最大の約 320 人が参加登録し、口頭発表 43 件、ポスター発表 9 件、パネルディスカッション 2 件を無事配信することができた。パネルディスカッションでは、実効的なデブリ低減策の議論・推進にはデブリの関係者だけでなく、様々なステークホルダーが広く参加することが大切という意見もあったが、一国だけでこれだけの規模の参加者がある機会は貴重であると海外の専門家からも高く評価されている。

本講演資料集には、日本におけるデブリ関連活動を網羅する各発表や、海外の高名な専門家からの世界の最新の動向に加え、パネルディスカッションでの民間事業者の事業化に向けた議論および法政策的見地からの議論も収録されている。本資料集が、全ての方にとって、最新の技術情報を入手できる資料として役立つことを、それがひいては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念している。

口頭セッション

Oral Session

A01

JAXAのスペースデブリ関連活動紹介

Space Debris Related Activities at JAXA

○山中 浩二（JAXA）
○YAMANAKA Koji (JAXA)

JAXA の最新のデブリ関連研究を紹介する。デブリ推移モデルの最新研究結果、地上からのデブリ観測能力の改善、微小軌道上デブリのモニタリング装置の開発状況、デブリ除去用の高効率なホールスラスタシステム開発、ロバスト性の向上を目指したデブリ捕獲機構の開発状況、デブリ捕獲の地上実証プラットフォームの開発など。また、デブリ除去に関しては、民間事業者の自立、国際競争力確保を促すための新たなパートナーシップ型の取り組みを開始し、フェーズⅠのパートナとして株式会社アストロスケールを選定した。その詳細に関しても紹介する。JAXA は今後も宇宙の持続的利用に貢献していく。

Space debris related activities at JAXA will be presented. They are, latest research results of the debris transition model, improvement of debris observation capability from the ground, development status of in-situ micro debris monitoring equipment, highly efficient hall-thruster system development for effective debris removal, development status of debris capture mechanism improving its robustness, ground platform for debris capture, etc. With regard to active debris removal, we have also launched a new partnership-type initiative to encourage the private sector activities, and have selected AstroScale, Inc. as a partner for Phase I. JAXA will continue to contribute to the sustainable use of future space.

Space Debris Related Activities at JAXA

Koji Yamanaka
Director, Research Unit I,
Aerospace Research and Development Directorate of JAXA
Feb. 24, 2021

JAXA's activities on ensuring stable use of outer space

- As space utilization expands worldwide, threats and risks posed by space debris become serious issue. Securing the stable use of space is one of the most important and urgent concerns of all.
- Japan's Basic Plan sets Space Policy's objectives, such as ensuring National Security in Space and strengthening of national security ability.

- JAXA's activities contribute to Basic Plan are:
  1. Contribution for Space Situational Awareness(SSA).
  2. R&D for Space debris threats and risks.
  3. Support government in making international standards and regulations on space utilization.

(February 28 2019, International Symposium on Ensuring Stable Use of Outer Space, JAXA Presentation).

2


Technology Background of JAXA
ETS-VII
Launched in 1997
• The world's first unmanned rendezvous docking experiments in 1998
HTV
Have been launched from 2009
• Total 9 flights were successfully accomplished from 2009.
• HTV rendezvous with ISS (Client) cooperatively utilizing GPS and precise sensing capability.
©NASA/JAXA
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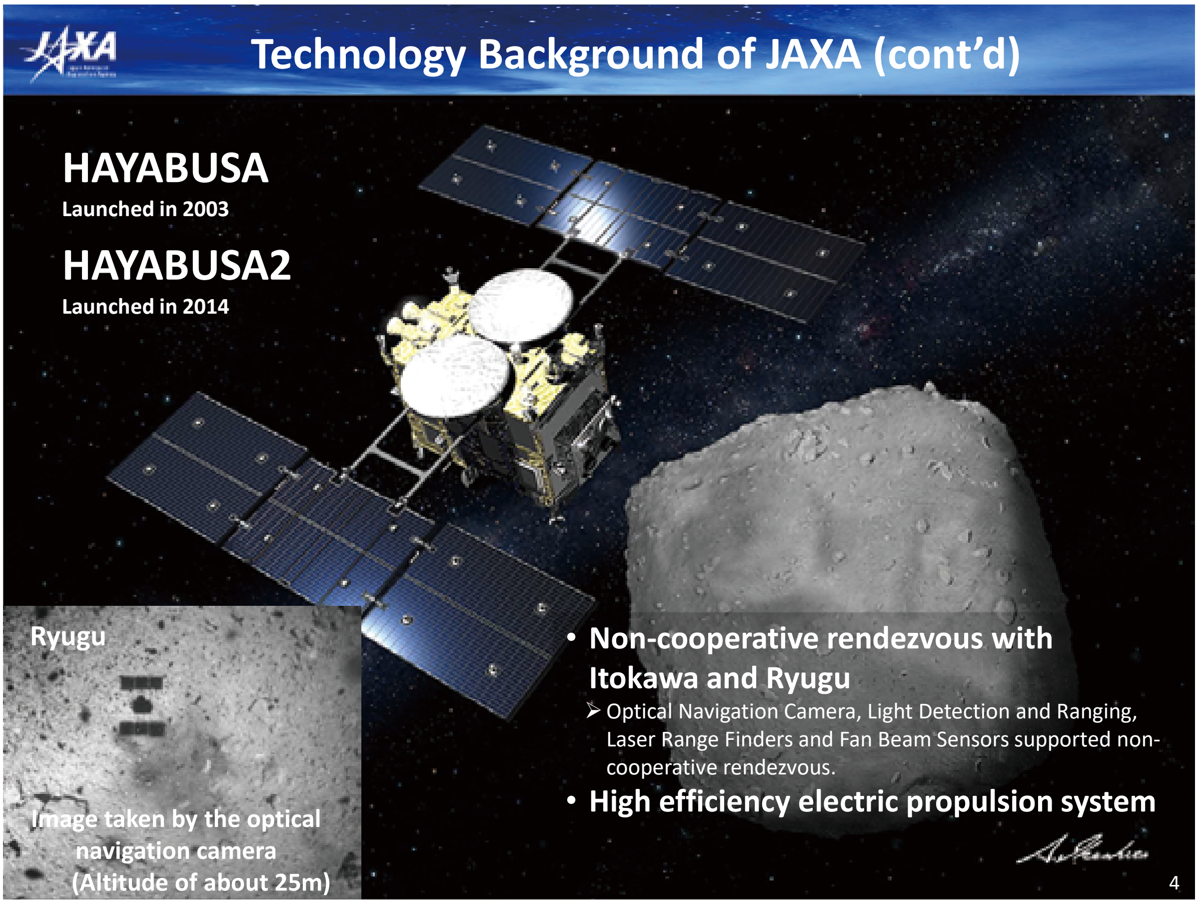
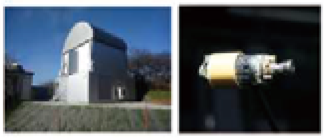
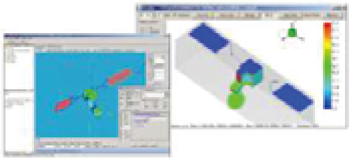

Technology Background of JAXA (cont'd)
HAYABUSA
Launched in 2003
HAYABUSA2
Launched in 2014
Ryugu
Image taken by the optical navigation camera
(Altitude of about 25m)
• Non-cooperative rendezvous with Itokawa and Ryugu
➢ Optical Navigation Camera, Light Detection and Ranging, Laser Range Finders and Fan Beam Sensors supported non-cooperative rendezvous.
• High efficiency electric propulsion system
4

Key Technologies

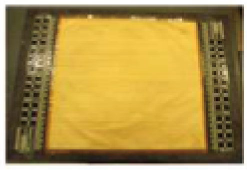
Observation



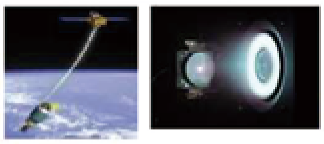
Modeling



In-Situ Measurement

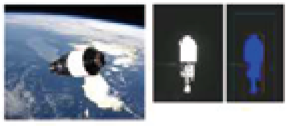


Propulsion

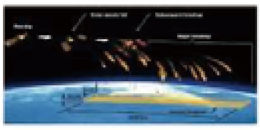


Capture

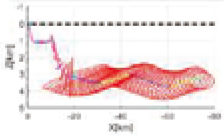
Rendezvous



Deorbit & Safe Reentry



Numerical Simulation



Ground Testing

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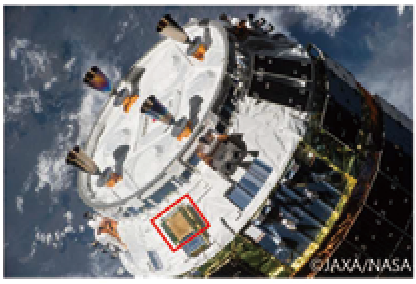
In-situ Measurement of Small Debris

■Space Debris Monitor (SDM)

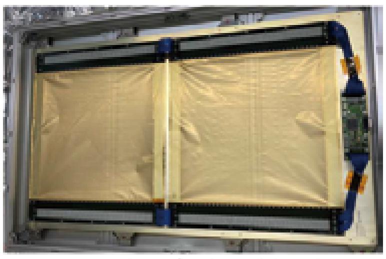
- 100 um to ~3 mm sized debris under 1000 km orbit
- Flight experienced on HTV-5/ISS

■ International Collaboration

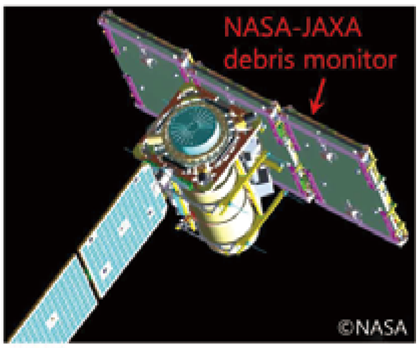
- JAXA/NASA Joint Work
- JAXA BBM is ready for Hyper Velocity Test in the US



SDM on HTV-5



New SDM BBM for the collaboration



Conceptual illustration of debris monitoring

2月26日（金）11：05～次世代型宇宙用デブリモニタBBMの開発,松﨑乃里子

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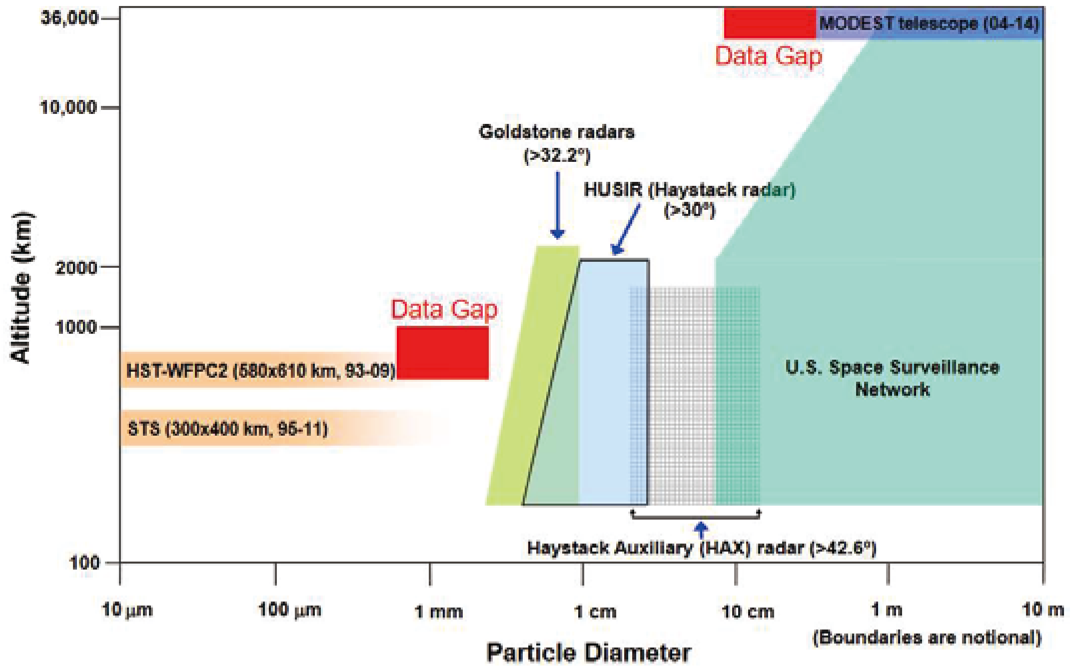
Space Debris Data Gaps

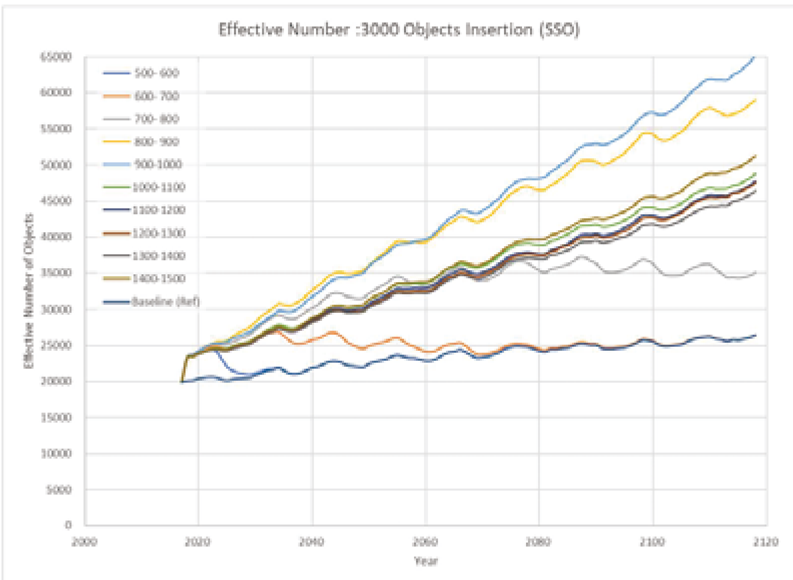


J.-C. Liou, “Risk from Orbital Debris”, RAS Specialist Discussion Meeting on Space Dust and Debris in the Vicinity of the Earth, 9 November 2018 より

7

Study of the environmental capacity tolerance

For the purpose of effective utilization of the orbital environment, the environmental capacity tolerance of orbital insertions (launch objects) is studied using an orbital debris evolutionary model (NEODEEM), developed in collaboration with Kyushu University.

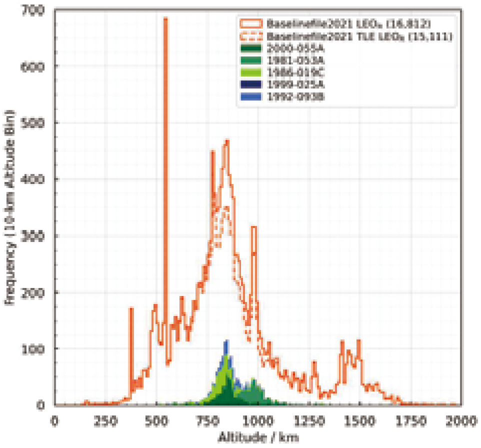


2月25日（木）10：20～推移モデルを用いた宇宙機の軌道投入許容量の検討,長岡信明

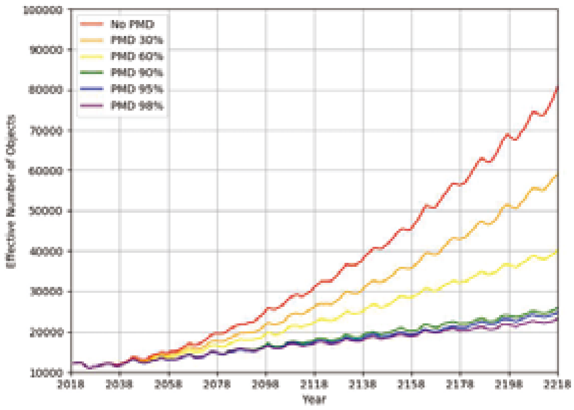
8

Development of JAXA's Original Baseline File for Debris Evolutionary Model

➢How to develop the baseline file, and evaluation results using the developed baseline file will be presented.



Altitude distribution

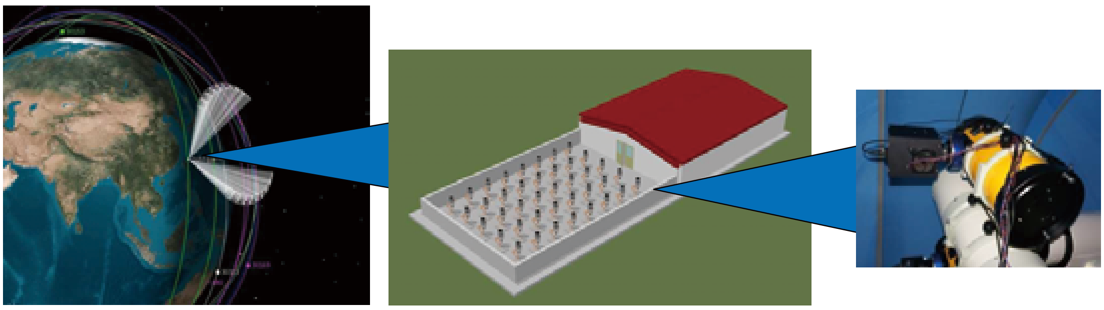


Sample results using JAXA's original baseline file and debris evolutionary model

2月25日（木）10：40～
JAXA独自のデブリ推移予測用ベースラインファイルの開発状況, 河本聡美

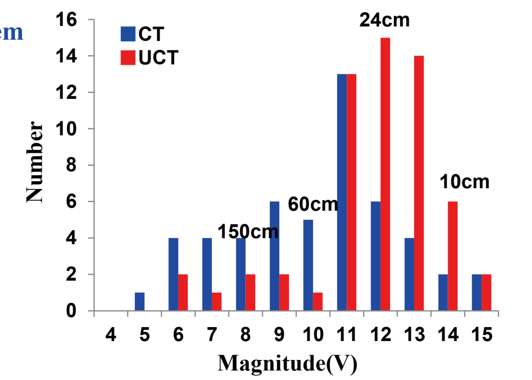
9

Optical Observation System for LEO Debris



Concept of optical observation system

By using optical sensors like CCD and CMOS, and using FPGA and GPU devices, the optical observation system that compensates current radar system for SSA will be developed with relatively low costs.

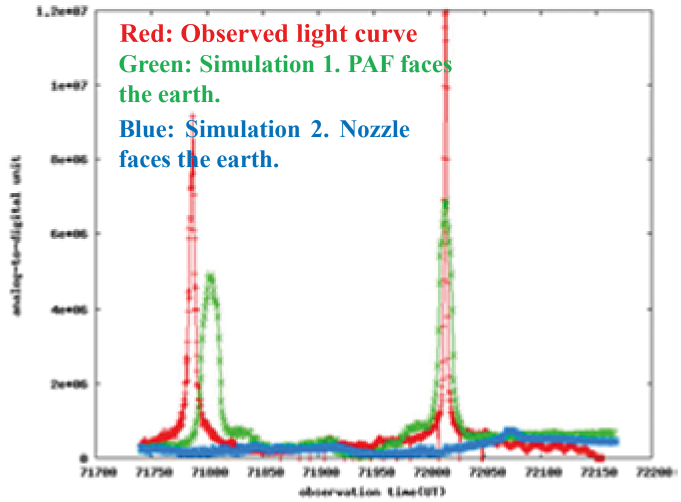


Detection ability of the basic optical equipment

2月25日（木）15：30～ 低軌道デブリ光学観測システム, 柳沢俊史

10

Light Curve Observation and Reproduction Experiment Using Model of H-2A R/B

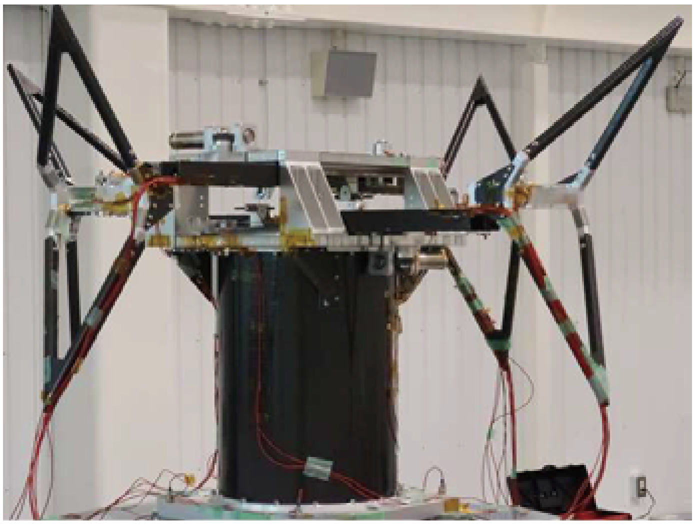


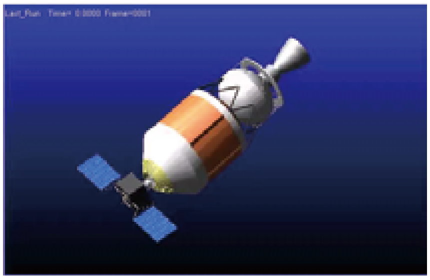
Comparison between observed light curve and simulated ones

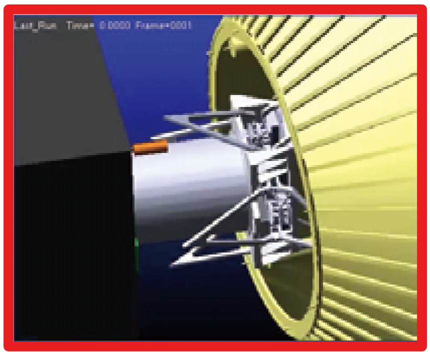
2月25日（木）16：40～
ライトカーブ観測とH-2A R/Bモデルを用いた再現実験, 黒崎裕久

Large Debris Capture System

Caging Based Debris Gripper (HKK)

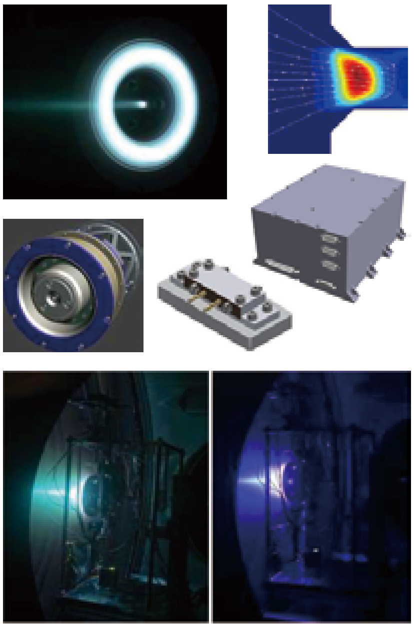






2月26日（金）16：35～
ロバスト性の向上を目指したデブリ捕獲機構のコンセプトと開発状況,谷嶋信貴

Novel 1-kW class Hall thruster system



- **Hall thruster with internal cathode**
- **Advanced materials and structures** (patents to be published)
- **High performance**: Isp 1600sec, 65 mN/kW
- **Long life**: 10,000 hrs, 10,000 cycles(expected)
- **System friendly**: low-plasma oscillation, high-environmental resistance, beam divergence~30deg
- **Cost-effective, low-mass power supply and flow controller**

2月26日（金）15：50～
デブリ除去に向けた1kW級ホールスラスタシステムの研究開発, 張科寅

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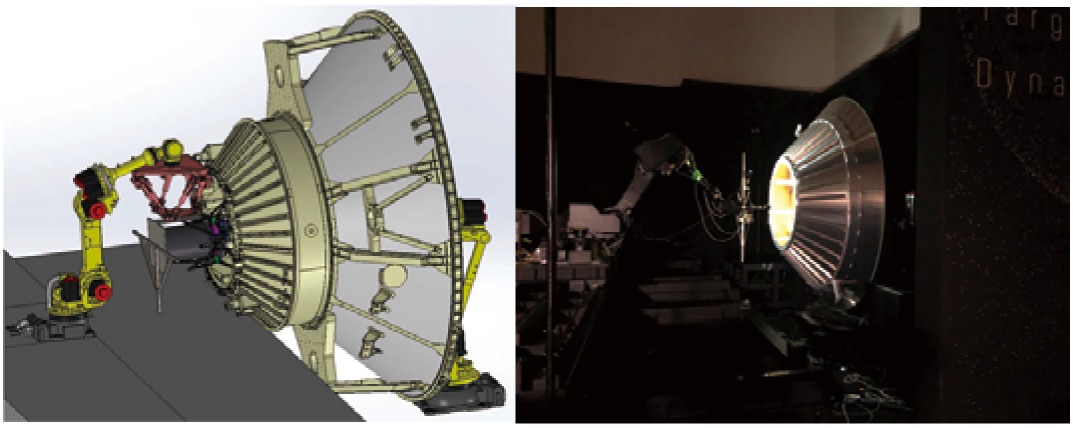
Debris Rendezvous Test Facility

SATDyn (Simulation Apparatus for Target capture Dynamics)

- ➢ Numerical and Physical hybrid simulation system including contact dynamics
- ➢ ADR proximity operation simulation with real hardware (navigation sensor systems, capturing mechanics)
- ➢ 10m x 7m stroke 2DOF Gantry table with 3x6DOF Robotic arms for the chaser's relative motion simulation with external force torque measurements
- ➢ Solar simulator (Xe lump) and Full area motion capture system



2月26日（金）16：55～
動ターゲット捕獲検証プラットフォーム（SATDyn）の開発, 岡本博之

14

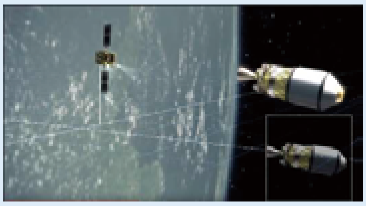
Commercial Removal of Debris Demonstration

Aiming at the world's first Active Debris Removal
in partnership with private enterprises

Demonstration of the removal of large space debris left in orbit in two phases

Phase-I Planned for launch in FY2022

Key technologies demonstration

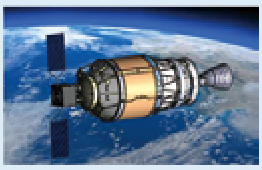


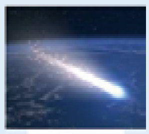
- **Non-cooperative rendezvous, proximity operation, inspection**

Phase-I demonstration satellite

Phase-II FY2025~

ADR demonstration





Re-entry

- Non-cooperative rendezvous, proximity operation, inspection
- **Removal and re-entry of 2nd stage of launch vehicle**

Phase-I partner, Astroscale Japan Inc.

2月24日（水）11：00～　JAXA 商業デブリ除去実証（CRD2：Commercial Removal of Debris Demonstration）の最新状況, 山元透

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And much more, stay on-line!!

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A02

JAXA 追跡ネットワーク技術センターにおける宇宙状況認識に関する活動の現状

Current Activities on Space Situational Awareness at STCC, JAXA

○渡邊 優人 (JAXA)
○WATANABE Masato (JAXA)

宇宙開発の開始以来、我々は衛星からもたらされる恩恵への依存が高まり、昨今では、市民生活まで浸透し、今や人工衛星は欠くことできない国際的なインフラとなっている。この恩恵を享受する一方で、宇宙開発は軌道上にスペースデブリという脅威を発生させている。欠くことのできないインフラである人工衛星を保護、維持していくために、宇宙環境の理解、物体の追跡、及び、接近解析を行う宇宙状況認識（Space Situational Awareness: SSA）は重要な意味を有する。 これまで JAXA 追跡ネットワーク技術センターでは、SSA として上齋原スペースガードセンターのレーダと美星スペースガードセンターの光学望遠鏡によるデブリ観測運用、観測物体の軌道決定、JAXA 運用衛星に接近するスペースデブリのリスク評価、スペースデブリ回避制御運用を実施してきた。 本発表では、過渡期を迎える JAXA の SSA に関する取組と開発・試験中の新 SSA システムについて紹介する。

Since the inception of space exploration, we have become increasingly dependent on the benefits that come from satellites, and nowadays, they have penetrated into our civilian lives, making satellites now an indispensable international infrastructure. While we enjoy this benefit, space exploration has generated the threat of space debris in orbit. Space Situational Awareness (SSA), which is the understanding of the space environment, object tracking, and conjunction analysis, is important for the protection and maintenance of satellites as an essential infrastructure. So far, JAXA's SSA has carried out debris observations using the radar at the Kamisaibara Space Guard Center and the optical telescope at the Bisei Space Guard Center, orbital determination of objects, risk assessment of space debris approaching JAXA's operational satellites, and space debris avoidance control operations. This presentation will introduce JAXA's efforts on SSA and the new SSA system under development and testing as it enters a transitional phase.

JAXA追跡ネットワーク技術センターにおける宇宙状況認識に関する活動の現状
Current Activities on Space Situational Awareness at STCC, JAXA

Watanabe Masato

Flight Dynamics Team
Space Tracking and Communications Center
Japan Aerospace Exploration Agency

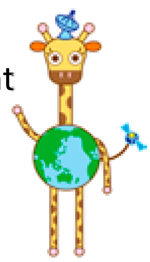
9th Space Debris Workshop
24 Feb 2021

Abstract

The objectives of this presentation

To introduce current SSA activities at STCC, JAXA.
Space ***T***racking and ***C***ommunications ***C***enter

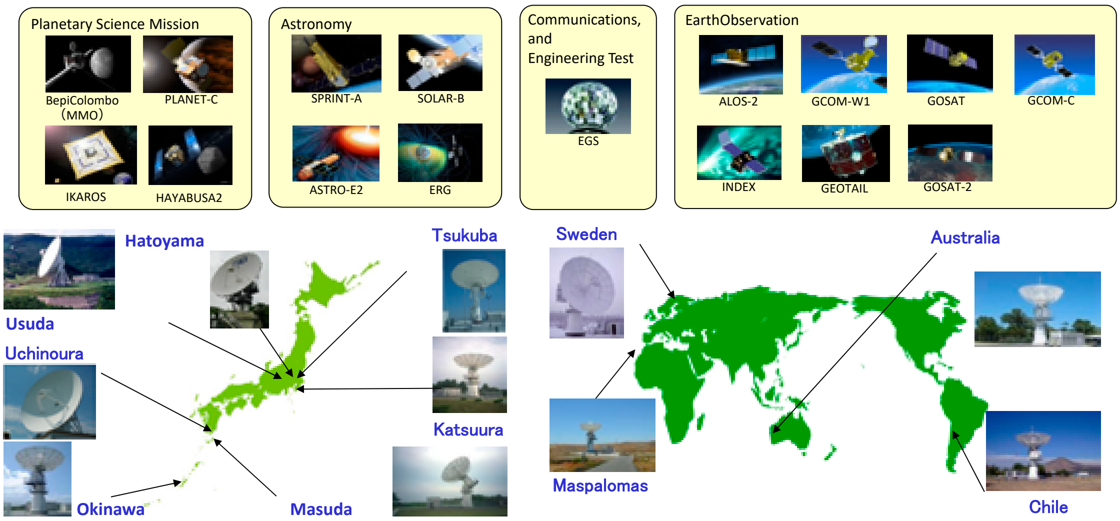
- Conjunction assessment
- Introduction of RABBIT
- Space Debris Observations
- Report the status of future SSA system development



TSUISEKIRIN

Introduction: Activities on STCC

We are operating spacecraft using ground stations not only in Japan but also around the world.



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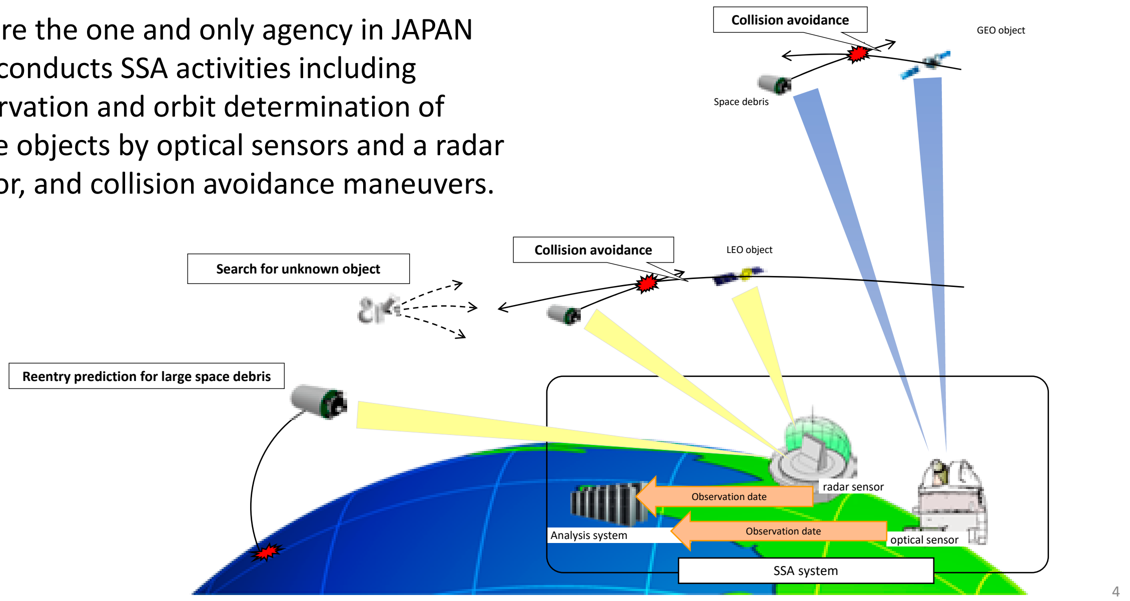
Introduction: SSA Activities

We are the one and only agency in JAPAN that conducts SSA activities including observation and orbit determination of space objects by optical sensors and a radar sensor, and collision avoidance maneuvers.



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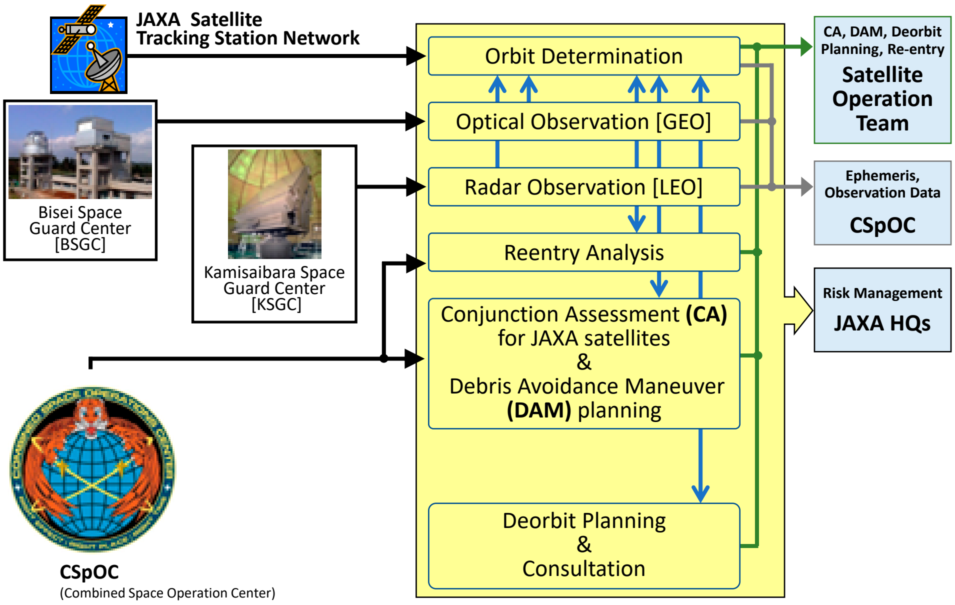
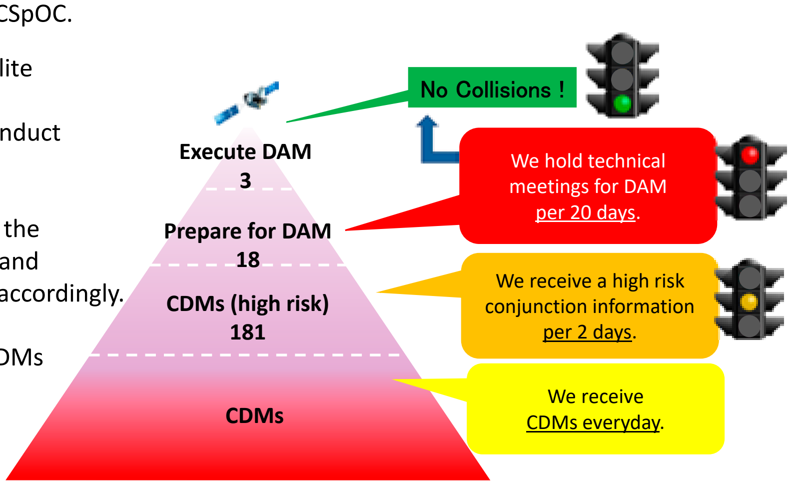
Introduction: SSA Activities



5

Conjunction Assessment

- We have received high risk alerts as CDM(Conjunction Data Message) from CSpOC.
- We analyze them and discuss with satellite operation team.
  If the risk is high, we prepare for and conduct DAM(Debris Avoidance Maneuver).
- We assess the criticality of events using the probability of collision and days to TCA, and categorize them into three levels to act accordingly.
- The right figure shows the number of CDMs and the measures we took last year.
- We executed 3 DAMs to mitigate threat of conjunctions per year.



Statistics for conjunction assessment towards JAXA satellites
1 Apr 2019 ～ 31 Mar 2020 / the number of satellites: 14

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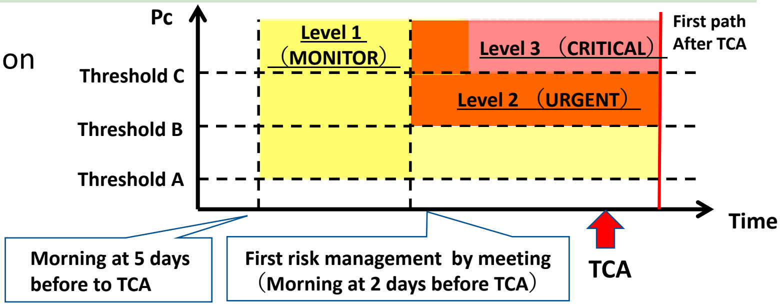
Conjunction Assessment (continued)

Category	Classification	Condition
Level 1	MONITOR	• We have enough time to perform DAM by TCA. • We pay close attention to the situations.
Level 2	URGENT	• Related parties take necessary measures for crisis-management. The first priority is to decrease the risk of collisions. • If necessary, we plan and conduct a maneuver to decrease the risk.
Level 3	CRITICAL	• We cannot perform DAM at this level because there is not enough time left or the satellite has some restrictions. At this point we can not control the risk. • We take all possible measures for crisis-management in order to maintain the operation of the satellite.

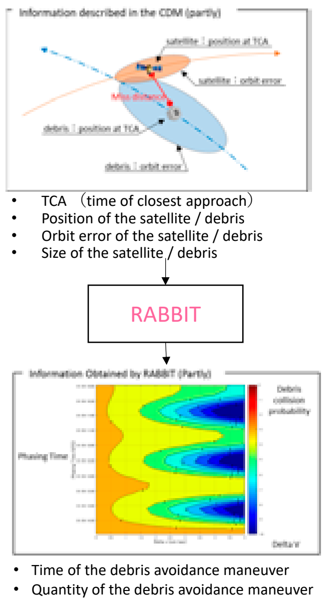
We evaluate the risk of conjunction in terms of both

1. Probability of Collision and
2. Days to TCA.



Introduction of RABBIT

- RABBIT (Risk Avoidance assist tool based on debris collision proBaBIliTy) An assistant tool developed by JAXA for decision-making on debris avoidance maneuver using CDMs provided by CSpOC.
- RABBIT is a GUI tool based on PCT (Probability of Collision Contour Tool) that calculates and visualizes collision probability and closest approach distance by taking the control values in the cross-track direction as input.
- RABBIT has two modes:
  - Calculator mode
    To calculate collision probabilities and miss distance at TCA corresponding to the CDM(s) and maneuver planning information
  - Visualizer mode
    To visualize the results obtained by Calculator mode



Introduction of RABBIT

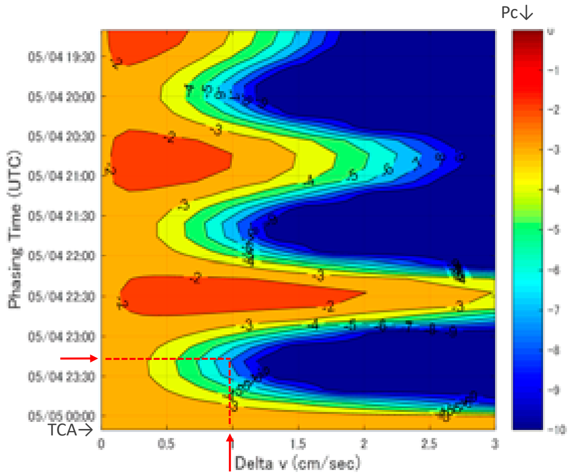
When the altitude of debris is lower than that of a satellite

- Consider the debris avoidance operation based on the right figure obtained by RABBIT :

  In order to lower the collision probability to 1.0E-06 order or less, recommend the following measures as a maneuver plan

  ✓ Maneuver time : Half a revolution before TCA

  ✓ Maneuver quantity : **<u>1.0 cm/s</u>**



Introduction of RABBIT

Soon to be published on the JAXA website

- RABBIT Environmental Conditions
  - Prepare the CDM
  - Computer specifications is equal to or greater than the following
    - OS ： Windows10
    - Processor ： Intel® Core™ i5-6300U CPU@2.40GHz 2.50GHz
    - Installed memory (RAM) ： 3.89GB
    - System type ： 64-bit Operating System
  - Need more than 7GB of free space
    - MATLAB Runtime : 6.5GB
    - RABBIT : 200MB

- Setting of satellite data
  - Individual designation of hard body radius is possible

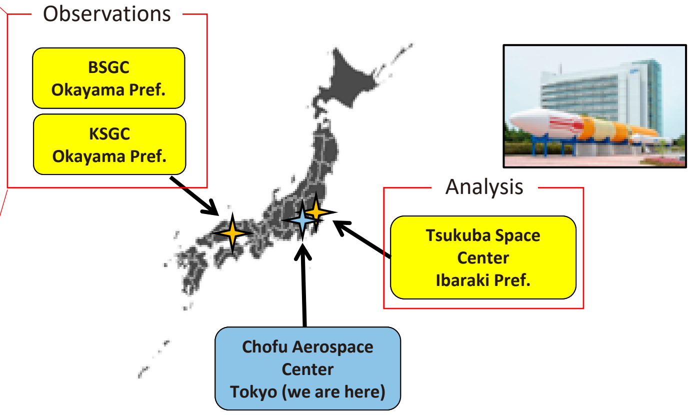
Space Debris Observations

Since 2002

Bisei Space Guard Center (BSGC)
[Telescopes]

From 2004 to 2020

Kamisaibara Space Guard Center (KSGC)
[Radar]



To migrate to the new system, the radar was taken out of operation in 2020.

Current Issues and Future SSA System

Current Issue

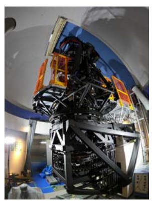
・Aging System: Both the radar and telescope systems were constructed more than 10 years ago.
・Low Capability: Current radar can observe only 6% of LEOs in CSpOC catalog.

→ **SSA analysis JAXA can perform with our own data is limited.**

NEW SSA System

・**Radar**: *Newly developing*
Enhances capability for LEO debris observation.
・**Telescope**: *Refurbishing*
Maintains the current capability.
・**Analysis System**: *Restructuring*
Enhances the capability for conjunction assessment and re-entry analysis with the data that will be provided by the new radar and the telescopes.

→ **Constructing now!**



1m telescope

New radar

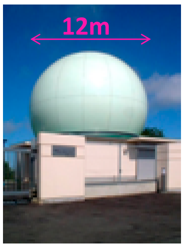
New Radar Concept

Scope

- Improving the ability to understand the trajectory of space debris in the low orbit zone (altitude 500-800 km) where many JAXA satellites are active
- Space debris detection of 10 cm or more in diameter at altitudes below 650 km
- More than 200-fold improvement in detection capability against current radar at 650 km altitude in comparison

To achieve the above

- Adopt a semiconductor capable of transmitting high power and long pulses
- Increasing the number of elements in the antenna
- (i.e. increasing the size of the antenna aperture)
- Increase the sensitivity of the receiver
- Adoption of digital beamforming
- Hardware configurations
- that can be enhanced by later software modifications



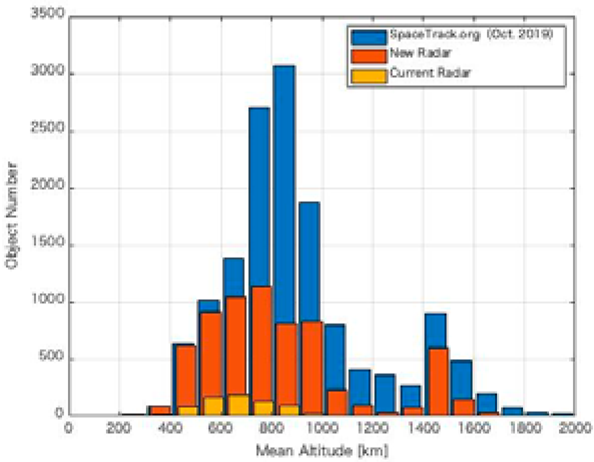
Current Radar

17m

New Radar

New Radar

Comparison of Current Radar and New Radar



This graph shows the mean altitude distribution of objects that can be observed by JAXA's current radar (yellow) and that of the future SSA radar (orange), in comparison to the number of space debris published by CSpOC as of October 2019 (blue). CSpOC publication includes the number of objects that cannot be observed by JAXA's radar located at Okayama Prefecture.

New Radar

Aiming to acquire the ability to observe unknown objects

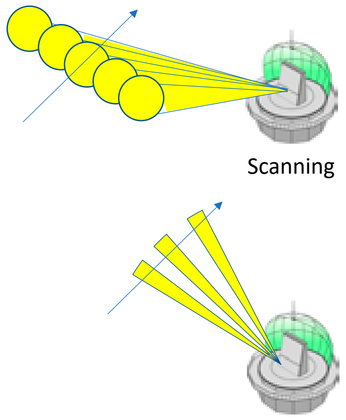
The key technology elements required for unknown object observation

- Scanning Methods for Initial Acquisition in Radar
- Tracking filter
- Integral Processing and Integrated Phase Correction

e.t.c.

The above is expected to be improved through accumulation, analysis and further study of operational data.

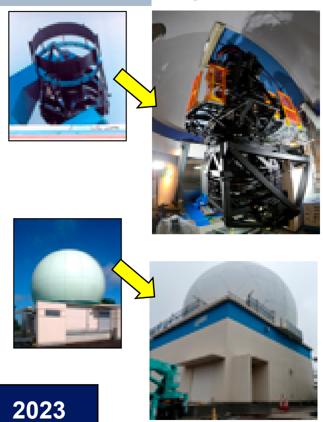
It also has the ability to reflect research results in the system by improving software.



AZ Mechanical Axis Rotation Combined with Electron Beam Scanning

Major Specifications and Schedule

		New System	Present System
Radar	Observation capability	10 cm Φ (650 km high)	1.6 m Φ（650 km high）
	# of simultaneously observable objects	Max 30	Max 10
Telescope	Limiting magnitude	18th (1mΦ telescope) 16.5th (50cmΦ telescope)	18th (1mΦ telescope) 16.5th (50cmΦ telescope)
Analysis system	# of managed objects	Max 100,000	Max 30,000
	# of observation paths（radar）	10,000 paths/day	200 paths/day
	Observation planning	Automatically	Manually



	2016	2017	2018	2019	2020	2021	2022	2023
Basic Plan on Space Policy	Construct SSA facilities and an operational framework integrated with MOD, JAXA and other Japanese governmental institutions.							
	Preliminary Design	Detail Design				Integration Test	Trial Operation	Operation
			Development		Now			

New radar will be completed soon

Transmitter hanging operation

17

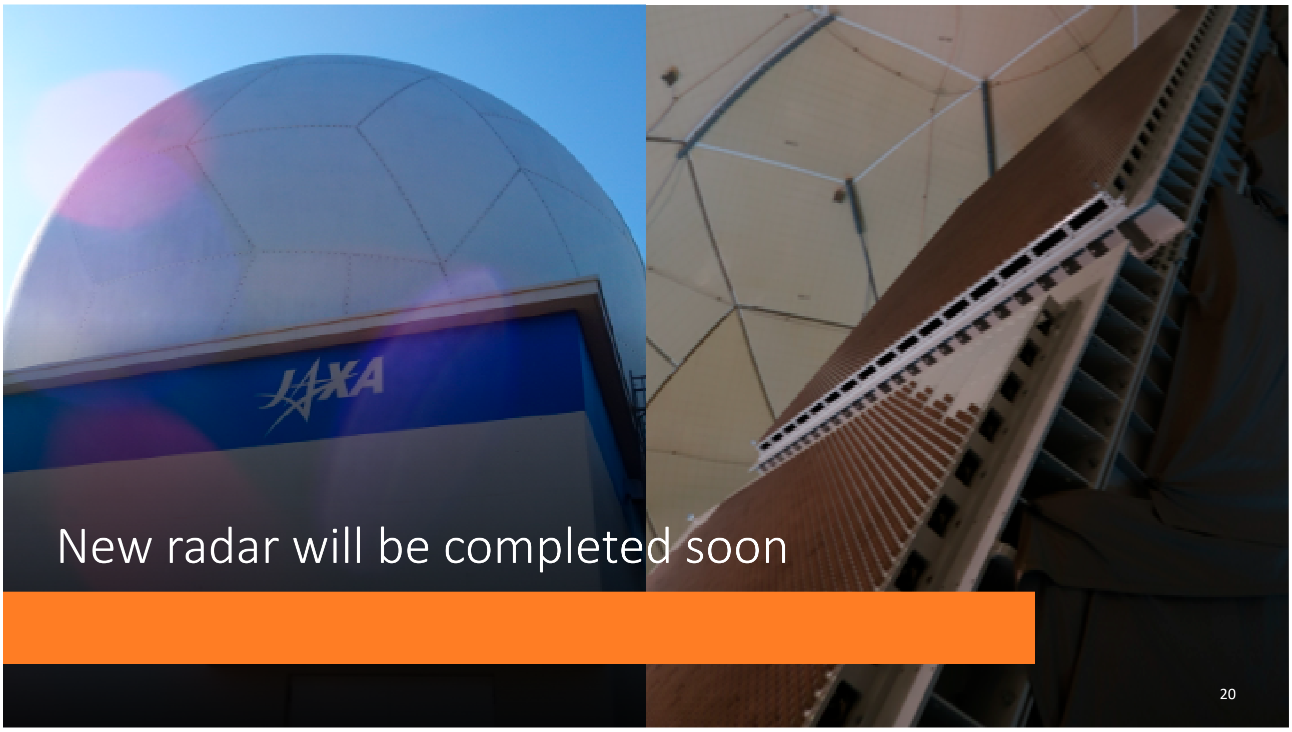
New radar will be completed soon

Fixed-point camera video

18

New 1m telescope will be completed soon

19



New radar will be completed soon

20

Summary

<u>JAXA works on SSA activities using both our own sensors and analysis system, and data from CSpOC.</u>

・We observe space debris using optical sensors(1mφ and 50cmφ) and a phased array radar for GEO and LEO respectively.

・At the same time, we are developing the new SSA system and will start its operation from 2023.

・We do conjunction assessment and collision avoidance maneuvers to defend our satellites against threats of space debris.

・We do re-entry analysis of large space objects using own system.

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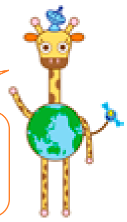
Thank you for your kind attention.

There is a movie that summarize our SSA activities.
↓↓↓ Click Here! ↓↓↓
https://www.youtube.com/watch?v=zcYE9JH5_UY



A03

JAXA 商業デブリ除去実証 (CRD2:Commercial Removal of Debris Demonstration)の最新状況

Latest updates on JAXA Commercial Removal of Debris Demonstration (CRD2)

〇山元 透（JAXA）
○YAMAMOTO Toru (JAXA)

JAXA は「デブリ除去を新規宇宙事業として拓き、民間事業者が新たな市場を獲得する」ことを目的として「商業デブリ除去実証 Commercial Removal of Debris Demonstration (CRD2)」を開始した。このプログラムの目標は二つある。軌道上大型デブリ除去技術の実証と、民間企業がデブリ除去をビジネスとして実施する道筋をつけることである。フェーズ I と II の 2 段階で構成されている。フェーズ I では軌道上に存在する日本のロケット上段に接近し近傍制御と映像撮影を行う。フェーズ II ではフェーズ I 実証範囲に加えてターゲットの当初軌道からの除去を行う。フェーズ I のパートナー企業には株式会社アストロスケールが選定され、プロジェクトが 2020 年 3 月に開始された。現在は基本設計が進行している。本講演では、CRD2 の概要と、フェーズ I プロジェクトの最新状況についてご紹介する。

JAXA has launched the Commercial Removal of Debris Demonstration (CRD2) program with the purpose of establishing debris removal as a new business and developing a market by private sector. The program has two goals: to demonstrate active debris removal (ADR) technology and to pave the way for the private sector to implement ADR as a business. The program consists of two phases, Phase I and Phase II. In Phase I, the demonstration spacecraft will approach the Japanese rocket upper stage in orbit to perform proximity operations and take detailed images. In Phase II, the target will be removed from the initial orbit in addition to the Phase I mission sequences. Astroscale Corporation has been selected as the partner company for the Phase I, and the project has been launched in March 2020. The preliminary design activities are currently underway. This presentation will provide the overview of CRD2 program and the latest updates on the Phase I project.

JAXA 商業デブリ除去実証（CRD2：Commercial Removal of Debris Demonstration）の最新状況

9th Space Debris Workshop

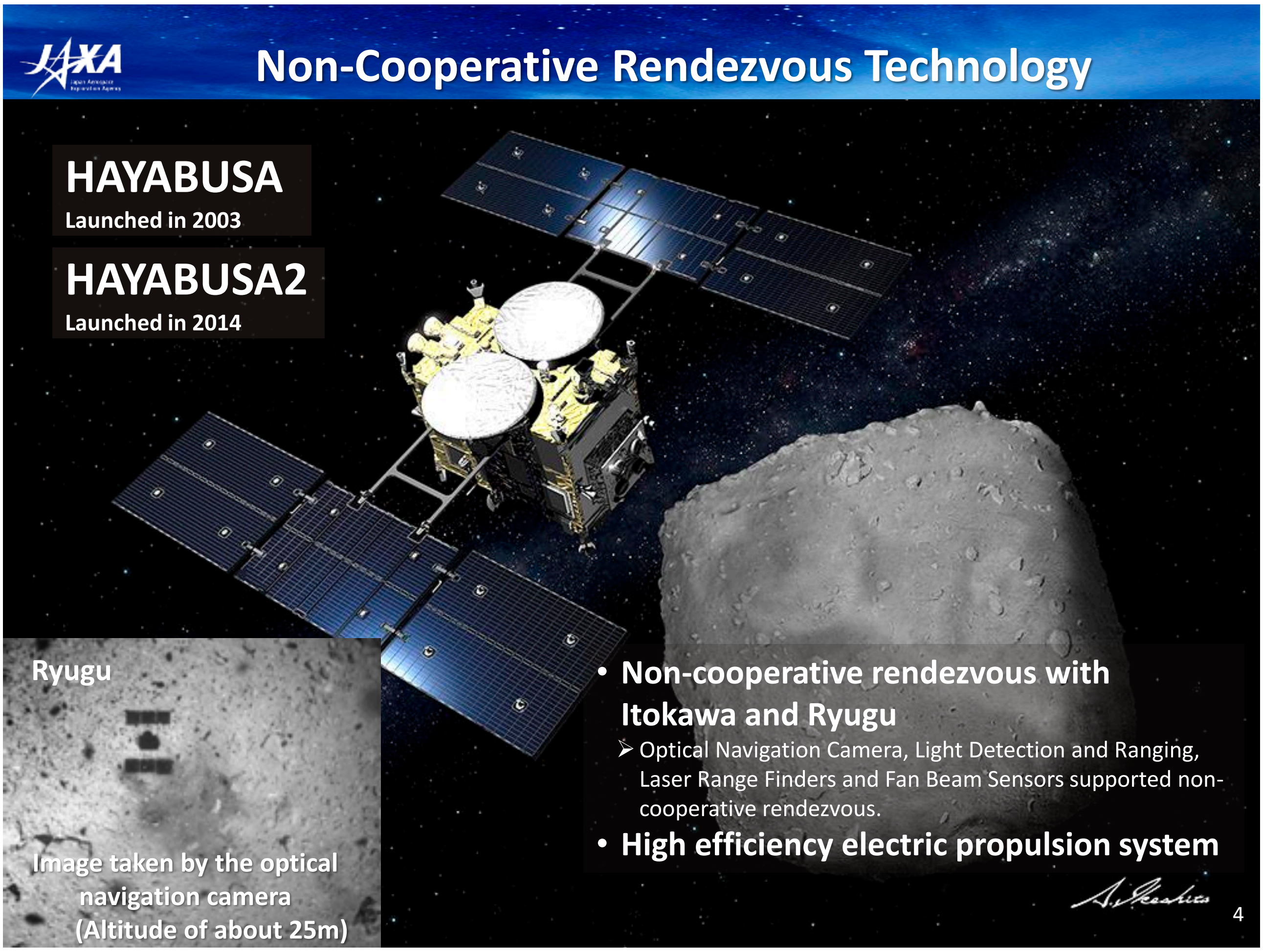
Japan Aerospace Exploration Agency
Toru Yamamoto
Feb. 24, 2021

JAXA's Activities on Ensuring Stable Use of Outer Space

- As space use activities grow, threats and risks posed by space debris increase. Securing stable use of outer space is one of the most important issues.
- Basic Plan on Space Policy of Japan includes ensuring national security and enhancement of national security ability as objectives.
- JAXA's activities include:
  - Space Situational Awareness (SSA)
  - Contribution to international standardization activities on space utilization
  - **R&D to mitigate threats and risks of space debris** ⇨ **CRD2**

2


JAXA
Cooperative Rendezvous Technology
ETS-VII
Launched in 1997
• The world's first unmanned rendezvous docking experiments in 1998
HTV
Have been launched from 2009
• Total 9 flights were successfully accomplished from 2009.
• HTV rendezvous with ISS (Client) cooperatively utilizing GPS and precise sensing capability.
©NASA/JAXA
3

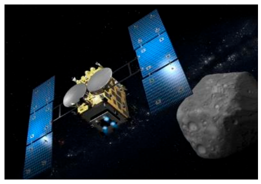

JAXA
Non-Cooperative Rendezvous Technology
HAYABUSA
Launched in 2003
HAYABUSA2
Launched in 2014
Ryugu
Image taken by the optical navigation camera (Altitude of about 25m)
• Non-cooperative rendezvous with Itokawa and Ryugu
➢ Optical Navigation Camera, Light Detection and Ranging, Laser Range Finders and Fan Beam Sensors supported non-cooperative rendezvous.
• High efficiency electric propulsion system
4

Technologies for Active Debris Removal

■ Past results

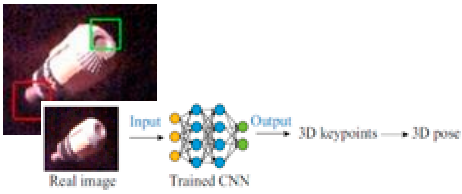
ETS-VII (1997)
Rendezvous and docking technology demonstration

HTV
ISS approach using cooperative rendezvous

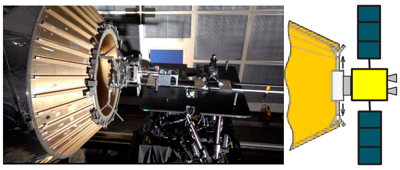


HAYABUSA/ HAYABUSA2
Small lightweight propulsion system

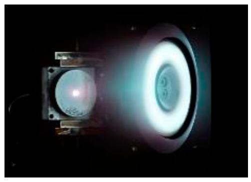
■ Ongoing elemental technology R&D



Rendezvous
Onboard real-time image navigation using deep learning-based pose estimation



Capture
Dedicated capturing mechanism for non-cooperative object



Removal
Low power, high total-impulse electric propulsion

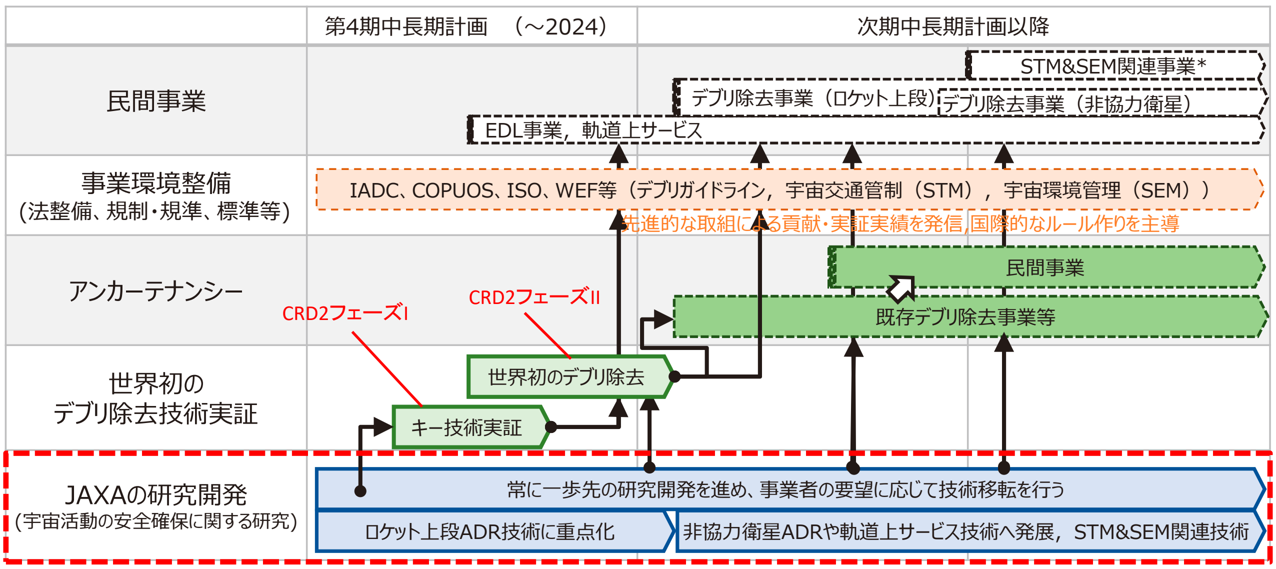
5

Commercial Removal of Debris Demonstration (CRD2)

意義・目的

- スペース・デブリ対策の事業化を目指す民間事業者等と連携し、新たな市場の創出と我が国の国際競争力確保に貢献する取組を行う
- 大型のロケットデブリを対象とした世界初の低コストデブリ除去サービスの技術実証を目指す

目指す姿：**「デブリ除去を起点に新規宇宙事業を拓き、民間事業者が新たな市場を獲得する」**



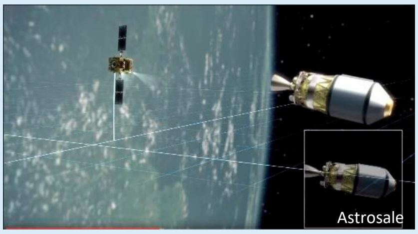
*)衝突回避サポート（観測（監視），予測，回避），EOLサポート，軌道変更など

Commercial Removal of Debris Demonstration (CRD2)

Aiming at the world's first Active Debris Removal
in partnership with private enterprises
Demonstration of the removal of large space debris left in orbit in two phases

Phase-I
Planned for launch in FY2022

Key technologies demonstration

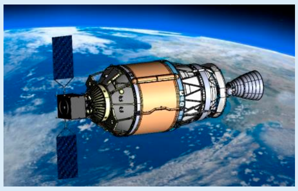


- **Non-cooperative rendezvous, proximity operation, inspection**

Phase-I demonstration satellite

Phase-II
FY2025~

ADR demonstration



Re-entry

- Non-cooperative rendezvous, proximity operation, inspection
- **Removal and re-entry of 2nd stage of launch vehicle**

Phase-I partner, Astroscale Japan Inc.

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Partnership with private sectors

A new partnership initiative with private sectors.

- As new partnerships with our industries, JAXA will focus on taking an "oversight role" with all the R&D assets, having partners strongly lead the system design to fulfill both our technical requirements and their business strategies.
- This new partnership will give our industries opportunities to advance their business to an upper stage.

Phase-I partner, Astroscale Japan Inc.

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CRD2における新たな取り組み（事業者が主体性を発揮するためのマネジメントの特徴）

事業者が事業戦略に基づき主体的に宇宙機開発・技術実証を行うための JAXAによる総合的マネジメントおよび技術的支援

JAXAは衛星ではなく、サービスと研究開発成果を調達する

- JAXAは「目標デブリに接近し、映像を取得する」サービスへの要求を提示
- 民間事業者がサービス要求に応える衛星開発仕様決定、製造、運用を実施
- 信頼性・品質基準を、事業者から提案できる

マイルストン・ペイメント方式で支払いを行う

- 当初契約時にサービス要求を確定し全額を契約
- 契約時に複数のマイルストン（その開発段階の達成基準）を設定、マイルストン審査結果による支払い

民間事業者と資金を出し合うパートナーシップ事業

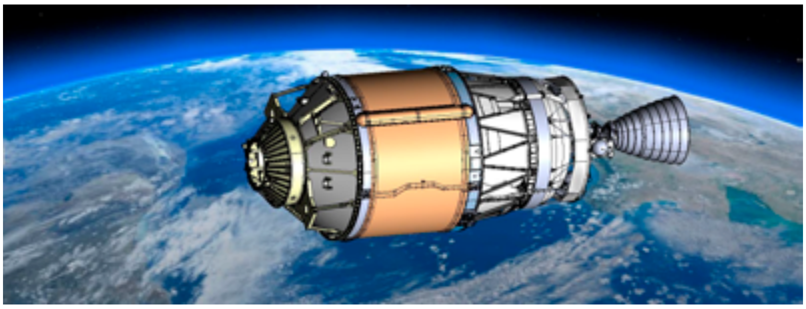
- JAXAは民間事業者に対して技術アドバイスの提供と試験設備の供与を行う
- JAXAはサービスと研究開発成果を得る
- 民間事業者は事業化へ向けた技術開発成果、事業開発成果を得る
- 競争参加資格を拡大

9

CRD2 Phase-I / Target

- Target candidates
  - **Real** upper stages left in Low Earth Orbit
  - **Domestic** upper stages
  - Altitude = **approx. 600km** for safe demonstration

Catalog ID No.	Flight No.	Main payload
28932	H2A F8	ALOS
33500	H2A F15	GOSAT
38341	H2A F21	GCOM-W1
39771	H2A F24	ALOS-2
43067	H2A F37	GCOM-C1
43682	H2A F40	GOSAT-2



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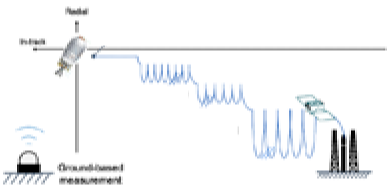
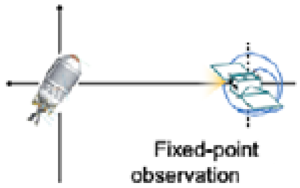
CRD2 Phase-I / Service Specification

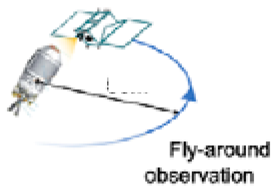
- Service specification（サービス仕様）is defined in the document “**GKD-2019013 CRD2 (phase-I) service specification**”
- Required services:



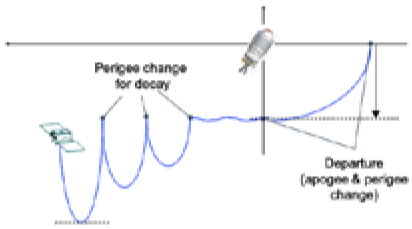
(1) Rendezvous performance report service



(2) Fixed-point observation service



(3) Fly-around observation service



(4) Mission termination service

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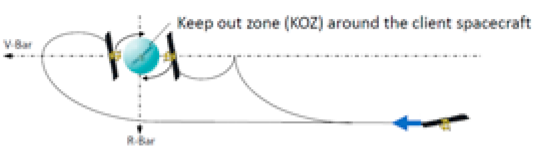
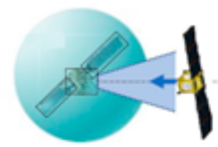
CRD2 Phase-I / Safety Requirement

- In order to limit, manage or avoid the risk or collision upon rendezvous, proximity and servicing operation, the safety standard ”**JERG-2-026 Safety Standard for ON-ORBIT Servicing Missions**“ is defined and required for CRD2.



Sample trajectory in the far field



Sample approach path into KOZ

Basics in trajectory design

In the far field, the servicing spacecraft takes safe trajectory which does not interfere with Keep Out Zone (KOZ) even in the passive state. In the closed approach, the servicing spacecraft comes into the designated approach path without crossing over the path boarder.

General requirements

- The total system shall be one fault tolerant (1FT) to the critical event such as breakup. Hence no single failure shall not lead to collision, or loss of mandatory function for proper disposal.
- Analysis, evaluation and safety reviews are based on the system safety engineering practices. A spacecraft developer performs hazard analysis based on its design and operation.

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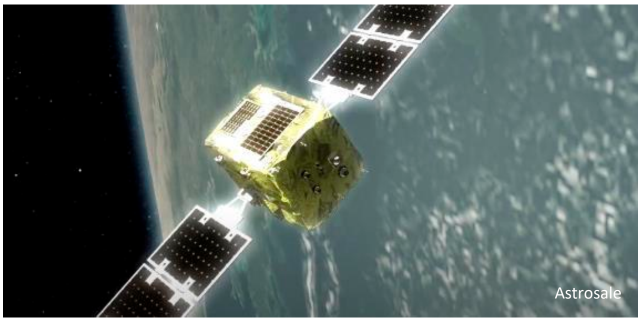
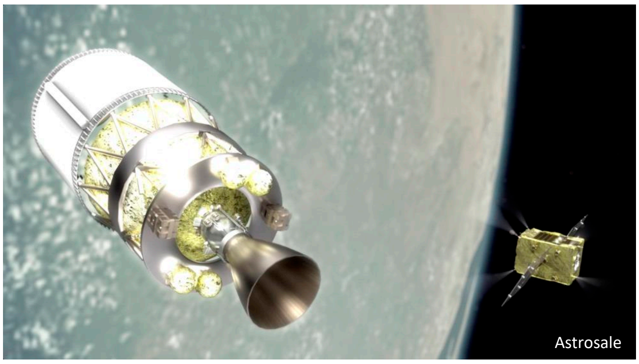
CRD2 Phase-I / Chaser Spacecraft

- **ADRAS-J** : Spacecraft for CRD2 Phase-I **manufactured and operated by Astroscale Japan Inc.**
- Wet mass: approx. 180kg
- **Full-range rendezvous and proximity operation capability** targeting a non-cooperative H2A rocket upper stage left in orbit





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CRD2 Phase-I / Mission

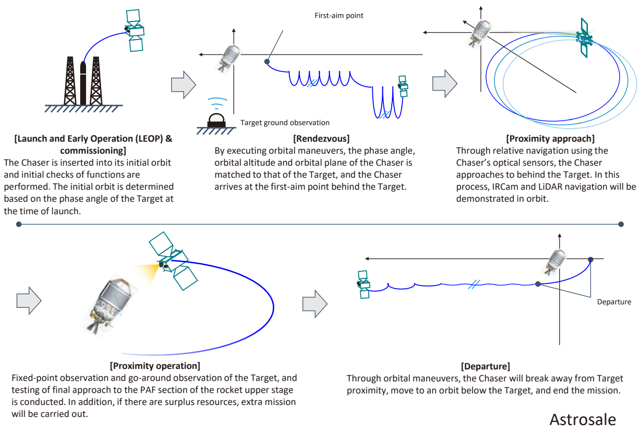
商業デブリ除去技術実証フェーズIプロジェクト

JAXAサービス仕様

1. デブリ接近計画に対する実績の確認サービス
2. 定点観測サービス
3. 周回観測サービス
4. 終了処理サービス

事業者が実施する技術実証

1. フェーズIIの事前診断
2. ターゲットPAF直上までの極近傍接近
3. エクストラミッション



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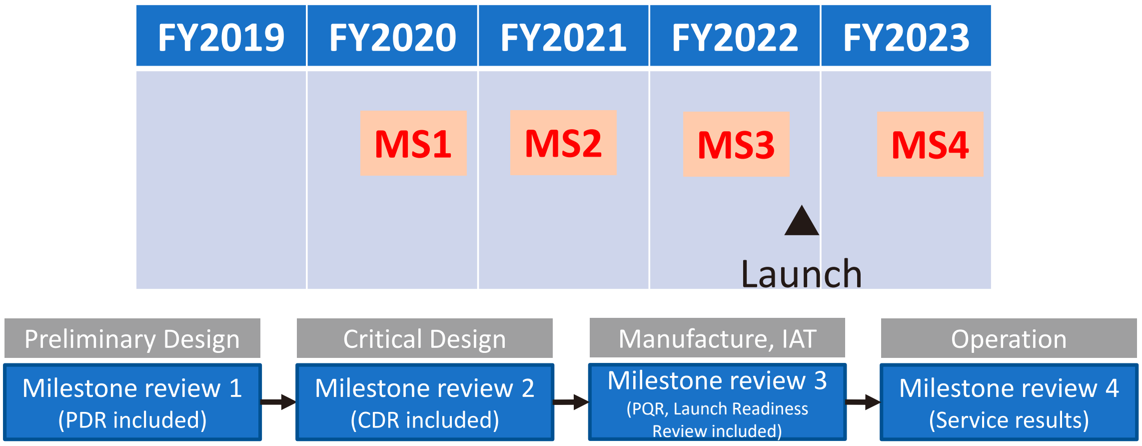
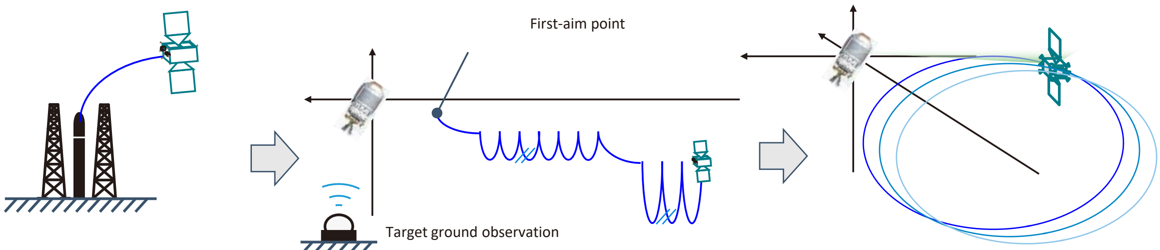
CRD2 Phase-I / Milestones

- Four milestones are defined
- For each milestone achieved, a pre-determined amount is paid
- The final milestone payment (Milestone 4) is more than 25% of the total payment
- Launch: FY2022



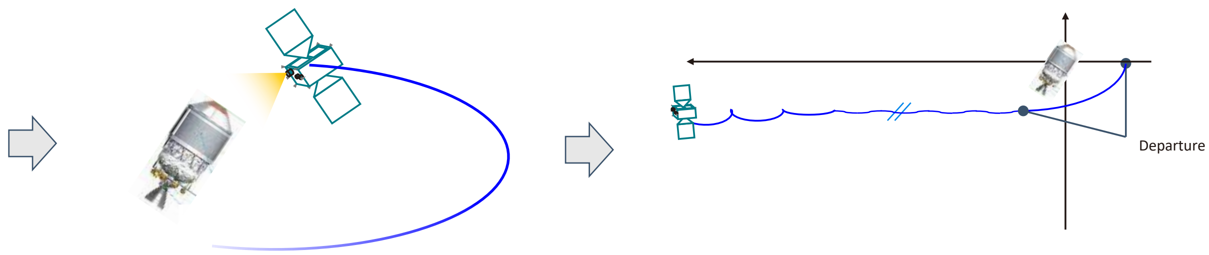
CRD2 Phase-I / Concept of Operation



[Launch and Early Operation (LEOP) & commissioning]
The Chaser 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 Target at the time of launch.

[Rendezvous]
By executing orbital maneuvers, the phase angle, orbital altitude and orbital plane of the Chaser is matched to that of the Target, and the Chaser arrives at the first-aim point behind the Target.

[Proximity approach]
Through relative navigation using the Chaser's optical sensors, the Chaser approaches to behind the Target. In this process, IRCam and LiDAR navigation will be demonstrated in orbit.



[Proximity operation]
Fixed-point observation and go-around observation of the Target, and testing of final approach to the PAF section of the rocket upper stage is conducted. In addition, if there are surplus resources, extra mission will be carried out.

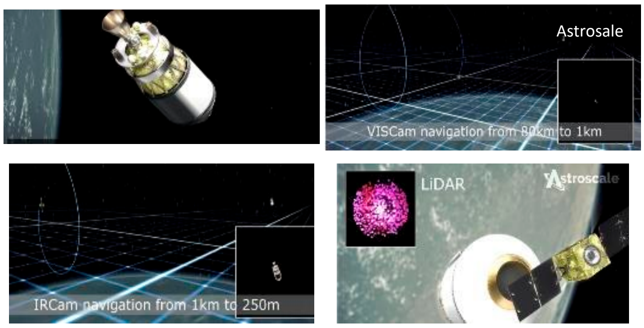
[Departure]
Through orbital maneuvers, the Chaser will break away from Target proximity, move to an orbit below the Target, and end the mission.

This chart provided by Astroscale

CRD2 Phase-I / Milestone-1 status

- Preliminary design has been conducted
  - Concept of Operation design
  - System/Subsystem requirement definition
  - System design
  - Subsystem design
  - Test and verification of COTS rendezvous sensor BBMs
  - Safety design
  - Manufacture, integration, assembly and test planning
- Milestone 1 review is currently underway

COTS rendezvous sensor BBM test at the JAXA SATDyn facility



Preliminary design of navigation system for non-cooperative target with multiple types of COTS sensors

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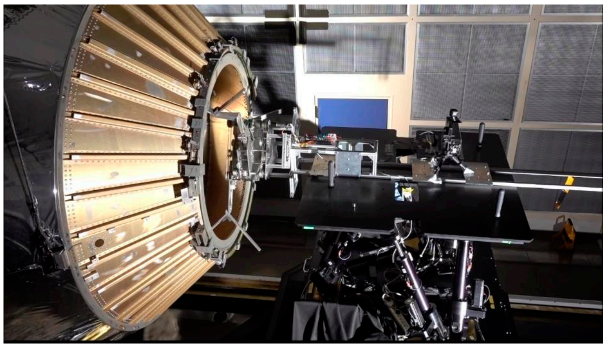
Way forward

- As a result of Phase-I, establishment of technologies for full-range rendezvous and stable proximity operations with space debris is expected
- In parallel, JAXA is conducting R&Ds on the key technologies required for Phase-II
- The activities of CRD2 will continue for sustainable space activities and creation of new on-orbit services



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A04

JAXA スペースデブリ発生防止標準 JMR-003 の最新状況
Status on JAXA Space Debris Mitigation Standard JMR-003

○佐藤 健一，仁田 工美，吉原 徹 (JAXA)
○SATO Kenichi, NITTA Kumi, YOSHIHARA Toru (JAXA)

JAXA は 1996 年に最初のスペースデブリ発生防止標準を制定して以降、最新の情報を踏まえて適宜標準の改定を進めている。ISO 24113 スペースデブリ低減要求が出来て以降は、24113 の改定に合わせて JAXA 標準である JMR-003 の改定も実施している。2019 年に ISO 24113 が第 3 版となった。これは近年の軌道環境悪化を反映した新しい規制を含んでおり、これらの新しい要素を JMR-003 に取り込んで改定する検討を実施した。新しい JMR-003 には、宇宙機・ロケット軌道投入段の運用終了後の廃棄成功確率 0.9 以上の達成、デブリ・メテオロイドの衝突確率の評価、ロケット関連規制の強化等の種々の要求を含んでいる。本講演では、JMR-003 に新たに加えられた規制の概要について紹介する。

JAXA has been working on the mitigation of space debris since 1990s, and since the first space debris mitigation standard was established in 1996, the standard has been revised appropriately based on the latest study. After the ISO 24113 space debris mitigation requirement was published, the JAXA space debris mitigation standard JMR-003 has been revised in line with the revision of ISO 24113. In 2019 the third revision of ISO 24113 was published. This includes new regulations reflecting the deterioration of the orbit environment in recent years, and a study was conducted to incorporate these new regulations into JMR-003 and revise them. The new JMR-003 includes various requirements such as achievement of a probability of successful disposal of 0.9 or more after completion of operation of the spacecraft or launch vehicle orbital stage, evaluation of debris/meteoroid collision probability, and strengthening of launch vehicle-related regulations. This presentation includes the explanation of the regulations newly added to JMR-003, the discussion within JAXA when incorporating regulations, and the explanation of the standard revision process within JAXA.

Status on JAXA space debris mitigation standard JMR-003

Japan Aerospace Exploration Agency
Safety and Mission Assurance Department
SATO Kenichi, NITTA Kumi, YOSHIHARA Toru

1.Background

◆In July 2019, ISO 24113:2019 Space systems- Space debris mitigation requirements was published which includes some new requirements.

◆A working group for JAXA Space debris Mitigation Standard (JMR-003) which includes Japanese manufacturers and operators discussed how to reflect new requirements of ISO 24113:2019.

◆In September 2020, new JMR-003D was published.

◆This presentation introduces overview of the JMR-003D.

JMR-003D is available in the following site. (Japanese only)
http://sma.jaxa.jp/TechDoc/

Old version JMR-003C is available in English site.
http://sma.jaxa.jp/en/TechDoc/index.html

2.1 The total number of launch vehicle-related objects

The revised parts are shown in red.

5. Planning and implementation of the space debris mitigation measures
5.1 Minimizing the objects released during normal operations
5.1.1 Limitation of released components, parts and its fragments
(1) As a general rule, the total number of launch vehicle-related objects (launch vehicle orbital stages and other payload support structures, etc.) left in orbit after launch shall be limited to **one for the launch of a single payload** and **two for the launch of multiple payloads**.

[Rationale of update]
Since the launch vehicle-related debris remaining in orbit has a large impact on the orbital environment, the regulation on the number of objects was adopted in accordance with ISO 24113:2019.

[Additional note]
Violation of the number of objects may be acceptable if the on-orbit collision risk and the ground casualty risk is lower than in case of smaller number of objects.

2.2 SRM slag emission limit in LEO protected region

5.1.2 Suppression of combustion products from pyrotechnics and solid motors
(1) Pyrotechnics, except for solid rocket motors 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 **larger than 1 mm** 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 moon, planetary and other missions with highly elliptical orbit.

Note: The main aim of this requirement is to limit the generation of slag debris ejected into GEO protected region and LEO protected region during the final phase of combustion. Slag debris is potentially hazardous to 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**.

2.2 SRM slag emission limit in LEO protected region

[Rationale of update]

- The requirement was proposed by ISO based on the ESA's space debris environment model (MASTER). This model shows SRM slag is major contributor on space debris population in LEO.
- Besides, NASA standard does not require limitation of SRM slag because their environmental model (ORDEM 3.0) shows different characteristics on SRM slag.
- Although NASA and ESA have different evaluations, JAXA decided that the SRM slag limitation is appropriate and adopted the requirement in accordance with ISO.
- JAXA just started developing slag less solid motor.

[Additional note]
Slag emission is possible if the orbit is sufficiently low (for example, below the inhabited orbit).
If slag emission is beyond the inhabited orbit, the risk should be evaluated each time.

Figure: Spatial density of each debris with respect to altitude (number per km ^ 3), SRM-Slag is a solid motor slag. (Source: ESA Environmental Model MASTER2009)

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2.3 Improvement of visibility from the ground

> 5.2.3 Prevention of break-ups caused by a collision with orbital objects
> 5.2.3.4 Improvement of visibility from the ground
> Improving the visibility from the ground and improving the orbit determination accuracy is effective for improving the accuracy of conjunction analysis and collision avoidance. For this reason, especially for systems that have potential problems with visibility, should be considered adding optical or radio wave reflection means, or transmission means.

[Rationale of update]
For the conjunction analysis and the preparation of the collision avoidance plan, it is desired that the orbit determination accuracy of both the satellite in operation and the approaching object is high. Specifically, it is conceivable to mount a laser reflector or the like on the system.

This requirement is unique to JAXA not in ISO.

Mt.FUJI (EM model)

(Source: Status Report of Tanegashima SLR Station (GMSL) and Developing Status of JAXA's Next SLR Station, ILRS Technical Workshop 2019)

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2.4 Evaluation of probability of break-ups caused by a collision

5.2.3 Prevention of break-ups caused by a collision with orbital objects
5.2.3.5 Evaluation of the probability that space debris and meteoroid will collide and cause complete break-ups
(1) When determining the orbit, size, mass, etc. of the spacecraft in the early phase of spacecraft development (for example, the conceptual design phase), the spacecraft body and major large components (service module, payload module, solar array paddle, large antenna etc.) shall be evaluated the probability that space debris or meteoroids will collide and cause complete break-ups during operation.
(2) The probability that the high-pressure vessel and propellant tank of the spacecraft will be completely broke by small space debris and meteoroids shall be evaluated, and if necessary, their arrangement and protection design should be considered.

[Rationale of update]
Due to the increase in orbital debris, an evaluation of the break-up probability due to external factors (collision of debris and meteoroids) was adopted.
[Additional note]
The debris flux model is open to the public by ESA (MASTER) and others. JAXA owns a debris damage analysis tool (TURANDOT) that incorporates the flux model and can carry out such an evaluation.

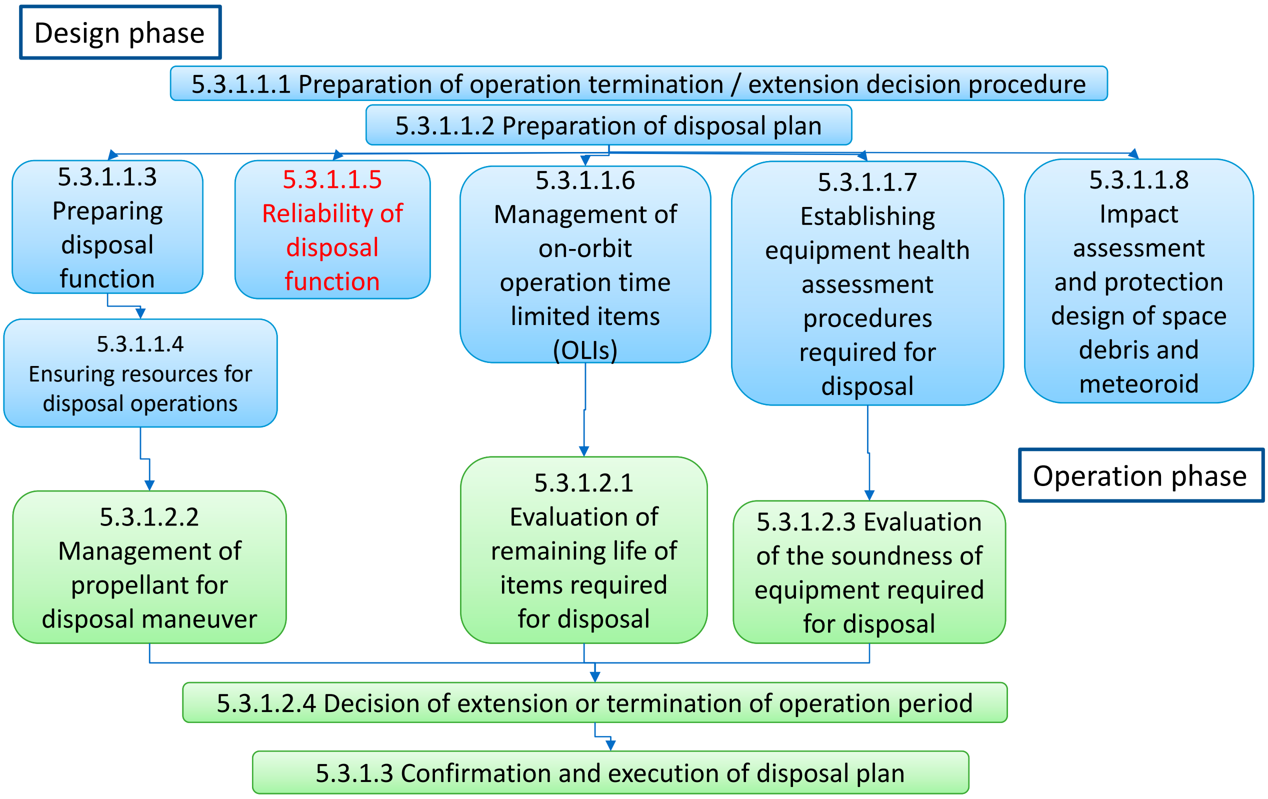
2.5 The target for the probability of successful disposal

5.3 Removal of space systems from protected orbital regions after the end of mission
5.3.1 Basic requirements
After the end of mission, the space system shall avoid the interference with the protected regions and minimize the possibility of break-ups according to Section 5.2.1. **The target for the probability of successful disposal is 0.9 or higher.** **This goal is considered to be achieved by complying with the requirements of Sections 5.3.1.1 to 5.3.4**.

[Rationale of update]
- The Inter-Agency Space Debris Coordination Committee (IADC) has shown that the probability of successful disposal (PSD) is required 0.9 or higher for sustainable LEO environment.
- In the past version of ISO 24113:2011, the conditional PSD was defined, but changed to the nonconditional in ISO 24113:2019
- ISO 24113:2019 does not provide a specific calculation formula for evaluation.
- Since JAXA cannot define a formula* for calculating the PSD at this time, we aim for reliable successful disposal by listing the possible design and operational measures as requirements.

* In Europe and the US, a **quantitative** evaluation method based on the reliability calculation of the disposal function is implemented, but JAXA does not currently adopt the quantitative evaluation method for several reasons.

2.5 Framework for requirements for successful disposal



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2.5 Framework for requirements for successful disposal

5.3.1.1.5 Reliability of disposal function
For spacecraft, the reliability of the disposal function at the end of the disposal operation following the planned operation period shall be evaluated in relation to the reliability prediction work based on JMR-004 “Reliability Program Standard”.
The target value shall be the value determined for each project.

Note 1: The planned operation period is the period guaranteed by the design.
Note 2: If the period from the end of mission to the completion of disposal work is short enough and the reliability is not significantly affected, the reliability prediction value at the end of mission may be used for evaluation.
Note 3: The reliability of the launch vehicle is evaluated in the activities based on JMR-004 "Reliability Program Standard".

- It is not suitable to apply JAXA’s regular reliability calculation method based on MIL-HDBK-217F to PSD evaluation because it is unreasonably conservative for this purpose and not showing realistic prediction.
- JAXA still tackle how to quantitively evaluate the probability of successful disposal based on the reliability. Some option can be considered…
  - Change of calculation condition such as temperature.
  - Change of reliability database such as FIDES.

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3. Conclusion

- ◆A working group of JAXA Space debris Mitigation Standard (JMR-003) discussed how to reflect new requirements of ISO 24113:2019.
- ◆In September 2020, new JMR-003D was published.
- ◆The new requirements in JMR-003D are very challenging because they have some technical issues such as the SRM slag and the probability of successful disposal.
- ◆JAXA will continue to study the reduction of SRM slag and the quantitative evaluation of the probability of successful disposal.

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Information on the 11th IAASS Conference in Osaka

- ➢ The 11th conference of the International Association for the Advancement of Space Safety (IAASS), an academic society whose activities aim to promote international cooperation and technology in the field of space system safety and sustainability, will be held in Asia for the first time since the establishment of the academic society.
- ➢ In the past conference, the participants were mainly in Europe and the United States, but since it will be held in Osaka, participation from Japan and the Asia-Pacific region is also expected.
- ➢ Recent hot topics include space debris mitigation, space situational awareness (SSA), and space traffic management (STM).

19-20-21 October 2021
Osaka International Convention Center (Grand Cube Osaka)
http://iaassconference2020.space-safety.org/

Fees：Early Registration Presenting Authors $735 (YEN 80000)
Early Registration non-IAASS members $870 (YEN 95000)
(Early registration include the first day luncheon and the Gala Dinner)

Inquiries: yoshihara.toru@jaxa.jp

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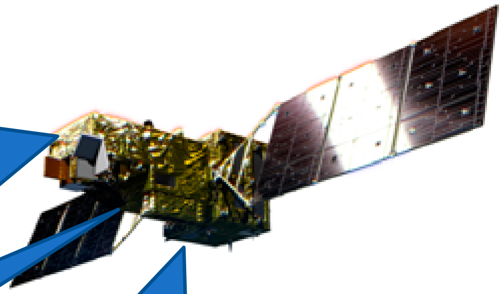
Back up

Monitoring and Managing items (Example)

5.3.1.1.7 Establishing equipment health assessment procedures required for disposal
- -Batteries
- -Generated power from solar array paddle
- -Pressure of gas tank
- -Thrusters
- -Electric power consumption
- -Communication
- -Attitude orbit control
- -etc…



5.3.1.1.6 Management of on-orbit operation time limited items (OLIs)
- -Wheels
- -Thruster valves
- -Batteries
- -Paddle driving mechanisms
- -Other mechanical devices
- -etc…

5.3.1.1.4 Ensuring resources for disposal operations
- - The amount of propellant remaining

A05

Space Debris Related Activities in Russia

○Vladimir Agapov (Astronomical Scientific Center)

Astronomical Scientific Center (ASC), JSC since 2010 has being developing and operating optical observation network around the globe, including the dedicated network of telescopes for ROSCOSMOS. More than 40 telescopes collect daily about 180-210 thousand of measurements for more than 9000 space objects in GEO, MEO and HEO. ASC analyze those data to identify new objects and maintain the orbits of existing objects for ROSCOSMOS. The network is capable to detect and track objects as faint as 18.5-19th magnitude at GEO distance. It had quickly identified the debris clouds created in three fragmentation of Atlas 5 Centaur R/B in GTO in Aug 2018, Mar and Apr 2019 (see Figure 1). Quality of measurements permits to maintain GEO, HEO and MEO orbits for larger space objects at the accuracy level better than 200-300 m in normal mode and ca. 50-60 m in the special mode. The detail of the network, its outcomes and other space debris related activities in Russia will be discussed in this talk.

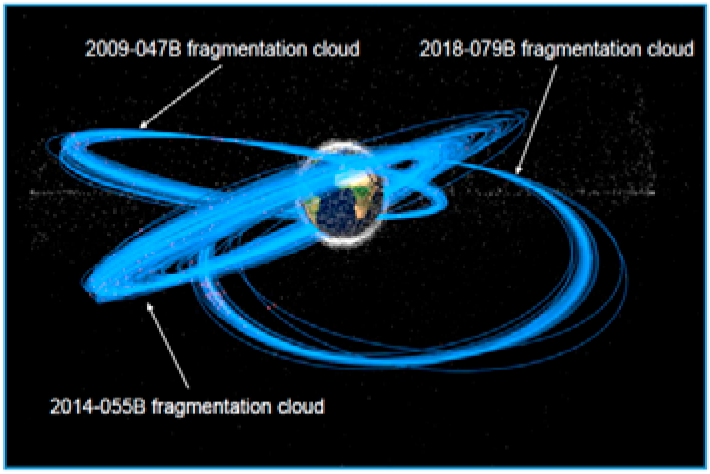


Figure 1. Three debris clouds identified by the Roscosmos optical observation network.

Biography

Vladimir Agapov

Vladimir Agapov is the Senior Research Fellow of Keldysh Institute of Applied Mathematics, Russian Academy of Sciences and Designer General of the Astronomical Scientific Center, JSC. For many years he was working as a leading expert of the Russian delegation on space debris, LTSSA, STM and SSA in COPUOS and other international fora. His research interests are space flight mechanics, SSA, STM and international space law. He is the author of over 150 scientific papers. He is also the member of the Working Group 1 (space debris observation) of the Inter-Agency Space Debris Coordination Committee (IADC)

Space Debris Related Activities in Russia

Vladimir Agapov

Astronomical Scientific Center, JSC

agapov@ancprotek.ru

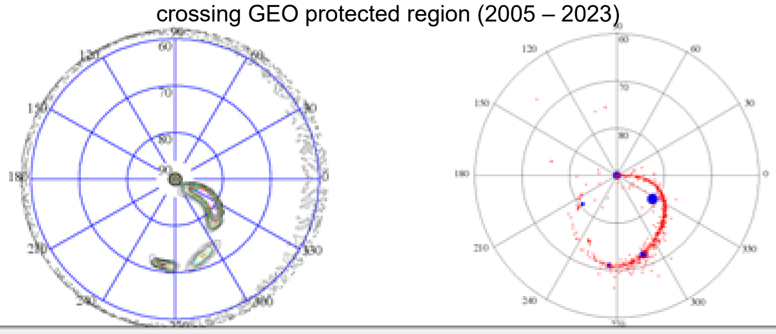
9th Space Debris Workshop
JAXA, 24 Feb 2021

Major Space Debris Related Activities in Russia

- Regulatory and organizational
- **Space debris modeling**
- **Optical and radar observations**
- Protection and mitigation
- Situational awareness
- Space operations support, including conjunction assessment
- Space debris removal

Model of space debris distribution and evolution (research conducting jointly by KIAM and TsNIIMash)

Evolution of direction of normal to orbital planes for space objects residing in or crossing GEO protected region (2005 – 2023)



Statistical approach to description the space debris spatial distribution

Distribution of valuable parameters represented as normal distributions mixture

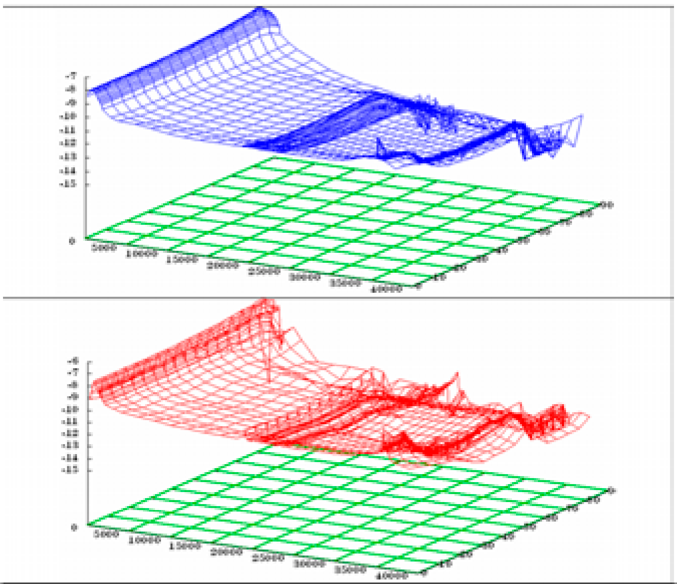
$$f(a, e, i, \Omega, \omega, M) \to f(\boldsymbol{r} \times \boldsymbol{v}, a) \to \sum N(q_i, C_i)$$

Advantages of the approach:

- information on distribution by latitude is preserved (*essential for objects in high orbits*)
- compact description of objects grouping in selected phase space (*independent calculation of flux for each group – components of the mixture*)
- a universal tool for approximating complex distributions of the orbital parameters of space objects

3

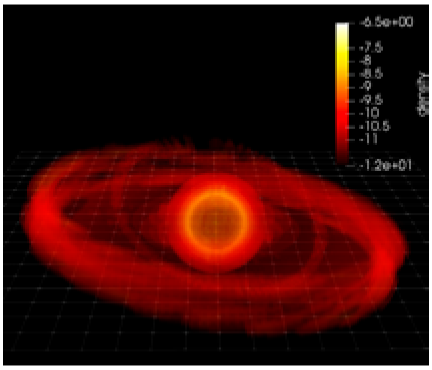
Model of space debris distribution and evolution (research conducting jointly by KIAM and TsNIIMash)

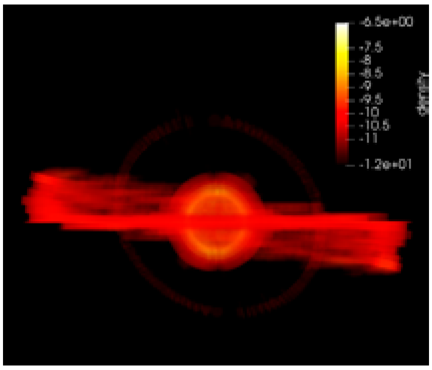


Comparison of distributions provided by the improved model (top) and calculated based on information taken from orbital catalogue (bottom)

4

Model of space debris distribution and evolution (research conducting jointly by KIAM and TsNIIMash)





Sum of spatial densities of distribution of space objects for each group describes the complete distribution of all space objects

Resulting distribution highly depends of latitude and longitude for objects in high orbits (*due to uneven distribution by Ω, unlike LEO*)

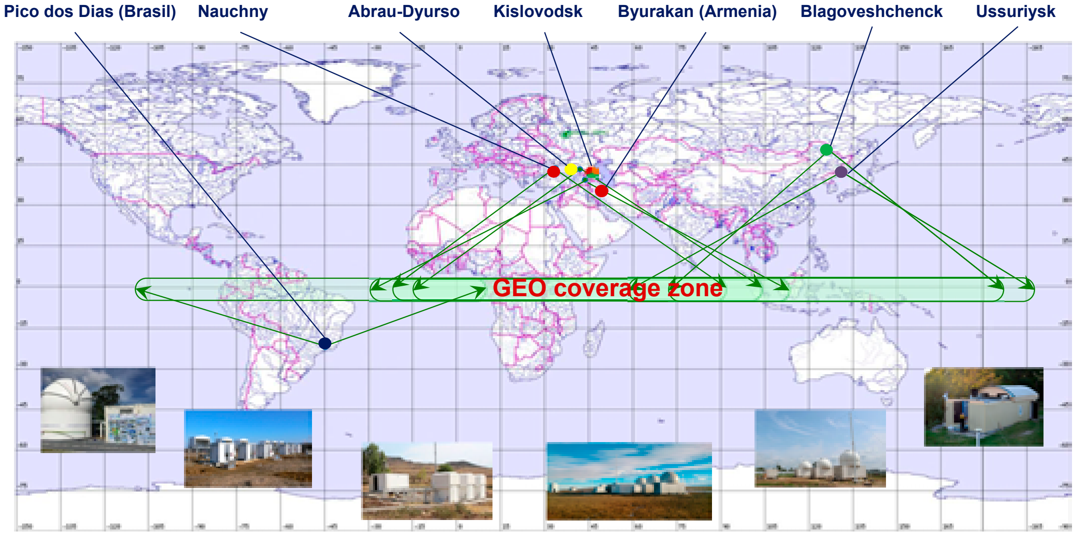
5

Russian Civilian Observation Networks and Facilities

- Automated Warning System on Hazardous Situations in Outer Space (ASPOS OKP) with a network of dedicated optical observation facilities — operated by ASC for ROSCOSMOS
- Network of optical observation facilities owned and operated by Astronomical Scientific Center (ASC)
- Dedicated optical observation facilities operated by various organizations in partnership with KIAM RAS (ISON)
- Observation facilities operated by other scientific institutes (CrAO, INASAN – optical, ISTP RAS – optical and radar) and universities (MSU, KFU – optical) supervised by the Ministry of High Education and Science
- Optical observation facilities operated by industry organizations (Vympel JSC, NPK SPP)

6

Operational network of optical facilities of ASPOS OKP (ROSCOSMOS)



EOP-1 (4 facilities)
Each facility includes
2 telescopes with 19 cm aperture
1 telescope with 25 cm aperture
1 telescope with 40 cm aperture

EOP-2 (2 facilities)
Each facility includes
4 telescopes with 19 cm aperture
1 telescope with 40 cm aperture
1 telescope with 65 cm aperture

OES-50

OES-65

RKS-25

OEK OKM

Total:
22 instruments

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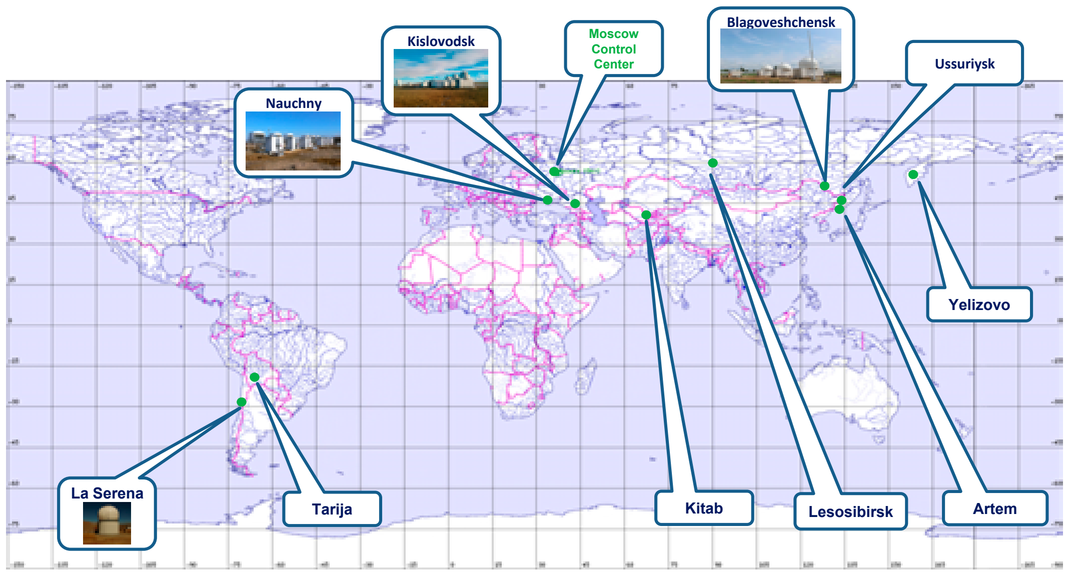
ASC Optical Network



8

Current Catalogue of Tracked Objects in High Orbits

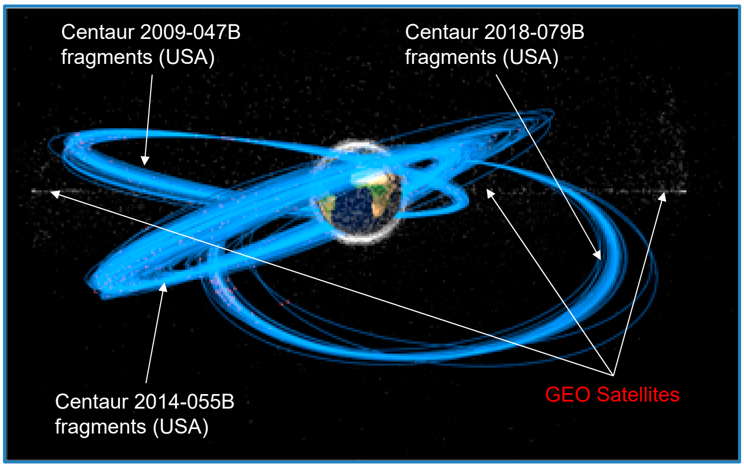
As of Feb 23, 2021

Orbit type	Definition	Number of tracked objects
GEO	1100 <= T <= 2000 min e <= 0.25 i <= 25°	2791
MEO	600 <= T < 1100 min e <= 0.25	433
HEO	Ha >= 3500 km e > 0.25	5373
Other	Not included into the groups above	408
TOTAL		9005

925 new space debris objects in various high orbits were detected in 2020 by Russian civilian optical facilities
Yet more ca. 3000 previously detected and tracked objects in high orbits are considered lost for a while

9

Objects Population Grow in High Orbits. Three Fragmentation Events of 2018-2019 with the Largest Number of Long-Lived Trackable Space Debris Objects Created



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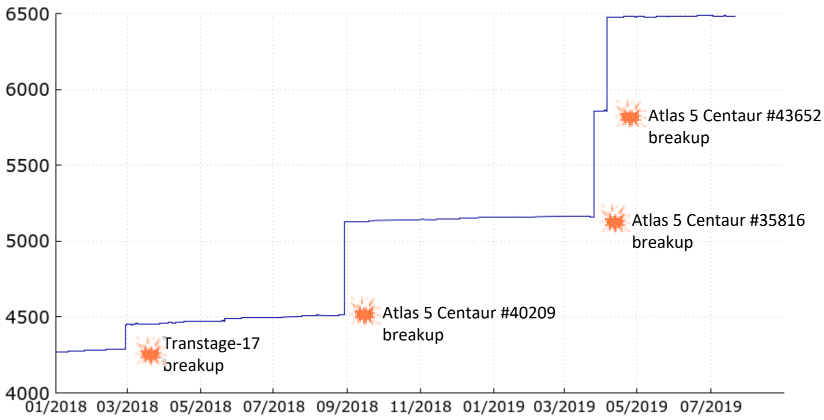
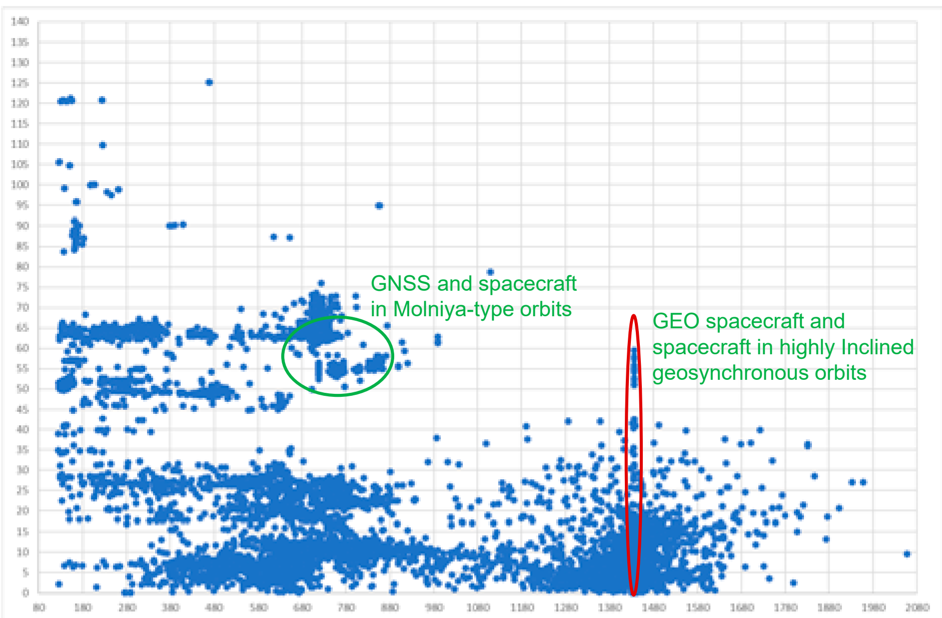
Objects Population Grow in High Orbits

More and more space debris in HEO and GEO



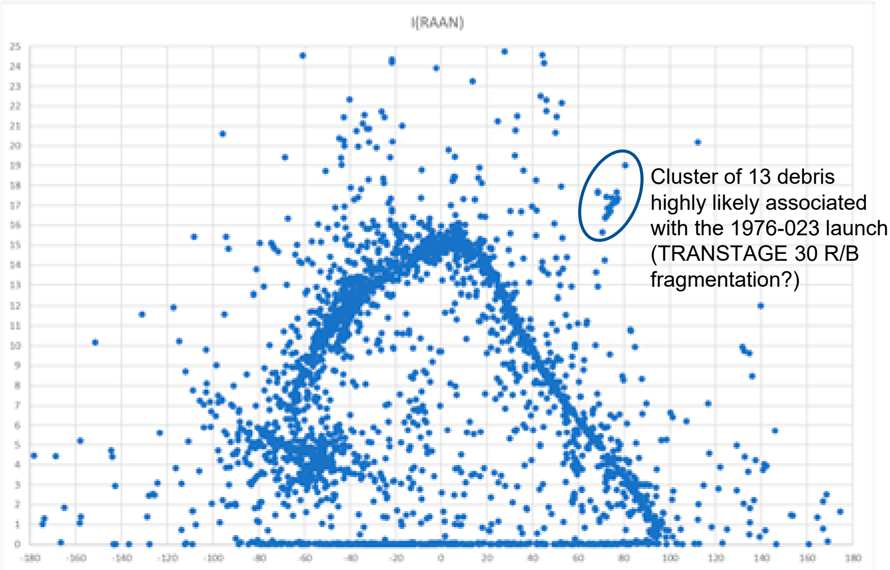
Up to date more than 2100 new fragments of these fragmentations are discovered

Current Distribution of Objects in High Orbits Tracked by Russian Civilian Optical Facilities



Inclination vs. Period

Distribution of Objects in GEO Region (29.11.2019)



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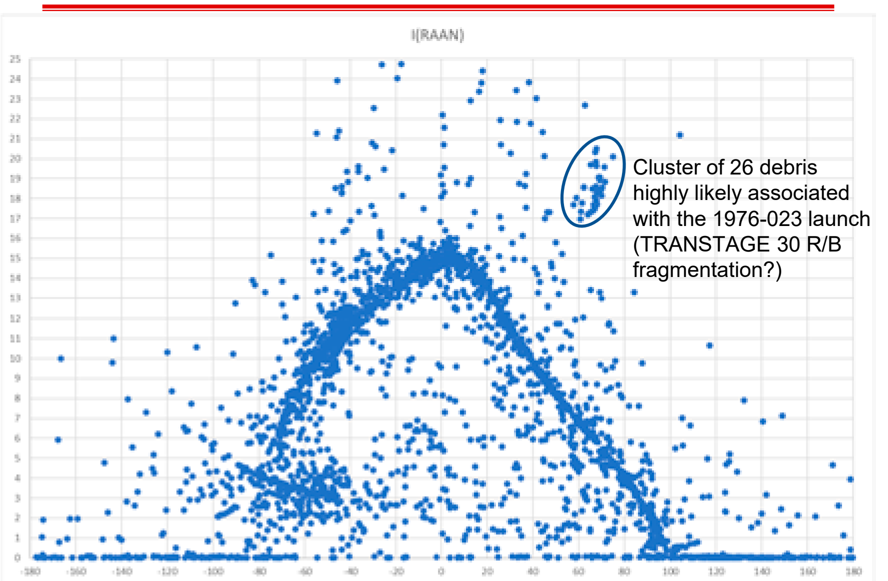
Distribution of Objects in GEO Region (23.02.2021)



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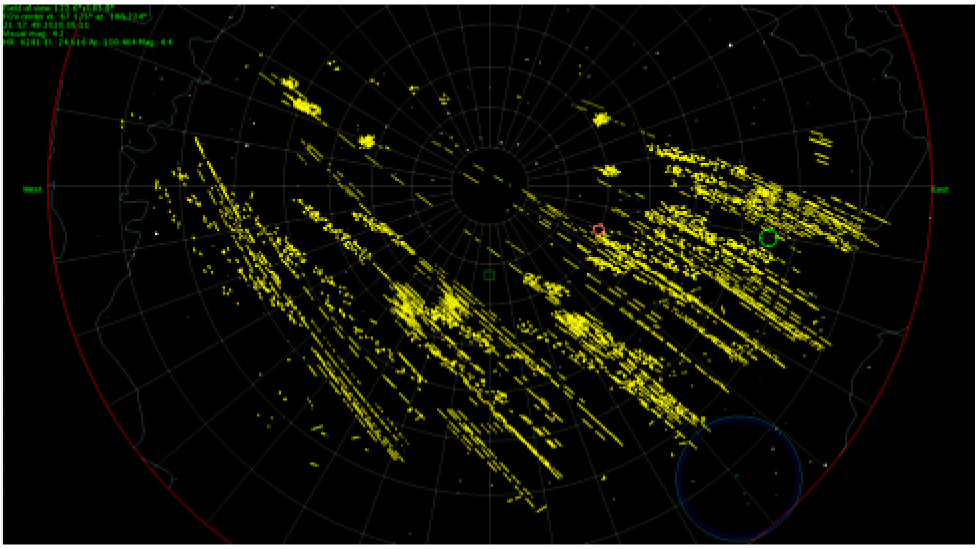
Improved Performance of Telescopes for Observation of Objects in LEO

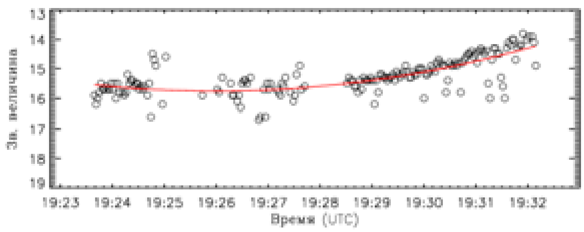


Test observations on May 8, 2020 in the “optical fence” mode. Debris of Fregat R/B fragmentation (range: 1000…3600 km, estimated size of the smallest observed objects: 5-7 cm)

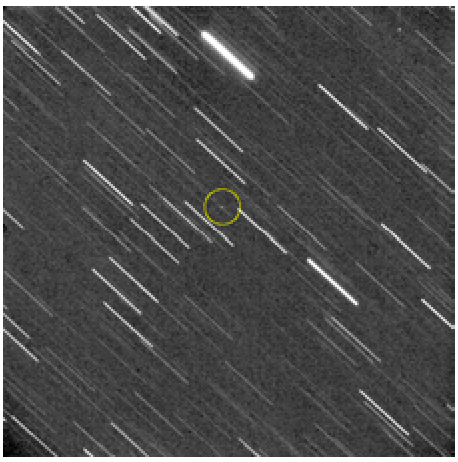
Observations of Small Objects in LEO

Object: SSN 12329 (KYOKKO 1 DEB)
RSC: < 0.0095 m²

Phase angle: 76.0 – 124.4 deg
Range: 2258 – 4070 km

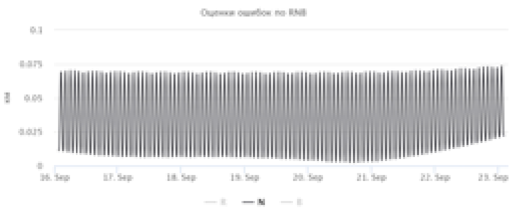


Light curve

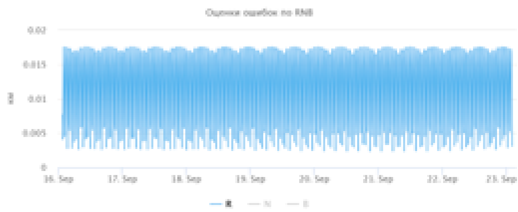


Measured position precision: 1.80 arcsec (1σ)

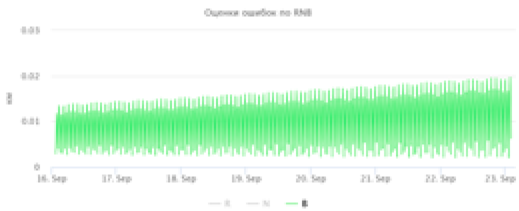
Achieved Precision of OD for LEO Object Using Optical Measurements Only



Along-track (3-75 m)



Radial (3-17 m)



Cross-track (3-20 m)

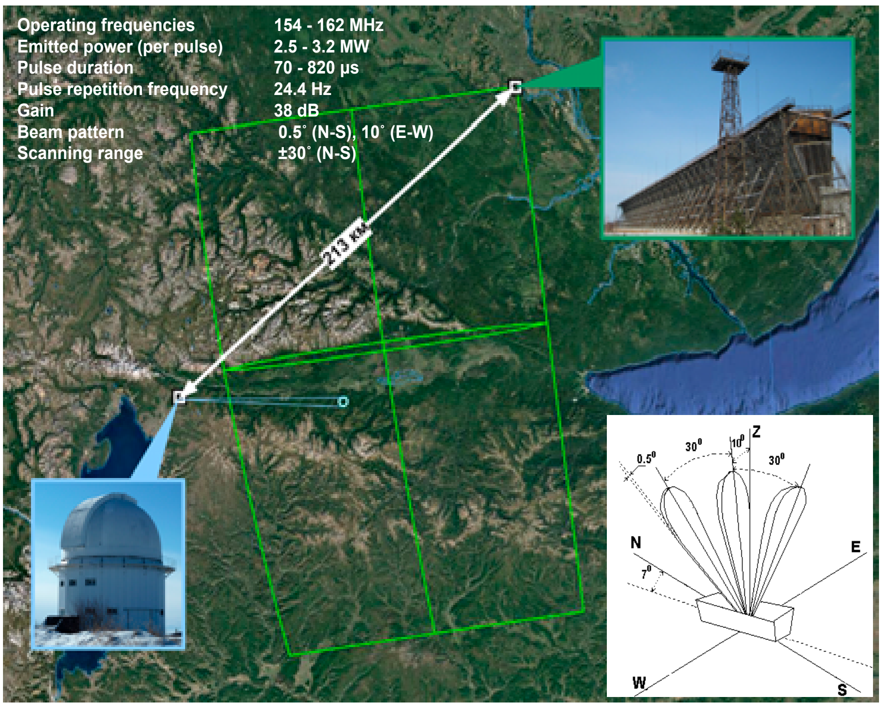
Object: SSN 12138, 394x1448 km, 84°

OD fit interval: 7 days

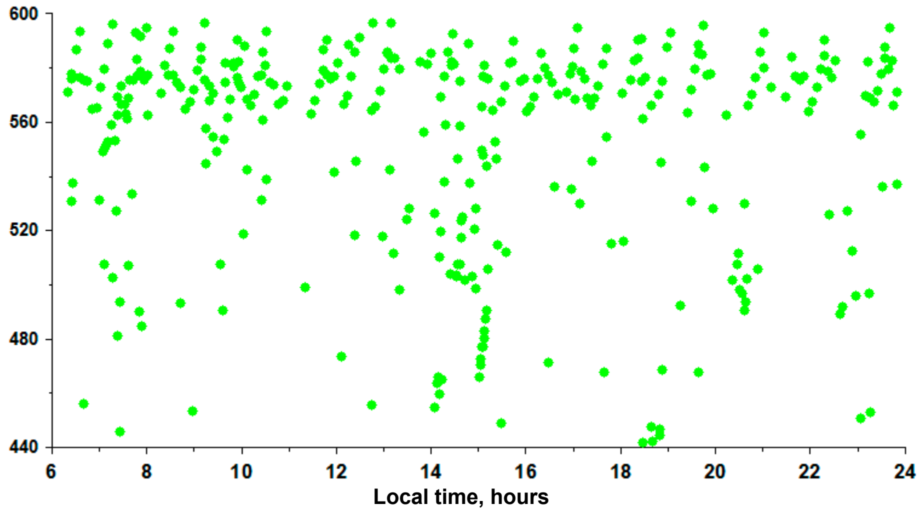
Achieved OD precision: 5-75 m

Raw measurements precision: 0.2-0.3 arcsec (1σ)

Radar and Optical Facilities by ISTP RAS



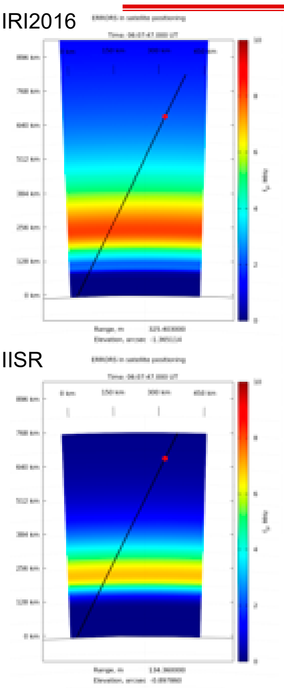
Radar Test Observations on Nov 10,2020

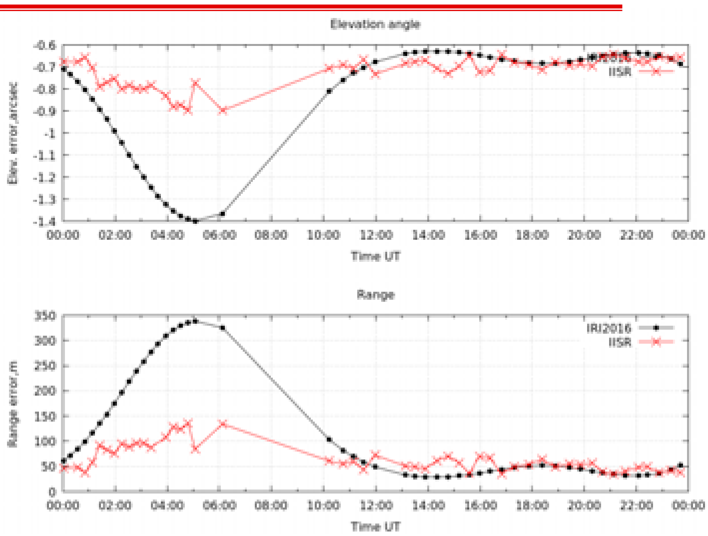


Scanning heights range: 440 – 600 km
Duration of survey: 18 hours
Number of registered tracks: 342

19

Improved Ionospheric Propagation Error Model

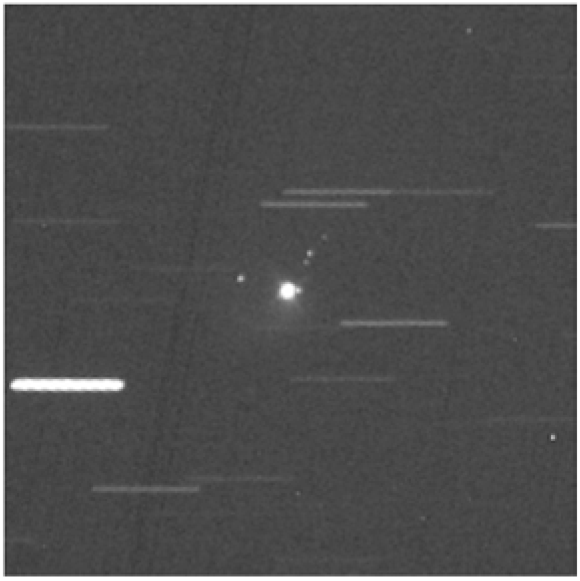




Comparison of IRI2016 and IISR models
Assessment of range and elevation errors during 24 hours for height 670 km [frq 159.8 MHz]

20

Minor breakup example



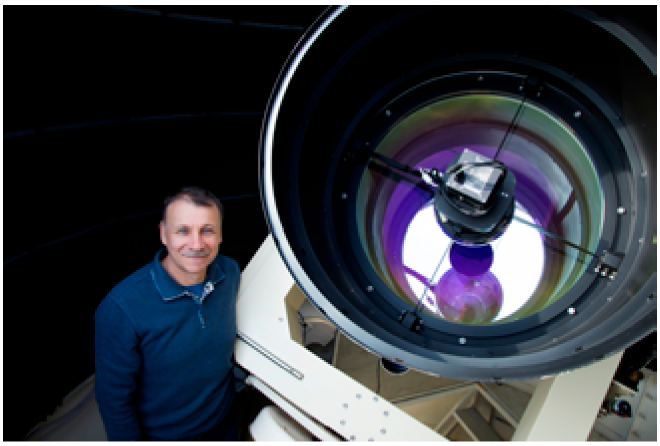
Apr 8 2019 – Intelsat 29E in GEO

Non Space Debris Related Matters

First known for humanity interstellar comet 2I/Borisov was discovered in August 2019 with a 65 cm telescope by a scientist, Gennady Borisov, working for ASC.

He develops modern optical instruments for ASC and supports different observation programs.

Nine comets and several near-Earth asteroids – current score of Gennady's achievements using his own telescope which was built using the same technologies we are using in ASC.



Thank you for your attention!

A06

New Space and the Continued Need for Space Debris Mitigation

○Stijn Lemmens (ESA)

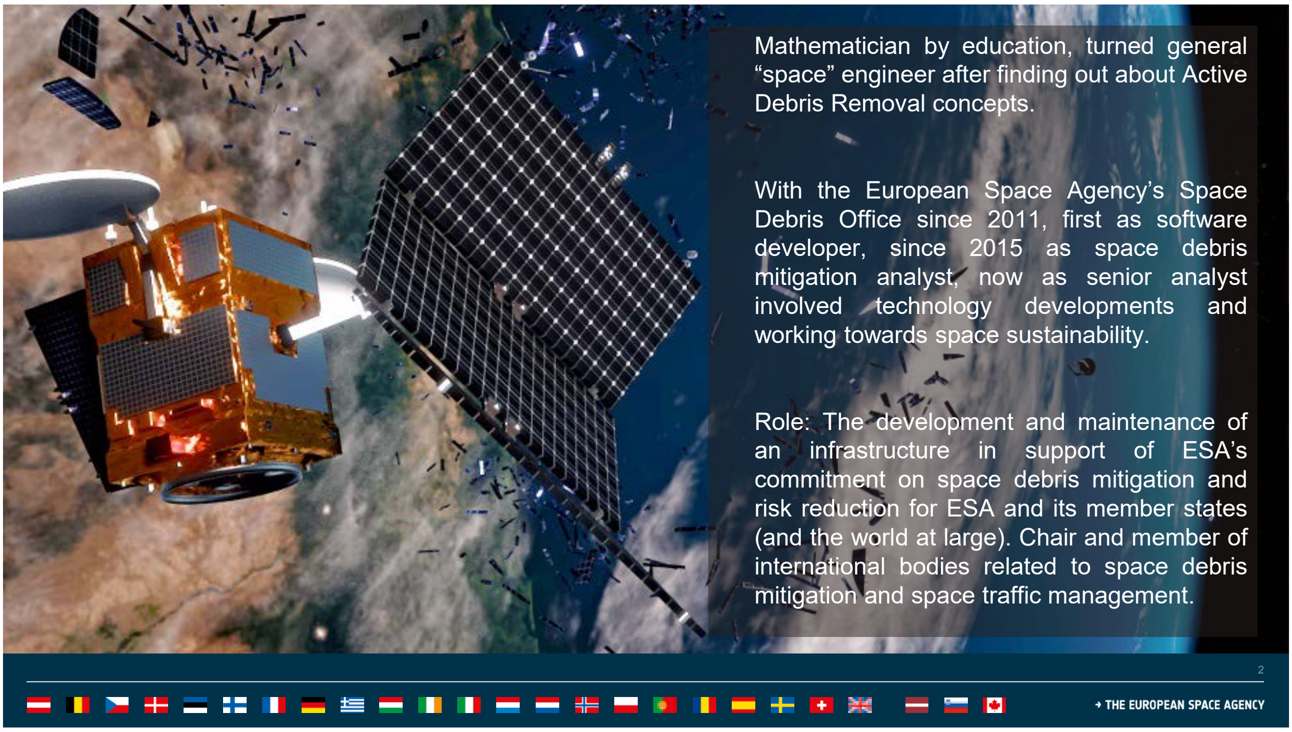
The on-going revolution in the way the space environment is used, with ever smaller and more versatile platforms and the deployment of large constellation, is creating not only opportunities but also concerns when it comes to assuring the long term sustainability of outer space for operations.
Space debris mitigation, and remediation, requires to use the data being produced by space situational awareness systems to design technologies to be implemented on space missions, based on a solid scientific understanding of the environment. At the European Space Agency's (ESA) last ministerial council in 2019, its member states endorsed the creation of a Space Safety programme to, among others, address some of the challenge which are coming up. This includes the development of surveillance sensors and new data products such as attitude motion, a platform for automated collisions avoidance operations, technologies to aid safe disposal and re-entry, and a mission to demonstrate the viability of active debris removal by removing an ESA owned object from orbit. This is complemented with a research component in ESA's Space Debris Office, looking into, among others, uncertainty quantification and metrics to assess the orbital use of the environment.
This lecture will give an overview of how the changes in the space environment has driven the need for the new developments in technologies which are taking place at ESA. The focus will be on how the new space situational awareness capabilities are needed for evolutions in space debris mitigation, such as the development of rating schemes, and enablers for active debris removal.

Biography

Stijn Lemmens
Senior Space Debris Mitigation Analyst
Space Debris Office, European Space Agency

Stijn Lemmens graduated from the Catholic University of Leuven, Belgium, with a degree in Mathematics in 2009. He started his career at the European Space Agency two years later, at the space debris office in Darmstadt, Germany, after discovering the technical and legal problems associated with active debris removal. After working on software engineering and various scientific investigation related to space debris, his current duties involve running and coordinating activities on the boundaries between technology development, modelling, and observations to the advancement of space debris mitigation and remediation. He is actively involved in international bodies dedicated to standardisation and advancement of the field, currently chairing the Inter-Agency Space Debris Coordination Committee's working group on mitigation, and taking the next steps towards sustainable space operations in an ever more congested space environment.


esa
New Space and the continued
Need for Space Debris Mitigation
Stijn Lemmens
Space Debris Office, European Space Agency
9th JAXA Space Debris Workshop, 2021-02-24
→ THE EUROPEAN SPACE AGENCY


Mathematician by education, turned general “space” engineer after finding out about Active Debris Removal concepts.
With the European Space Agency’s Space Debris Office since 2011, first as software developer, since 2015 as space debris mitigation analyst, now as senior analyst involved technology developments and working towards space sustainability.
Role: The development and maintenance of an infrastructure in support of ESA’s commitment on space debris mitigation and risk reduction for ESA and its member states (and the world at large). Chair and member of international bodies related to space debris mitigation and space traffic management.
2
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Abstract

esa

The on-going revolution in the way the space environment is used, with ever smaller and more versatile platforms and the deployment of large constellation, is creating not only opportunities but also concerns when it comes to assuring the long term sustainability of outer space for operations.

Space debris mitigation, and remediation, requires to use the data being produced by space situational awareness systems to design technologies to be implemented on space missions, based on a solid scientific understanding of the environment. At the European Space Agency's (ESA) last ministerial council in 2019, its member states endorsed the creation of a Space Safety programme to, among others, address some of the challenge which are coming up. This includes the development of surveillance sensors and new data products such as attitude motion, a platform for automated collisions avoidance operations, technologies to aid safe disposal and re-entry, and a mission to demonstrate the viability of active debris removal by removing an ESA owned object from orbit. This is complemented with a research component in ESA's Space Debris Office, looking into, among others, uncertainty quantification and metrics to assess the orbital use of the environment.

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Overview

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1. New Space, the ongoing evolution of how we use the near Earth environment and its implications.
2. European Space Agency's Space Safety programme. Focus points for debris mitigation and research.
3. What is next? From changing environment to new technologies and active debris removal (, back to measuring the impact).

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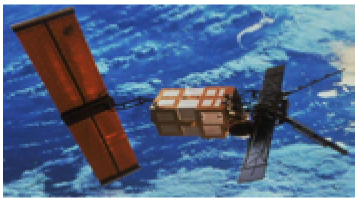
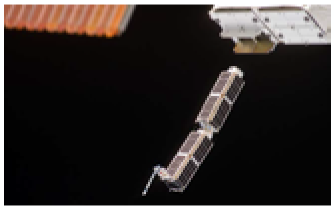
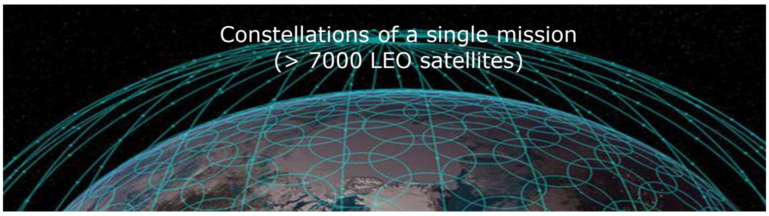
New Space: Changes in the Environment

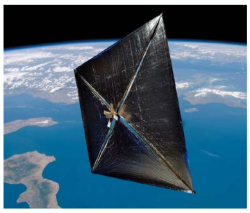


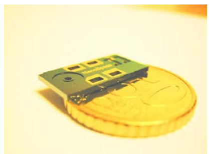
Large
Complex,
institutional

Lean,
agile,
commercial









5

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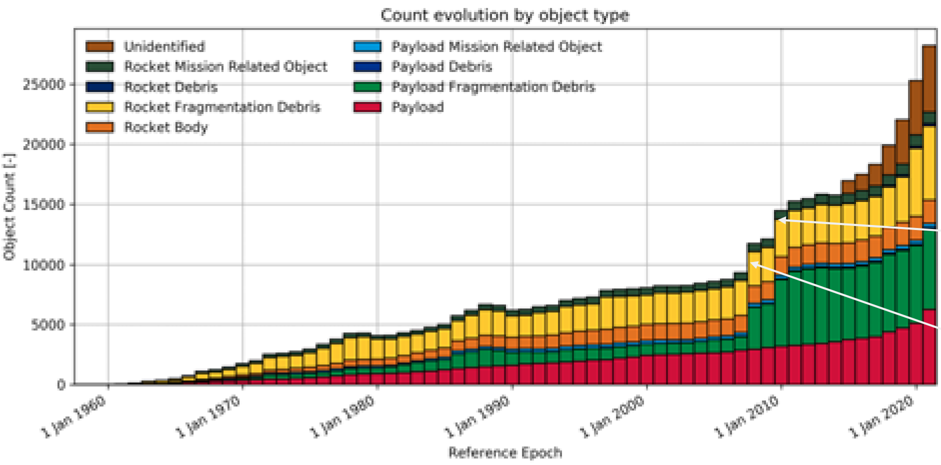
Realities on orbit #1



2015-...
Improved surveillance

10/02/2009
Cosmos-Iridium collision
3294 new objects

11/01/2007
Chinese anti-satellite test
3439 new objects

6

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Realities on orbit #2: Stable GEO usage trends

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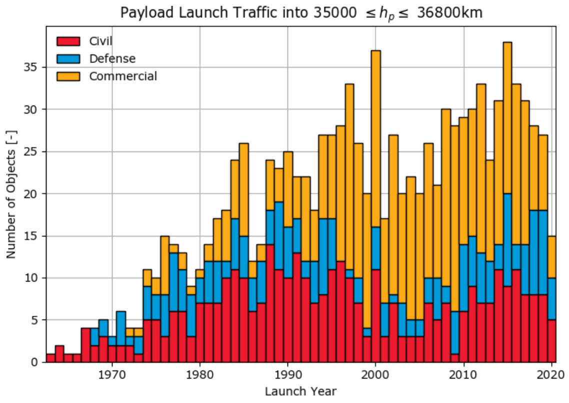
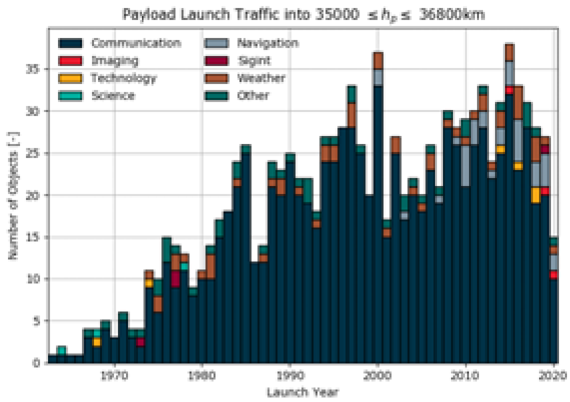
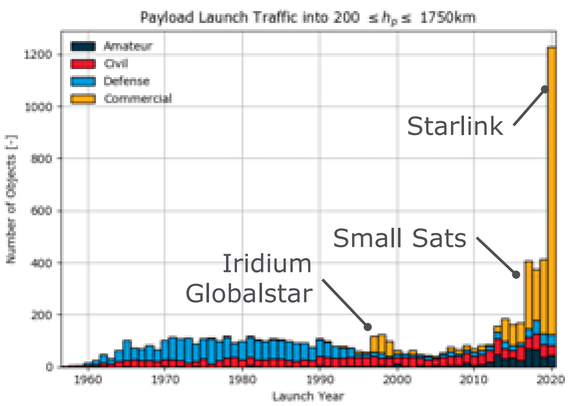


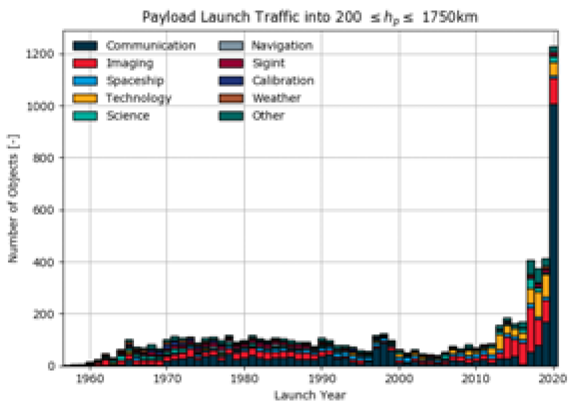


h_p: perigee altitude

Realities on orbit #3: changing LEO usage trends

esa

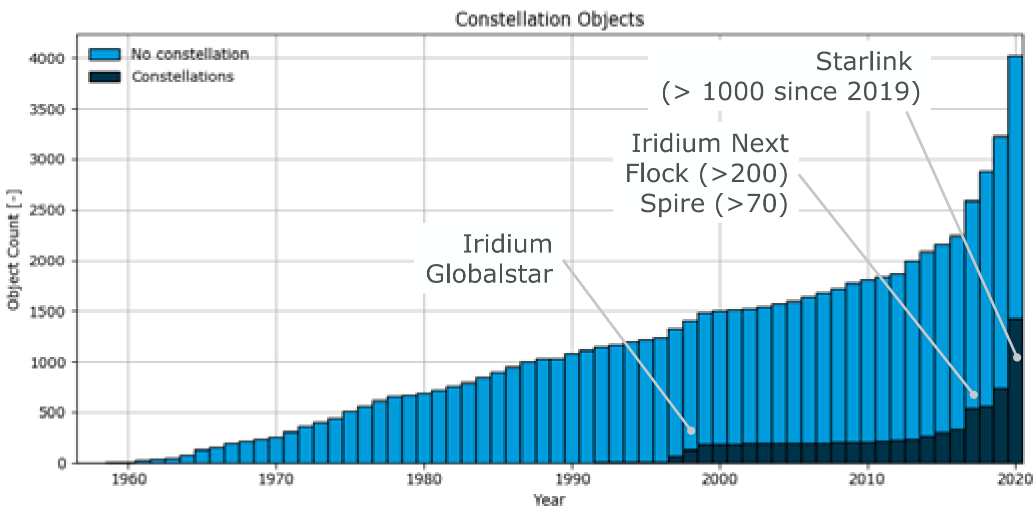




h_p: perigee altitude

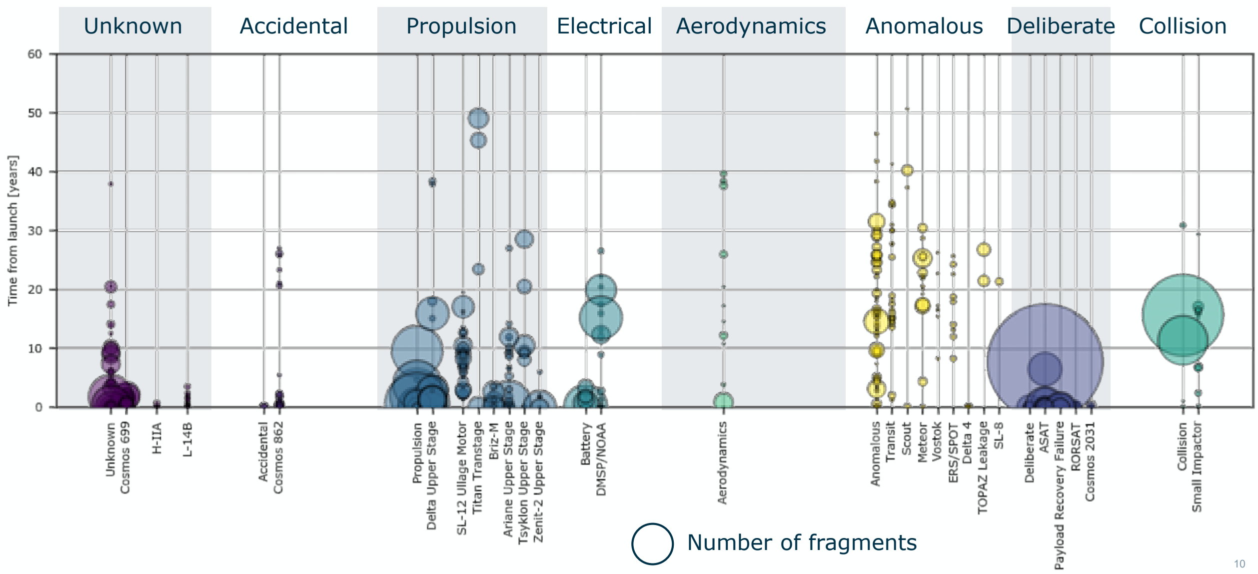
Realities on orbit #4: Use of constellations

esa



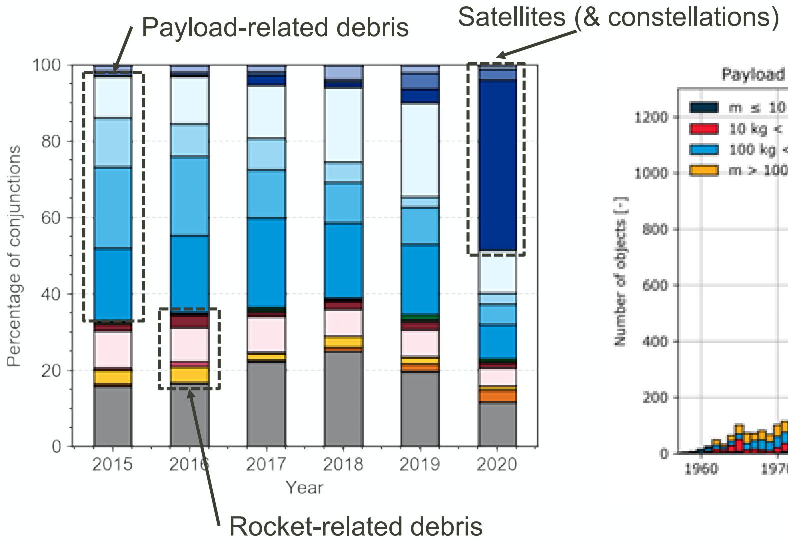
Realities on orbit #6: Fragmentation trends

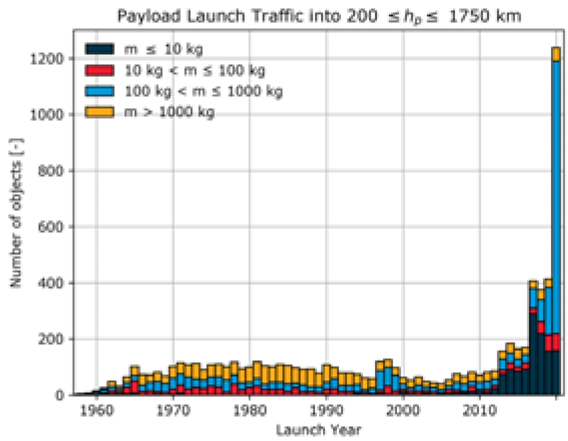
esa



Realities on orbit #6: Collision avoidance in LEO

esa





Space Debris Mitigation Objectives: Sustainability

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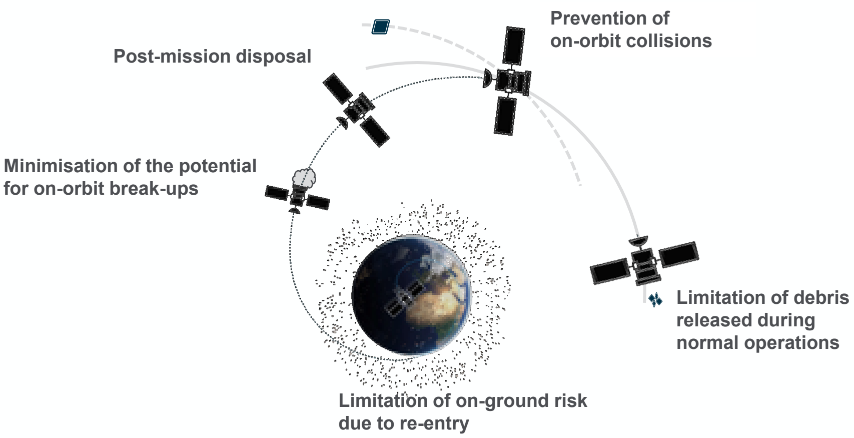



INTERNATIONAL STANDARD

ISO 24113

Second edition 2011-05-15

Space systems — Space debris mitigation requirements

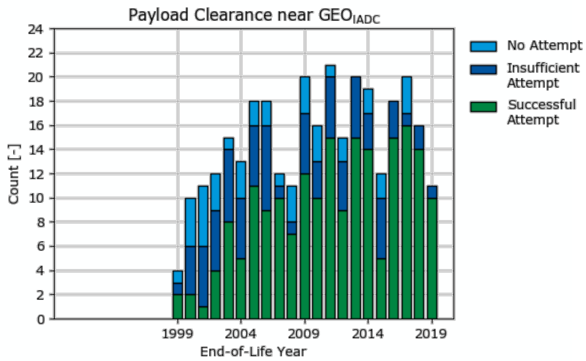
Systèmes spatiaux — Exigences de mitigation des débris spatiaux

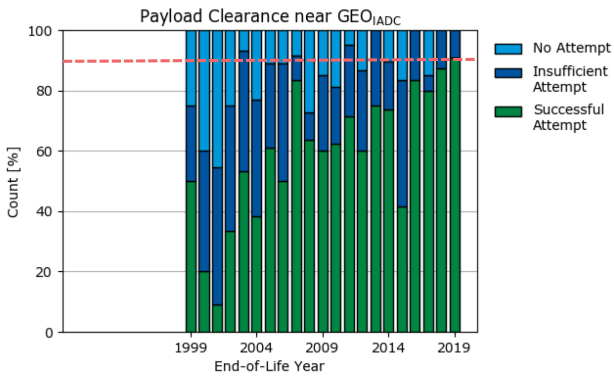
Reference number ISO 24113:2011(E)

© ISO 2011

Post mission disposal: GEO Payloads

esa





---------------- 90% success rate requirement

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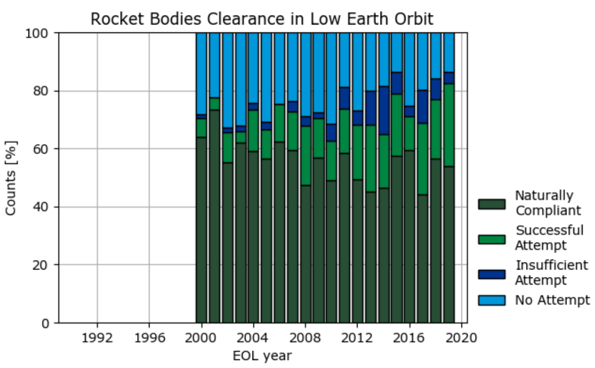
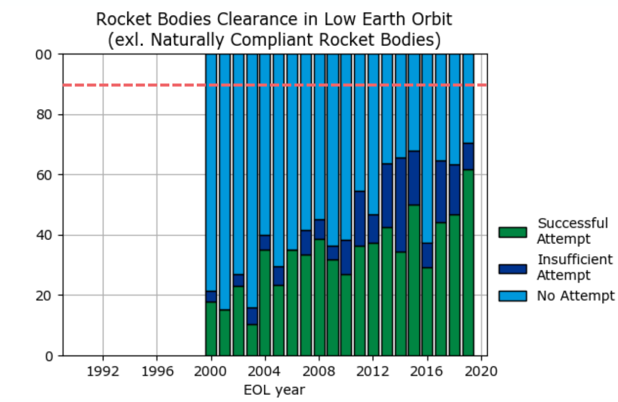
Post mission disposal: LEO Rocket Bodies

esa





---------------- 90% success rate requirement

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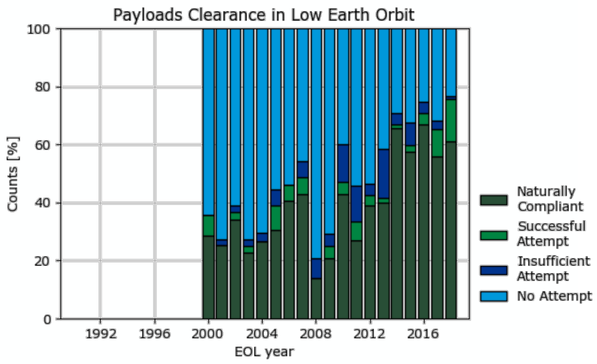
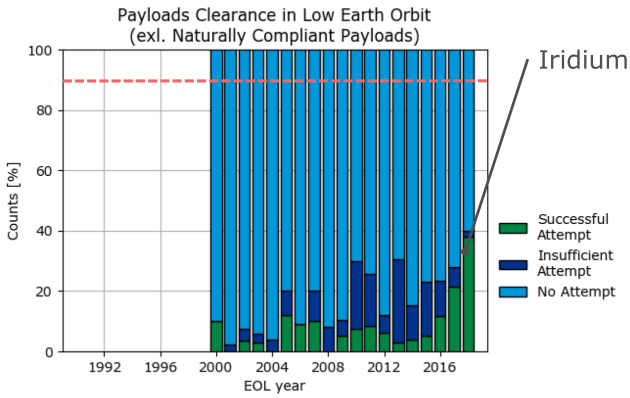
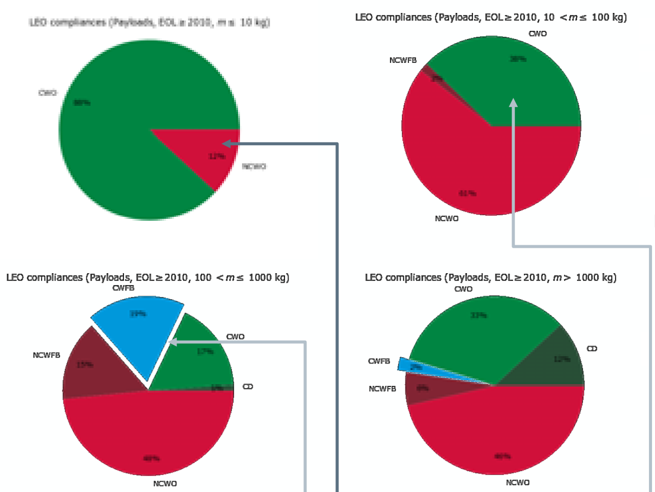
Post mission disposal: LEO Payloads





90% success rate requirement

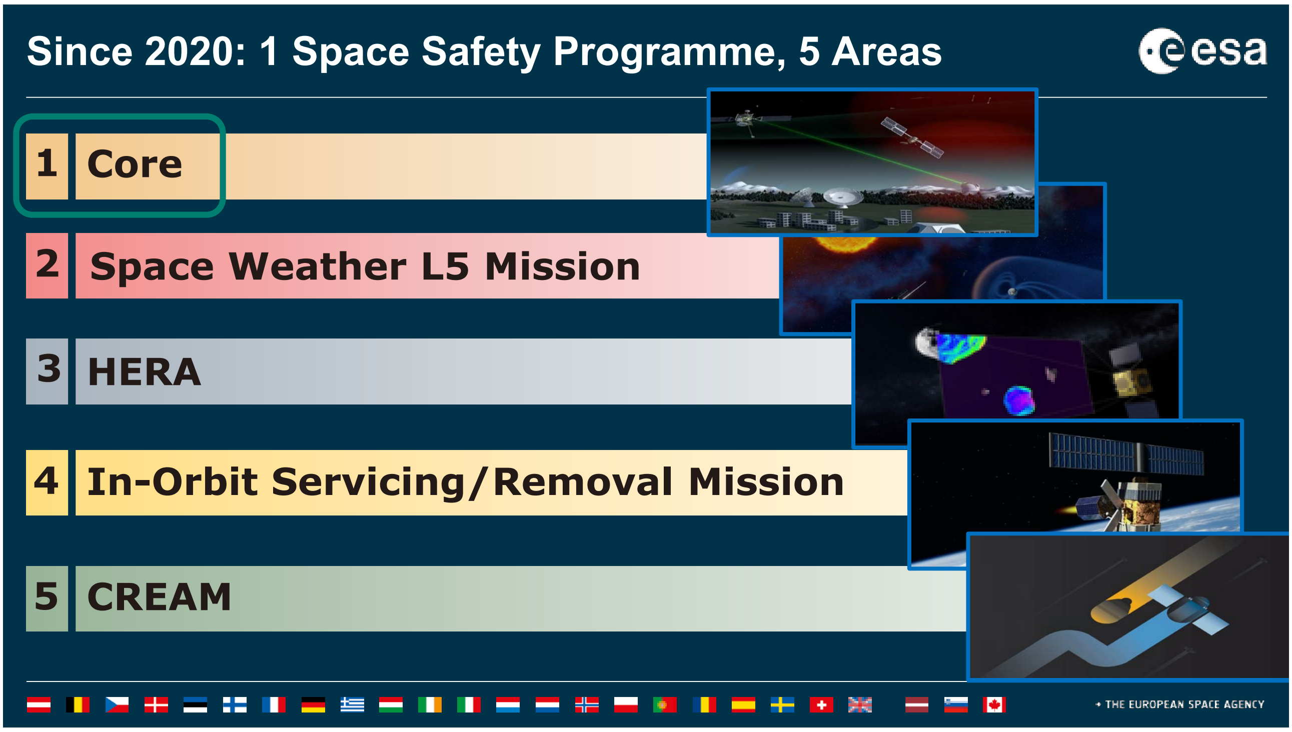
Post mission disposal: LEO Payloads

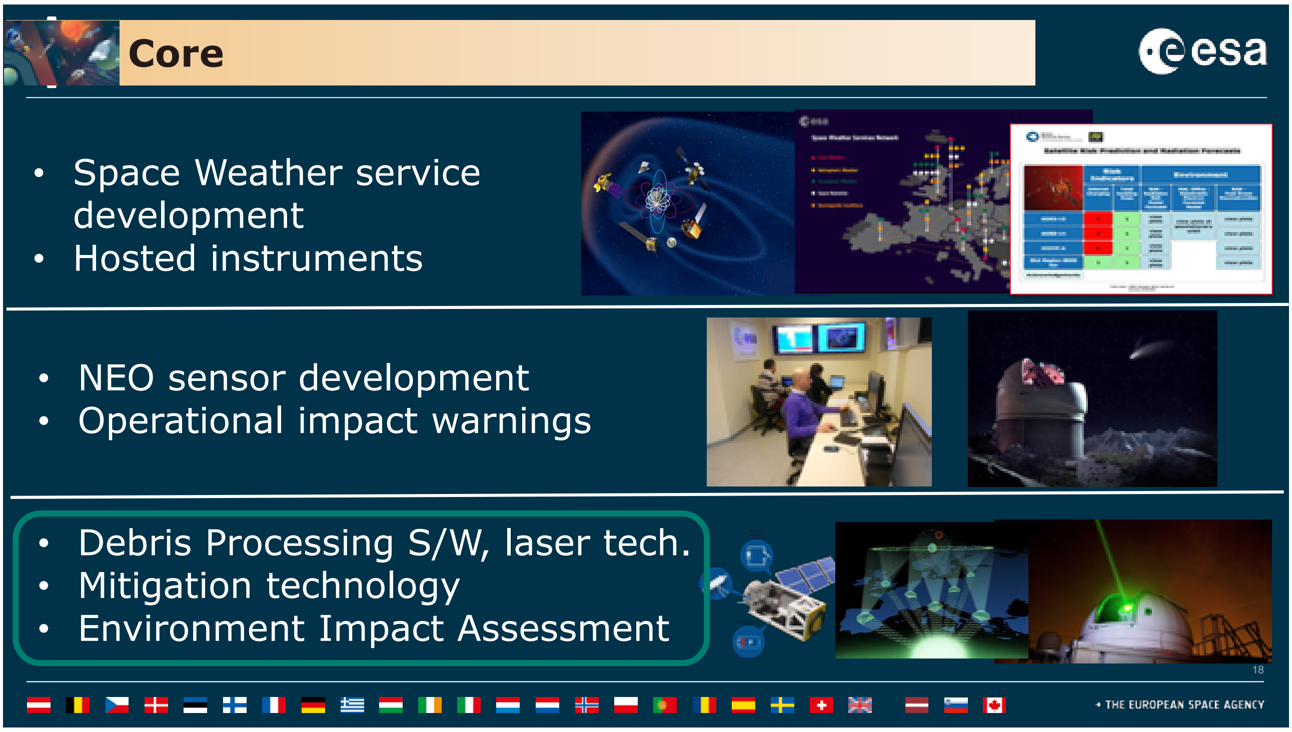


- **CD:** Compliant with direct re-entry
- **CWFB:** Compliant with attempt where the destination orbit would not have been compliant (with False Before)
- **CWTB:** Compliant with attempt where the destination orbit would have been compliant (with True Before)
- **CWO:** Compliant without an attempt
- **NCWFB:** Not compliant with attempt where the destination orbit would not have been compliant (with False Before)
- **NCWTB:** Not compliant with attempt where the destination orbit would have been compliant (with True Before)
- **NCWO:** Not compliant without an attempt.

Worst performance (compliance ≈ **35%**) in the **10-1000** kg range

12% small objects left in long-life orbits with no manoeuvre capability


Since 2020: 1 Space Safety Programme, 5 Areas
esa
1 Core
2 Space Weather L5 Mission
3 HERA
4 In-Orbit Servicing/Removal Mission
5 CREAM
THE EUROPEAN SPACE AGENCY


Core
esa
• Space Weather service development
• Hosted instruments
• NEO sensor development
• Operational impact warnings
• Debris Processing S/W, laser tech.
• Mitigation technology
• Environment Impact Assessment
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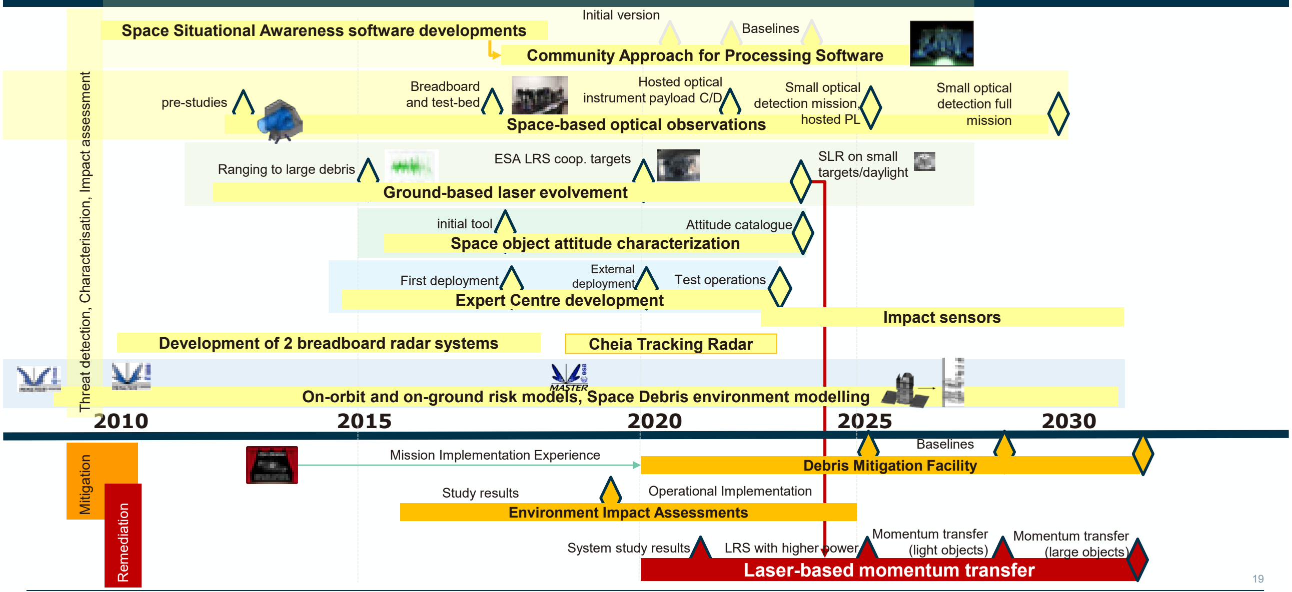
THE EUROPEAN SPACE AGENCY

S2P Core – Debris Technologies

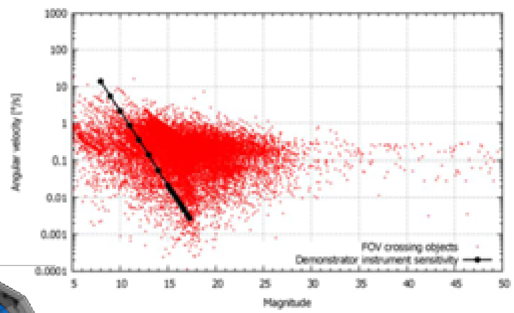


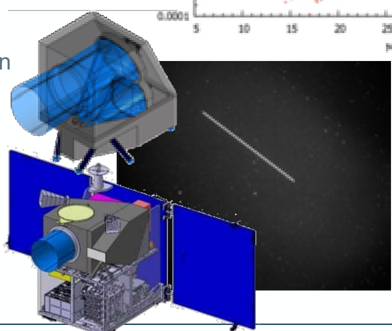
S2P Core – Space Debris

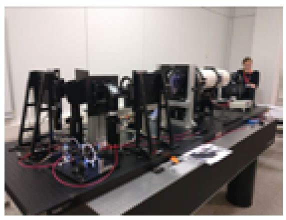
Space-based Optical Component

Small-sized space debris characterisation from a LEO mission (hosted & demo mission)

- Current TRL / Heritage
  - Pre-studies (2005)
  - Detection algorithm prototyping (mm-sized)
  - Phase A mission design (2015)
  - Breadboard, test-bed, algorithm risk reduction
- In the pipeline:
  - Engineering model, ground segment, qualification ("instrument C/D")
  - Flight opportunities for hosted payload to demonstrate ~2024
  - **Full mission** ~2030



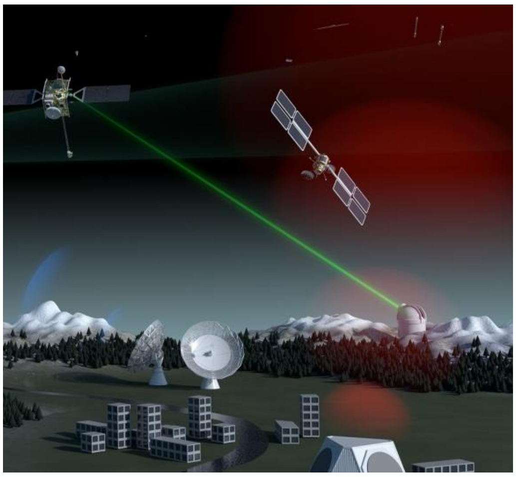




S2P Core – Space Debris

Laser Ranging to non-cooperative Targets

- Satellite Laser Ranging for non-cooperative targets for independent detection and tracking of un-known non-cooperative targets for space object cataloguing
- Successful first demonstration experiments are promising
  - Need for networking, "stare and chase"
  - Laser ranging demonstrated during daytime
- Support to European technology development
- ESA build laser ranging station (LRS) on Canaries



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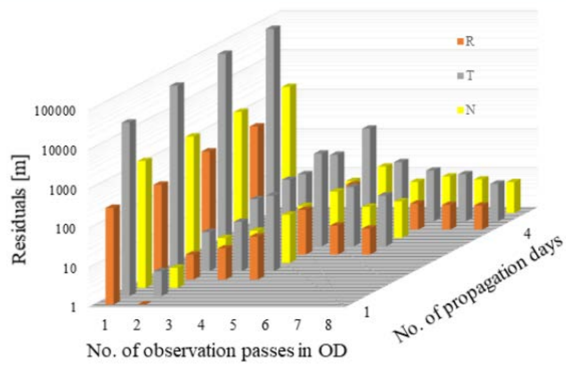
S2P Core – Space Debris

Laser Ranging to non-cooperative Targets

https://conference.sdo.esoc.esa.int/proceedings/neosst1/paper/116/NEOSST1-paper116.pdf



Covariance matrix with	
$20m \times 150m \times 30m$ at TCA	$10m \times 10m \times 10m$ at TCA
An action threshold of 10^{-4} would have to be applied to reduce the collision risk by > 90%	For the same risk reduction of > 90% an action threshold of 10^{-2} will be sufficient
This leads to about 2 annual manoeuvres per spacecraft on average	This leads to 0.025 annual manoeuvres per spacecraft on average
The false alert rate is at 99.9%	The false alert rate is at 10%

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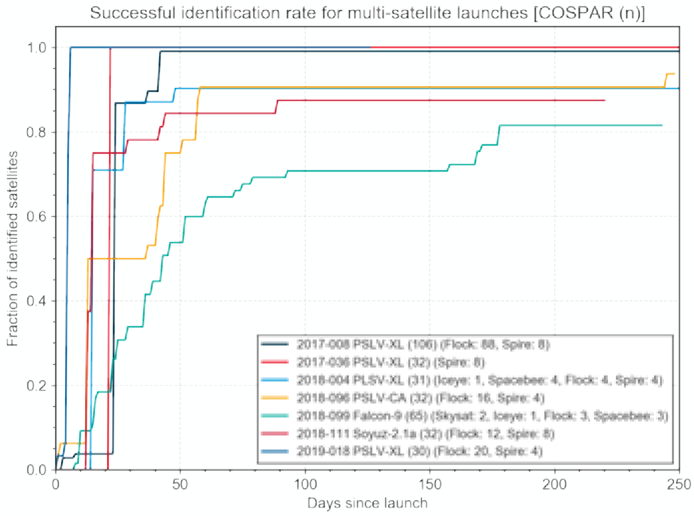
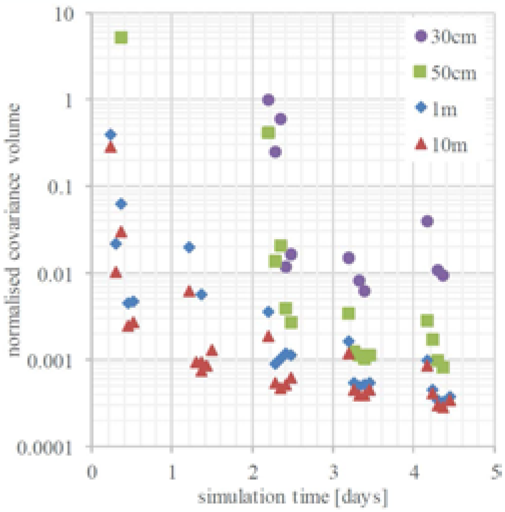
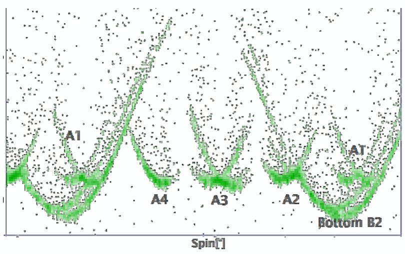
Emerging trends: small satellites & trackability issues



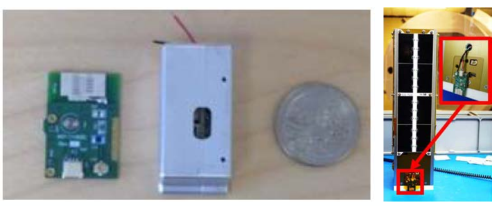


Trackability, Attitude, and Identification solutions

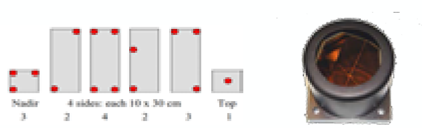
1. Radar Passive Electrical Dipole
2. Active Radar Repeater
3. Inverse Synthetic Aperture Radar
4. Passive Optical Tracking
5. **Passive Laser Retro-reflector**
6. Modulated LED
7. Coloured LED
8. Modulated Laser
9. **Space Transponder**
10. **Radio Beacons**



https://cddis.nasa.gov/lw21/docs/2018/presentations/Session6_Wang_presentation.pdf



https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4451&context=smallsat



https://www.thorlabs.com/navigation.cfm?guide_id=2539

S2P Core – Space Debris

Re-entry & Impact Safety

Significant knowledge and implementation gaps, and routes to address them, have been established but not brought to full maturity.

Shape-effect modelling for risk evaluation

- Leverage computational and test facilities to close known gaps.

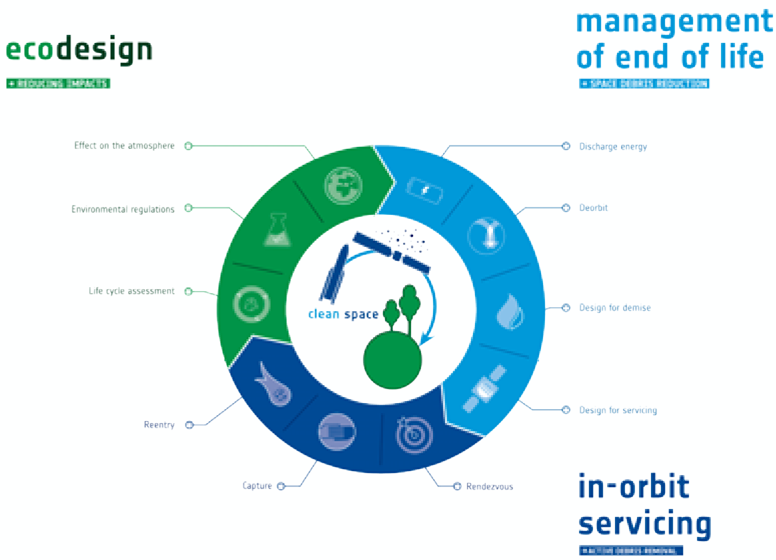
Creation of material and component databases for high risk objects

- Demonstration a process based risk methodology aiming to significantly reduce licencing/verification work by creating databases (MBSE).

Baseline for a generic re-entry break-up instrument

- low-cost & generic flight sensors to hook on missions with controlled re-entry or short orbital lifetimes

Mitigation Technologies: Clean Space



Mitigation Technologies: Life Cycle Assessment

esa

To quantitatively assess the potential environmental impacts of a product or service

Multi-steps

Multicriteria

Consumption of non-energy natural resources →

Energy consumption →

Design → *Qualification and production* → *Launch and commissioning* → *Utilisation* → *Disposal*

→ Emissions to air

→ Emissions to water

→ Emissions to soil

→ Waste

Mineral resource depletion | *Fossil resource depletion*

Global Warming | *Air acidification* | *Ozone Depletion*

Mitigation Technologies: CleanSat

esa

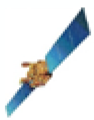
Space Debris Mitigation Requirements

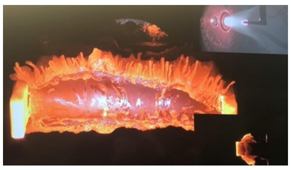
- **DEORBITING**
  - Passive deorbit systems
  - Active deorbit systems
- **CASUALTY RISK**
  - Design for Demise
- **RELIABILITY**
  - Autonomous deorbit systems
- **PASSIVATION**
  - Propulsion systems
  - Power systems

Selection of priority building blocks

- Demisable **TANK**
- Demisable **RWs**
- Demisable **MTQ**
- Electric passivation in **PCDU**
- Fluidic Passivation Valve
- Propulsion upgrade for controlled reentry
- De-orbit add-on kit

Evolved LEO Platforms





RW: Reaction Wheel

MTQ: Magnetorquer

PCDU: Power Conditioning and Distribution Unit

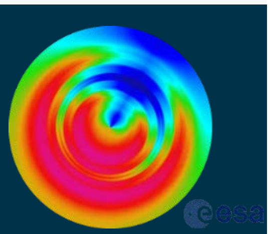
Mitigation technologies: software

Space Debris User Portal | Home | Tools | Space Environment Statistics | Contact Us

https://sdup.esoc.esa.int/

~3000 worldwide users

MASTER



- **DRAMA (3.0.4)**
- **MASTER (8.0.2)**

*"The **aim of DRAMA is** to support the objectives of the ESA Space Debris Mitigation Requirements by **enabling satellite programs** in **to assess their compliance** with the recommendations contained in that document."*

- Environment Report
- Documentation, support, howto's

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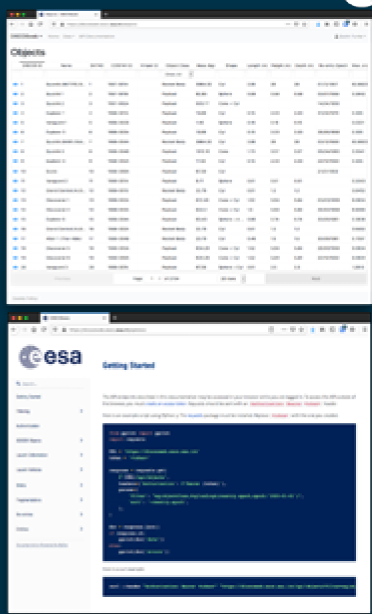
Mitigation technologies: DISCOS(web)

Database and Information System Characterising Objects in Space: Agency's single source on space debris data, supporting operations

Partially publically accessible (~500 worldwide users):

- https://discosweb.esoc.esa.int
- Graphical user interface, targeted to human users
- Shares information on:
  - Objects (incl. physical properties)
  - Fragmentations, Re-entries
  - Launches, Launchers and launch sites
  - Countries and organisations
- https://discosweb.esoc.esa.int/apidocs
  - API available for everyone, Same data as GUI
  - Enables app development



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THE EUROPEAN SPACE AGENCY

Since 2020: 1 Space Safety Programme, 5 Areas

esa

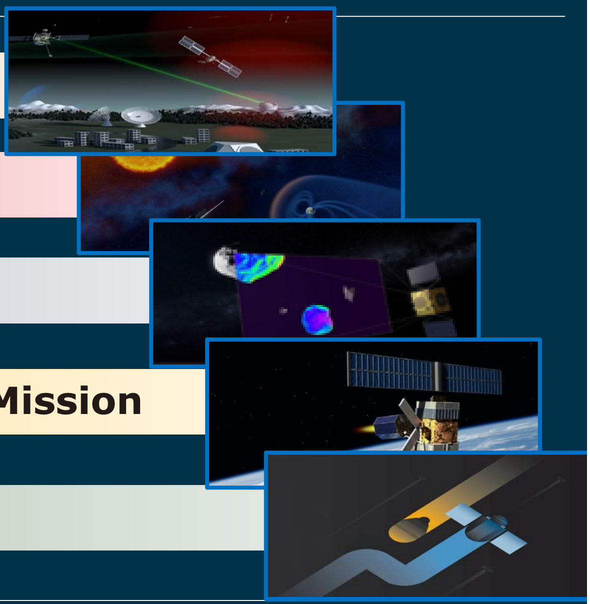
1 Core

2 Space Weather L5 Mission

3 HERA

4 In-Orbit Servicing/Removal Mission

5 CREAM

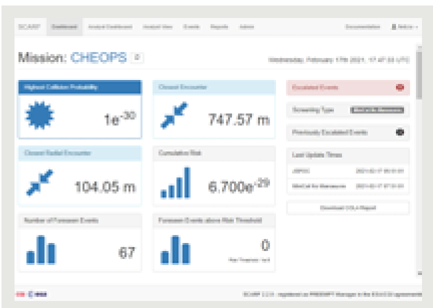


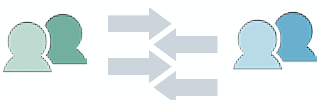
THE EUROPEAN SPACE AGENCY

Towards automated collision avoidance systems

esa

Current approach





Flight control team

Collision analysts

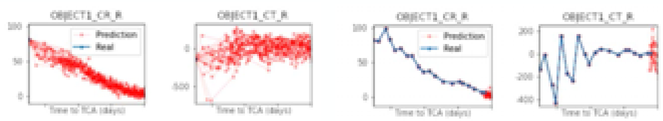
Known risks and opportunities

Expected increase in conjunction alerts (improved **sensors** & **constellations**)

On-going research of techniques such as **machine learning** to predict the likely evolution of an event.

On-going research of techniques such as **uncertainty quantification** allows to get a better grip on the situation.

ESA released a **dataset** with collected conjunction alerts for researchers to test their algorithms.
https://kelvins.esa.int/collision-avoidance-challenge/data



F. Pinto et al, NeurIPS, 2020

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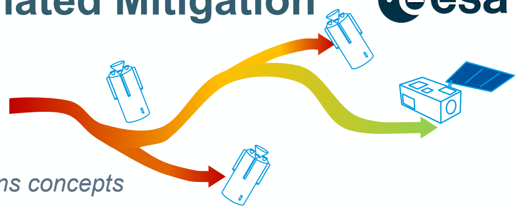
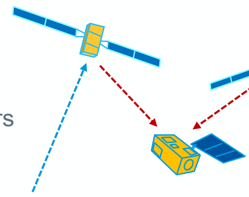
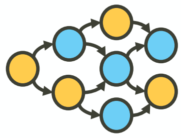
Collision Risk Estimation and Automated Mitigation

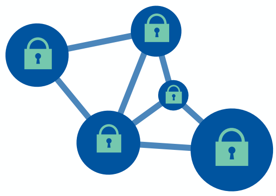


- 1. *Automated avoidance manoeuvre decision and design*
  robustness, explainability, data fusion, global optimisation
- 2. *Development and test of late commanding paths and operations concepts*
  on-ground and in-space processing, platform constraints, data-link constraints, demonstration





- 3. Means for coordination of operators and catalogue providers
  coordination protocols, efficiency, resilience, traceability
- 4. Software technologies supporting CREAM
  communication protocols, access control, data integrity, validation, encryption



- 5. Rules4CREAM
  simulation and assessment of possible rulesets for Collision Avoidance in STM

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→ THE EUROPEAN SPACE AGENCY

Since 2020: 1 Space Safety Programme, 5 Areas

1 Core

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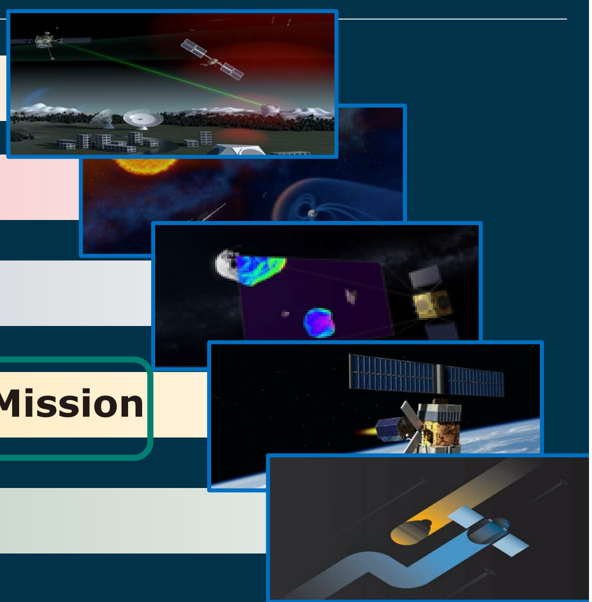
5 CREAM



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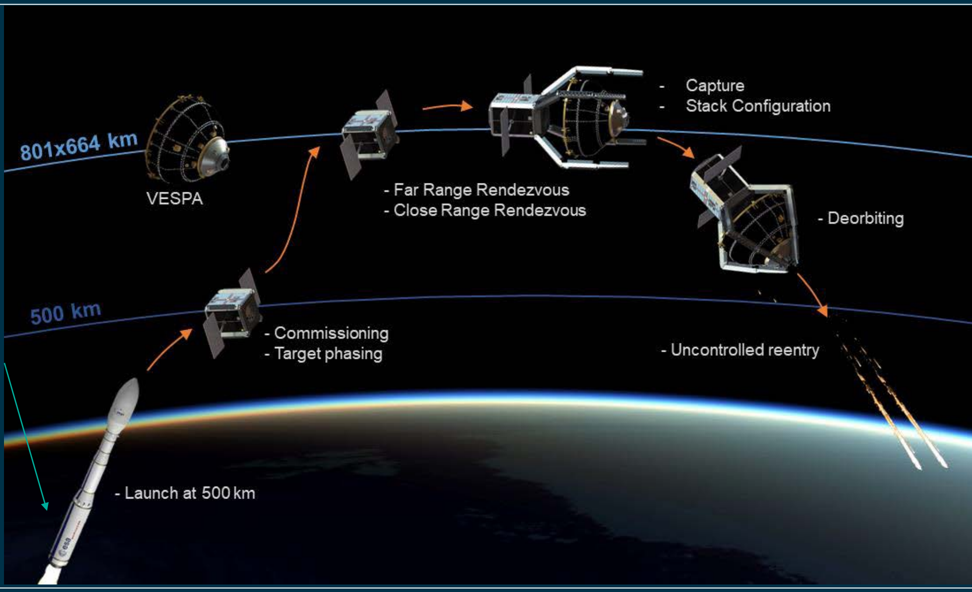
ADRIOS – De-Orbiting VESPA (2025)



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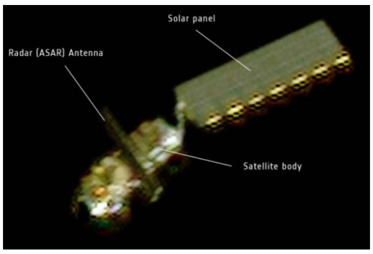
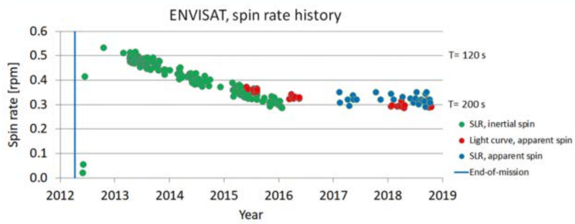
Active Debris Removal: issues

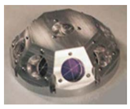
➔ Active debris removal with **unprepared** target is very challenging…

Debris are not designed for capture



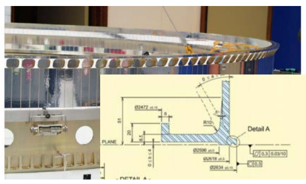
Debris objects spin





ENVISAT Retroreflector

Missing Capture interfaces



If not prepared, each satellite ADR solution would be different

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Active Debris Removal: issues

ENVISAT Tumbling Motion

- Synchronised motion with high rates

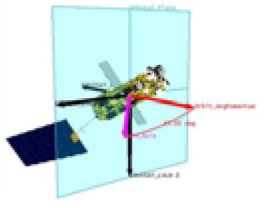
→ RCS thrusters sizing

- Large uncertainty box

→ Long robotic arm needed

- Sizing for torques of robotic interface
- Complex trajectory planning to avoid appendages
- Complex CAM planning
- RdV cameras + scanning LIDAR

→ No-markers for relative navigation



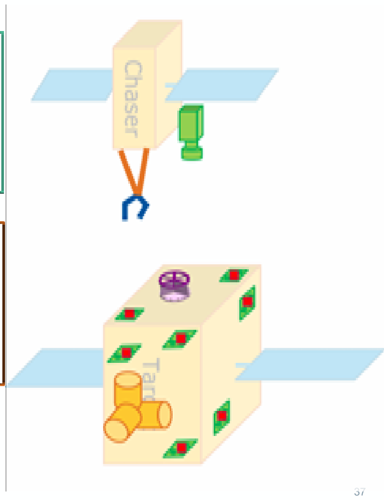
Design for Removal

- **Markers to Support Navigation** (MSN)
  2D markers and 3D markers to help relative navigation (attitude, distance, velocity, etc.)
- **Mechanical Interface for Capture (MICE)**
  Passive interface on satellite for capture

For cooperative & uncooperative

- **Stabilisation of tumbling motion (FOME)**
  Short-circuit magnetorquers to detumble at EoL
- **Passive Identification System (PAIS)**
  LRR embedded in 2D Markers to enhance ground based attitude reconstruction

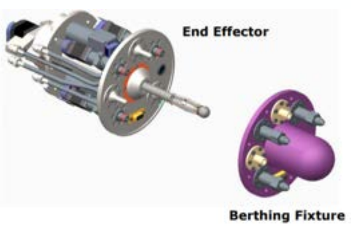
Only for uncooperative



In-Orbit Servicing: Enablers

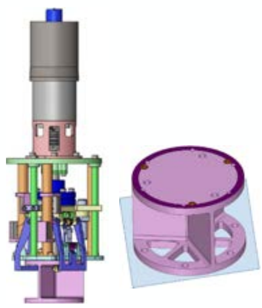
Enabling satellites in LEO/GEO for servicing through standardized interfaces / technologies e.g.:

- Design for removal for Copernicus/LEO
- Design for servicing for GEO satellites



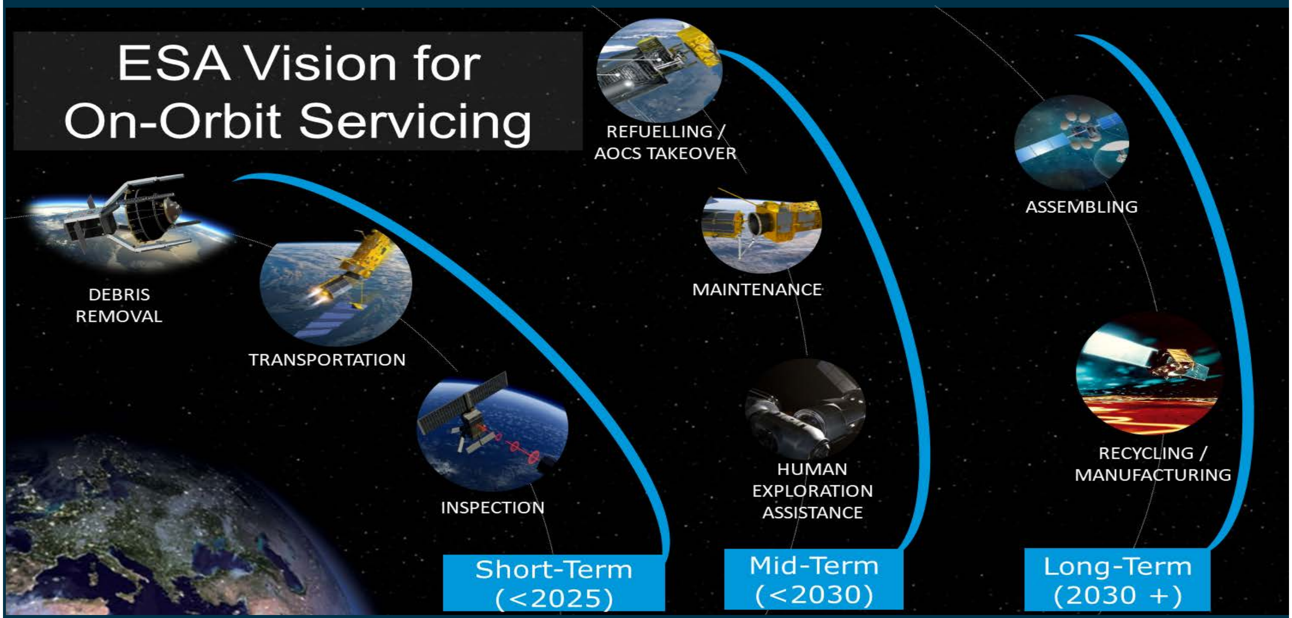
ASSIST – Standardised Refuelling Interface
Credits: GMV

Rendezvous markers for close proximity Operations / Laser ranging
Credits: NTUA/TAS-F, GMV/AVS



Gripper (left) and passive standardized interface for capture (right)
Credits: GMV/AVS

ADRIOS – Mission



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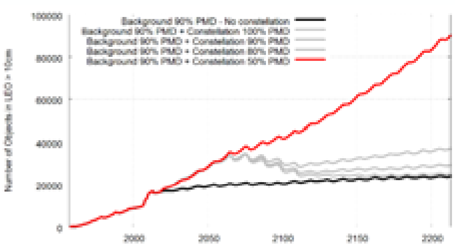
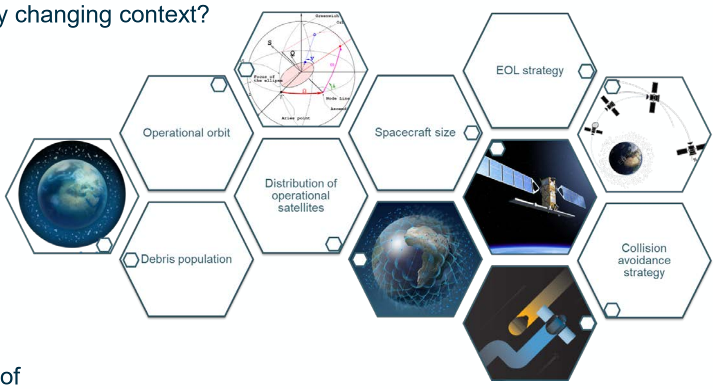
What is next? Towards environmental impact assessments

Mission types -> Changed , **Technologies used** -> Changed, **The environment** -> Changed

How to effectively mitigate space debris in an every changing context?





Can one measure for each mission or group there-of

- How detrimental is it to its **orbital neighbours**? (short-term, collision avoidance is now a fact of life)
- How does it contribute to the **Kessler syndrome**? (long-term, the raison d'etre for debris mitigation)

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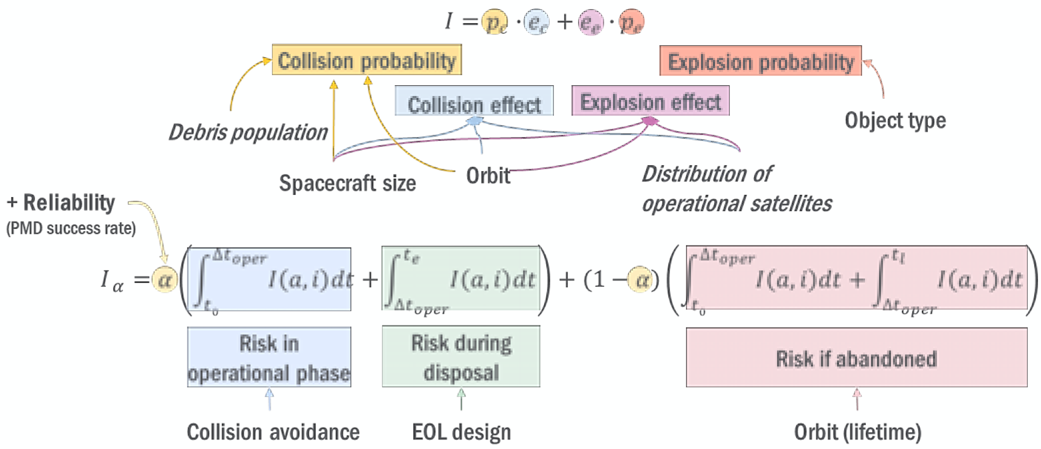
What is next? Object impact assessment (interference)



Letizia et al, https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/417/SDC7-paper417.pdf
Letizia et al, https://www.sciencedirect.com/science/article/pii/S009457651930222X

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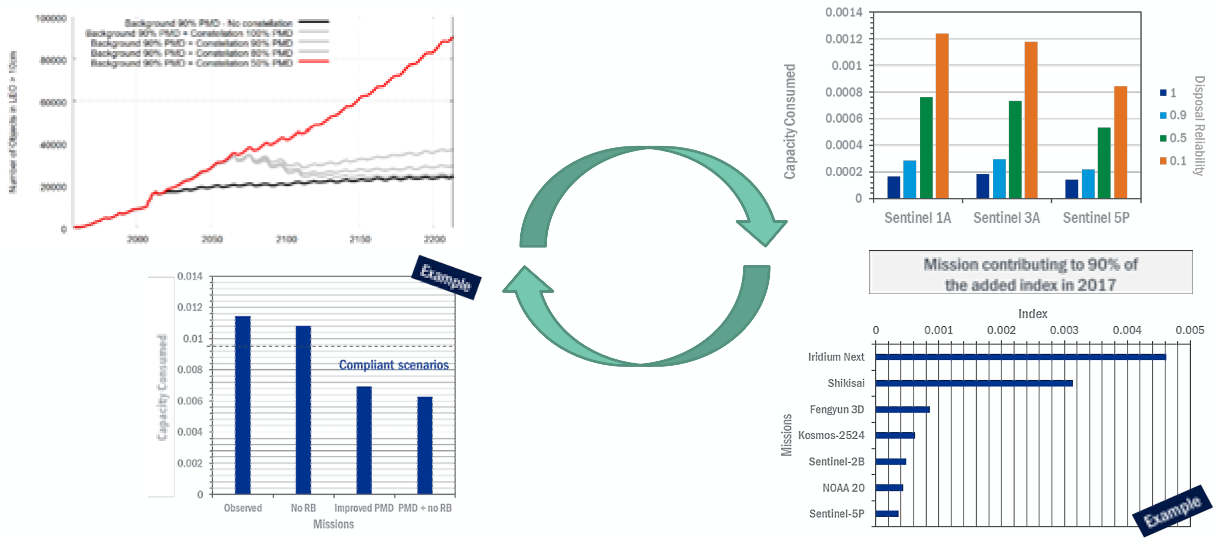
→ THE EUROPEAN SPACE AGENCY

What is next? From object to environment capacity



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What is next? Towards environmental impact assessments

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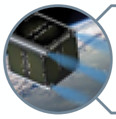
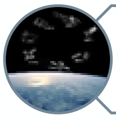
Which is the impact of operating at different altitude from the space debris point of view? (e.g. for large constellations)

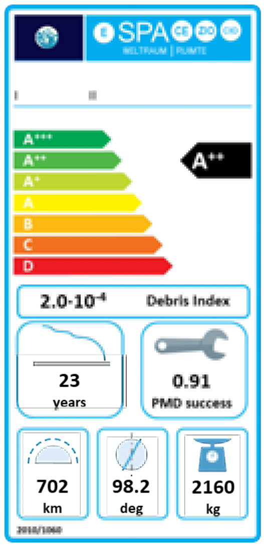


Which is the impact of having/not having propulsion capabilities?



Which is the impact of implementing a mission with a single large satellite vs a fleet of smaller ones?

Which is the impact of using passive disposal systems?



Concluding remarks

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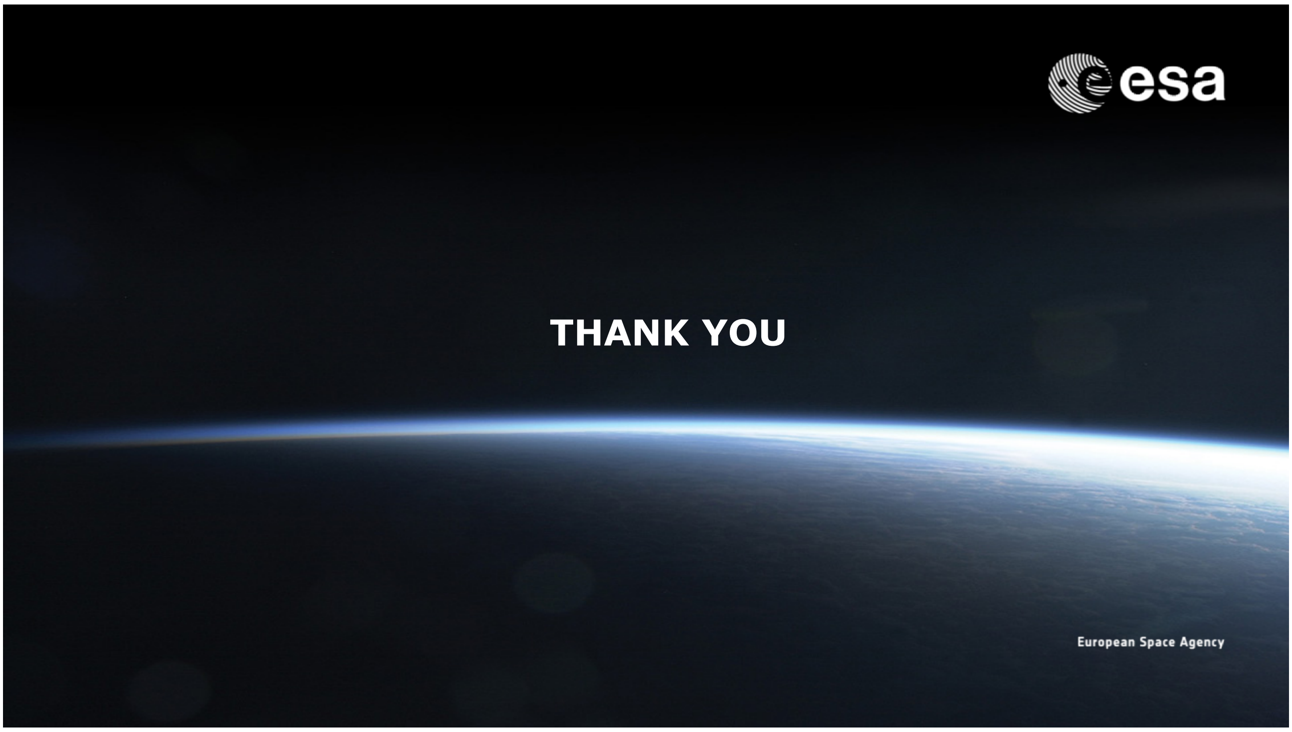
New Space, the ongoing evolution of how we use the near Earth environment has implications:

1. Increased focus on operating in a congested environment: improved/additional sensors such as laser ranging and automated collision avoidance.
2. Adoption of space debris mitigation requirements are still too low: Investment into technologies to improve compliances for all.
3. The environment changes faster than the mitigation counter-measures: need to become adaptive, rather than reactive, by quantifying impact and interference.


esa
THANK YOU
European Space Agency

A07

Brief Overview of the Current Status of Space Traffic Management

○Christophe Bonnal (CNES)

Following the drastic increase in orbital population observed since numerous years now, three key organizations have decided to join their efforts in order to come out with a good synthesis of the situation associated with clear recommendations to deciders, at international level.
IAF, International Astronautical Federation, IAA, International Academy of Astronautics and IISL, International Institute of Space Law, have signed a joint MOU on the subject of STM, Space Traffic Management, asking for a clear presentation of the situation, the lacks, and the solutions within a couple of years.
The most modern topic today is linked to STM, Space Traffic Management, with variants stemming from SST, Space Surveillance and Tracking, SSA, Space Situational Awareness, with variants linked to SEM, Space Environment Management which includes actions such as ADR Active Debris Removal of JCA Just-in-time Collision Avoidance.
A dedicated IAF Technical Committee, TC.26, has started to deal with this important global topic. Some 23 sub-topics have been identified, each with a dedicated working group specifically devoted to it, coming from a very wide span of geographical, gender and generation origins.
The paper will present the status of this international effort, detailing the current achievements and expected calendar.

Biography

Christophe Bonnal

Christophe Bonnal, Senior expert at CNES Launcher Directorate, in in charge of Space Debris topic since 1987. He currently chairs the IAA Space Debris Committee and the IAF TC.26 STM Committee. Member of IAA, AAE, AIAA, 3AF, he is French delegate to IADC, ECSS and ISO.

BRIEF OVERVIEW OF THE CURRENT STATUS OF SPACE TRAFFIC MANAGEMENT

JAXA Workshop – Feb. 24th, 2021

Christophe BONNAL AAE, IAA, AIAA, IAF, ISO, ECSS
CNES – Launcher Directorate – Paris, France

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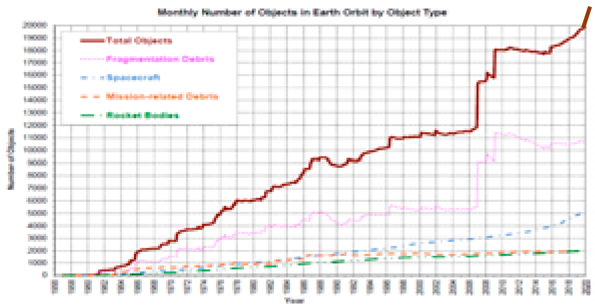
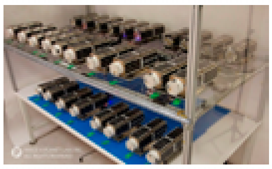
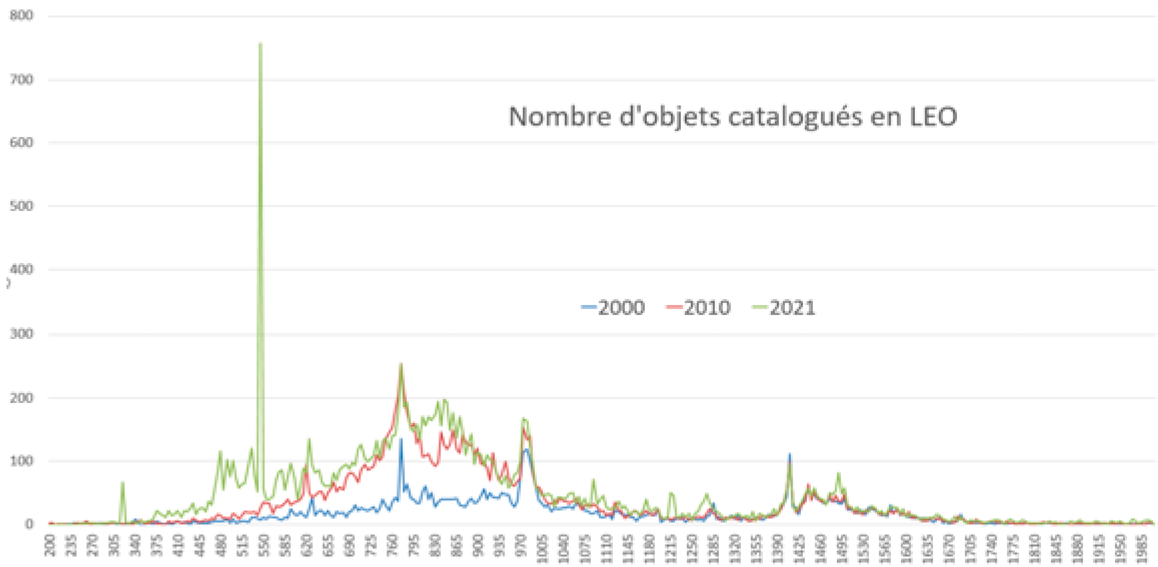
Context



- Rapid increase of the orbital population
  - 34000 objects larger than 10 cm (ESA Master)
  - 22300 cataloged objects (Space-Track)
    - ❖ ≅ 66% of the > 10 cm population
    - ❖ Collisional energy of a 10 cm Steel debris ≅ 500 MJ
  - ≅ 2700 active satellites including 2000 with propulsion
    - ❖ Active satellites ≅ 12% of the cataloged population
    - ❖ Maneuvering satellites ≅ 9% of the cataloged population
      ≅ 6% of the larger than 10 cm population
- Potentially critical evolution, even at short term
  - Large constellations of Telecommunication or Earth Observation satellites:
    - ❖ Already 1,021 Starlink in orbit; 12,000 for 1st generation; 42,000 for 2nd generation
    - ❖ OneWeb, Kuiper, … to come
  - Large number of small satellites, in general with no propulsion on board, as small as 0,25 U
    - ❖ 264 Flock from Planet
    - ❖ 69 Spacebee…



Context



Context

- Major concerns
  - Collisions: uncontrolled increase of the orbital population due to collisions between non-maneuvering objects. Risk of Kessler syndrome ⇨ Space Environment Management SEM
  - Collisions: loss of active satellites ⇨ Space Traffic Management STM (or Coordination STC)
  - Atmospheric reentry ⇨ SEM and STM
  - ↳ All require a good knowledge and analysis of the orbital population: Space Surveillance and Tracking SST et Space Situational Awareness SSA
- Relatively unclear definitions at international level
  - Need identified since a very long time: Space Traffic Control (Nagatomo, 1971)
  - Numerous initiatives, past or ongoing:
    - ❖ International IADC, UN LTS
    - ❖ Standardization ISO WG3, ECSS ad-hoc WG
    - ❖ Academic world AIAA, IAA, SWF, EPSI, IAASS, SSC, WEF, AAE
    - ❖ National CNES, ESA, NASA, JAXA…
  - These groups are very well coordinated, often with the same experts, converge progressively and appear to be coherent

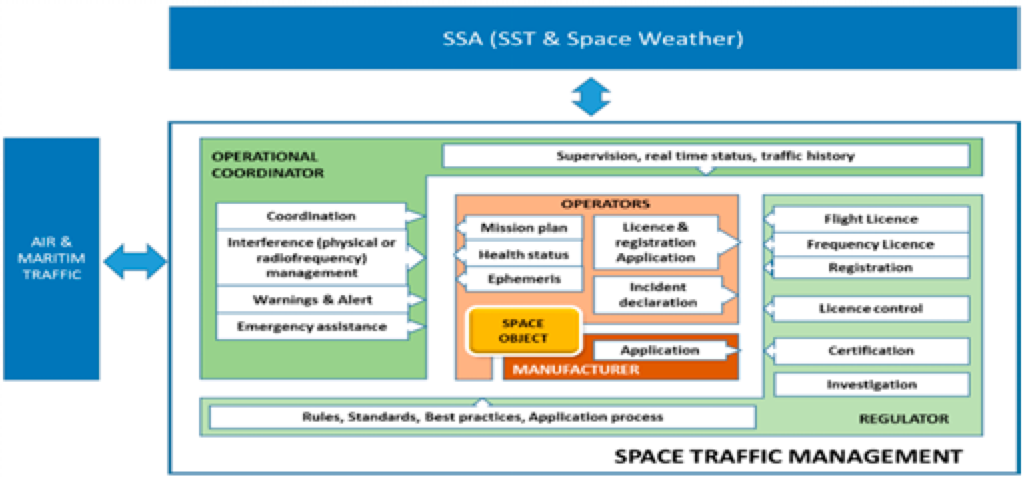
Space Traffic Management in France

- STM-STC is still an open question: the French Space Operations Act is under revision and will include a specific focus of the topic
- Definition of the Space Traffic Management: dedicated activity at CNES level
  - Numerous definitions in the literature: complex subject
  - We did a prospective approach at the horizon of 2030:
    - ❖ What are les main objectives of STM?
    - ❖ What would be the main services provided by the?
  - CNES Inter-Direction Working Group
    - ❖ Numerous meetings necessary to reach a convergence and some consensus
    - ❖ Presentation at IAC 2019
    - ❖ Publication in Acta Astronautica « *CNES technical considerations on space traffic management » AA 167(2020)296-301*

- High level objectives of STM
  - Coordination and optimization of the use of orbital space,
  - Safety of populations and ground installations, and of active satellites in orbit,
  - Identification of conditions necessary for a sustainable use of space,
  - Definition of common rules for a shared space,
  - Management of the physical interferences in orbit:
    - ❖ Coordination of actions for proximity operations, servicing, maintenance, Active Debris Removal ADR
    - ❖ Collision Avoidance CA
    - ❖ Other interferences, including Radio Frequencies RF, astronomical observations perturbations…

Publication in Acta Astronautica

- Two main domains of responsibilities very distinct: Regulation and Coordination



UNCOPUOS

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- Remarkable work: 21 high level requirements covering the complete domain

UN COPUOS Guidelines on Long-term Sustainability of Outer Space Activities

A. Policy and regulatory framework for space activities

Guideline A.1	Adopt, revise and amend, as necessary, national regulatory frameworks for outer space activities
Guideline A.2	Consider a number of elements when developing, revising or amending, as necessary, national regulatory frameworks for outer space activities
Guideline A.3	Supervise national space activities
Guideline A.4	Ensure the equitable, rational and efficient use of the radio frequency spectrum and the various orbital regions used by satellites
Guideline A.5	Enhance the practice of registering space objects

B. Safety of space operations

Guideline B.1	Provide updated contact information and share information on space objects and orbital events
Guideline B.2	Improve accuracy of orbital data on space objects and enhance the practice and utility of sharing orbital information on space objects
Guideline B.3	Promote the collection, sharing and dissemination of space debris monitoring information
Guideline B.4	Perform conjunction assessment during all orbital phases of controlled flight
Guideline B.5	Develop practical approaches for pre-launch conjunction assessment
Guideline B.6	Share operational space weather data and forecasts
Guideline B.7	Develop space weather models and tools and collect established practices on the mitigation of space weather effects
Guideline B.8	Design and operation of space objects regardless of their physical and operational characteristics
Guideline B.9	Take measures to address risks associated with the uncontrolled re-entry of space objects
Guideline B.10	Observe measures of precaution when using sources of laser beams passing through outer space

C. International cooperation, capacity-building and awareness

Guideline C.1	Promote and facilitate international cooperation in support of the long-term sustainability of outer space activities
Guideline C.2	Share experience related to the long-term sustainability of outer space activities and develop new procedures, as appropriate, for information exchange
Guideline C.3	Promote and support capacity-building
Guideline C.4	Raise awareness of space activities

D. Scientific and technical research and development

Guideline D.1	Promote and support research into and the development of ways to support sustainable exploration and use of outer space
Guideline D.2	Investigate and consider new measures to manage the space debris population in the long term

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Current standardization activities

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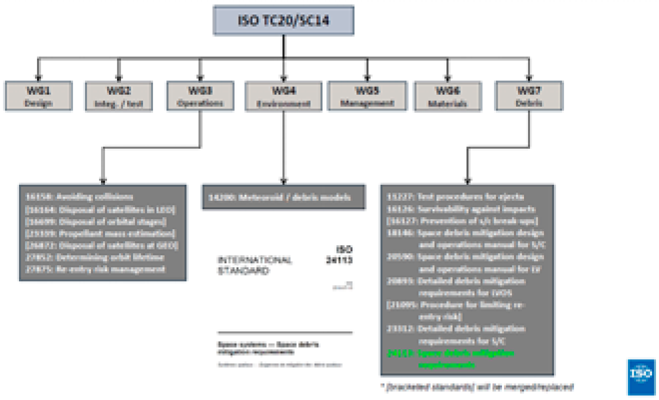
- ISO TC20/SC14 – WG3 et WG7
  - TC20 = Aircraft and Space Vehicles
  - SC14 = Space systems and Operations
  - WG3 = Operations and Ground support - WG7 = Orbital debris
- ECSS (European Cooperation for Space Standardization)
  - Two "mirror" working groups in preparation of European position in ISO, one on STM, the other on debris



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Current standardization activities

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- Preparation of a Standard dedicated to STCM within ISO WG3 (Space Traffic Coordination & Management)
  - NWIP (New Work Item Proposal) #5847 dated May 22nd, 2020
  - Prepared by Dan Oltrogge (AGI, Comspoc)
- Technical content very oriented towards "ground support tools", inspired from US…
  - Numerous meetings at ECSS level but globally negative vote of ISO members on Nov. 18th, 2020
  - Important recall of the independence and individual responsibility of States: No international management
  - New proposal under preparation, limited to Space Traffic Coordination

ii

CNES ST

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On-going IAF – IISL - IAA activities

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- MOU signed between:
  - IAF (International Astronautical Federation) ⇨ Mostly industrials, operators, manufacturers… (750 member entities)
  - IISL (International Institute of Space Law) ⇨ Legal aspects
  - IAA (International Academy of Astronautics) ⇨ Academic, members are individual experts not representing their entity
- Final goal: preparation of a reference report providing status on STM and suggesting improvements

IAF, IISL and IAA join in a cooperative initiative to develop comprehensive approaches and proposals for STM to be addressed to decision-makers on national and international level in order to promote the safe use of outer space.

- Creation of a Technical Committee dedicated to the topic within IAF: TC26 on Space Traffic Management
  - Structured following 5 major themes,
    themselves subdivided into 23 thematic sub-groups
  - 104 active members to date coming from 21 countries
    Good participation of all the key actors identified in previous pages
  - Very good contribution from US, Russia, China,
    but also India, Japan, ESA and all the European countries…
  - In priority 9 sub-groups (underlined in the list on the right)
    - Prepare an intermediate report for mid-March 2021
    - Final draft report from these 9 expected by October 2021
    - Then Kick-off of the remaining sub-groups
  - Final final report expected to be published by IAC 2022 in Paris

1	Terminology - Common understanding and Definitions
2.1	Improving the knowledge - New technical means of space objects monitoring
2.2	Improving the knowledge - Improve trackability and identification of small objects
2.3	Improving the knowledge - Data fusion - Merging of information
2.4	Improving the knowledge - Improvement of orbital data precision and accuracy
2.5	Improving the knowledge - Improvement of the UN registration
2.6	Improving the knowledge - Shared Catalog
2.7	Improving the knowledge - Hazards associated with reentry
3.1	Space capacity management
3.2	Management of RF interferences
3.3	Improvement of the collision avoidance process
3.4.1	Future operations - Spacetugs, IOS, IOM, IOR
3.4.2	Future operations - Massive constellations
3.4.3	Future operations - Sub-orbital activities
3.4.4	Future operations - Ground support activities such as spaceports
3.4.5	Future operations - Transits through airspace
3.4.6	Future operations - Impact of constellations on Astronomical observations
3.5	Future operations - Preparation of future activities
3.6	Future operations - Traffic from orbit to Moon (and Mars)
4.1	Technical regulations - Current references
4.2	Technical regulations - New activities
4.3	Technical regulations - Effective compliance to Technical Regulations
5	Outreach

CNES STM – JAXA Workshop – Feb. 24th, 2021

INTERNATIONAL ASTRONAUTICAL FEDERATION

Topics for consideration by the TC

1. Terminology

Common understanding and definitions

Definition of the commonly used terms
Numerous definitions are currently used, slightly different: concepts of Management, Coordination, Control, Synchronization, Regulation, Harmonization, even Environment

[Related to UN LTS #C1]

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Connecting @ll Space People

INTERNATIONAL ASTRONAUTICAL FEDERATION

Topics for consideration by the TC

2. Improving the knowledge of the orbital population, including functional and non-functional space objects (1/5)

1. New technical means of space objects monitoring
Radars, telescopes, lasers
both ground- and space-based
Including private, e.g. private optical networks and monitoring satellite constellations
↳ Potential recommendation: study and promote additional systems, such as in-orbit sensors, laser detection from ground or from orbit, etc.

[Related to UN LTS #D1 and #D2]

2. Improve trackability and cataloging of small spacecraft

[Related to UN LTS #B8, #D1 and #D2]

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Topics for consideration by the TC

2. Improving the knowledge of the orbital population, including functional and non-functional space objects (2/5)

3. Data fusion - Merging information coming from various sensors

↳ Potential recommendation: develop and share methodologies at international level

[Related to UN LTS #B1 and #B3]

4. Improvement of orbital data precision and accuracy

Improved mathematical models of motion
Improved computational means and filters
Use of star background
Laser ranging from ground or orbit
Representation of uncertainties
↳ May be one of the top priorities

[Related to UN LTS #B2]

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Topics for consideration by the TC

2. Improving the knowledge of the orbital population, including functional and non-functional space objects (3/5)

5. Improvement of the UN registration

Currently rather poor despite regulation
Stress the need to record end of operations
Consider insufficiency, for STM purposes, of the information recommended currently for use in the registration process and identification of space objects

↳ Potential recommendation: unified (accepted worldwide) system of the space objects identification and identity confirmation

↳ Could there be a systematic pre-registration prior to any launch?

[Related to UN LTS #A5 and #C4]

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Topics for consideration by the TC

2. Improving the knowledge of the orbital population, including functional and non-functional space objects (4/5)

6. Shared catalog

. Question of protection of the data: legal solutions?

. Question of maintenance (integrity of data, control of completeness for certain blocks of information, e.g. orbital launch list, payloads etc., common rules for naming/ID assignment for referencing purposes etc., responsibility)

. Question of military systems

. Merging (data fusion, not just using individual outputs) information coming from various independent SSA centers

. Question of the reference source for such catalog (or multiple sources?)

➷ Possibility of cross-correlation of information coming from such “independent” centers due to use of the same batches of measurement information?

[Related to UN LTS #B1]

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Topics for consideration by the TC

2. Improving the knowledge of the orbital population, including functional and non-functional space objects (5/5)

7. Hazards associated with reentry disposal

. Radar and other measurement campaigns to assess and verify reentry hazards prediction models

. Design-for-demise approaches for minimizing reentry hazards

. Design-for-demise concepts

. Flight-verification of Design-for-Demise approaches

. Models predicting hazards to aircraft

[Related to UN LTS #B9]

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Topics for consideration by the TC

3. Use of such information (1/4)

1. **Space capacity management**

   Space Sustainability quantification
   Space Traffic assessment
   Capacity coordination

↳ Potential recommendation: additional LTS guidelines to be considered by COPUOS

[Related to UN LTS #A4 and #C3]

2. **Management of RF interferences**

[Related to UN LTS #A4]

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Topics for consideration by the TC

3. Use of such information (2/4)

3. Improvement of the collision avoidance process

1. Probability evaluation and common understandings
2. Specific problematic associated with electric propulsion on large constellations
3. Maneuver coordination
4. Assessment prior to a launch

↳ Potential recommendation: sharing at ISO level through dedicated technical standards

5. Thresholds for Collision Avoidance,
6. Data exchange protocols

↳ Potential recommendation: harmonization at international level (IADC, ISO)

[Related to UN LTS #B1, #B3, #B4 and #B5]

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Topics for consideration by the TC

3. Use of such information (3/4)

4. Use for future operations

1. Spacetugs, In Orbit Servicing, In Orbit Manufacturing, In Orbit Recycling
2. Massive constellations, including such aspect as use of AI in on-board control systems for autonomous decision making (without involvement of ground control services), especially in case of collision avoidance
3. Sub-orbital activities
4. Ground support activities such as spaceports
5. Transits through airspace (launch and controlled/uncontrolled re-entry)

6. Impact of Constellations on Astronomical observations
Question at STAC astronomy committee on how we could limit light interference to astronomy observations by satellite constellations

[Related to UN LTS #A4, #B8, #D1 and #D2]

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Topics for consideration by the TC

3. Use of such information (4/4)

5. Preparation of future activities

1. ADR: Removal of the relevant debris from crowded orbits to avoid statistical collisions
2. JCA: Nudging of a debris to avoid a predicted collision
3. LDTM: Cataloging and maintenance of precise orbits of large orbital debris and light nudging to avoid further critical situations

➯ Potential recommendation: identify a shared position at international level (IAA studies, IADC tasks, National studies, …)

[Related to UN LTS #D1 and #D2]

6. Traffic from orbit to the Moon (and in the future to Mars)

How to minimize perturbations to the natural environment and useless debris left at the surface?

[Related to UN LTS #A4]

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Topics for consideration by the TC

4. Technical regulations (1/3)

1. Current references

↳ Can be based on ISO?

Converged at international level since more than 10 years
Coherent with IADC and National Standards established 20+ years ago
Already applied by ESA and China
Strong similarities with other International Standards and Laws
Dedicated WG on STM within ISO WG3

Numerous new ongoing activities

ISO standard for collision probability calculation and impact risk assessment
Inclusion of a threshold in the standard
ISO standard for the casualty risk calculation
Inclusion of a threshold in the standard

[Related to UN LTS #A1 and #C1]

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Topics for consideration by the TC

4. Technical regulations (2/3)

2. But new activities required

Shall include elements related to Space Tugs, IOS, ADR, JCA, LDTM
Shall include sub-orbital
Can include criteria for risk based evaluations, and acceptance, of certain operations
May include Spaceports
Open to extension of the domain to Moon and Mars

[Related to UN LTS #A1]

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Topics for consideration by the TC

4. Technical regulations (3/3)

3. Major question: why are the Mitigation Rules so badly complied to?
Immature on-board technology for mitigation? Impact on performances?
Examine how changes to debris mitigation guidelines reduces STM burdens

- Potential recommendation: Education: Systematic inclusion of ISO in any contract
- Potential recommendation: Naming & Shaming (Naming already done at IADC level…)
- Potential recommendation: Compliance file prepared before any space operation, transparent follow-up by the launching state

[Related to UN LTS #A3]

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Topics for consideration by the TC

5. Outreach

Need to improve the dissemination of information

How to pass efficiently the messages and reach consensus over the proposed actions?

Who should we address, when, where, at which step of discussion: An essential link to operators is required, as they will be affected most.

This might require some dedicated fora / workshop with discussions on this topic as sole focus.

[Related to UN LTS #C4]

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Congress – Conferences – Symposia – Colloquium - Workshops…

- Very dynamic activity at international level
- Numerous congress or similar on the topic:
  - International Astronautical Congress IAC
    - 11 sessions every year, covering all the Space Debris topics, but also SST-SSA-SEM-STM
    - Numerous associated publication in Acta Astronautica
  - International Association for the Advancement of Space Safety
    - Covers well all the Space Debris field, mainly under the Safety aspects
    - Well implicated in the Regulation aspects
    - Good publications in Journal of Space Safety Engineering JSSE
  - IAA
    - International congress every two years devoted to SSA-STM
    - STM Conference organized every two years at University of Texas
  - ESA Space Debris Conference in Darmstadt
    - Every 4 years since 1993
    - Reference conference on the topic of debris in its "wide" understanding, including SST-SSA-SEM-STM
  - International workshops organized by CNES, each every two years
    - Collision Avoidance
    - End of Life of Satellites
    - Modeling and Remediation
  - International workshop organized by JAXA every two years, covering all domains
  - Very high number of Webinars and similar since mid-2020, always with the same speakers and messages…

CNES STM – JAXA Workshop – Feb. 24th, 2021

Thank you for your attention

Christophe.bonnal@cnes.fr

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A08

Latest Developments on Space Debris Modelling Activities at CNES

○**Juan-Carlos Dolado-Perez (CNES)**

The space debris modelling and risk assessment office of CNES is in charge, on the flight dynamics domain, of the activities linked with the analysis, the modelling, the development of tools and the R&D activities related to Space Surveillance and Tracking, space debris and the French Space Operations Act. The activities developed within the CNES space debris modelling and risk assessment office, are therefore structured around key technical domains, as the active and passive detection of space objects from ground or from space, the correlation and cataloguing of the objects orbiting the Earth, the short and long term propagation of the space objects, the computation of on-orbit collision risk in case of close approaches or on-ground casualty risk in the event of a re-entry as well as the evaluation of the long term evolution of the orbital environment.

The work that will be presented will be focused on this very last key technical activity, this is the long term evolution of the orbital environment. The presentation will provide a focus of the most recent work done by CNES on this topic, as the analysis evaluating the decoupled effect of the background and of the future space activity on the long term evolution of the orbital population. A focus will be also given to the last CNES efforts to develop a space object criticality index allowing to identify the missions posing the biggest threat to the orbital environment. Finally, these latest developments will be presented on the perspective of a new framework being developed by CNES with the aim to have a global view of the state of the orbital environment at every moment.

Biography

Juan-Carlos Dolado-Perez

Juan-Carlos Dolado-Perez is the head of the space debris modelling and risk assessment office at the “Centre National d’Etudes Spatiales” (French Space Agency). Since 2008 he has worked at the system engineering and orbital dynamics sub directorate, where his main research topics concerns the long and middle term re-entry prediction, the long term evolution of the space debris population, the on orbit collision risk assessment, the orbit determination from radar and optical measurements and the uncertainty characterization and propagation.
He is a member of the Inter Agencies Space Debris Committee (IADC)’s French Delegation and of the International Academic of Astronautics (IAA). Juan-Carlos owns a B.S. in Aerospace Engineering from the Madrid’s Polytechnic University and a MSc. in Aerospace Engineering from the Institut Supérieur de l’Aéronautique et de l’Espace (ISAE).

LATEST DEVELOPMENTS ON SPACE DEBRIS MODELLING ACTIVITIES AT CNES

9TH JAXA SPACE DEBRIS WORKSHOP

24th to 26th February 2021
Virtual

Juan Carlos Dolado Perez.

Head of the Space Debris Modelling and Risk Assessment Office

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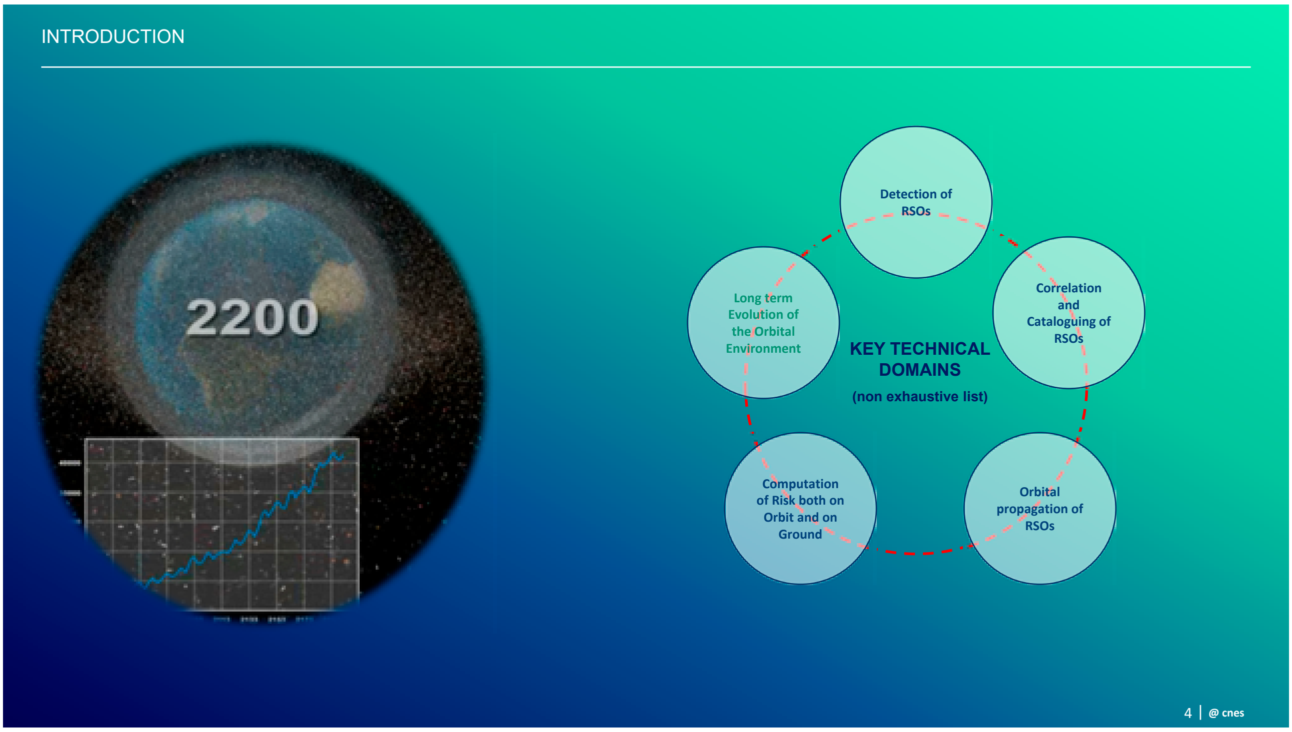
1 INTRODUCTION


INTRODUCTION
Detection of RSOs
Correlation and Cataloguing of RSOs
Orbital propagation of RSOs
Computation of Risk both on Orbit and on Ground
Long term Evolution of the Orbital Environment
KEY TECHNICAL DOMAINS
(non exhaustive list)
3 | @ cnes


INTRODUCTION
2200
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(non exhaustive list)
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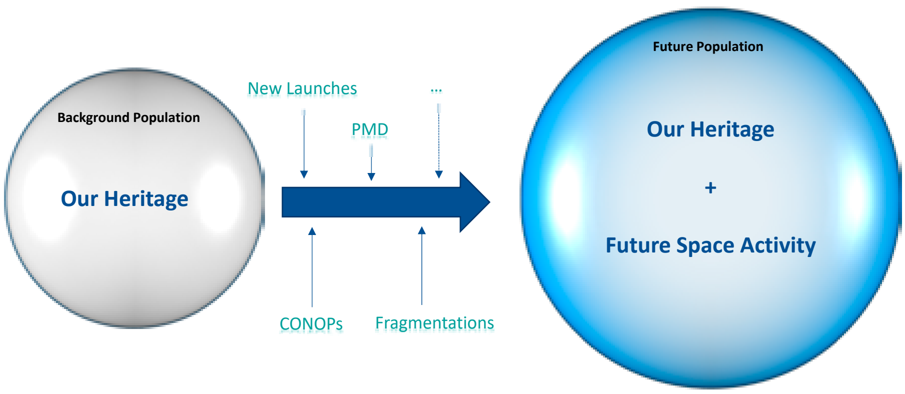
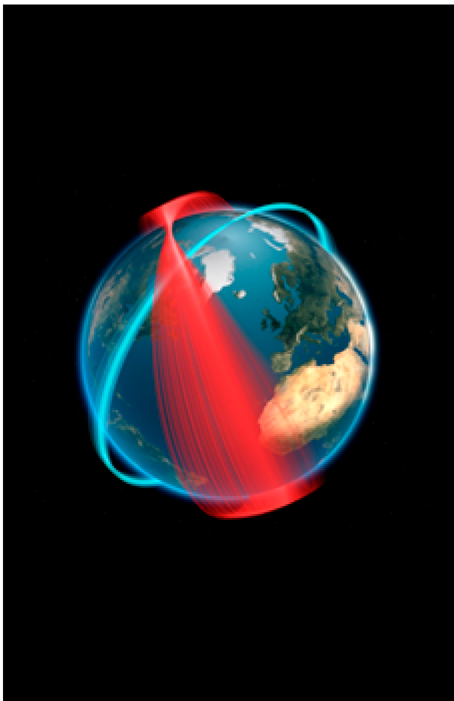
2 LONG TERM EVOLUTION OF THE ORBITAL ENVIRONMENT

Future Population

What's more important, our Heritage or How do we use space?





LONG TERM EVOLUTION OF THE ORBITAL ENVIRONMENT

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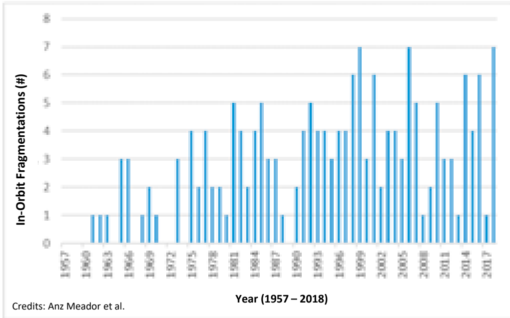
Our Heritage



More than 5000 Launches since 1957

First orbital fragmentation in 1961

Fragmentation occurs regularly since

Non-deliberated Fragmentations is the main source of debris generation since 1957

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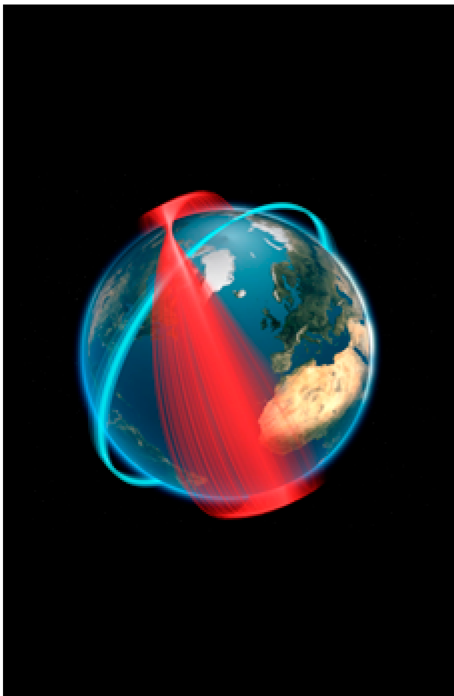

LONG TERM EVOLUTION OF THE ORBITAL ENVIRONMENT

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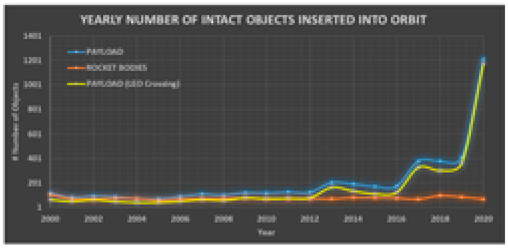
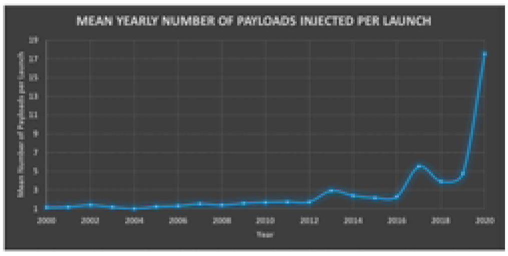
How do we use Space → New Space is Old





Radical Change on the way the Space is used (missions, actors, …)

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3

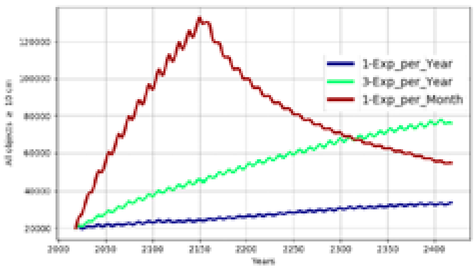
OUR HERITAGE

HOW IT IMPACT US?

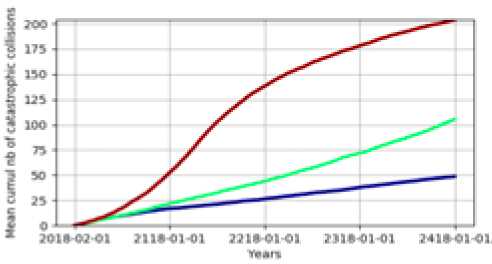
OUR HERITAGE

How our heritage Impact us?

Effective LEO population (>10cm) as a function of the explosion rate



Number of Catastrophic collisions as a function of the explosion rate



More than 5000 Launches since 1957

First orbital fragmentation in 1961

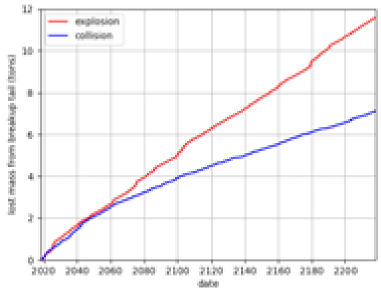
Fragmentation occurs regularly since

Non-deliberated Fragmentations is the main source of debris generation since 1957

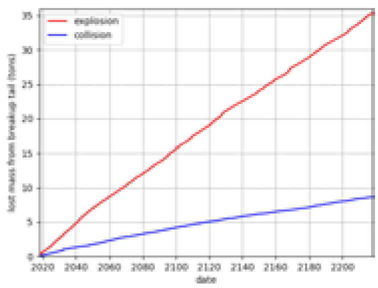
OUR HERITAGE

How our heritage Impact us?

Mass Lost "Effect" induced by minimal size threshold (>10cm) for 1 explosion / year



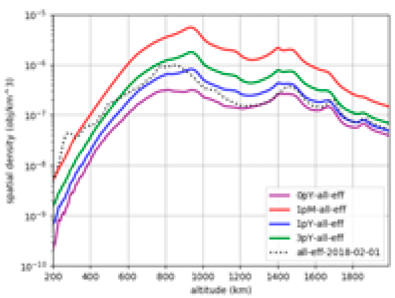
Mass Lost "Effect" induced by minimal size threshold (>10cm) for 3 explosion / year



Need to consider smaller objects (>1cm), to evaluate long term population trends

OUR HERITAGE

How our heritage Impact us?



Mean Spatial Density Increase for LEO population (>1cm) after 100 years of simulation

- In the **absence of new explosions**, the spatial density decreases at all altitudes regimes
- In the event of **1 Exp/year**, spatial density increases above 900 Km and decreases below due to drag
- In the event of **3 Exp/year**, spatial density increases above ~500 Km and decreases below (**x 2 - x3 increase at 900 Km**)
- In the event of **1 Exp/Month**, spatial density increases above 300 Km (**x 8 – x 9 increase at 900 Km**)

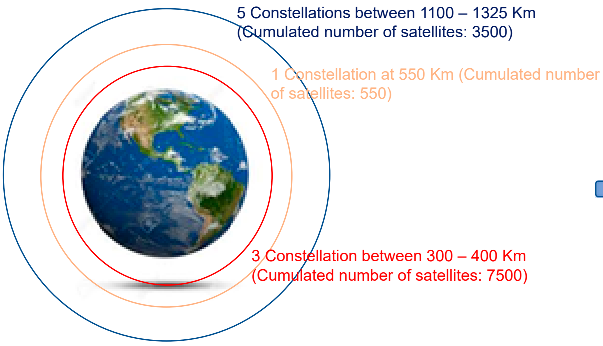
Need to consider smaller objects (>1cm), to evaluate long term population trends

4 FUTURE POPULATION

WHAT IF WE COULD BENEFIT FROM A "FRESH" START?

FUTURE POPULATION

What if we could benefit from a « fresh » start (i.e. no past space activity) ?

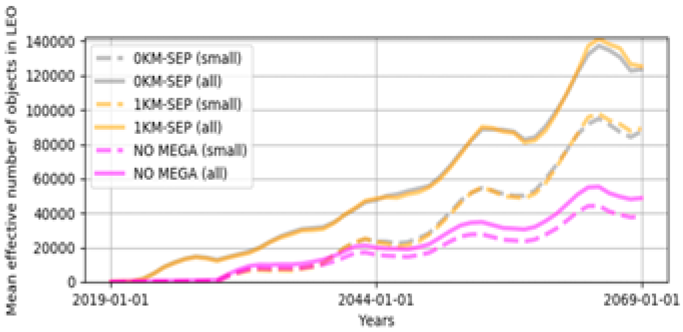


+

- "2012 type Space Activity" (Launch cycles representatives of past activity, non including small satellites launches) with linear increase (50% increase after 50 years)
- 90% Post Mission Disposal Success Rate (25 years Rule)
- 100% CAM Success Rate during Operational Lifetime
- 1 / 1000 probability of unintentional Fragmentation

FUTURE POPULATION

What if we could benefit from a « fresh » start (i.e. no past space activity) ?



All scenarios result in a very important increase of the population, most of all due to small satellites and constellations

5

FUTURE POPULATION

HAVE ALL THE OBJECTS THE SAME POTENTIAL TO CHANGE THE ORBITAL ENVIRONMENT?

FUTURE POPULATION

Need to Evaluate the Criticality of Space Objects to the Environment

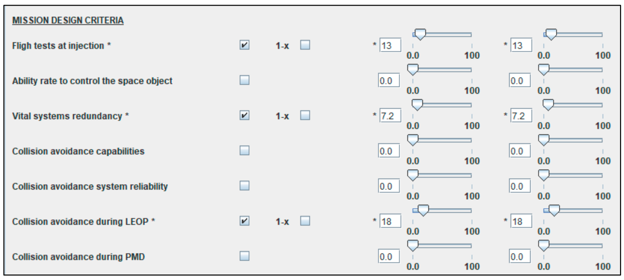
The criticality of Space Objects to the environment, shall be used

- **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

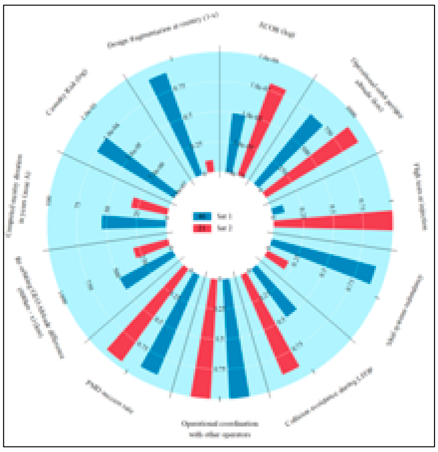
Different Indexes for different purposes (e.g. regulatory, footprint of mission on the environment, ,,,)

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 (**Regulatory purposes**)

Qualitative Output Example



SUSTAINABLE SPACE & REGULATION

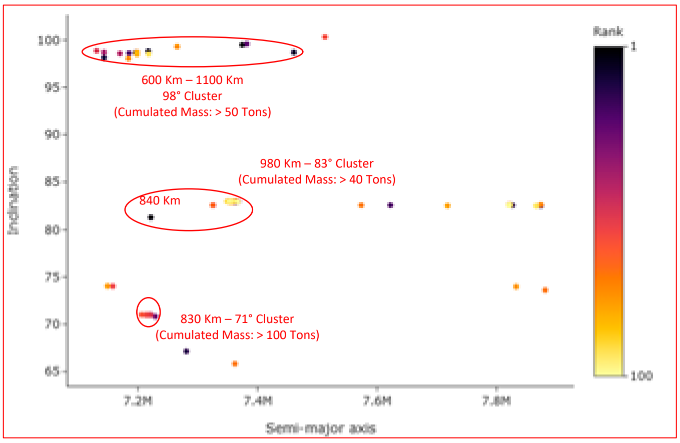
Need to Evaluate the Criticality of Space Objects to the Environment

All the objects do not represent the same risk to the Environment

Existence of several indexes at international level mostly centered on the debris generation capability, and consequent risk increase, of space objects

International effort, assembling 11 Criticality Evaluation algorithms and 13 organizations (Centauri, ESA, CNES, CNR, AXA XL, JAXA, Samara University, University of Southampton, LeoLabs, CNSA, KIAM, Bauman Moscow State University)

- First identification of a consolidated list of the top 50 statistical most concerning objects in LEO
- D. McKnight et al. Identifying the 50 Statistically Most Concerning Objects in LEO. Acta Astronautica, volume 181, April 2021, Pages 282-291 https://doi.org/10.1016/j.actaastro.2021.01.021



6 CONCLUSION

CONCLUSION

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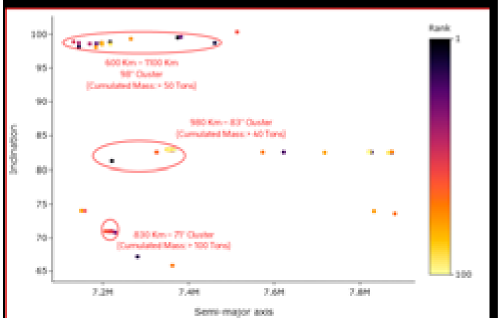


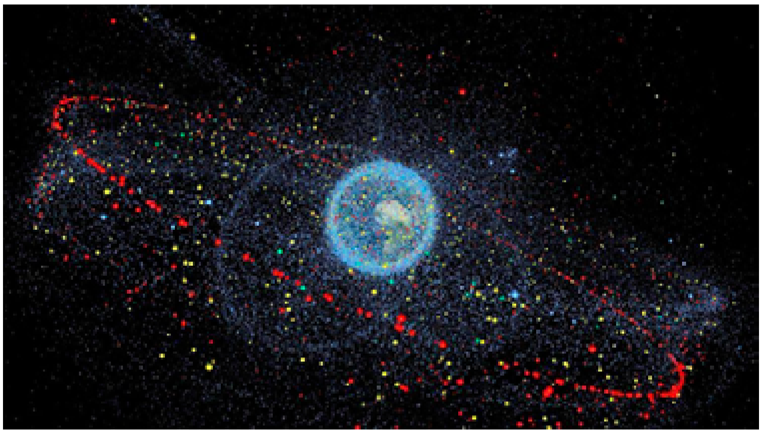
- Strong Heritage, inducing several fragmentations per year
- Need to consider (<10cm) population to properly represent the evolution of the environment and the collisional process
- **<u>Without new space activity</u>**, even at 1 Exp/year, without new launches, population continue to increase
- Considering a "fresh" start, <u>current mitigation guidelines</u> (90% PMD, 1/1000 probability of unintentional fragmentation), <u>does not allow to maintain a stable population</u> in particular in the presence of mega-constellations

A09

Modeling the Space Debris Environment - Latest Improvements and Updates

○Carsten Wiedemann, A. Horstmann (TU Braunschweig), S. Hesselbach (DLR), V. Braun, H. Krag (ESA), S. Flegel (unaffiliated), M. Oswald (Airbus Defence & Space), E. Stoll (TU Braunschweig)

The latest improvements and updates in the current European reference model for describing the space debris environment are presented. The model with the abbreviation MASTER was completed with a reference epoch from November 2016. It replaces the previous version MASTER-2009. The new model has the internal version number "8". MASTER is made available by ESA via the Space Debris User Portal, including all updates. The model takes into account all known sources of space debris. This includes contributions that can be traced back to individual events, such as fragmentation, as well as continuous sources in the small particle size-range, such as surface degradation products or ejecta. The model consideres all objects that are larger than 1 µm. The new population is shown as an example for objects larger than 10 cm in comparison to the previous model. Spatial density is chosen as the form of representation. The current modeling results have shown that the spatial density has increased significantly at an altitude of 800 km compared to the previous version. This is mainly due to a reevaluation of historical fragmentation events. The main events that led to the significant increase in fragments are shown. The high-resolution particle flux analysis capability of the model is discussed using the example of two selected orbits.



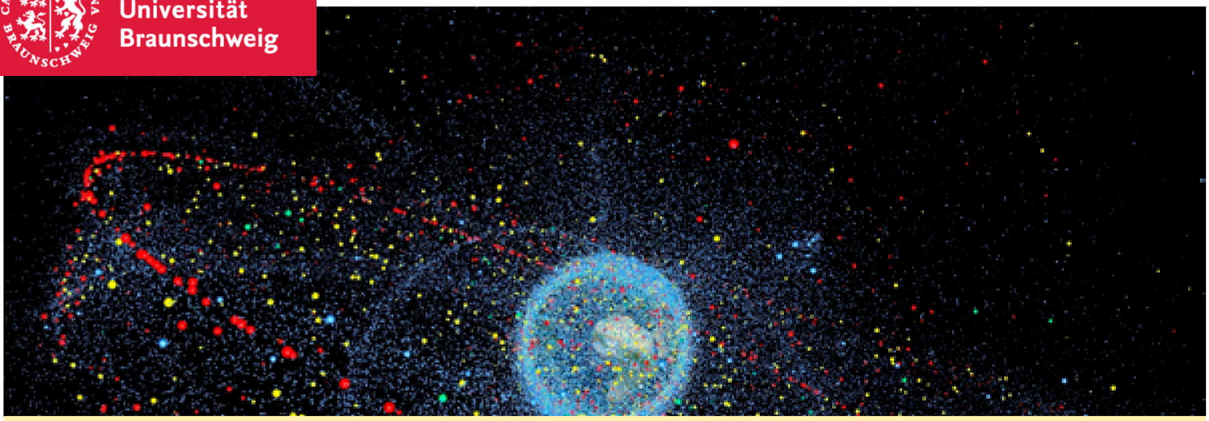
Biography

Carsten Wiedemann

Dr.-Ing. Carsten Wiedemann is a permanently employed senior scientist at the Institute of Space Systems at the Technische Universität Braunschweig (Germany). His tasks include the following positions: quality manager of the institute, team head of the space debris group, organization and presentation of lectures, supervision of student research projects, and scientific project work. He is member of the DLR delegation at the Inter-Agency Space Debris Coordination Committee (IADC). His field of research is the modeling of the space debris environment. One important research project was the development and upgrading of the ESA MASTER model.

Technische Universität Braunschweig
Institute of Space Systems

Technische Universität Braunschweig



Modeling the space debris environment - latest improvements and updates

C. Wiedemann[1], A. Horstmann[1], S. Hesselbach[2], V. Braun[3], H. Krag[4], S. Flegel[5], M. Oswald[6], E. Stoll[1]

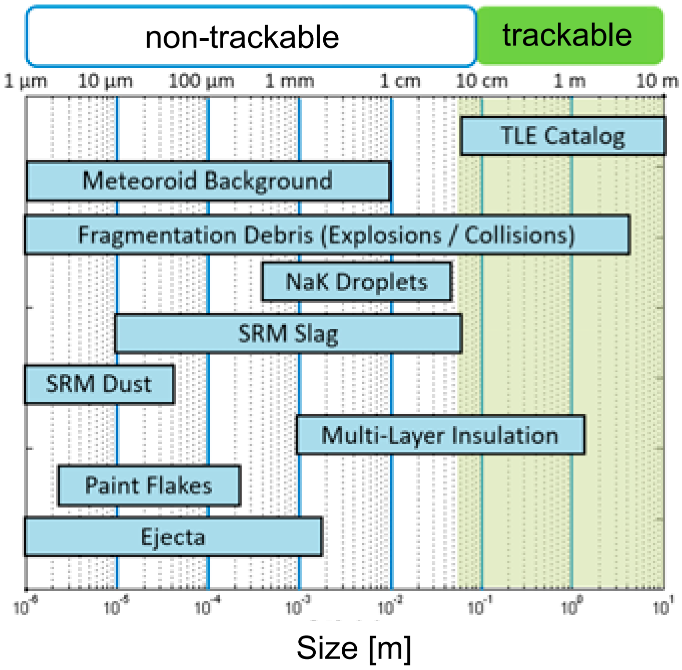
[1]Institut für Raumfahrtsysteme (IRAS), Technische Universität Braunschweig, Hermann-Blenk-Str. 23, 38108 Braunschweig
[2]Deutsches Zentrum für Luft- und Raumfahrt, Weltraumlagezentrum, 47589 Uedem
[3]Space Debris Office, ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt
[4]ESA Space Safety Programme Office, Robert-Bosch-Str. 5, 64293 Darmstadt
[5]unaffiliated
[6]Airbus Defence & Space GmbH, 88039 Friedrichshafen

Introduction

- The latest improvements and updates in the current European reference model for describing the space debris environment are presented.
- The model with the abbreviation MASTER was completed with a reference epoch from November 2016.
- It replaces the previous version MASTER-2009. The new model has the internal version number "8".
- MASTER is made available by ESA via the Space Debris User Portal, including all updates [1].
- The model takes into account all known sources of space debris.
- This includes contributions that can be traced back to individual events, such as fragmentation, as well as continuous sources in the small particle size-range, such as surface degradation products or ejecta.
- The model considers all objects that are larger than 1 µm.

[2] ESA/ESOC, Space Debris User Portal, https://sdup.esoc.esa.int

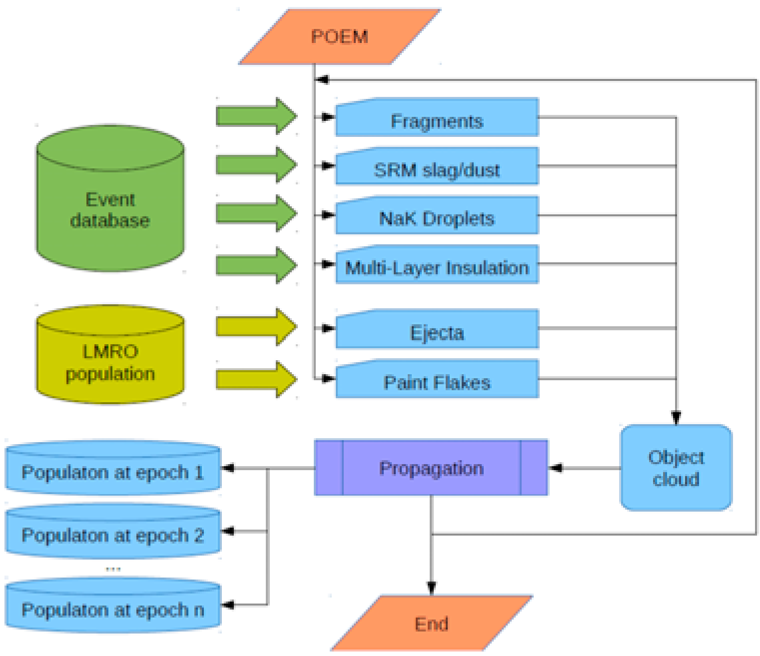
Sources of Debris and Meteoroids



The contribution of the explosion and collision fragments covers the entire size range considered. In practice, however, the fragments only make a dominant contribution to space debris above 1 cm particle diameter.

The small-size regime is dominated by two different particle groups, ejecta and paint flakes, which occur in extremely high numbers.

Schematic View of the Data Flux in POEM

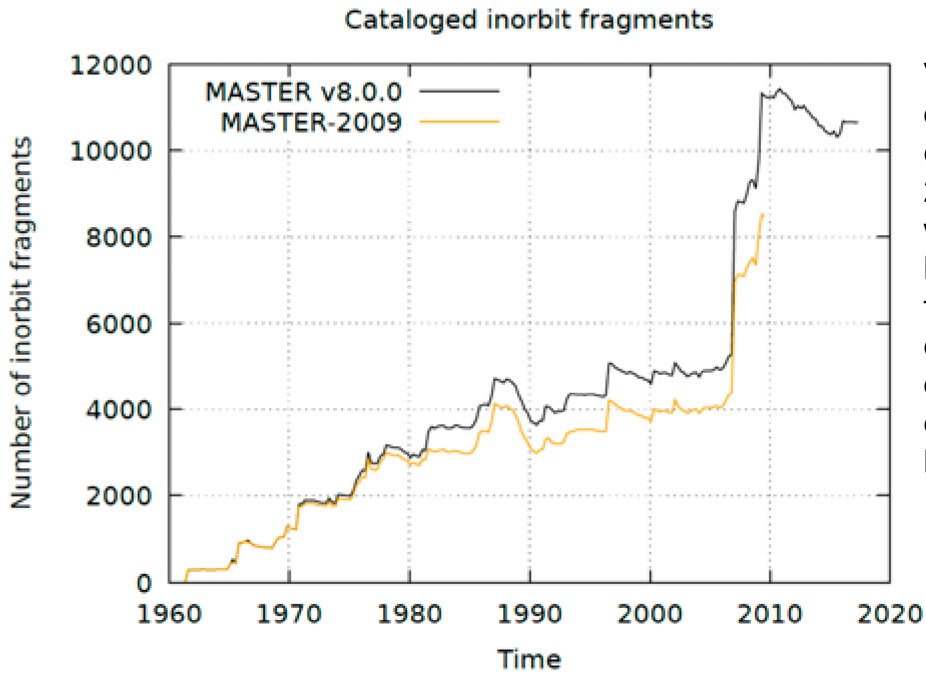


One input file is the list of all events in which space debris objects were released.

The second input file is the population of Launch and Mission Related Objects. The LMRO themselves are included in the model as a population.

In addition, LMRO are the source for further contributions to space debris. These are the ejecta and the paint flakes which are permanently released from these objects.

Comparison of Fragments: MASTER-2009 and MASTER-8



Various new TLE objects have been cataloged between 2009 and 2016, which can be traced back to fragmentation events that occurred in the early 1980s or even before.

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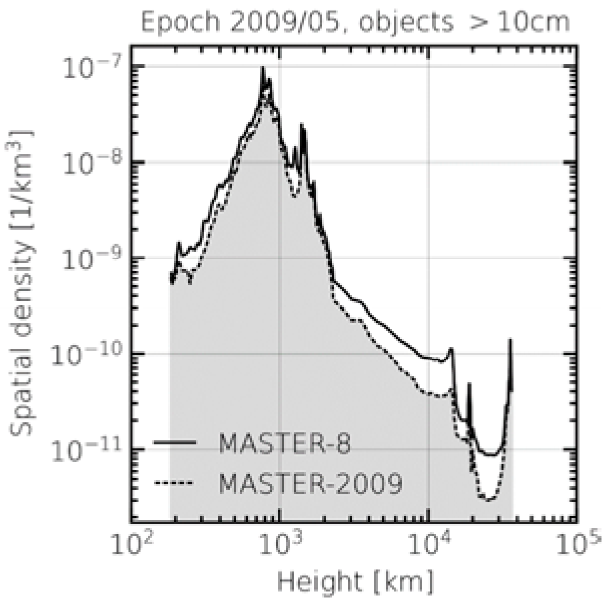
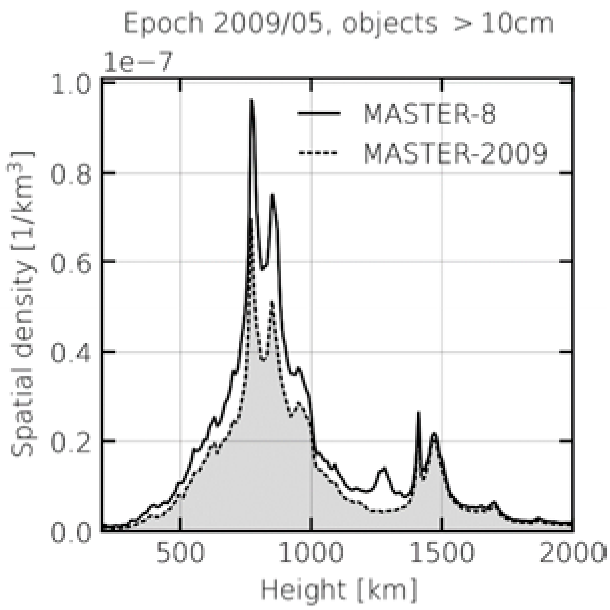
Comparison of 10 cm Populations (2009)





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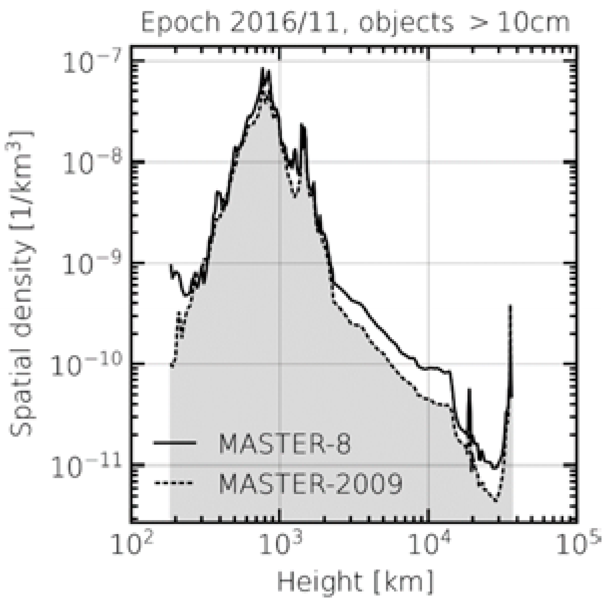
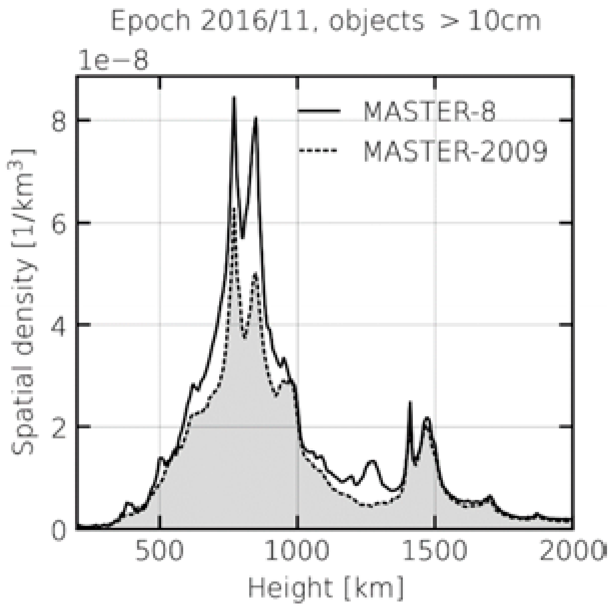
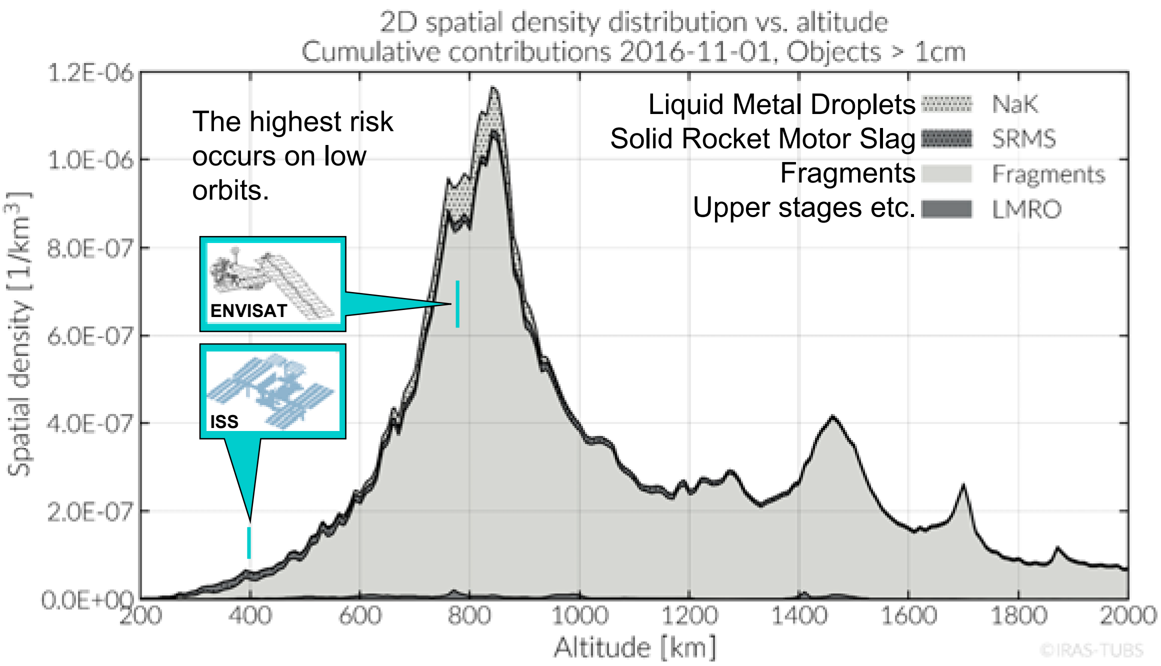
Comparison of 10 cm Populations (2016)



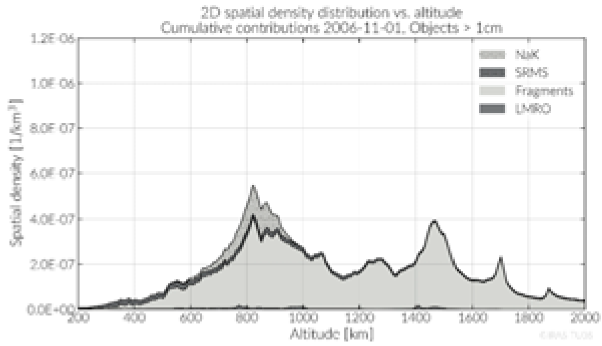


Distribution of space debris (2016)

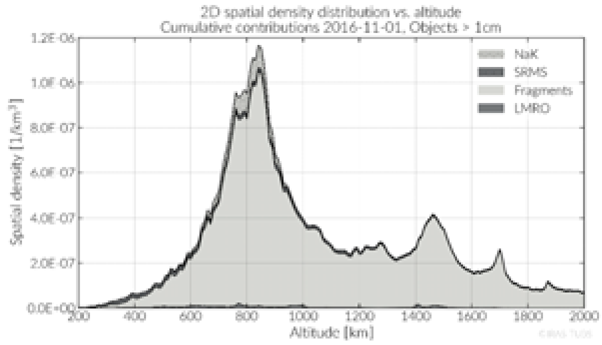


Increase of space debris

Significant increase in fragments due to two events:
- FengYun-1C (2007)
- Cosmos/Iridium (2009)



2006



2016

Spatial density of objects greater than one centimeter according to MASTER

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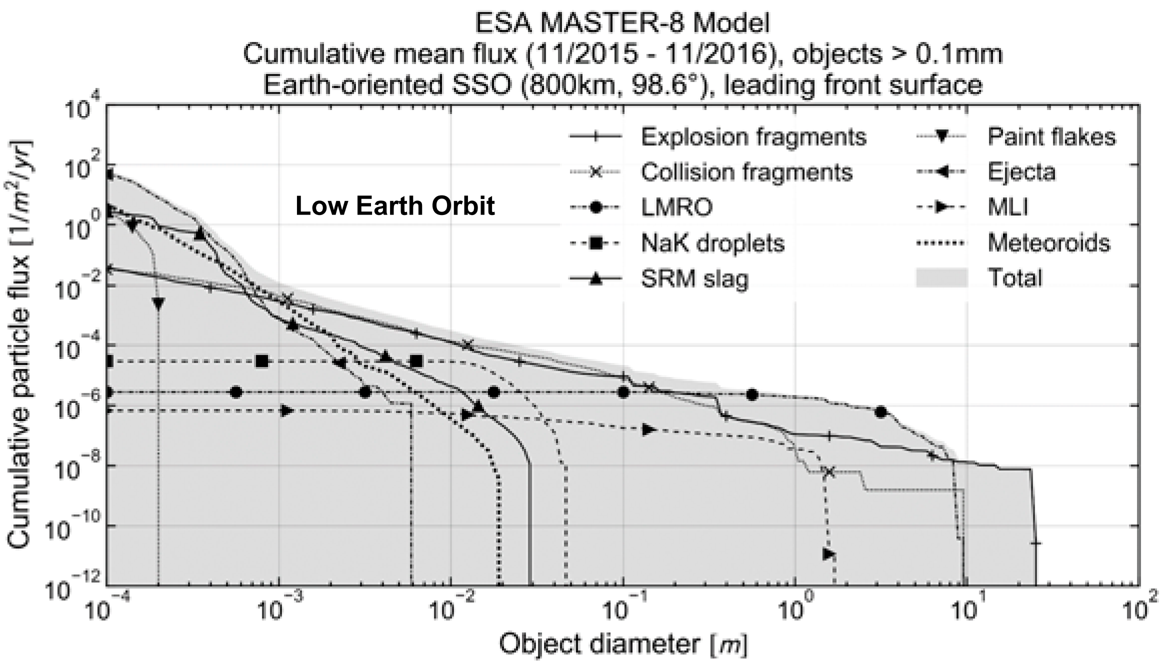
Size Distribution LEO



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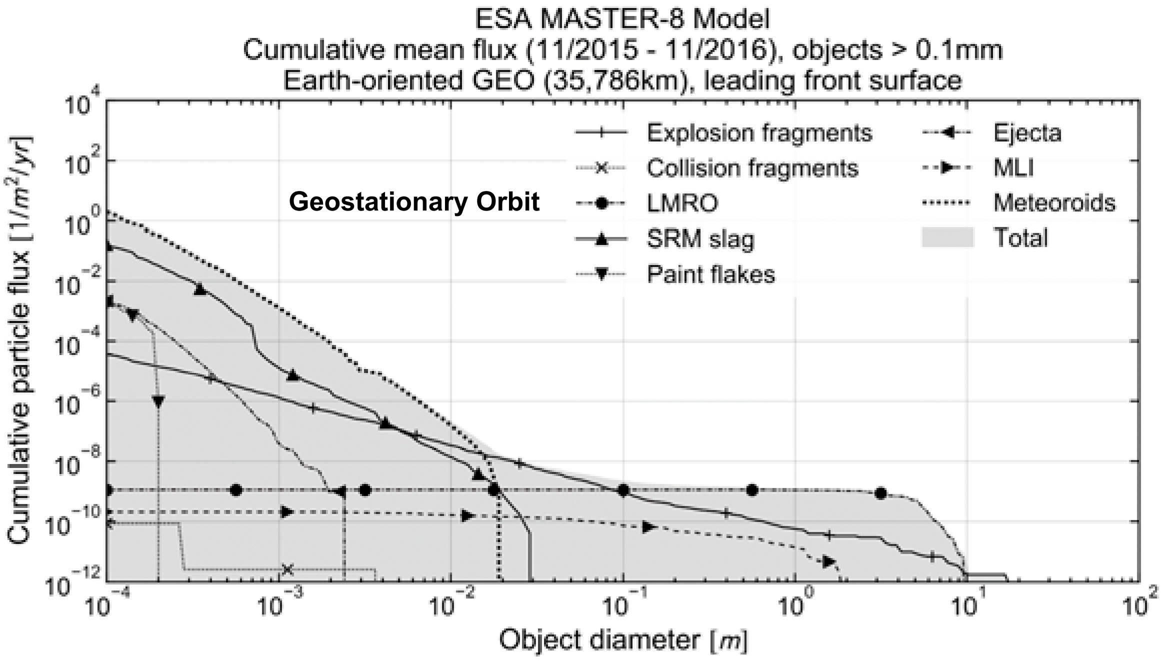
Size Distribution GEO



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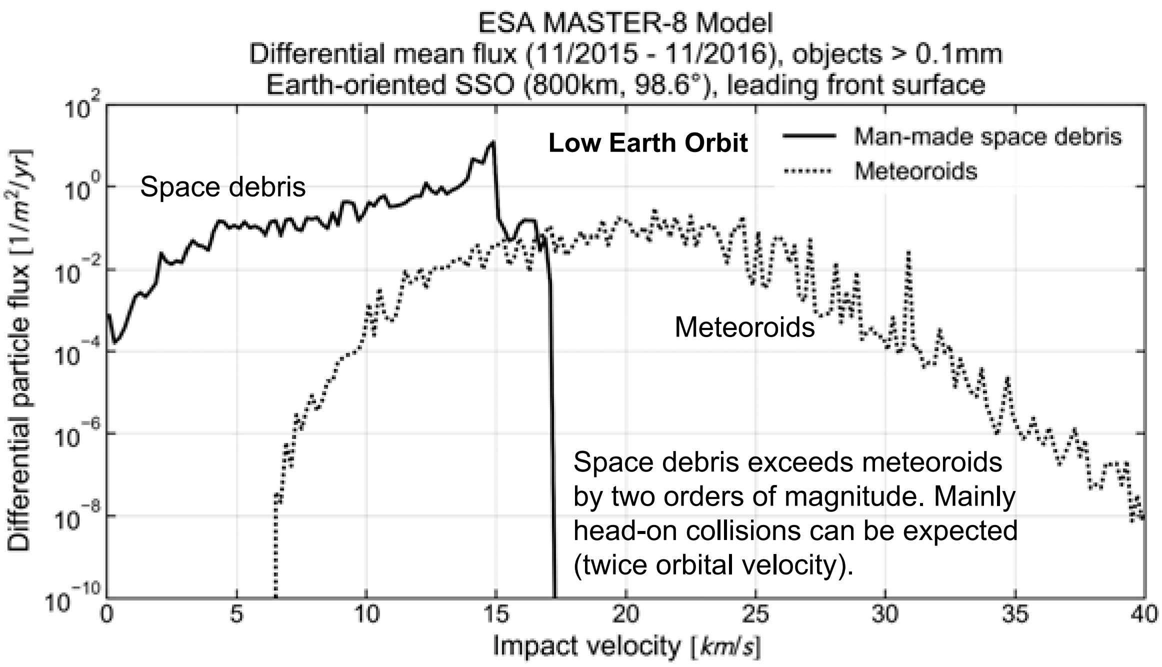
Impact Velocity Distribution on LEO



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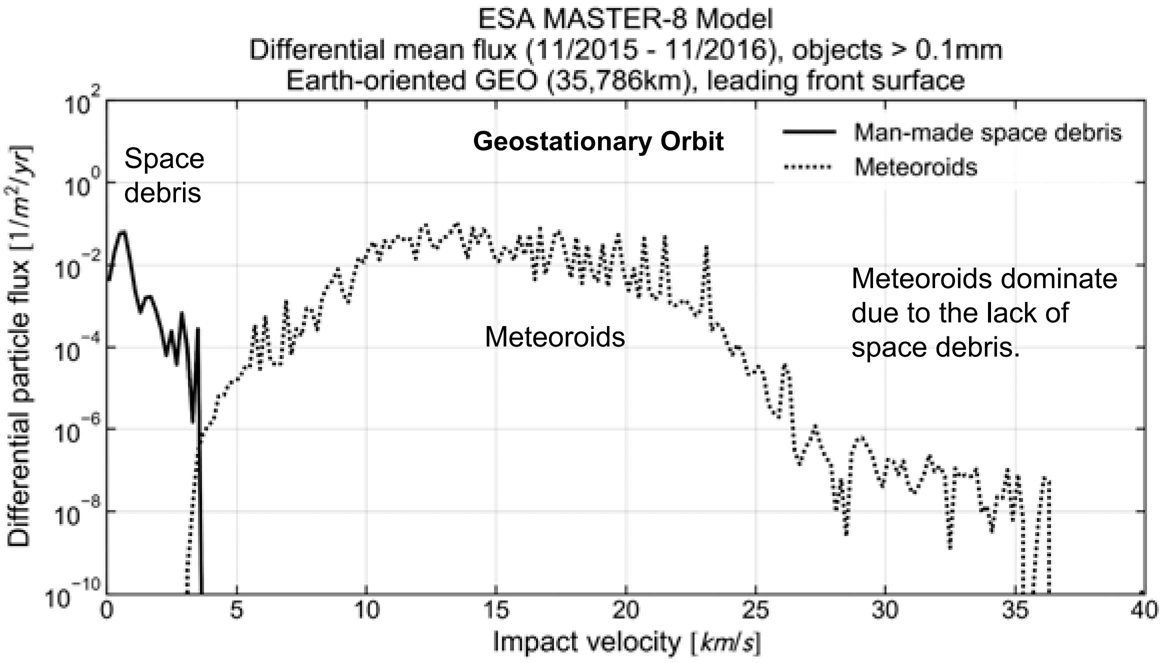
Impact Velocity Distribution on GEO



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Summary

- The new population is shown as an example for objects larger than 10 cm in comparison to the previous model.
- Spatial density is chosen as the form of representation.
- The high-resolution particle flux analysis capability of the model is discussed using the example of two selected orbits.
- The current modeling results have shown that the spatial density has increased significantly at an altitude of 800 km compared to the previous version.
- This is mainly due to a reevaluation of historical fragmentation events.
- The main events that led to the significant increase in fragments are explained.

Acknowledgement

The update of MASTER is supported by ESA under ESOC contract No. 4000115973/15/D/SR.

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B01

九州大学における宇宙デブリのモデリング

Orbital Debris Modeling in Kyushu Univ.

丸山 貴大，吉村 康広，○花田 俊也（九州大学），河本 聡美（JAXA）
MARUYAMA Takahiro, YOSHIMURA Yasuhiro, ○HANADA Toshiya (Kyushu Univ.),
KAWAMOTO Satomi (JAXA)

軌道環境推移モデルの構築により，どのようにすれば宇宙デブリを低減し，軌道環境を改善することができるのか，を議論することができる．よりよい議論を行うためには，推移モデルの推定精度の向上が不可欠である．現在の推移モデルに実装されている衝突破砕モデルでは，衝突の際に生じる破片の分布が，質量の大きい方の物体に依存しており，やや現実性に欠けている．そこで、本講演では，衝突の際に生じる破片がどちらの物体から生じた破片なのかを判別し、両物体の周りに破片の分布を形成する手法を提案する．また，本講演では，衝突破砕モデルの改良前後の将来予測結果を比較し，衝突破砕モデルの改良がもたらす軌道環境の変化について考察したことを述べる．

The building of space debris evolutionary models makes it possible to discuss how to reduce space debris and improve future orbital environment. In order to have a better discussion, it is essential to improve the accuracy of estimation in space debris evolutionary models. In collision breakup models implemented in current space debris evolutionary models, it is somewhat unrealistic that the distribution of fragments generated during a collision depends on the primary object. Therefore, this paper proposes a method to determine which object generated each fragment and form the distribution of fragments not only around the primary object but also around the secondary object. This paper also compares future orbital environment before and after the improvement of collision breakup models and describes differences of future orbital environment by improved collision breakup models.

九州大学における宇宙デブリのモデリング

Orbital Debris Modeling in Kyushu Univ.

丸山 貴大，吉村 康広，花田 俊也（九州大学），河本 聡美（JAXA）
Takahiro Maruyama, Yasuhiro Yoshimura, Toshiya Hanada (Kyushu Univ.), Satomi Kawamoto (JAXA)

The 9th JAXA Space Debris Workshop
February 25, 2021

KYUSHU UNIVERSITY

Orbital Debris Modeling

Orbital debris modeling mainly consists of debris generation and orbit propagation.

- Debris generation can characterize and predict physical properties of fragments originating from explosions or collisions.
- Orbit propagation can characterize, track and predict the behavior of space objects.

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Evolutionary Models

With collision flux estimation, orbital debris modeling can build evolutionary models as essential tools:

- to predict the current or future space debris environment, and also
- to discuss what and how to do for space debris mitigation and environmental remediation.

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Evolutionary Models in Kyushu Univ.

GEODEEM (GEO space Debris Environment Evolutionary Model)

- To track objects in the Geostationary region (or with eccentricity < 0.2, mean motion between 0.9 and 1.1 rev. per day, and inclination < 30 deg).

LEODEEM (Low Earth Orbital Debris Environment Evolutionary Model)

- To track objects in the low Earth orbit region (or with perigee altitude < 2000 km).

NEODEEM (Near-Earth Orbital Debris Environment Evolutionary Model)

- To track objects orbiting around the Earth.

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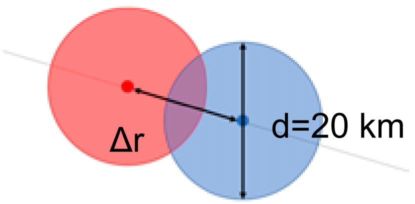
NEODEEM revision 3.02.1

Debris generation
- NASA Standard Breakup Model of EVOLVE 4.0
  - A/M distribution proposed by Anz-Meador and Matney

Orbit propagation
- First-order solution
- Zonal harmonics (J_2, J_3, J_4), Solar-Radiation Pressure, Sun, Moon, Atmospheric Drag (Jacchia-Roberts 1971, Jacchia-Bowman 2008)

Collision flux estimation
- Two-Sphere collision probability estimation (T-Scope)



● : Object 1
● : Object 2
○ : Collision sphere of Object 1
○ : Collision sphere of Object 2

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Improvements of NEODEEM

In order to have a better discussion, it is essential to improve the accuracy of estimation in evolutionary models.

NEODEEM plans to
- Revise collision breakup models that **the distribution of fragments** generated during a collision spreads only around **the primary object**.
- Implement **STELA Drag Coefficient**, which is drag coefficient corresponding to the **altitude**.

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Distribution of Fragments

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Objectives

- Proposing a method to determine **which object generated each fragment**.
- Forming the distribution of fragments around both **primary and secondary** objects.
- Comparing future orbital environment **between previous and revised** collision breakup models.

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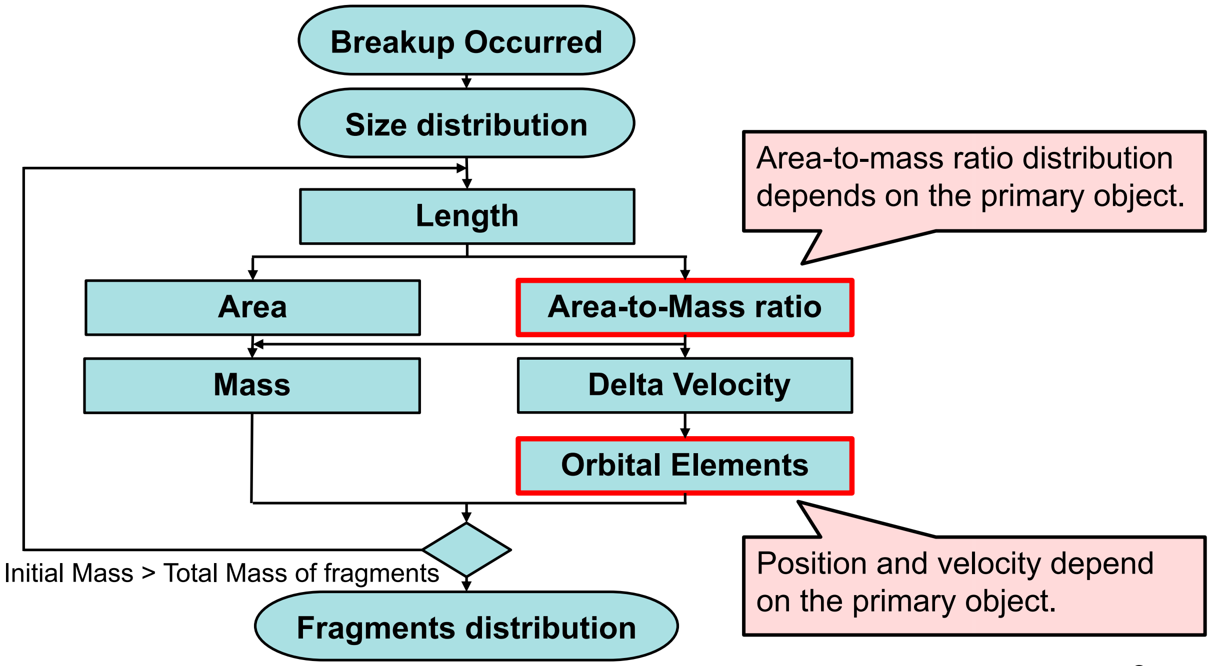
Previous Collision Breakup Models



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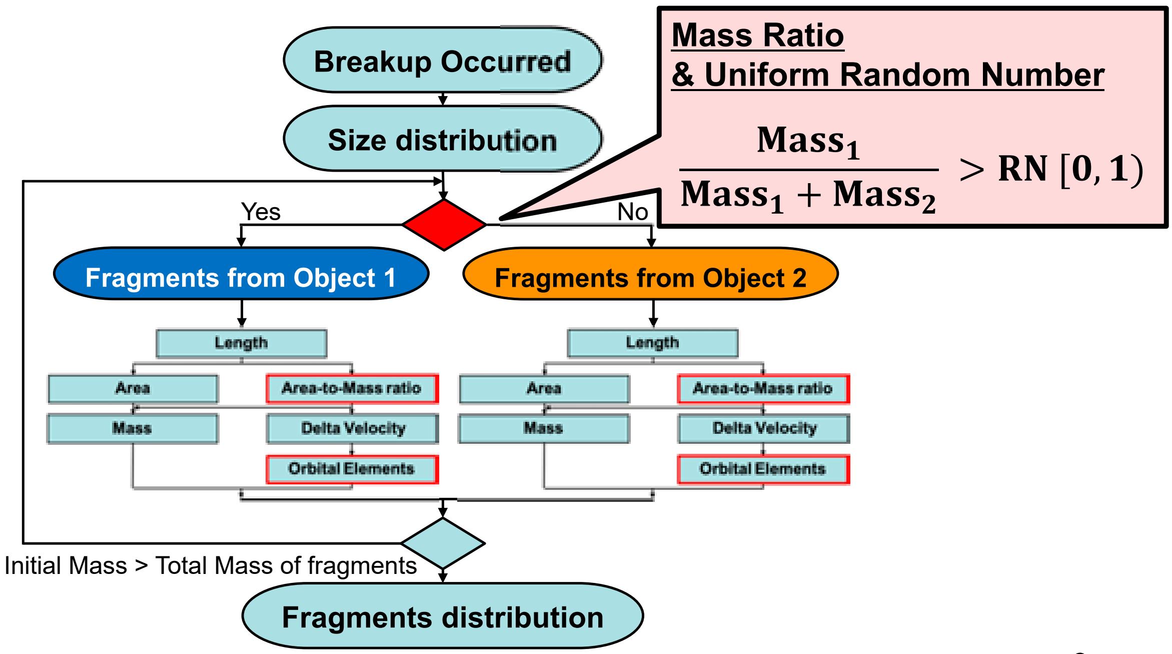
Revised Collision Breakup Models



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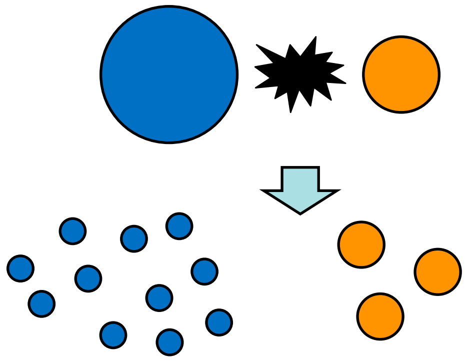
Concerns

The mass distribution of the fragments may be biased when objects have a large mass difference.

Example) Object 1 (2000 kg) vs Object 2 (250 kg)



Initial mass ratio

$$\frac{2000}{2000+250} \approx 0.89$$

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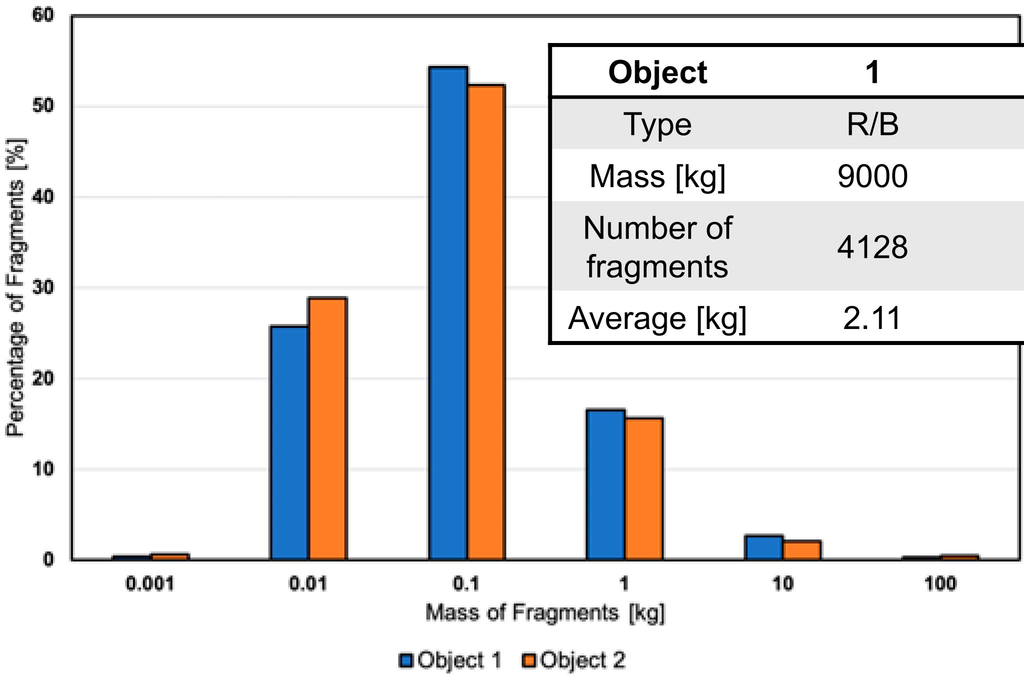
Mass Distribution of Fragments



Object	1	2
Type	R/B	R/B
Mass [kg]	9000	1400
Number of fragments	4128	676
Average [kg]	2.11	1.98

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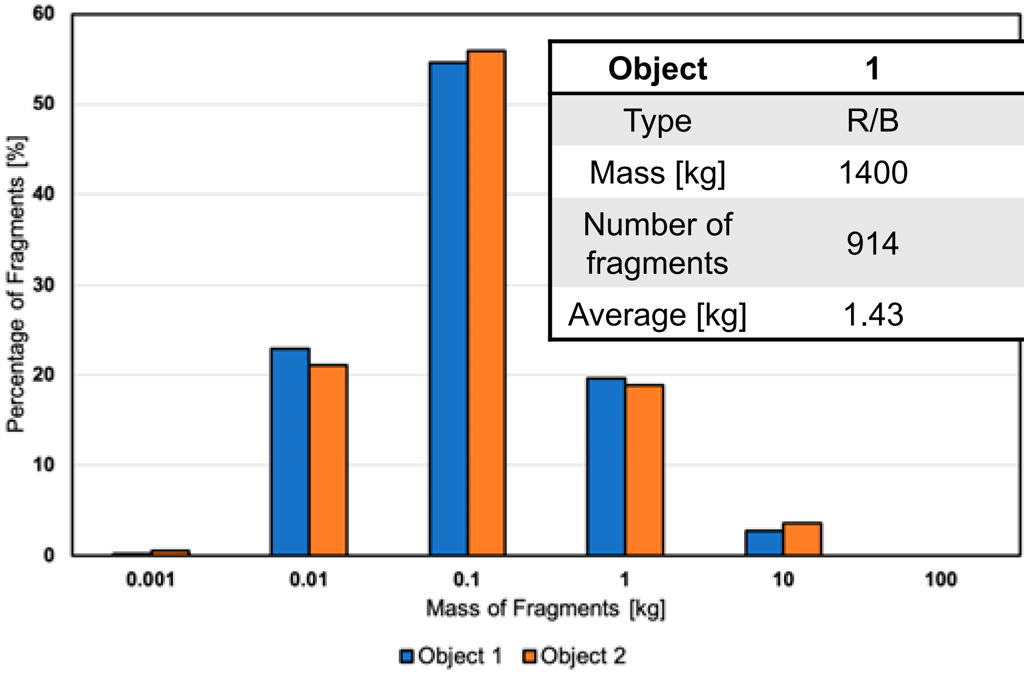
Mass Distribution of Fragments



Object	1	2
Type	R/B	S/C
Mass [kg]	1400	556
Number of fragments	914	361
Average [kg]	1.43	1.49

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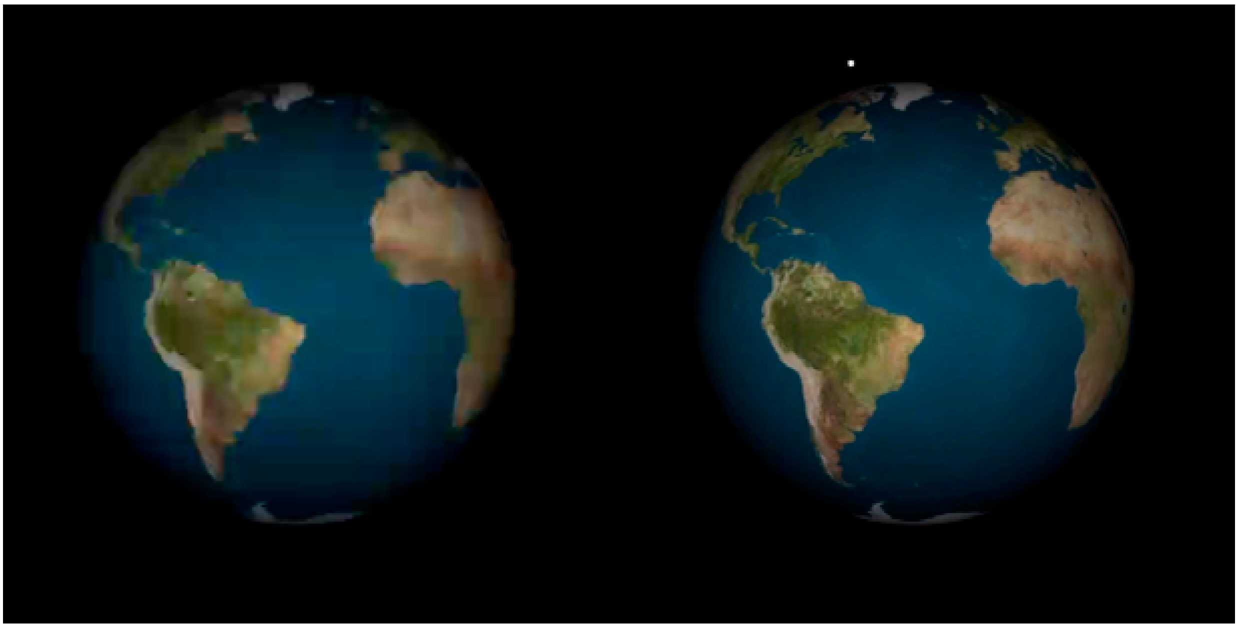
Comparing Distribution of Fragments

[Previous model] [Revised model]



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Conditions of the Simulation

Initial Population	As of February 1, 2018
Space Activities	New Launches (8-year cycle) (2010 – 2017) PMD (90%)
Debris Generation	Collision
Projection Span	2018 ~ 2217
Minimum Size	10 cm
Monte Carlo Runs	100
Time Step	5 days
Events Evaluation	Every 1 year

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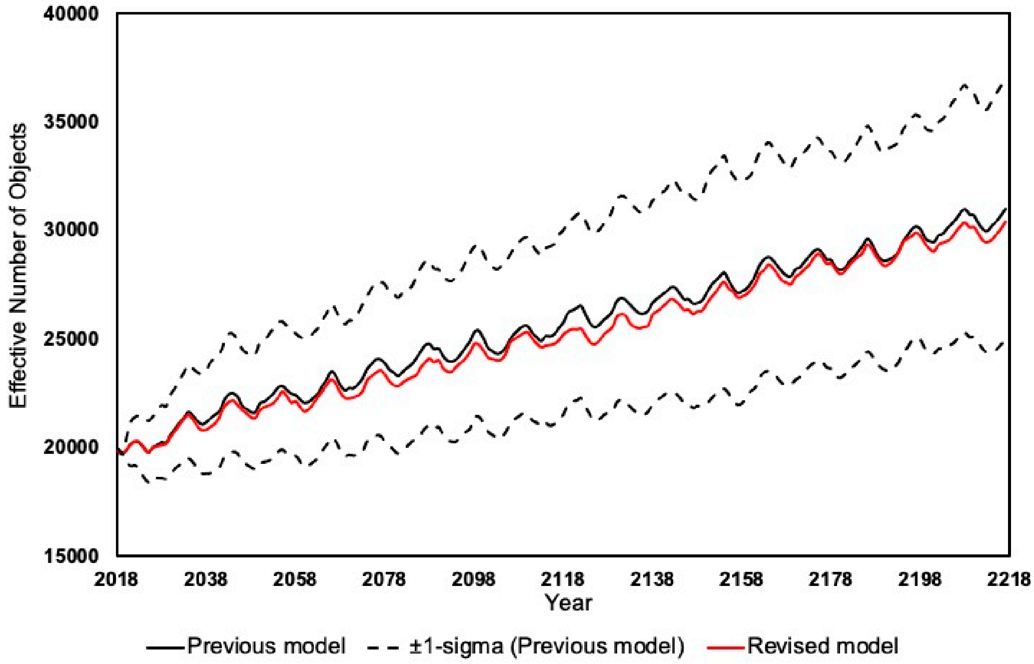
Effective Number of Objects



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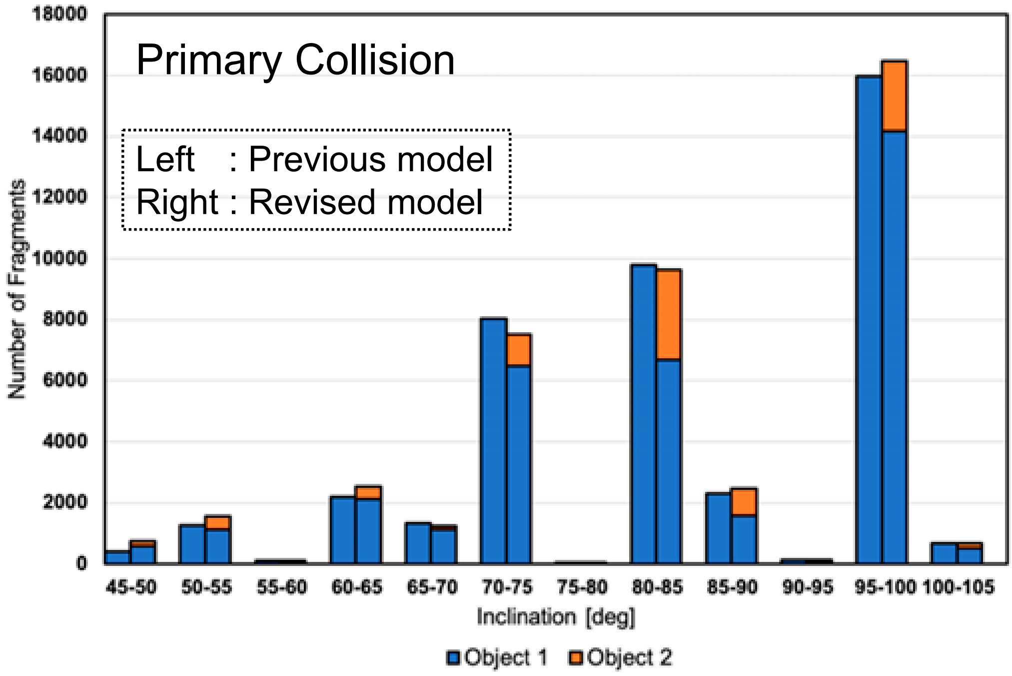
Number of Fragments



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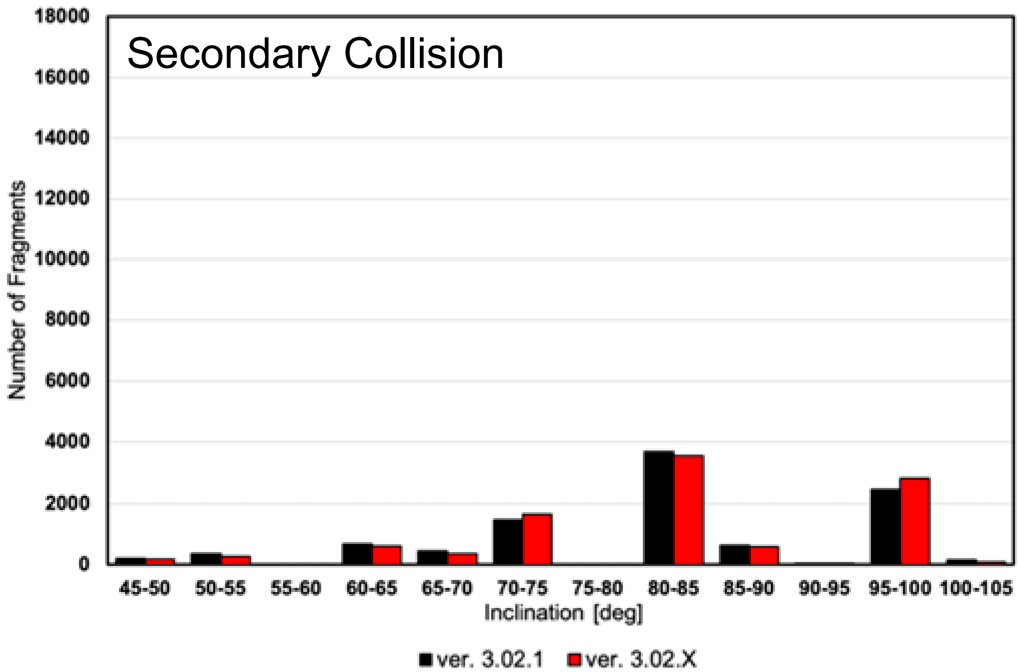
Number of Fragments



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Conclusions

- This paper briefly introduced efforts to orbital debris modeling.
- Mass ratio and uniform random number were able to determine **which object generated each fragment**.
- The distribution of fragments was formed around both **primary and secondary** objects.
- There were **no significant differences** in the transition of the number of objects.
- These results supported the significance of past analyzes.

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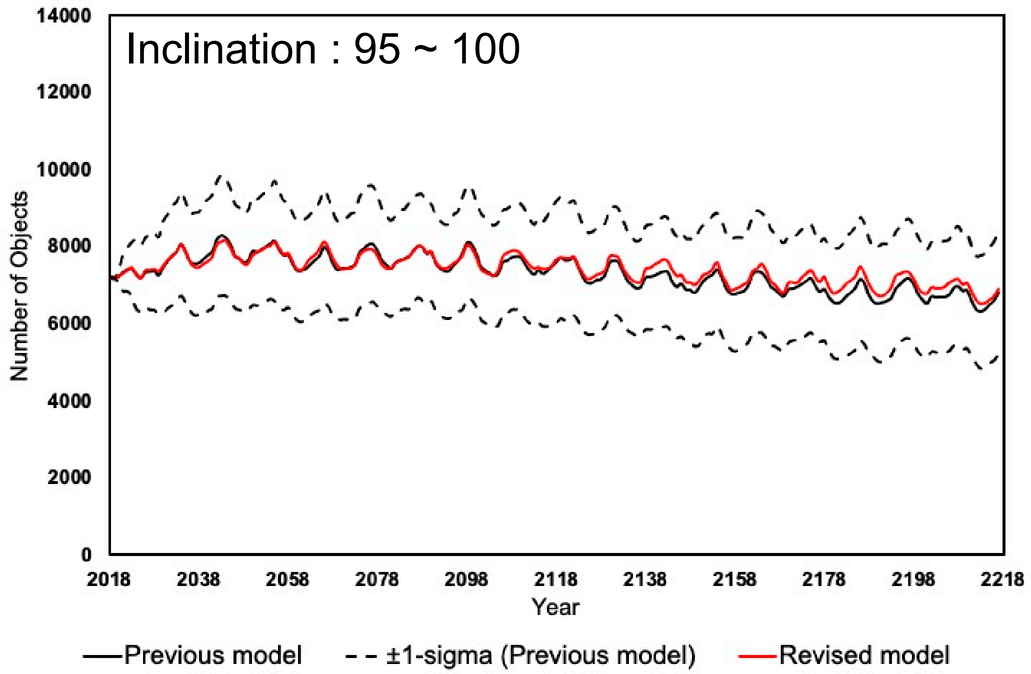
Number of Objects



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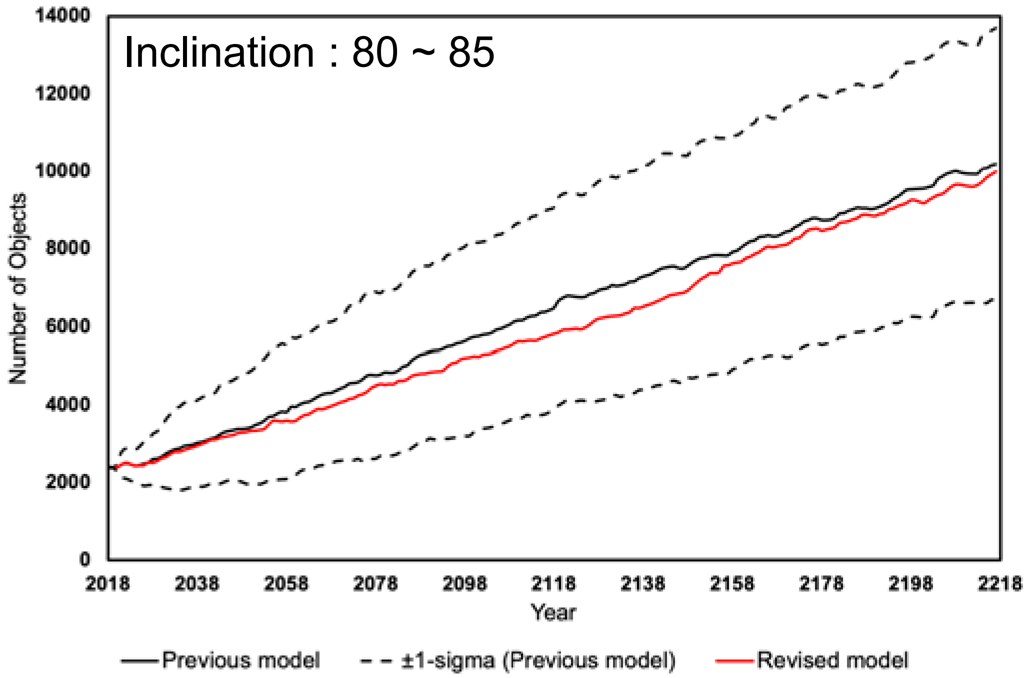
Number of Objects



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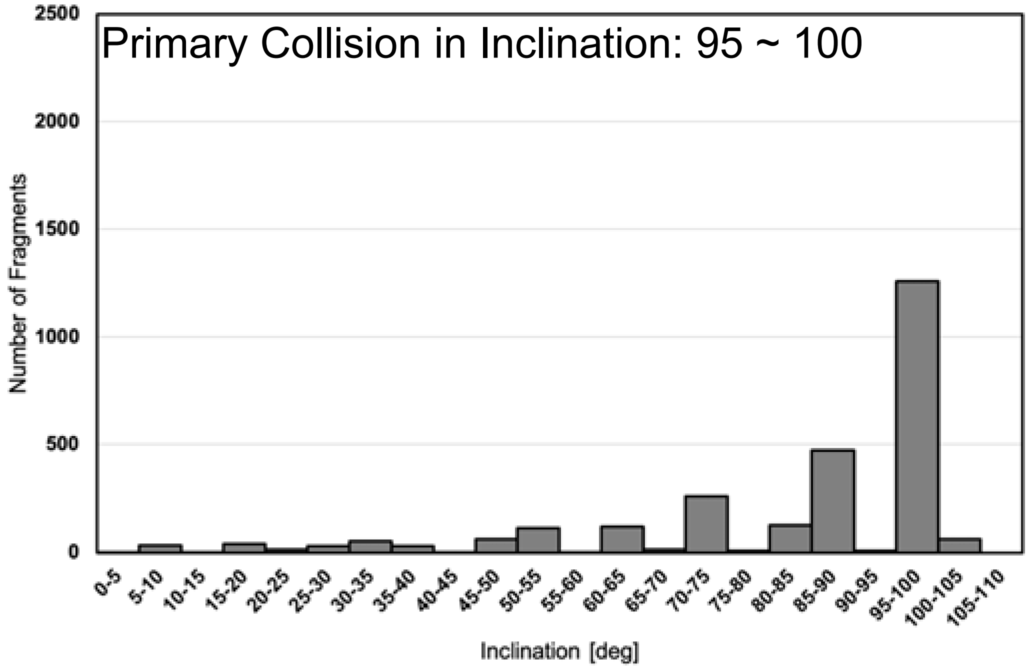
Number of Fragments



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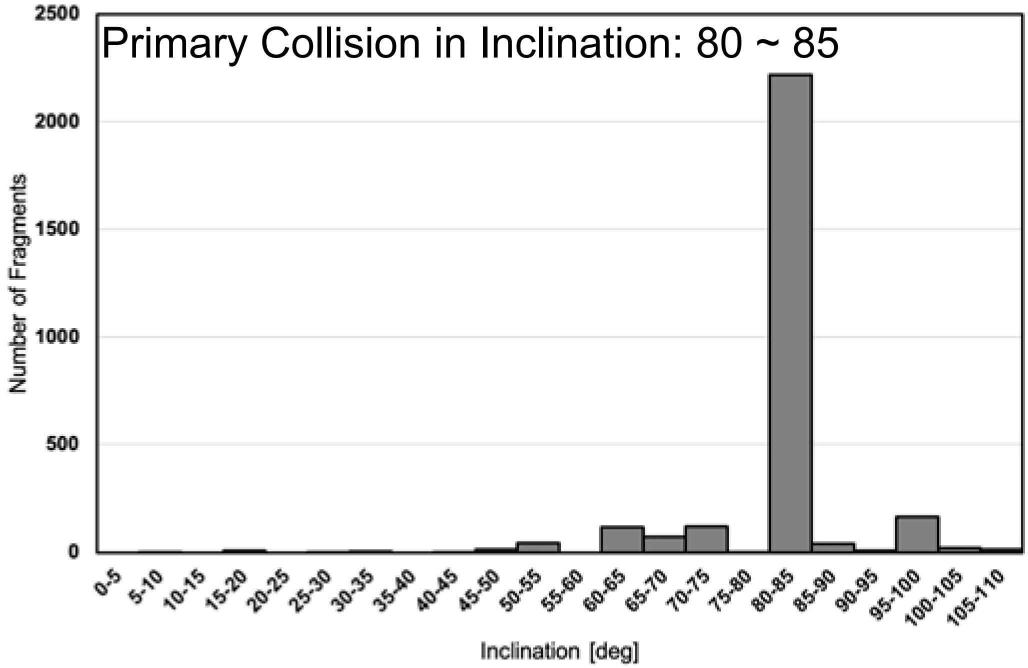
Number of Fragments



B02

推移モデルを用いた宇宙機の軌道投入許容量の検討

Study of the Environmental Capacity Tolerance of Insertions Using the Orbital Debris Evolutionary Model

○長岡 信明, 河本 聡美, 北川 康弘（JAXA）, 花田 俊也（九州大学）
○NAGAOKA Nobuaki, KAWAMOTO Satomi, KITAGAWA Yasuhiro (JAXA),
HANADA Toshiya (Kyushu Univ.)

軌道環境の有効活用を目的に、宇宙機の軌道投入可能数の許容レベルの検討を、九州大学と共同開発したデブリ推移モデルを用いて行った。特定軌道に複数の宇宙機を投入し、軌道上環境への影響を見ることで、軌道投入可能物体数（軌道投入許容量）を評価する。本講演では投入軌道、投入機数等の差異による軌道投入許容量の検討結果を示す。図1には凡例に示す各高度に 3000 機の宇宙機の投入の有無によるLEO（Low Earth Orbit:高度 200～2000km）を通過する物体の個数（Effective Number）の差異を示している。高度 800km までは大気抵抗の影響で投入物体（および生成されたデブリ）が落下することで長期間の影響は抑制されるが、軌道上残存物が多い高度 800～1000km では顕著な物体の増加が見られる。

For the purpose of effective utilization of the orbital environment, the environmental capacity tolerance of insertions is studied using an orbital debris evolutionary model, developed in collaboration with Kyushu University. By inserting multiple spacecraft into a specific orbit regime and observing the impact on the orbital environment, the number of spacecraft that can be inserted into orbit (orbit insertion capacity tolerance) is evaluated. In this presentation, the results of studying the orbit insertion capacity tolerance due to differences in orbital regime, the number of inserted spacecraft, etc. Fig.1 demonstrates the difference in Effective Number of objects in LEO (Low Earth Orbit: altitude 200 to 2000 km) with and without 3000 spacecraft inserted into various orbital regimes. At altitudes below 800 km, natural decay due to the atmosphere may suppress the impact of insertions (and the generated debris). At altitudes between 800 and 1000 km, however, a remarkable increase in objects can be observed because of the many orbital residuals.

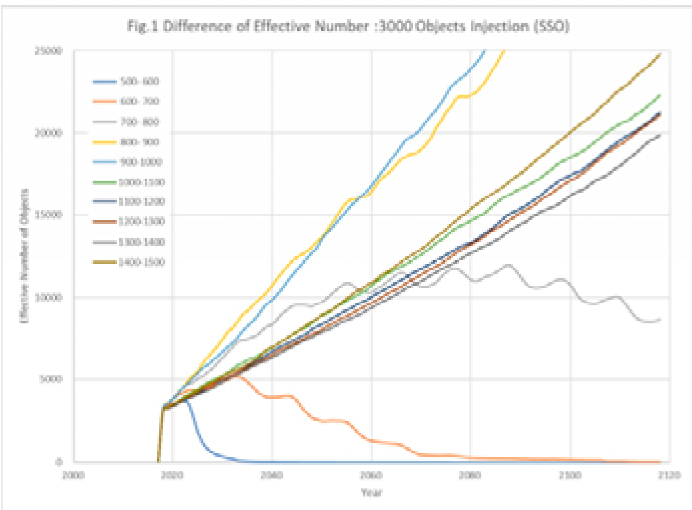


Fig.1 Difference of Effective Number :3000 Objects Injection (SSO)

第9回スペースデブリワークショップ
9th JAXA Space Debris Workshop

B02.推移モデルを用いた宇宙機の軌道投入許容量の検討

Study of the environmental capacity tolerance of insertions using the orbital debris evolutionary model

○長岡 信明、河本 聡美、北川 康弘（JAXA）
花田 俊也（九州大学）
NAGAOKA Nobuaki, KAWAMOTO Satomi, KITAGAWA Yasuhiro (JAXA)
HANADA Toshiya (Kyushu Univ.)

目的・手法 （Purpose and Method）

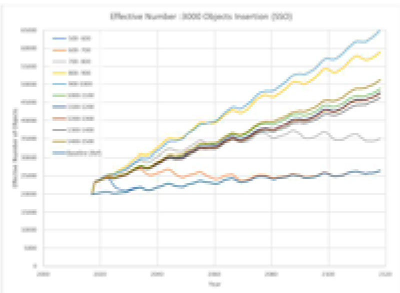
- 目的 （Purpose）
  - 今後の軌道環境の有効的活用を目的に、軌道上推移モデルを用いて特定軌道に物体（宇宙機）を投入し、軌道上環境への影響を見ることで、軌道投入可能物体数（軌道投入許容量）を予測する。
    - ➢ For the purpose of effective utilization of the orbital environment, the environmental capacity tolerance of orbital insertions (launch objects) is studied using an orbital debris evolutionary model (NEODEEM), developed in collaboration with Kyushu University.

- 手法 （Method）
  - 特定高度ごとに物体を投入、投入しない場合との比較から軌道環境への影響を調べる。
    - EN、衝突率による軌道環境への影響の評価
    - 投入高度、投入機数、軌道環境の差異（PMD、軌道タイプ）の影響の評価
    - ➢ Investigate the impact on the orbital environment by comparing with and without inserting objects at specific altitudes
      - ➢ Evaluation of the impact of orbital environment by Effective Number and collision rate.
      - ➢ Evaluation of the effects of insertion altitude, number of insertion objects, and differences in orbital environment (orbit type, PMD)

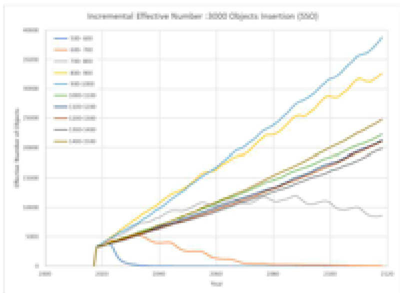
軌道投入キャパシティの評価（Evaluation）

- ベースライン：IADC2018の初期軌道上分布による推移結果
- 対象軌道に多数（300〜6000機）の衛星を投入
  - 軌道高度：100km幅（500〜1500km）
  - 離心率：0.001±0.0005
  - 軌道傾斜角：目標±0.25度
  - 昇交点赤経：60度毎の6面±1度
- EN、衝突率等で評価

➢ Baseline: Evolutional results by initial orbital population of IADC 2018
➢ Insert 300 to 6000 objects into the target orbit
  ➢ Altitude: 100km width （500〜1500km）
  ➢ Eccentricity: 0.001 ± 0.0005
  ➢ Inclination: Target ± 0.25 degrees
  ➢ RAAN: 6 planes every 60 degrees ± 1 degree
➢ Evaluate the impact of orbital environment by Effective Number and collision rate



Effective Number after 3000 objects insertion in each altitude.



Incremental Effective Number

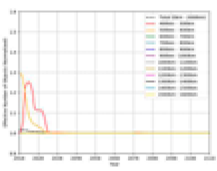
Acknowledgement: Initial population are provided by ESA for IADC studies

2

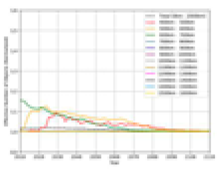
投入高度の比較（Comparison of Insertion Altitude）

- 300機投入時の各高度の正規化EN比較

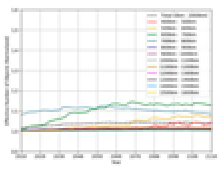
➢ Comparison of normalized EN at each insertion altitude （300 objects）



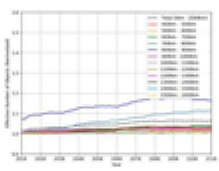
Insertion Altitude:500〜600km



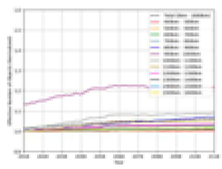
Insertion Altitude: 600〜700km



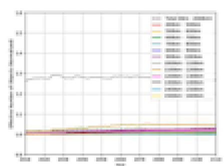
Insertion Altitude: 700〜800km



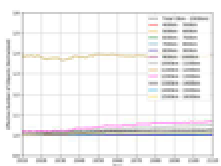
Insertion Altitude: 800〜900km



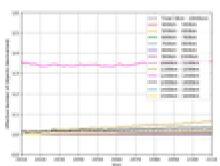
Insertion Altitude: 900〜1000km



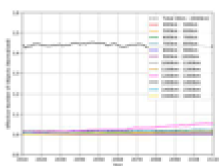
Insertion Altitude: 1000〜1100km



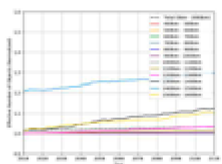
Insertion Altitude: 1100〜1200km



Insertion Altitude: 1200〜1300km



Insertion Altitude: 1300〜1400km

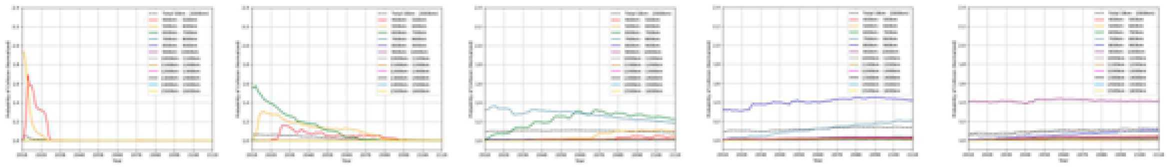


Insertion Altitude: 1400〜1500km

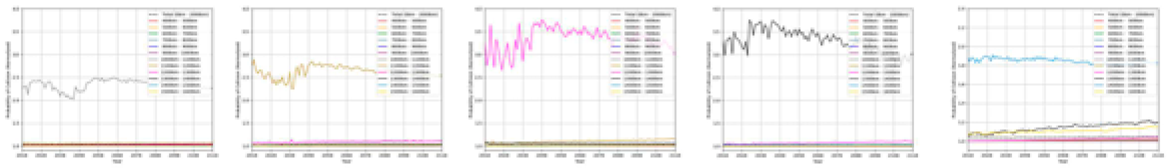
3

投入高度の比較（Comparison of Insertion Altitude）

- 300機投入時の各高度の正規化衝突率比較
- ➢ Comparison of normalized collision rate at each insertion altitude （300 objects）



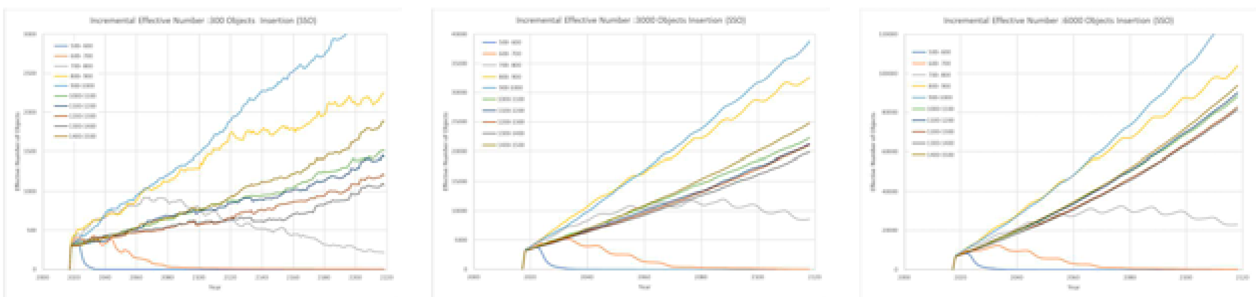
Insertion Altitude:500〜600km　Insertion Altitude: 600〜700km　Insertion Altitude: 700〜800km　Insertion Altitude: 800〜900km　Insertion Altitude: 900〜1000km



Insertion Altitude: 1000〜1100km　Insertion Altitude: 1100〜1200km　Insertion Altitude: 1200〜1300km　Insertion Altitude: 1300〜1400km　Insertion Altitude: 1400〜1500km

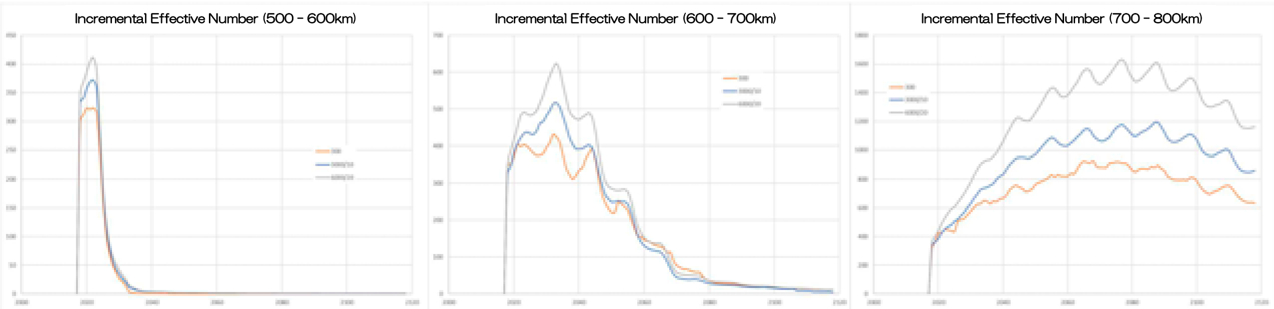
投入機数の効果 （Comparison of the Number of Insertion Objects）

- 300、3000、6000機投入時のEN比較
- Comparison of EN at 300, 3000, 6000 objects insertion



投入機数の高度別比較（Comparison of the Number of Insertion Objects in each Altitude）

- 300～6000機投入の効果を300機相当の値で評価
  - 投入高度：500～800km
- ➢ Evaluate the effect of inserting 300 to 6000 objects by EN equivalent to 300 objects
  - ➢ Insertion Altitude：500～800km

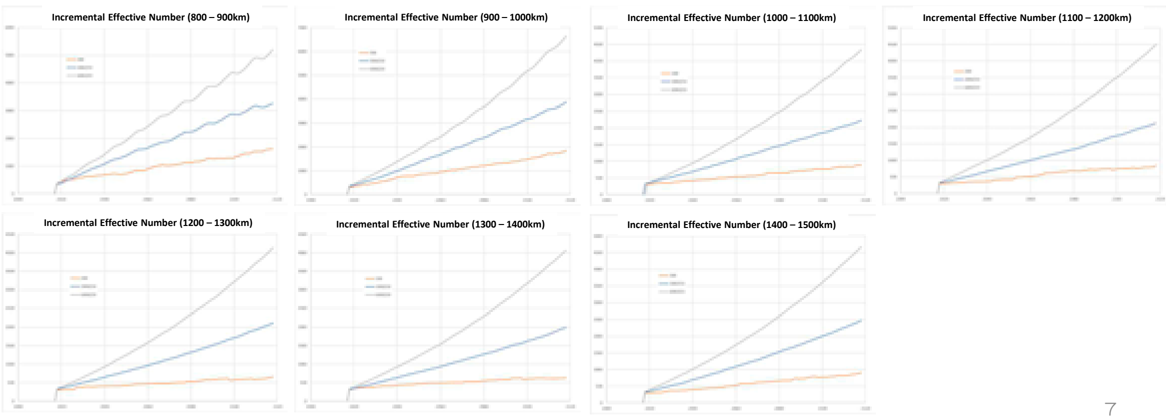


注：凡例の6000/20は6000機投入時の値を1/20していることを示している。
Remark: “6000/20” at the legend shows the value of the graph is 1/20 of real one.

6

投入機数の高度別比較（Comparison of the Number of Insertion Objects in each Altitude）

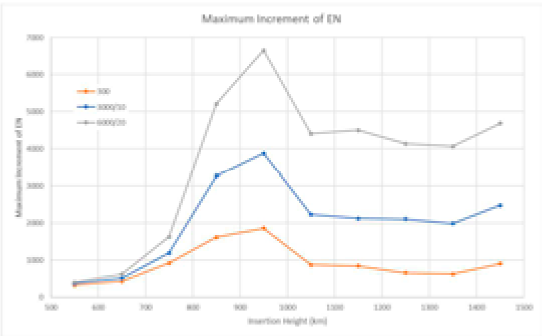
- 300～6000機投入の効果を300機相当の値で評価
  - 投入高度：800～1500km
- ➢ Evaluate the effect of inserting 300 to 6000 objects by EN equivalent to 300 objects
  - ➢ Insertion Altitude：800～1500km

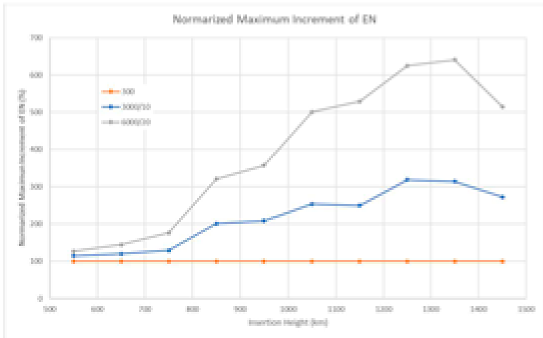


7

キャパシティ評価 （Evaluation of the Capacity Tolerance of Insertions）

- EN増加の最大数での比較
  - ENの絶対数と300機投入時の値で正規化した値で比較
- ➢ Comparison at maximum increment of EN
  - ➢ Comparison both the absolute number of EN and the normalized value by EN of 300 objects insertion

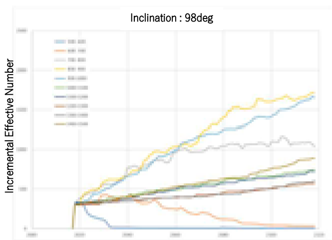


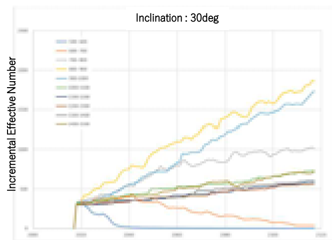


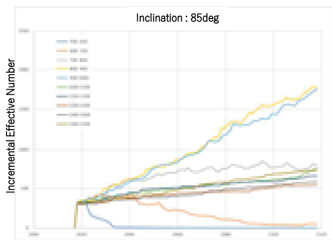
軌道傾斜角依存性 （Dependency of Inclination）

- 軌道傾斜角：30度、85度、98度での比較
  - ➢ Inclination for comparison：30, 85, 98deg

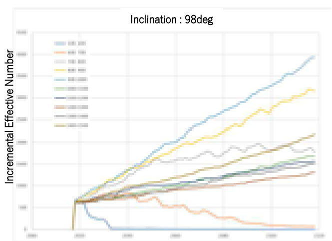
300 Objects Insertion

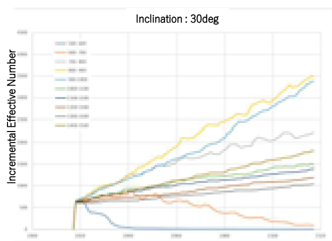


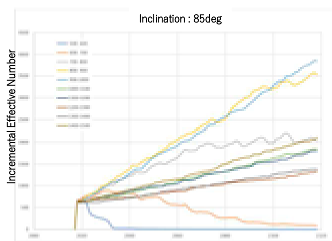




600 Objects Insertion

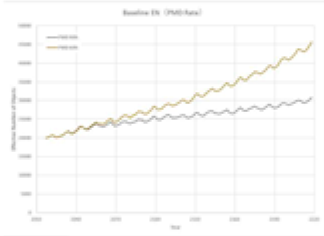






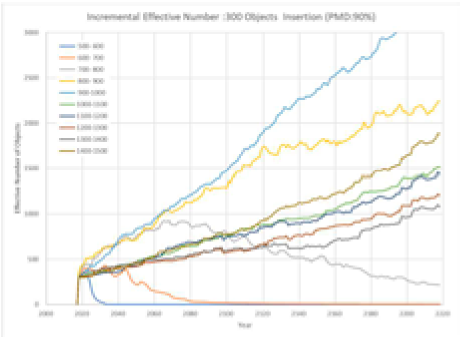
PMD率の影響 （Effect of Baseline Objects PMD）

- PMD90%と60%の比較
  - ➢ Difference between Baseline Objects PMD 90% and 60%

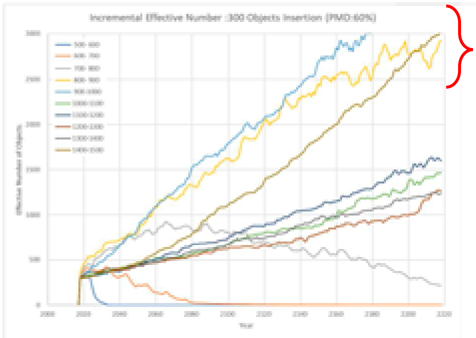


Without Objects Insertion

Baseline Objects PMD : 90%



Baseline Objects PMD : 60%



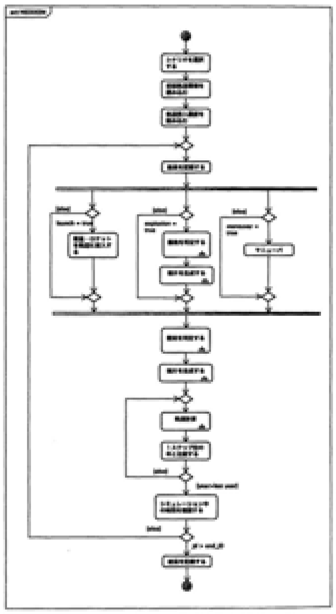
まとめ Summary

- 特定の軌道への宇宙機の投入許容量を、推移モデルにより予測する一手法を示した。
- 軌道上物体数（Effective Number）による評価
  - 高度700km以下では、投入物体が短期で落下するため、投入許容量への影響は小さい。
  - 高度800～1000kmでは顕著な増加が見られる。
  - 現状の軌道で物体分布の多い高度では、投入物体が軌道上物体の増加を引き起こしている。
  - 投入軌道の選定や高度のPMD遵守率が必須になる。

- ➢ The method for evaluate the orbit insertion capacity tolerance by checking the impact on the orbital environment using the orbital debris evolutionary model is shown.
- ➢ Evaluation by Effective Number
  - ➢ At an altitude of less than 700 km, insertion objects fall in a short period, at 800 – 1000km, they cause a significant increase of Effective Number.
  - ➢ Suitable selection of insertion orbit and high PMD compliance rate are important.

Backup sheet

Debris evolutionary model （NEODEEM）

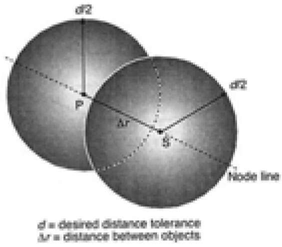


Initial Input：
- Set the scenario
- Initial population

Population Transfer: (Selectable)
- Traffic Model: New Launch（8-year cycle）
- Explosion: Anz-Meador Model(MC)
- Maneuver: PMD(MC)、ADR(MC)

- Collision: Anz-Meador Model(MC)
- Collision avoidance

Propagation:
- Earth Gravity（Zonal:4^{th}/Tesseral）
- Air Drug（Jacchia-Roberts/Jacchia-Bowman）
- Solar・Lunar attraction
- Solar Pressure



Collision Sphere Model

B03

JAXA 独自のデブリ推移予測用ベースラインファイルの開発状況

Development of JAXA's Original Baseline File for Debris Evolutionary Model

○河本 聡美，長岡 信明，北川 康弘，柳沢 俊史，上野 浩史（JAXA），中渡瀬 竜二，
上田 裕子，八田 真児（MUSCAT スペース・エンジニアリング），花田 俊也（九州大学）
○KAWAMOTO Satomi, NAGAOKA Nobuaki, KITAGAWA Yasuhiro, YANAGISAWA Toshifumi,
UENO Hiroshi (JAXA), NAKAWATASE Ryuji, UEDA O. Hiroko, HATTA Shinji (MUSCAT Space
Engineering), HANADA Toshiya (Kyushu Univ.)

デブリ推移モデルはデブリ低減策の有効性評価や国際的ルールの議論に不可欠である。JAXA では九州大学と共同開発したデブリ推移モデルを用いてデブリ数の将来推移を評価してきた。デブリ推移モデルでは、軌道上環境の初期状態として、考慮する全物体の質量特性や軌道等の情報が必要である。JAXA では公開されている TLE 履歴からの面積質量比評価や文献調査、JAXA 望遠鏡で観測された未カタログ物体等を考慮して、独自のベースラインファイルを作成した。今までは、IADC で ESA から提供されたベースラインファイルを、研究目的にのみ使用していたが、情報不足等により、具体的デブリ除去対象の評価等は不可能だった。本講演では、TLE 調査等のベースラインファイル開発方法や、開発されたベースラインの評価結果、それを用いた推移予測の結果等について報告する。特に、開発されたベースラインファイルを用いたデブリ除去対象の評価や、デブリ低減策効果の評価、また波及効果として TLE 履歴調査から分析できる情報等を紹介する。

A debris evolutionary model is indispensable for investigating effective debris mitigation measures and for developing international rules regarding space debris. JAXA has been evaluating the future space debris population using an evolutionary debris model named NEODEEM, developed in collaboration with Kyushu University. A baseline file is required for the debris Evolutionary model, which is the initial population data of the on-orbit environment, such as mass characteristics and orbits of all objects larger than 10 cm. JAXA has created its own baseline file by taking into account the area-mass-ratio evaluation from the TLE (Two Line Elements) history, literature review, and uncatalogued objects observed with the JAXA telescope, and so on. The baseline files provided by ESA at IADC have been used for research purposes only, but due to lack of information, for example, evaluation of specific debris removal targets was not possible. In this talk, the methods for developing the baseline file, the results of comparison with some debris models, and the results of debris evolutionary model predicted using the developed baseline files are reported. In particular, the evaluation of debris removal targets and the effectiveness of debris mitigation measures using the developed baseline files are introduced. In addition, the information that can be analyzed from the TLE history survey is introduced.

9th JAXA Space Debris Workshop
第９回スペースデブリワークショップ

Development of JAXA's Original Baseline File for Debris Evolutionary Model

JAXA独自のデブリ推移予測用ベースラインファイルの開発状況

KAWAMOTO Satomi, NAGAOKA Nobuaki, KITAGAWA Yasuhiro, YANAGISAWA Toshifumi(JAXA Research and Development Directorate), UENO Hiroshi (JAXA Business Development and Industrial Relations Department), NAKAWATASE Ryuji, UEDA O. Hiroko, HATTA Shinji (MUSCAT Space Engineering Co., Ltd.), HANADA Toshiya (Kyushu Univ.)

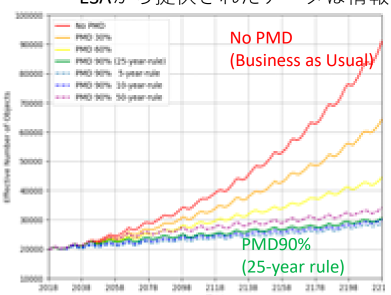
河本聡美、長岡信明、北川康弘、柳沢俊史(JAXA研究開発部門)、
上野浩史（JAXA新事業促進部）、
中渡瀬竜二、上田裕子、八田真児（MUSCATスペース・エンジニアリング株式会社）、
花田俊也（九州大学）

Introduction

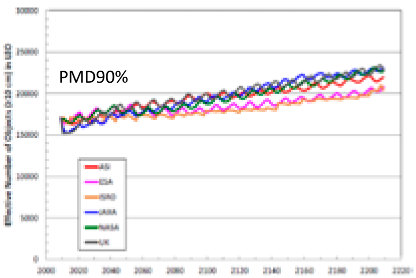
- Debris evolutionary model is indispensable as a technical basis for international rulemaking discussions such as for evaluating the effectiveness of debris mitigation measures, ADR targets, etc.
- Initial conditions (orbit, mass and other characteristics of all orbital objects larger than 10 cm, type of object, etc.) are necessary for the debris evolutionary model

⇒JAXA developed its own baseline file based on TLEs, observations, models, etc.

- デブリの国際ルール化議論にはデブリ推移モデルを用いた将来予測によるデブリ対策の有効性評価が不可欠
- デブリ推移モデルには初期条件として10cm以上全物体の軌道や質量特性等の情報が必要だが、今まで用いていたIADCでESAから提供されたデータは情報不十分かつ使用制限があったため、JAXA独自のベースラインファイルを開発

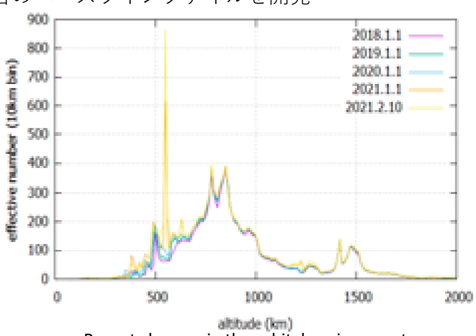


Effectiveness of PMD shown with debris evolutionary model, ***NEODEEM***, developed with Kyushu univ. and JAXA 九大と共同開発した推移モデルによる評価
Kawamoto et al. IOC 2019 (revised)



IADC-12-08, Rev. 1, Stability of the Future LEO Environment, January 2013.

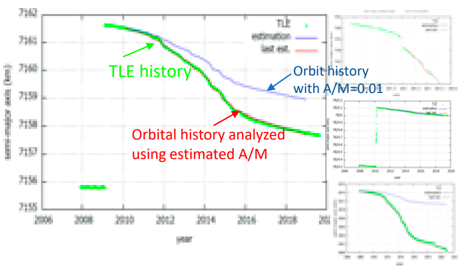
IADCで実施した６機関の推移予測



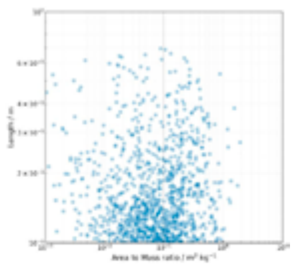
Recent changes in the orbital environment
(based on *spacetrack.org*)
近年環境激変のため最新データが重要

How to develop the baseline file

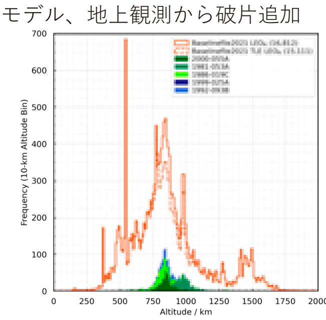
- Daily check of TLEs of all catalogued objects, about 20000 available from space-track.org, and estimation of area-to-mass (A/M) ratio from orbit history
- Mass characteristics of intact objects and other data are from literature survey
- Mass characteristics of fragment objects are randomly set to match the estimated A/M with fragments generated by NASA standard breakup model
  - Actual size of each object may be different from the assigned size, but it is acceptable since the goal is to be able to evaluate statistically
- Uncataloged objects from ground observation data are added(see next page for details)
- 約2万個のTLE（軌道履歴）データからの面積重量比(A/M)推定、文献調査、破砕モデル、地上観測から破片追加



Daily check of TLEs and A/M estimation



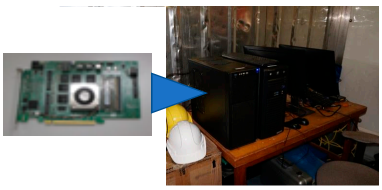
A/M and size distribution of fragments generated by standard breakup model



Altitude distribution of fragments added using breakup model

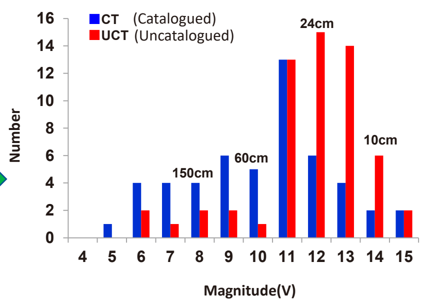
Addition of uncataloged objects from ground-based observations

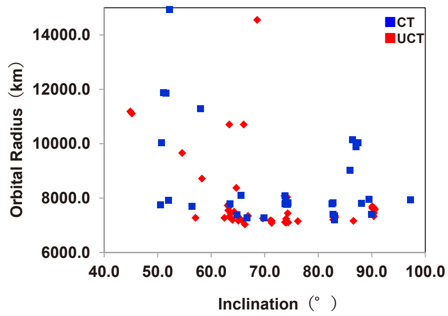
- LEO survey results conducted with JAXA remote observation site in Australia are added to the baseline file.
- 豪州遠隔観測所での観測データから未カタログ物体を追加



Data acquisition using the quadruple telescope and fast data analysis using FPGA system

Yanagisawa et al. ASR 2015



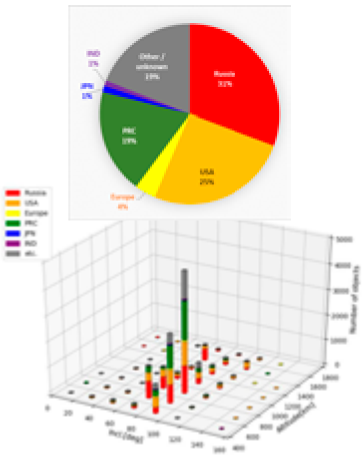


Calculation of the brightness (size) distribution and the simple orbital elements

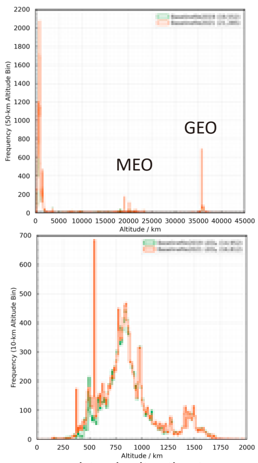
Reflection to the baseline file

Results of developed baselines

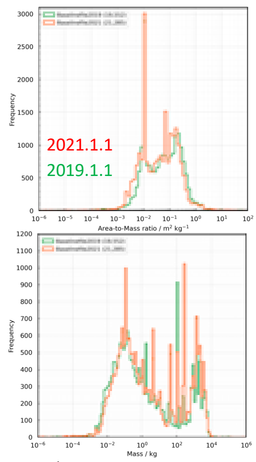
- About 21,000 objects were considered and baseline file as of January 1, 2021 has been developed
- Collision flux by size have been compared with debris environment models (ORDEM, MASTER) and confirmed that there is a lack of fragments debris at some altitudes while the sizes of some objects might be too large.
- 約21000個の物体を考慮し2021年1月1日時点のデータベースを開発、環境モデルと比較。破片不足、要サイズ修正



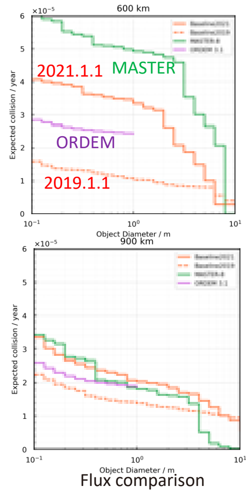
Origins of objects and their orbital distribution



Altitude distribution



A/M and Mass distribution



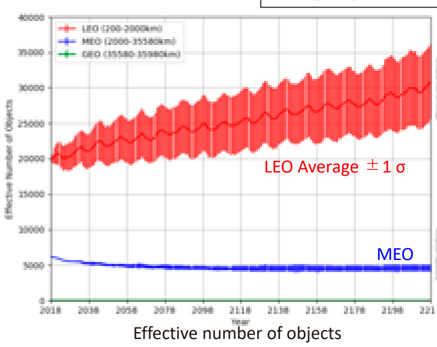
Flux comparison

5

Prediction results using the developed database (1)

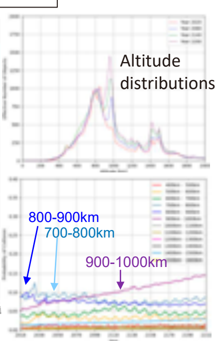
- **PMD90%** (8-year repeated launch, Post Mission Disposal compliance rate 90%)
  - Prediction with the JAXA database as of January 1, 2019 and with the January 1, 2018 of ESA database provided for IADC studies, as presented in previous papers
  - Total number of LEO objects (especially fragments) in JAXA baseline file is still insufficient
- 2019年１月１日時点データでPMD90%ケースの推移予測を比較。一致した傾向の結果を確認

IADC(ESA)-2018 version



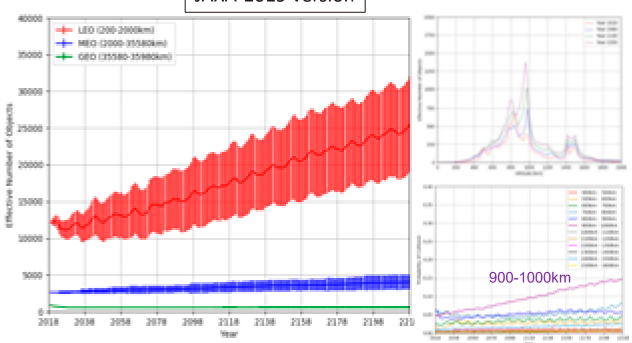
Effective number of objects

Kawamoto et al. IOC 2019 (revised. revision of atmospheric model and bug fixes)



Collision probabilities in each altitude band

JAXA-2019 version

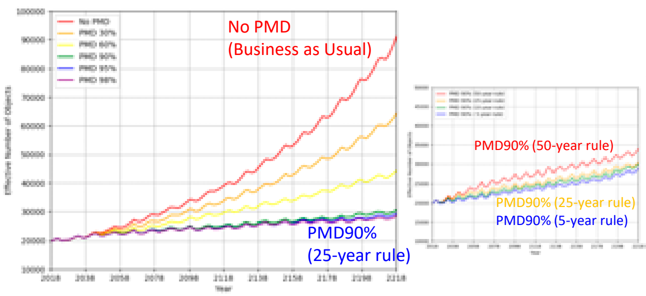


6

Prediction results using the developed database (2)

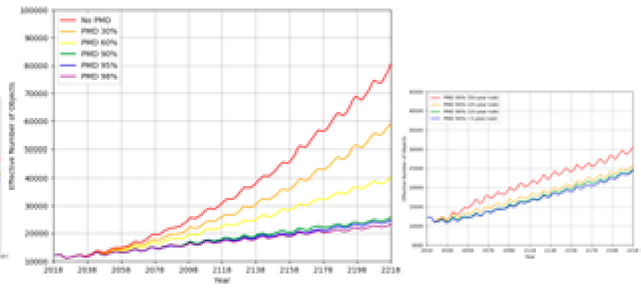
- Effectiveness of debris mitigation measures were evaluated, and the same results were obtained
  - High PMD compliance rate is important
  - As for PMD time period, 25-year rule is effective enough
- デブリ低減策評価についても、25年ルールの有効性等、一致した結果を確認

IADC(ESA)-2018 version



Effective number of objects

JAXA-2019 version



Effective number of objects

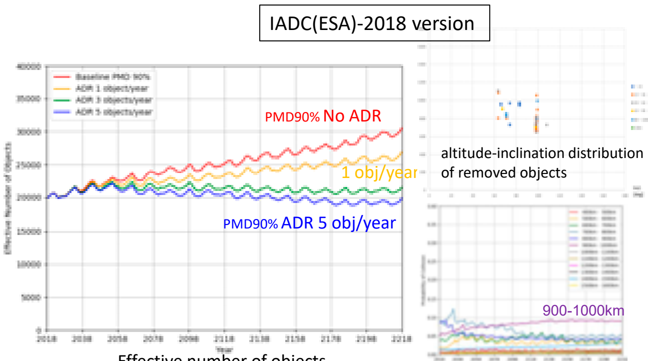
Kawamoto et al. IOC 2019 (revised)

7

Prediction results using the developed database (3)

- Effectiveness of ADR
  - The increase of future debris populations could be suppressed by ADR of about 3 – 5 debris objects per year
- デブリ除去についても、同様の効果を確認（年間３～５個程度大型デブリを除去すれば自己増殖を抑制）

IADC(ESA)-2018 version

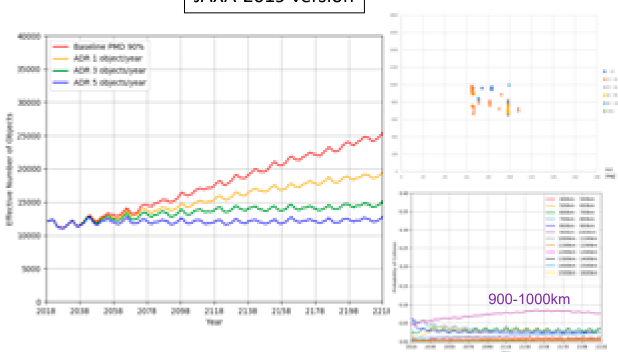


Effective number of objects

Collision probabilities in each altitude band

Kawamoto et al. IOC 2019 (revised)

JAXA-2019 version



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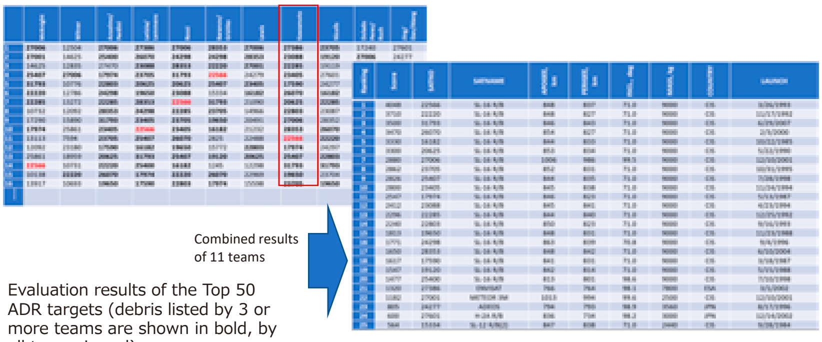
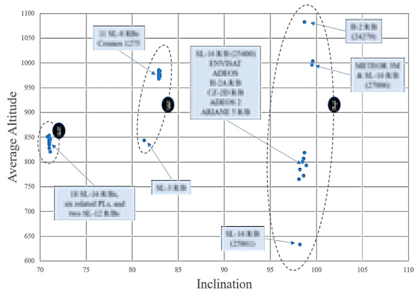
Specific targets for ADR

- IADC data did not show the specific target names, but now we can see them
- Participated to international paper “**Identifying the 50 Statistically-Most-Concerning Derelict Objects in LEO”** (McKnight et al., IAC 2020)
  - 11 teams listed ADR targets in their respective evaluations, and merged them into a Top 50 list, confirming that SL-16 and others are ADR targets.
  - Reasonable results with a high rate of agreement with other teams
- IADCデータにはデブリ名称等の情報がなかったが、除去対象を議論する国際論文にも参加できるようになった



Evaluation results of the Top 50 ADR targets (debris listed by 3 or more teams are shown in bold, by all teams in red)



Evaluation results of the Top 50 ADR targets

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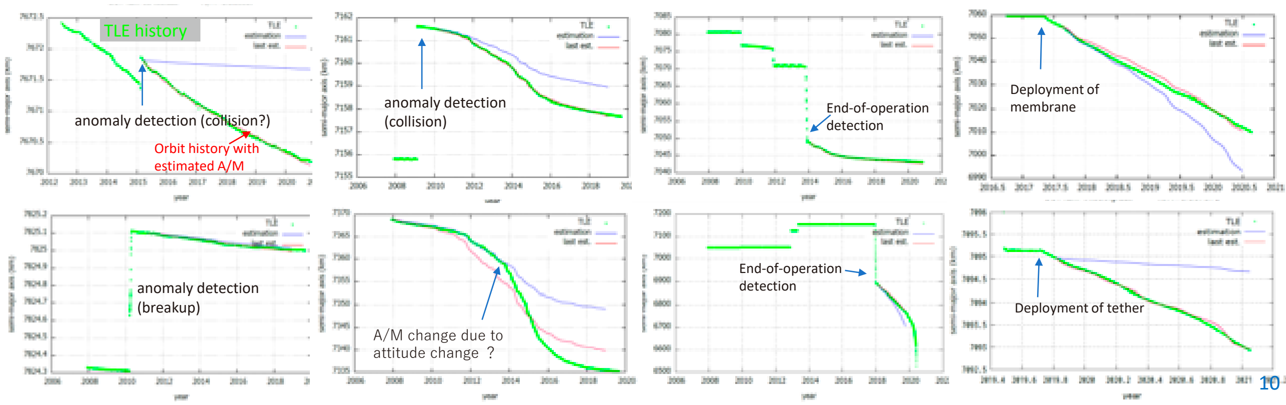
Byproducts of TLE surveys

- Daily check of the TLEs of all cataloged objects (about 20,000 available from space-track.org) to detect anomalies such as collisions, explosions, end-of-operation, deployment of deorbit devices, generation of new debris, disappearance from TLEs, etc.
- Possibility of detecting attitude mode change of an object based on the difference in the estimated A/M, or evaluating debris environment models
- 毎日のTLEチェックにより衝突・破砕等による軌道変化や、運用終了、PMDデバイス展開等を検出可能。



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Summary

- JAXA's original database for debris evolutionary model have been developed.
- Although the number of debris objects is still insufficient, we are now able to evaluate debris mitigation measures, and specific removal targets, etc. using the developed baseline file.
- We will continue to analyze the TLE and add data from surveys and observations to improve the completeness.
- デブリ推移予測に必要な、JAXA独自のデブリデータベースを構築した。破片等はまだ不足しているため、継続的に日々のTLEデータチェック等で改良する予定
- 最新・使用制限のないデータで、デブリ対策の有効性評価や具体的デブリ除去対象等を評価可能となった。国際議論に備えるためにどのような評価をすべきか、ご要望等があればご連絡ください

Acknowledgement:

- *We used JAXA Supercomputer System generation 2 (JSS2).*
- *Part of the initial population for this study was provided by the ESA Space Debris Office.*
- *Part of this study was supported by J-SPARC (JAXA Space Innovation through Partnership and Co-creation)*

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References

- S. Kawamoto, N. Nagaoka, T. Sato, T. Hanada, "Impact on Collision Probability by Post Mission Disposal and Active Debris Removal", First International Orbital Debris Conference, 2019. https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6100.pdf or The Journal of Space Safety Engineering, Volume 7, Issue 3, September 2020, Pages 178-191.
- S. Kawamoto, N. Nagaoka, T. Hanada, S. Abe, "Evaluation of Active Debris Removal Strategy Using a Debris Evolutionary Model", IAC-19-A6.2.10, 2019.
- T. Yanagisawa, H.Kurosaki, H.Oda, M.Tagawa, Ground-based optical observation system for LEO objects, Advances in Space Research 56 (2015) 414–420.
- D. McKnight, et al., "Identifying the 50 Statistically Most Concerning Derelict Objects in LEO", IAC-20-A6.2.1, 2020. or Volume 181, Pages 282-291, Acta Astronautica, 2021.

12

B04

低軌道 ADR ミッションにおけるターゲット物体の姿勢運動解析

Analysis on Attitude Motion of ADR Target in LEO

〇松下 悠里（九州大），板谷 優輝（スカパーJSAT），
吉村 康広（九州大），福島 忠徳（スカパーJSAT），花田 俊也（九州大）
○MATSUSHITA Yuri (Kyushu Univ.), ITAYA Yuki (SKY Perfect JSAT Corporation), YOSHIMURA Yasuhiro (Kyushu Univ.), FUKUSHIMA Tadanori (SKY Perfect JSAT Corporation), HANADA Toshiya (Kyushu Univ.)

高速大容量通信の実現を目的とする数千機規模のコンステレーション衛星の計画をはじめとした、宇宙利用の急速な拡大に伴い，軌道環境のより一層の混雑が懸念されている．その解決策の一つとして，スカパーJSAT 株式会社は不用な衛星等を対象にレーザーアブレーションの技術を応用した非接触方式の ADR 衛星の設計および開発に着手している． 一般に ADR ミッションでは，ターゲット機体の回転量を事前に把握し、ミッション運用に反映する必要がある。ターゲット機体には様々な外乱トルクが加わるため，複雑な運動が予測される．本発表では，低軌道衛星を対象に，重心位置のずれを考慮した，姿勢および角速度解析の結果を示す．

The orbital congestion is becoming an urgent issue with increasing space activities, such as satellite constellations for high-speed and large-capacity communications. Therefore, SKY Perfect JSAT Corporation has started out designing and developing an ADR satellite. The satellite applies laser ablation technologies so that it does not require any physical contact with a target object. ADR mission generally requires grasping the rotational motion of the target object in advance and reflecting it in its mission operations. The target object’s motion is usually complicated due to various disturbance torques acting on it. This presentation shows the short-term and long-term variation of attitude and angular velocities of the target object in Low Earth Orbit, considering the shift of the center of gravity.

Analysis on Attitude Motion of ADR Target in LEO

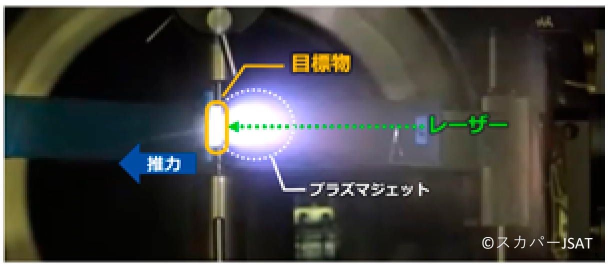
低軌道ADRミッションにおけるターゲット物体の姿勢運動解析

〇Yuri Matsushita,[1] Yuki Itaya,[2] Yasuhiro Yoshimura,[1] Tadanori Fukushima [2] and Toshiya Hanada [1]
([1] Kyushu University, [2] SKY Perfect JSAT Corporation)
〇松下悠里[1]，板谷優輝[2]，吉村康広[1]，福島忠徳[2]，花田俊也[1]
([1] 九州大学，[2] スカパーJSAT株式会社)

ADR satellite developed by SKY Perfect JSAT

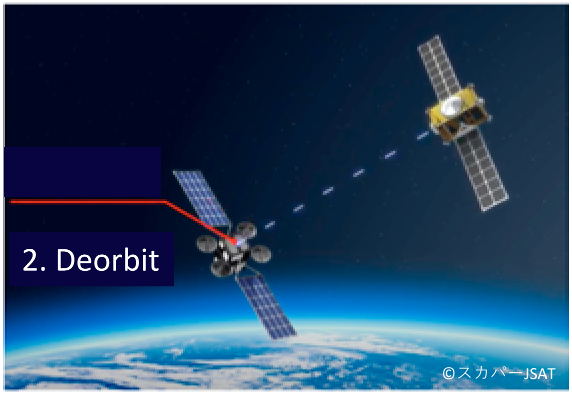
- The orbit congestion is becoming an urgent issue with increasing space activities.
- SKY Perfect JSAT Co. has started out designing and developing ADR satellite using laser ablation technologies.
- ADR system using laser is economical and does not require physical contacts.

ADR satellite designed and developed by SKY Perfect JSAT



Laser ablation technologies

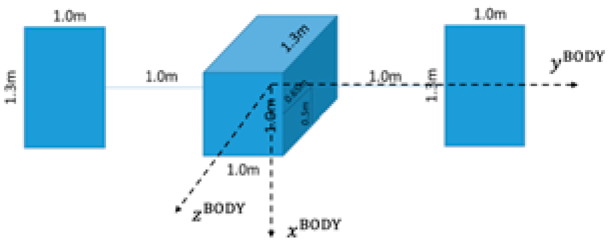
ADR mission using laser ablation technologies



Output of this research

- Quantitative analysis of attitude angles and angular velocities for debris in LEO to clarify mission requirements

Target object



The satellite model

■ Orbital elements

a	7578.14 km
e	0
i	87.9 deg.
Ω	0 deg.
ω	0 deg.

■ The satellite model parameters

Mass	150 kg (bass: 138 kg, panel: 6 kg)	assumption
Center of mass	(1) $[0.078, 0.030, 0.078]$ m	6% shift in all axes
	(2) $[0.078, 0.000, 0.000]$ m	6% shift in x axis
Moment of inertia	$[71.31, 24.00, 56.44]$ kgm^2	
Surface properties	$[0.1, 0.2, 0.7]$	

Conditions

■ Initial values

Attitude angles	[0.0, 1.0, 1.0] deg.
Angular velocities	① [0.0, 0.0, 0.0] deg./min. ② [0.0, 60.2, 0.0] deg./min.

assumption
Angular momentum of a reaction wheel (0.42Nms) on the minor axis of inertia (Max initial angular velocities)

■ Perturbations

- Gravitational gradient
- Aerodynamic drag
- Solar Radiation Pressure

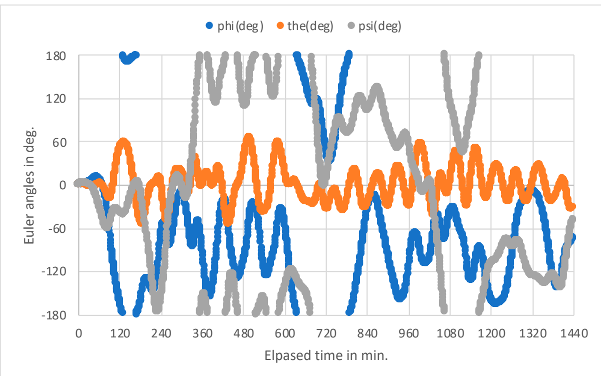
Need to be considered in Low Earth Orbit

■ Unconsidered conditions

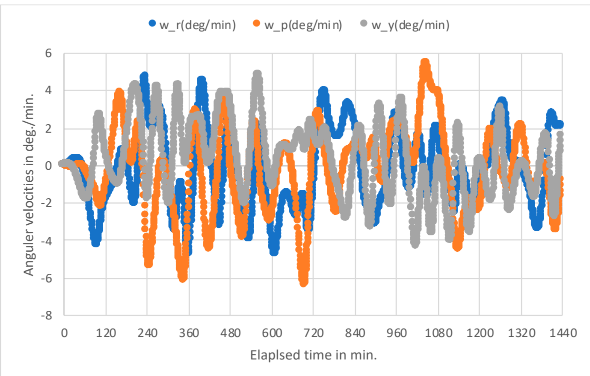
- Self-shadowing — Almost no effect on angular velocities in preliminary analysis
- Product of inertia — The moment of inertia in each axis increases by about 2%, which is a safe condition.

- No initial angular momentum

Center of mass	(1) [0.078, 0.030, 0.078] m
Angular velocities	① [0.0, 0.0, 0.0] deg./min.



Attitude angles in deg.



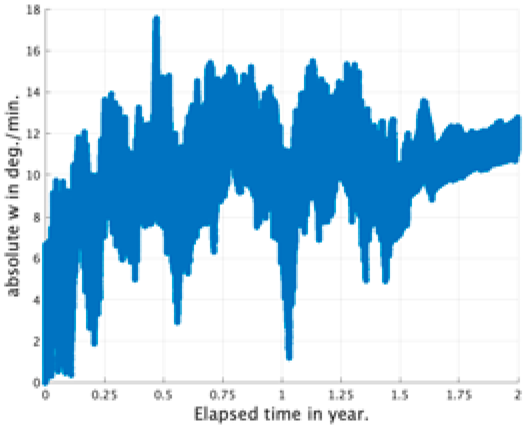
Angular velocities in deg./min.

2-years analysis

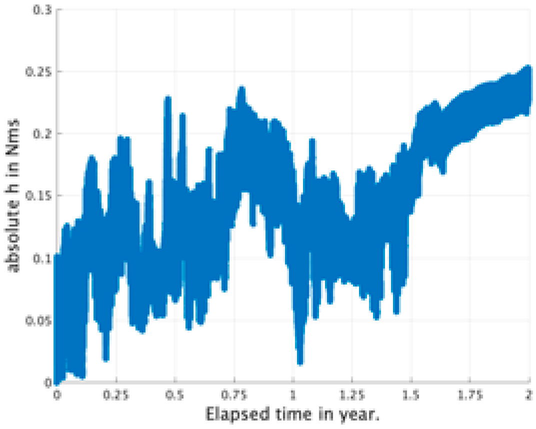
Assumption

- Center of mass deviated by 6% from center of geometry on all axes
- No initial angular momentum

Center of mass	(1) [0.078, 0.030, 0.078] m
Angular velocities	① [0.0, 0.0, 0.0] deg./min.



Norm of angular velocities in deg./min.



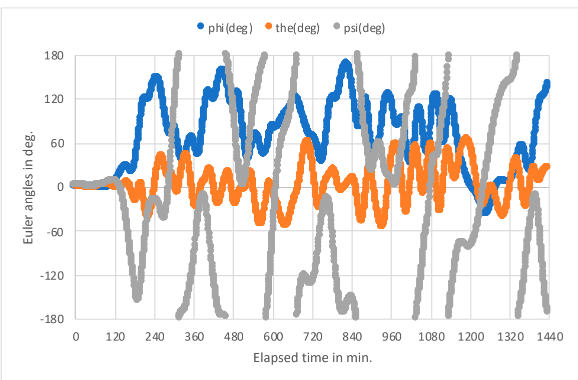
Norm of angular momentum in Nms

1-day analysis

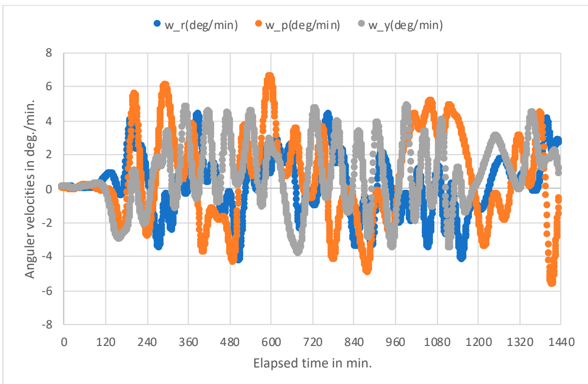
Assumption

- Center of mass deviated by 6% from center of geometry on x axis
- No initial angular momentum

Center of mass	(2) [0.078, 0.000, 0.000] m
Angular velocities	① [0.0, 0.0, 0.0] deg./min.



Attitude angles in deg.



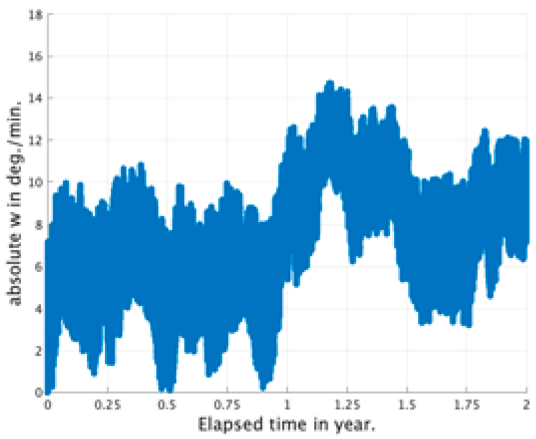
Angular velocities in deg./min.

2-years analysis

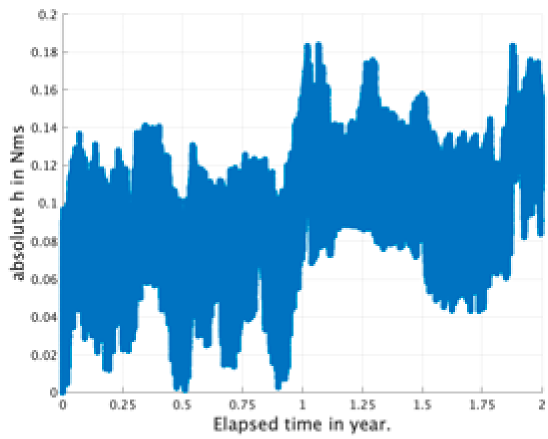
Assumption

- Center of mass deviated by 6% from center of geometry on x axis
- No initial angular momentum

Center of mass	(2) [0.078, 0.000, 0.000] m
Angular velocities	① [0.0, 0.0, 0.0] deg./min.



Norm of angular velocities in deg./min.



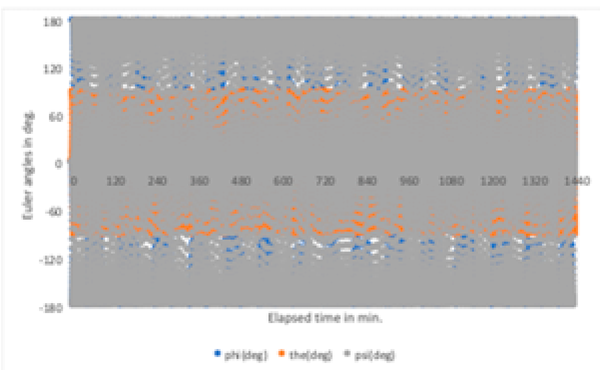
Norm of angular momentum in Nms

1-day analysis

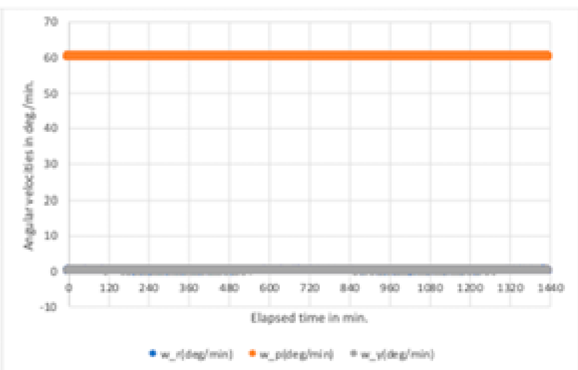
Assumption

- Center of mass deviated by 6% from center of geometry on all axes
- Angular momentum of a reaction wheel (0.42 Nms) on the minor axis of inertia (y-axis)

Center of mass	(1) [0.078, 0.030, 0.078] m
Angular velocities	② [0.0, 60.2, 0.0] deg./min.



Attitude angles in deg.



Angular velocities in deg./min.

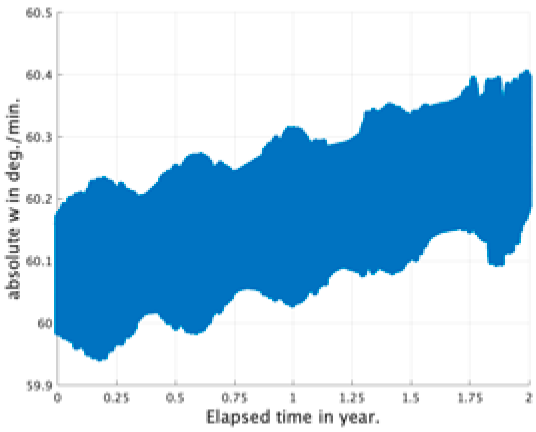
2-years analysis

Both the norm of angular velocities and angular momentum are almost same as the initial values

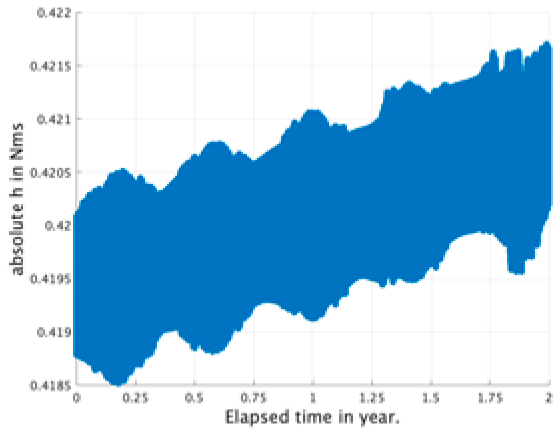
Assumption

- Center of mass deviated by 6% from center of geometry on all axes
- Angular momentum of a reaction wheel (0.42 Nms) on the minor axis of inertia (y-axis)

Center of mass	(1) [0.078, 0.030, 0.078] m
Angular velocities	② [0.0, 60.2, 0.0] deg./min.



Norm of angular velocities in deg./min.



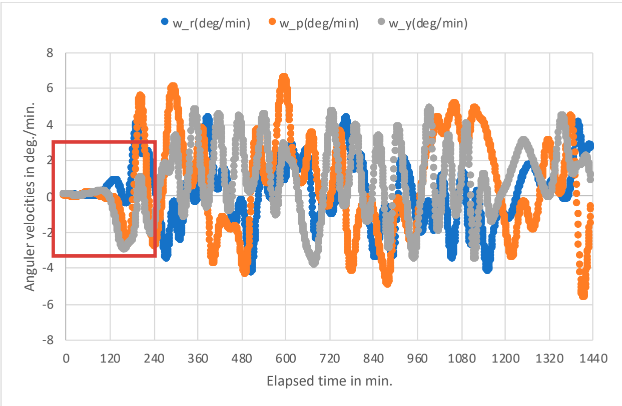
Norm of angular momentum in Nms

Summary

Center of mass	Residual angular momentum	Angular velocities	Angular momentum
6% shift in all axes	Zero	< ±6 deg./min.	Max 0.25 Nms
6% shift in x axes	Zero	< ±6 deg./min.	Max 0.18 Nms
6% shift in all axes	0.42 Nms	Single spin the rate of 60 deg./min.	0.42 Nms

Discussion

- The satellite starts rotating again after a certain period.
- The operation without increasing rotation of the satellite is necessary during the deorbit process.



Conclusion

- This research demonstrates the short-term and long-term variation of Euler angles and angular velocities of the target object in LEO.
- We obtained quantitative analysis of attitude for debris in LEO to clarify mission requirements.

Future work

- Redefinitions of the shift in center of mass and initial momentum are needed after detailed target determination.

B05

経済学からのデブリ問題分析

Overview of Space Debris from Economics

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斉藤 賢爾（早稲田大学）, 花田 俊也, 馬奈木 俊介（九州大学）
NAKAWATASE Ryuji, ○HATTA Shinji, UEDA O. Hiroko (MUSCAT Space Engineering Co., Ltd.),
SAITO Kenji (Waseda Univ.), HANADA Toshiya, MANAGI Syunsuke (Kyushu Univ.)

宇宙ゴミ問題は長期的なグローバルアクションの大切さ及び不確実性の大きさから気候変動と同様の特徴がある．PMD90%実行+ADR5~10 機/Year が低軌道環境維持に必須であることが IADC の取り組みによって明らかにされている．しかし、PMD は実行率が十分に上昇せず、ADR についてはコストの捻出方法が見通せない．技術力の問題もあるが、経済的側面が非常に大きい．過去の経済的側面からの取り組みは、他の環境問題からのアナロジーが多く、体系的とは言い難い．一方、環境経済学はミクロ経済学の一分野として急速に適用範囲が拡大している学問体系であり気候変動の IPCC 等において中心的な役割を担っている．そこで本発表では、この考え方を元に、国際的にデブリ問題並びに PMD と ADR のコストの位置づけを明らかにする．そして、各国が国際的に受け入れられる制度枠組みに要求される課題を検討する．

Space debris is an emerging global environmental problem. PMD of 90% and ADR of 5 to 10 every year is required for maintaining the status of LEO. Fulfillment rate of PMD is, however, still in unsatisfied level and its associated cost of ADR is unclear. This provides the challenge from both of technology and economics. Previous studies on economics of space debris are mostly analogy from environmental problems on the earth. Environmental economics, holding two Nobel Prize winners, can potentially provide key tool to understand this problem. In this study, we provide how environmental economics merits on understanding and solving debris problem including cost of PMD and ADR. Finally, we discuss requirements for economic scheme which are acceptable in international space scene.

Overview of Space Debris from Economics

〇 NAKAWATASE Ryuji (MUSE Co.), HATTA Shinji (MUSE Co.),
SAITO Kenji (Waseda Univ.),
HANADA Toshiya (Kyushu Univ.), MANAGI Shunsuke (Kyushu Univ.)

2020/12/08

9th Space Debris WS @ Chofu Space Center

Background (1)

- Space debris is urgent problem.
- Typical problem of ‘externality’
  - Externality or ‘fault of market’: Cost for mitigating debris is not included in economic activity for space development.
  - Pre-consumption over utility or pushing cost to the future generation.
- Field of ‘environmental economics’
  - Emerging field of economics since 1990s’.
  - Pollution, greenhouse gases, ocean plastics, over development, etc.
- Domestically, it’s not applied for space debris yet.

Background (2)

- Ex. SSR (Space Sustainability Rating) is proposed abroad.
- Letizia et al. Acta Astronautica, 2019

$$I = p_c \cdot e_c + p_e \cdot e_e$$ Effect of collision and explosion

$$I = \int_{t_0}^{\Delta t_{oper}} I(a,i)dt + \alpha\left(\int_{\Delta t_{oper}}^{t_e} I(a,i)dt\right) + (1-\alpha)\left(\int_{\Delta t_{oper}}^{t_l} I(a,i)dt\right)$$

Under operation　Under PMD　Under Natural decay

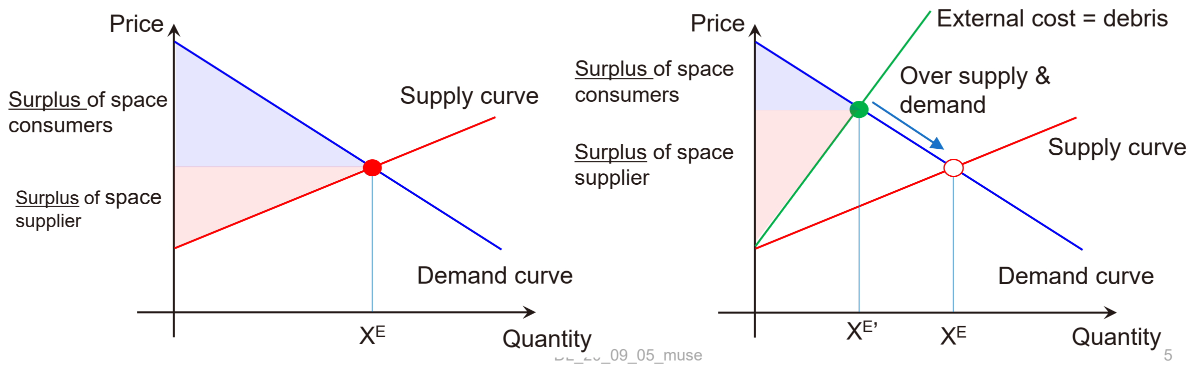
- Discussions are conducted form practical aspects.
- There is no basement for systematic estimation of economical and social influence of SSR to Japan.

Index

- Problem of externality
- Review of past literature.
  [1] Nodir Adilov*, Peter J. Alexander**, Brendan M. Cunningham***, "An Economic Analysis of Earth Orbit Pollution," Environ Resource Econ. 19 Jan. 2014, Springer.
  * Purdue Univ., ** FCC., ***USNA
  [2] Molly K. Macauley****, "The economics of space debris: Estimating the costs and benefits of debris mitigation," Acta Astronautica, volume 115, October–November 2015, Pages 160-164
  ****Resources for the Future (Thinktank)
- Our activity
- Evolution and target

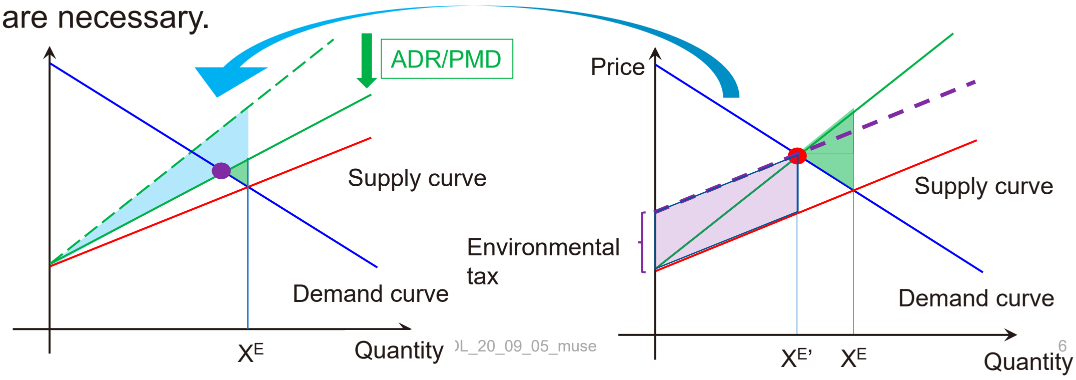
Problem of externality (1)

- External cost: If not, market price falls and goods are over supplied.
- Space consumers and suppliers over enjoy surplus from the development.



Problem of externality (2)

- PMD/ADR lowers inclination of the external cost curve.
  - ‘Environmental/Pigovian tax’ or sales of ‘emission right’ can be applied for the cost for lowering the inclination.
- Appropriate models of demand curve, supply curve, external cost curve are necessary.

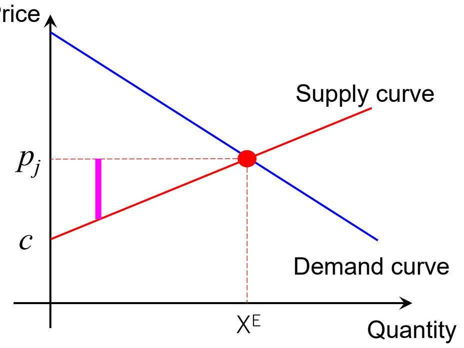


Review of Ref. [1] (1)

- Surplus (or profit) of a space supplier per one unit of space service by a satellite j.

$$\pi_j/q_j = p_j - c - r/q_j - F/q_j$$

π_j : Surplus (Profit)
p_j : Price of a unit of space service
c : Cost for a unit of space service
q_j : Quantity of service by one satellite of a supplier
r : Cost for launching a satellite
F : Fixed cost for operating a satellite



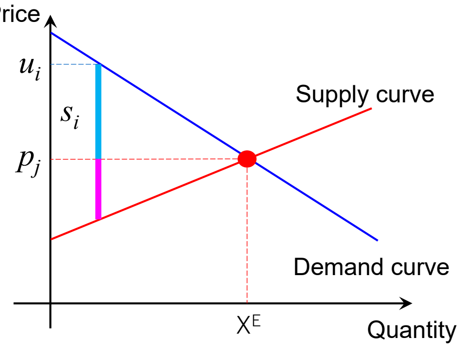
Review of Ref. [1] (2)

- Surplus of a space consumer i per one unit of space service.

$$s_i = u_i - p_j - t \cdot d(i,j)$$

s_i : Surplus which j serves to i
u_i : Utility
p_j : Price of a unit of space service
t : Accessing cost to a space service
$d(i,j)$: Distance for accessing a space service (abstracted inconvenience)

- Evaluation by introducing number of launching L which maximizes or .



Review of Ref. [1] (3)

- Neglecting existing satellites and existing debris. L: number of new launching
- Assuming fully competitive market.
- Assuming total quantity of the demand as one: the demand per a satellite is $1/L$.

Maximizing the suppliers' surplus $L_{com} = \sqrt{\frac{(\beta+(1-k\phi))t}{(1-k\phi)(r+F+\beta(1-k\phi)F)}}$

Maximizing the sum of surpluses of the suppliers and the consumers

$$L_{soc} = \frac{1}{2}\sqrt{\frac{(\beta+(1-k\phi))t}{(1-k\phi)(r+F+\beta(1-k\phi)F)}}$$

β: discount factor, ϕ: probability of a satellite which becomes debris. k : probability of a debris which destroys satellites.

Review of Ref. [1] (4)

- L_{com}, L_{soc} increase as $k\phi$ approaches unity.
  - The decrease of competitors becomes dominant and increase p: the price of services.
- The optimum number of launching for the suppliers is double of that of the whole society.
  - The tendency is similar even if you assume r, launching cost, as a function of preventing debris.
- Assertion and discussion
  - Voluntary approach is not effective.
  - Command and control is ineffective. Its not reasonable to force heterogeneous supplier to obey same regulations or to use same technology.
  - ADR
    - it's not clear how to distribute the cost to consumers.
  - Environmental tax (Pigovian tax) is reasonable.
- ADR should be conducted by some environmental tax.

Review of Ref. [2] (1)

- One Period Model (2011-2030, 2031-2050)
- Analysis of contribution of the number of satellites to the external cost.

- Using 'benefit ' instead of 'utility'. 'Benefit' is usually used for public works.
  - Emphasizing space development as infrastructure.

- Evaluating productivity loss of satellite by debris collision as externality.
  - In Ref. [1], the maximum value of sum of consumers' surplus and suppliers' surplus is used for evaluation of externality.

Review of Ref. [2] (2)

- Assumption
  C: Additional cost for debris including avoidance and defense
  P: Profit of decrease of collisional risks
  R: Rebate
  - Without rebate: Indifferent to the other suppliers' satellites.
    $$C = P$$
  - With rebate: Conscious to the other suppliers' satellites.
    $$C = P + R$$

- Combination of environmental tax & rebate is equivalent to a deposit system

Review of Ref. [2] (3)

- Result: Tax, Graveyard tax and rebate, Avoidance tax & rebate
- Environmental tax & rebate is more effective than straightforward tax

Loss of productivity: 10%, large collision probability

	Tax [M$]	Graveyard tax/rebate [M$]			Maneuver tax/rebate [M$]		
Low (0.003)	0.3	0.2	0.1	0.1	0.3	0.1	0.2
Medium (0.012)	1.2	0.9	0.3	0.6	1.0	0.2	0.8
High (0.020)	2.1	1.6	0.5	1.1	1.7	0.4	1.3

Loss of productivity: 50%, large collision probability

	Tax [M$]	Graveyard tax/rebate [M$]			Maneuver tax/rebate [M$]		
Low (0.0003)	1.2	0.9	0.3	0.6	1.0	0.2	0.8
Medium (0.001)	4.6	3.4	1.2	2.2	3.8	0.8	3.0
High (0.002)	8.0	6.0	2.0	4.0	6.5	1.4	5.1

Our activity (1)

- Previous studies require improvements from viewpoint of engineering.
  - By height of satellites → congestion degree, orbit decay
  - Division of intact objects from the others
- An example of modification;
  - Surplus (or profit) of a space supplier per one unit of space service by a satellite j.

$$\pi_j/q_j = p_j - c - r/q_j - F/q_j - C_m/q_j - C_p/q_j - C_a/q_j$$

C_m ：Avoidance cost for a satellite

C_p ：PMD cost for a satellite

C_a ：ADR cos for a satellite

Our activity (2)

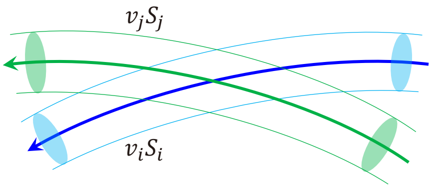
- Ex, we are considering about ‘Filed of utility density’, ‘filed of surplus density’ and ‘field of externality density’ in orbital space.

  v_j: velocity of a satellite

  Π_j : surplus produced by a satellite per unit time

  S: area of a circle which has avoidance distance

  π_j: density of the orbital space



$\Pi_j \propto v_j S_j \pi_j$ then, $\pi_j \propto \Pi_j/(v_j S_j)$

- If another satellite pass the orbit with v_i with avoidance radius of S_i,

$$\Pi_i \propto \Pi_j \frac{v_i S_i}{v_j S_j}$$

Next evolution and the target

- Prediction of appropriate cost for the orbital space utilization
- How to raids the funds for ADR
  - Orbital space utilization tax
  - Trading of launching
  - Deposit system for PMD/ADR
- Considering economical impact on satellite enterprise, ADR enterprise, space industry and whole society

- Important is, the externality is not from debris but from the moment of launching.

B06

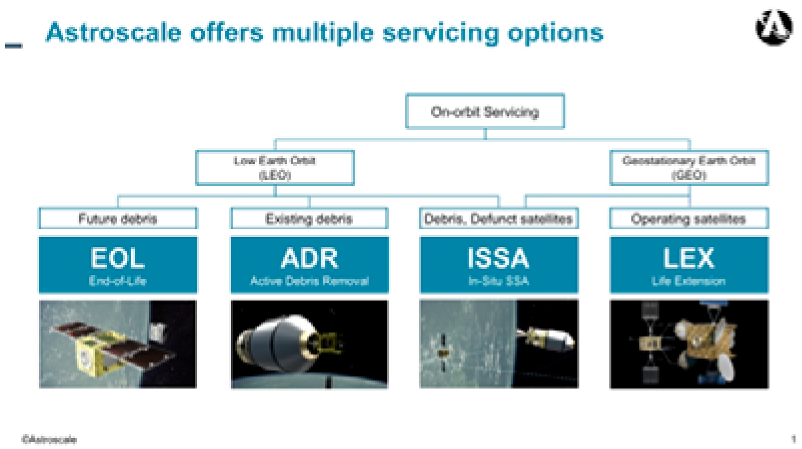
アストロスケールが取組む RPO 技術
−低軌道デブリ除去から静止軌道での軌道上サービスまで−

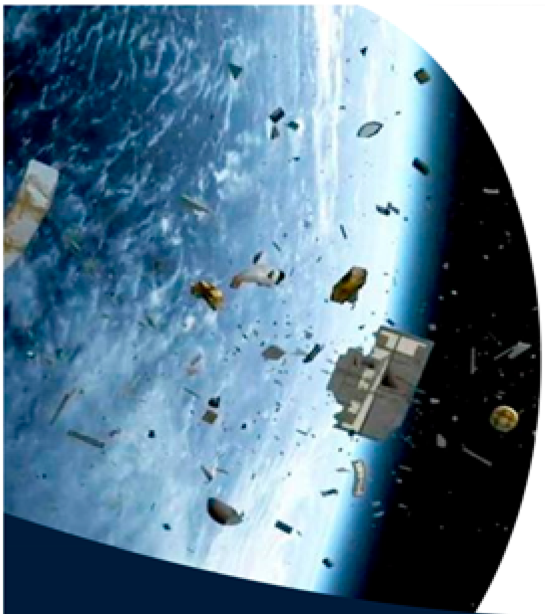
Leading the Development of an On-orbit Servicing Economy

○岡田　光信（アストロスケールホールディングス ）
○OKADA Nobu (Astroscale Holdings Inc.)

世界5カ国で 140 名以上を擁する、アストロスケールグループは、コアとなる「宇宙空間の非協力物体に対する RPO 技術」を用い、衛星オペレーターやロケット事業者へ安全で持続可能な事業継続に貢献することをミッションに、低軌道から静止軌道で以下4つの軌道上サービスを提供します。
①衛星運用終了時の除去サービス（End-of-Life Service：EOL）低軌道
②既存デブリの除去サービス（Active Debris Removal：ADR）低軌道
③軌道上観測サービス（In-situ Space Situational Awareness：ISSA）低軌道/ 静止軌道向け
④衛星寿命延長サービス(Life Extension Service：LEX) 静止軌道
セッションでは、当社提供の上記のサービスの内容とビジネスモデル、複数の関係企業・団体・機関と協働する、宇宙政策に関わる法規制への取り組みもご紹介します。

Astroscale has a growing team of over 140 people in five countries and is contributing to the safe and sustainable business continuity of satellite operators and launch service providers by using its core "RPO technology for non-cooperative objects in outer space". Astroscale is developing innovative solutions across the spectrum of on-orbit servicing missions and across all orbits including (1) End-of-Life services (2) Active Debris Removal (3) In-situ Space Situational Awareness and (4) Life Extension. In the presentation, we will provide an overview of our technical solutions, as well as discuss how we are working to define the business cases and working with government and commercial stakeholders to develop norms, regulations and incentives for the responsible use of space.





Astroscale

Leading the Development of an On-orbit Servicing Economy

9th JAXA Space Debris Workshop

Astroscale Holdings Inc.
February 25, 2020

On-orbit Servicing (OOS)

Space is not Sustainable

More than 25,000 objects larger than 10cm. Only 3,200 of them are active satellites*.
Both accidents and intentional breakup events can produce large quantities of orbital debris that remain as threats for years or centuries.
Because all objects travel at extremely high speeds, even very small ones can destroy active satellites or endanger astronauts.

LEO
(Low-Earth Orbit)
Takes 90 minutes to circle Earth.
Travelling at 7-8km/sec and takes at altitude of 200-2,000km

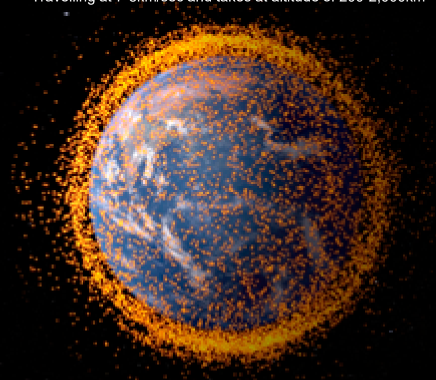


Image: © NASA Goddard Space Flight Center

* As of September 2020

GEO
(Geostationary Orbit)
Travelling at exactly the same rate as Earth (24 hours/day).
The speed is 3km/sec at an altitude of 36,000km

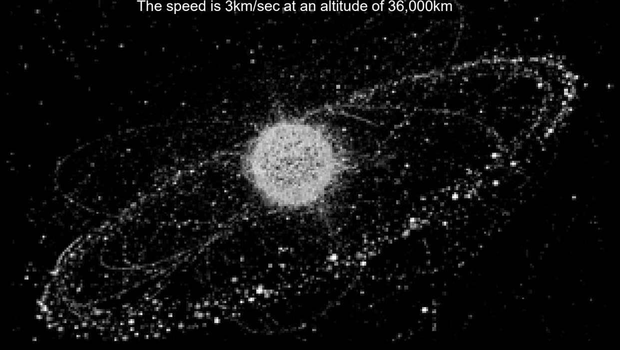
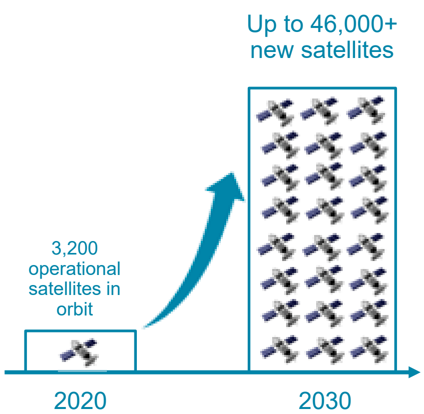


Image:: ESA
(https://www.esa.int/Safety_Security/ESA_and_the_United_Nations_team_up_for_space_debris)

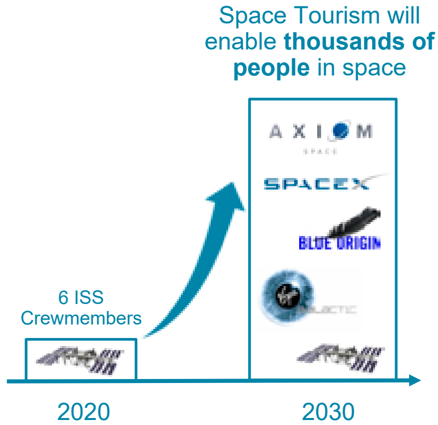
3

As space becomes more congested, safety is essential

Uncrewed Spacecraft



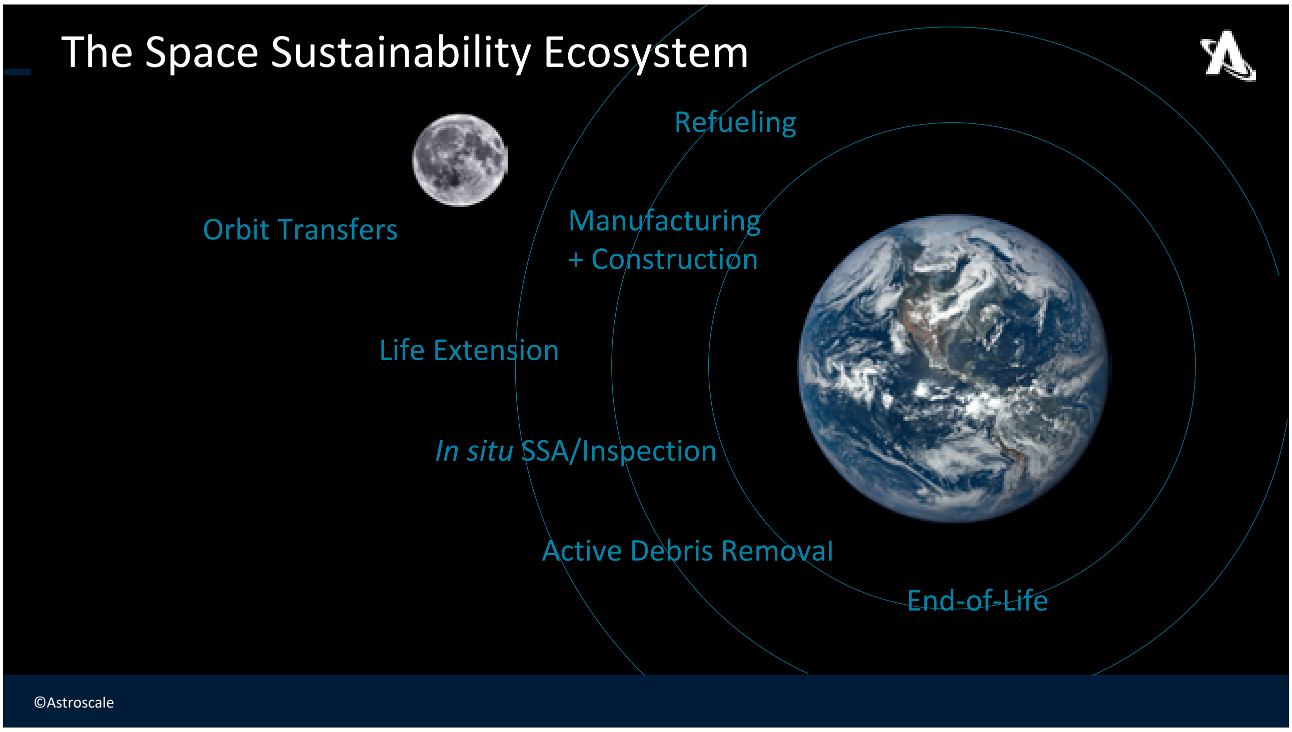
Crewed Spacecraft



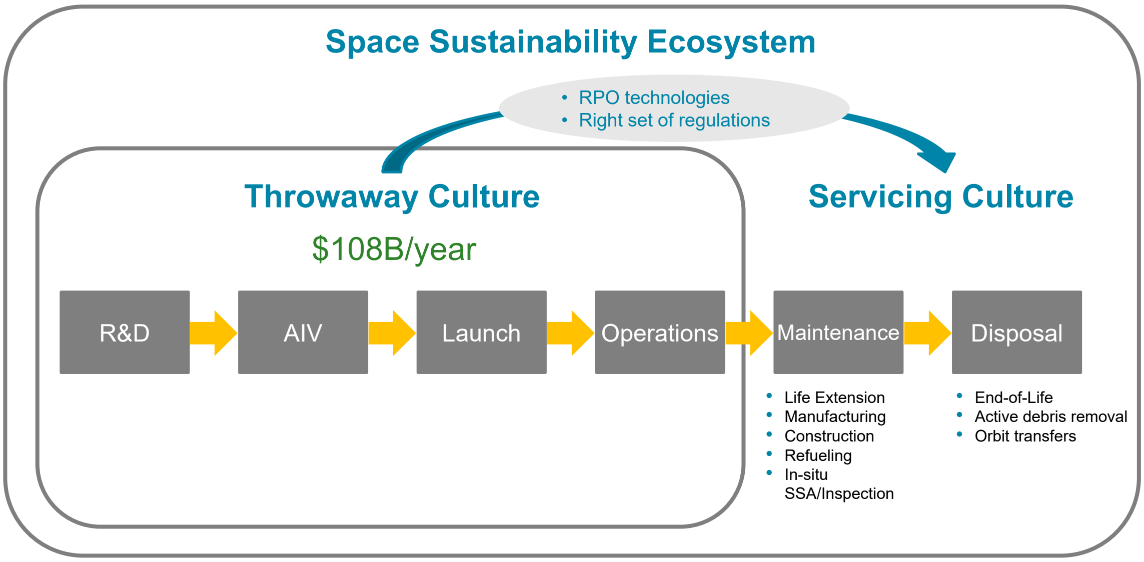
Source: Aerospace Corporation

4


What is Space Sustainability?
It's to Clear Orbital Highway.


The Space Sustainability Ecosystem
Refueling
Orbit Transfers
Manufacturing
+ Construction
Life Extension
In situ SSA/Inspection
Active Debris Removal
End-of-Life
©Astroscale

On-orbit servicing expands the value chain



 7

So.. what does space sustainability really mean?

A Net Positive.

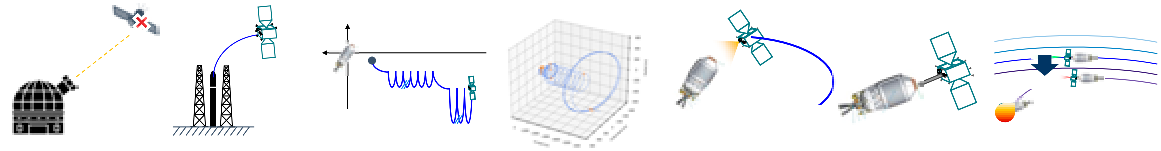
Company Overview

_ We are a global company solving a global problem

- 5 offices
- 170 members
- $191M
- >20 awards
- Key roles
- Multiple business lines for OOS

Core Technologies – RPO Technologies

①Observe client	②Launch	③Far-range approach	④Short-range approach	⑤Diagnosis and Fly-around	⑥Capture	⑦De-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.	Client fixed point and orbital observation. Fly-around the client and match the momentum (tumbling).	Capture with 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.

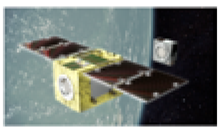
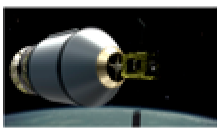
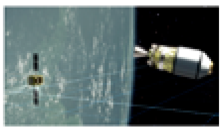
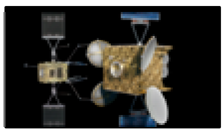


RPO Technology (Rendezvous and Proximity Operations)

Astroscale Offers Multiple Servicing Options

Securing sustainability across orbits by leveraging rendezvous and proximity operations technologies

On-orbit Servicing
- Low Earth Orbit (LEO)
- Geostationary Earth Orbit (GEO)

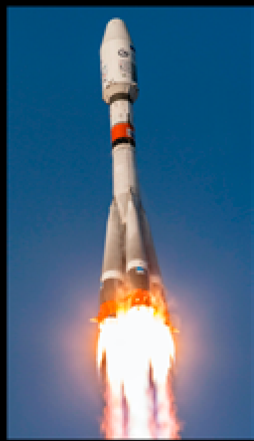
	Future debris	Existing debris	Defunct objects	Operating satellites
Segment	**EOL** End-of-Life Service	**ADR** Active Debris Removal	**ISSA** In-Situ SSA	**LEX** Life Extension Service
Servicer				
Client	Commercial and Government Defunct satellites from constellations	**Government** Existing debris (used rocket bodies, defunct satellites)	**Commercial and Government** Defunct satellites and unknown objects	**Commercial and Government** GEO satellites reaching end of life

ELSA-d

World’s first end-to-end debris removal demonstration

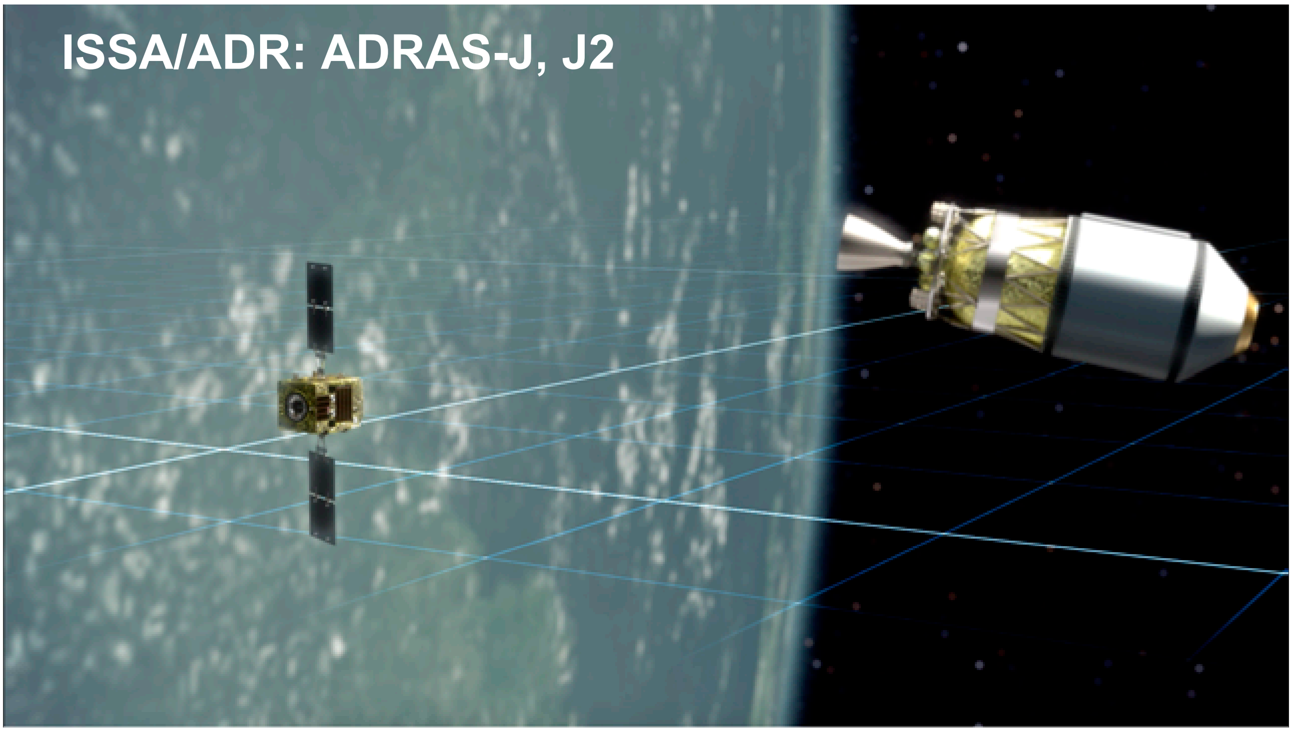
Test
(Early 2020)

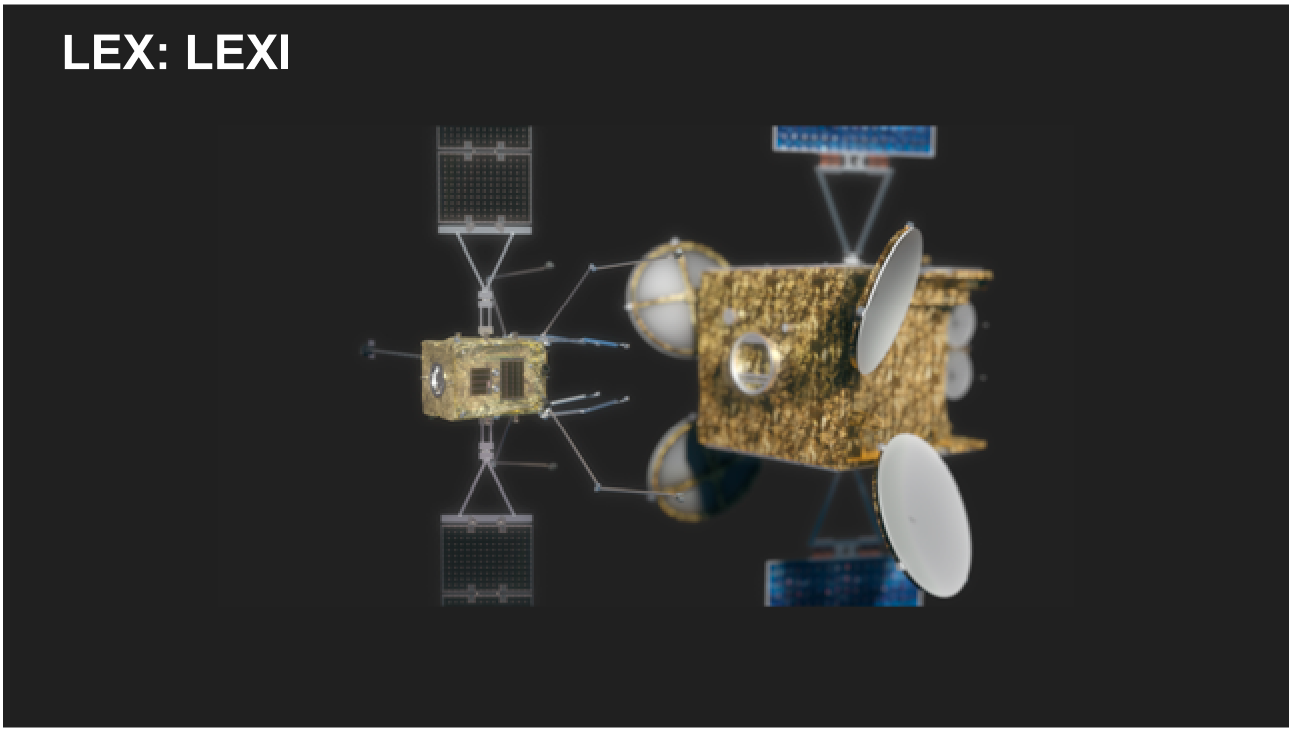
Shipment
(Dec 2020)



Launch
(Mar 20, 2021)

ISSA/ADR: ADRAS-J, J2




LEX: LEXI


In-Orbit Servicing Control Center National Facility, Harwell, UK

– We contribute to developing norms, regulations and incentives for the responsible use of space

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B07

スペースデブリ問題に係る規制・政策のトレンド、宇宙交通管理（STM）の議論について

Recent regulation trend on space debris and Space Traffic Management(STM)

○岩本 彩（アストロスケール）
○IWAMOTO Aya (Astroscale Japan Inc.)

米国においては、2019 年 11 月に軌道上デブリ低減標準プラクティス（Orbital Debris Mitigation Standard Practices (ODMSP) ）の見直しが行われた他、現在、米連邦通信委員会（FCC）によるデブリ低減ガイドラインの見直しの議論が行われており、米連邦航空局（FAA）も軌道上デブリについて、近く提案とそれに対するパブリックコメント（Further Notice of Proposed Rulemaking（FNRPM））が公表される見込み。これら米国内におけるデブリ規制の見直しにおける論点（FNPRM）を考察し、議論の傾向・米国内の議論がグローバルなデブリ規制の議論に与える影響を考察する。更に、これらの動きが将来の STM（宇宙交通管制：Space Traffic Management）の議論に与える影響についても考察する。

To address the increase in orbital debris in the near-Earth space environment, the United States Government Orbital Debris Mitigation Standard Practices (ODMSP) was updated in November 2019 and the Federal Communications Commission (FCC) is currently reviewing their debris reduction guidelines. The Federal Aviation Administration (FAA) is also expected to publish a proposal and a public comment (Further Notice of Proposed Rulemaking (FNRPM)) on orbital debris soon. In this presentation, we will consider these recent updates on debris regulation in the United States, and consider the impact on global debris regulation discussions. Furthermore, we will highlight the impact of these updates on future Space Traffic Management discussions.

スペースデブリ問題に係る規制・政策のトレンド、宇宙交通管理（STM)の議論について
Recent regulation trend on space debris and Space Traffic Management(STM)

第９回 JAXA スペースデブリワークショップ the 9th Space Debris Workshop

株式会社 アストロスケール Astroscale Japan
岩本（大工原）彩 / Aya Daikuhara Iwamoto, Lead, Japan Space Policy

_内容 contents

- スペース・デブリ低減策の最近の傾向
  Updates on Space debris mitigation efforts
- STMの議論の最近の傾向
  discussion on STM (mainly on national aspect)
- まとめ 将来の論点 summary and what’s next?

1　デブリ低減策の傾向
update on Space debris mitigation efforts

全体像　overall picture- space debris mitigation

多国間枠組み Multilateral (State)
- **Legally-binding**: There is no legally-binding treaty that directly deals with debris mitigation/remediation
- **Soft law/ Voluntary**: UNCOPUOS Space debris guidelines（２００７）　ITU Recommendation（ITU-R-S,1003)
  UNCOPUOS LTS guidelines（２０１９）

宇宙機関間組織 Inter-space agency
IADC Space debris mitigation guidelines（2002, recently updated in 2020）　※technical standards
ESA space debris mitigation XXXX（2004）

国際標準化機関 International technical standard
ISO 24113(2019)

Inputs?

Need domestic measures to implement these guidelines.

Today's focus

国内措置 Domestic measure (laws, regulations, Guidelines)
US　商業打上げ法（51 USC Chapter 509）、space debris mitigation guideline (FCC, FAA)
ODMSP
JAPAN　Space Activity Law
日本　宇宙活動法　衛星打上げ・運用許可申請の際の規制として適用

Inputs?

産業界の取組 Industry
Satellite Industry Association (SIA)のSpace Sustainability guidance
World Economic Forum : Space Sustainability Rating (SSR)

How to incorporate best practices/guidelines among commercial industry

_米国の事例　Case Study- The U.S

SPD-3 and review process of existing guidelines on space debris mitigation

Space Policy Directive 3(SPD-3) (June 2018)
米国大統領令第3号（SPD-3）（2018年6月）

Sec. 6 Roles and Responsibilities
(b) Mitigation of the Effect of Orbital Debris on Space Activities

- NASA Administrator, in coordination with other related agencies, shall lead efforts to update the U.S. Orbital Debris Mitigation Standard Practices and establish new guidelines for satellite design and operation, as appropriate and consistent with applicable law.
- The Secretaries of Commerce and Transportation, in consultation with the Chairman of the FCC, will assess the suitability of incorporating these updated standards and best practices into their respective licensing processes, as appropriate and consistent with applicable law.

2019 revised Government Orbital Debris Mitigation Standard Practices（OSMDP）
2019年　OSMDP改訂版公表

FCC space debris mitigation guideline 2020 April R&O, ongoing FNPRM
米連邦通信委員会（FCC）のデブリ低減ガイドライン見直し（見直し実施中）

FAA

NOAA's debris mitigation guidelines

Applied for USG space activities
米国政府衛星・政府の宇宙活動に適用

Guidelines applied for licensing for commercial satellites
民間企業に対して適用。ミッションライセンス付与の際に考慮される

_米国の事例　Case Study- The U.S

Orbital Debris Mitigation Standard Practices：ODMSP

- ODMSPは米国政府機関によって運用・調達されたミッションに適用。The ODMSP apply to missions operated or procured by U.S. government agencies.
- 2001年の策定後初めての改定。2019年12月に公表。The first update since 2001. The revised ODMSP was released Dec 2019.
- 今後国際的なガイドラインに発展させることが念頭に置かれている。The ODMSP intends to provides a guideline for USG activities and provides a reference to domestic and international operators.
- 今後の技術の進歩や政策の変更に対応するために更新が必要との認識。The USG intends to update and refine it as necessary in the future to address advances in both technology and policy.

Objectives/Elements	2001 ODMSP	2019 ODMSP
Obj. 1. Mission-related debris (area-time product limit)	—	Less than 100 object-years per upper stage or spacecraft in LEO.
Obj. 2. Accidental explosion probability limit	—	Less than 0.001 during deployment and mission operations.
Obj. 3. Accidental collision probability (with large debris)	—	Less than 0.001 during orbital lifetime.
Obj. 3. Accidental collision probability (with small debris)	—	Less than 0.01 during deployment and mission operations.
Obj. 4. Preferred disposal option	—	Immediate removal from Earth orbit (direct reentry or Earth escape).
Obj. 4. PMD storage between LEO and GEO	GPS ± 500 km no-crossing, keep out zone.	1. Allow low-risk, eccentric (such as GEO transfer orbit) PMD storage and limit GPS ± 300 km zone dwell time to less than 25 years over 200 years. 2. Allow near-circular PMD storage and avoid crossing GPS ± 300 km for 100 years and limit the risk to other operational constellations.

Objectives/Elements	2001 ODMSP	2019 ODMSP
Obj. 4. PMD storage above GEO	Maneuver to GEO + 300 km.	Maneuver to GEO + 200 km and stay away for 100 years.
Obj. 4. Long-term reentry	—	Allow a new, long-term reentry option (using orbital resonances) while limiting potential risks associated with the new option.
Obj. 4. Direct retrieval (time constraint)	As soon as practical after completion of mission.	Preferably at completion of mission but no more than 5 years after completion of mission.
Obj. 4. PMD reliability	—	No less than 0.9 with a goal of 0.99 or better.
Obj. 4. Reentry human casualty risk (impact kinetic energy)	—	Exclude surviving components with impact kinetic energies less than 15 joules.
Obj. 5. Large constellations	—	Provide 2 guidelines on how to establish PMD reliability limit. Identify immediate removal as the preferred disposal option.
Obj. 5. Small satellites, including CubeSats	—	Clarify the applicability of the ODMSP to small satellites, including CubeSats. Establish a 100-object-years per mission limit for satellites smaller than 1U CubeSats.
Obj. 5. Rendezvous, proximity operations, and satellite servicing	—	Provide guidelines on mitigating unique risks associated with the operations.
Obj. 5. Safety of Active debris removal operations	—	Provide guidelines on mitigating unique risks associated with the operations.

2019年の最新版では、2001年版で取り上げられなかった以下の事項が含まれている。
Below are introduced to the 2019 version.

- 処分方法のオプション options for disposal
- 運用終了後の処分（PMD）の確実性 PMD reliability
- 大型コンステレーション(100以上） large-constellation
- RPO(ランデブー・接近運用）、衛星サービス RPO and satellite servicing
- 能動的デブリ除去（ADR)の安全性 the safety of ADR

米国の事例　米FCC　Case Study- FCC

- FCCは2004年にデブリ低減ガイドラインを策定。小型衛星の数の増加、メガコンステレーションの登場などの宇宙をめぐる環境変化を踏まえて、2018年11月から見直しプロセス開始。The Commission first adopted comprehensive rules on orbital debris mitigation in 2004 and this is the first revision. The changes include the increasing use of lower-cost small satellites, such as CubeSats, as well as plans for the deployment of large constellations of non-geostationary orbit systems, some involving thousands of satellites.
- 2020年4月に同ルールを改定し（Office of management and Budgetの承認を得たのちに効力を生じる。、一部の論点は継続協議。FCC issued R&O (Rule and Order) in April, 2020 and also seeks comment in a Further Notice of Proposed Rulemaking (FNPRM) on several issues with divergent views.
- 本件ルールはFCCがライセンスを付与する全ての衛星及び米市場へのアクセスを認められた国外の衛星に適用される。The Commission's orbital debris rules cover all Commission-licensed satellites and satellites granted access to the U.S. market.

2020年4月改訂版の主な内容(Report and Order) Major updates made in April 2020
申請時に必要となる衛星運用者からの情報開示の要件・内容の明確化 the new rules improve the specificity and clarity of rules that require disclosure of debris mitigation plans by satellite companies.
衝突リスクへの数値の導入　numerical values to collision risk
PMD成功率　probability of successful post-mission disposal
大気圏に再突入する衛星により引き起こされる人的な損害リスク casualty risk associated with those satellites that will re-enter earth's atmosphere
その他、有人の宇宙機保護、マヌーバビリティ、衛星放出機構、残存する液体、接近運用、追跡可能性、SSAのための情報共有などに係る情報開示など new disclosure requirements related to protecting inhabitable spacecraft, maneuverability, use of deployment devices, release of persistent liquids, proximity operations, trackability and identification, and information sharing for situational awareness.

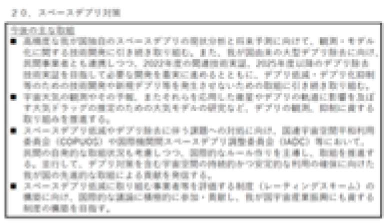
現在FNPRM(提案の告示とパブコメ)に付されている主な論点 Issues that additional comments are invited （FNRPM)
偶発的な爆発の確率の導入　the probability of accidental explosions
「衛星コンステレーション」について、衝突リスクと人的損害リスクをコンステレーション全体で計算するべきか否か。 collision risk and casualty risk for satellite constellations on a system-wide basis
LEOの特定の軌道上におけるマヌーバビリティー要求 requiring maneuverability for space stations located above a certain altitude in the low earth orbit region
・25年ルール見直し limiting post-mission orbital lifetime/ the revision of so called 25 year rule?
・(政府の)免責及びPMDの成功率と結び付けられた保証金 an indemnification requirement and a surety bond tied to post-mission disposal

日本の事例 The case study Japan

政府の取組　initiative by the GOJ

The Basic Plan on Space Policy

工程表 Road map



vi Space debris management – Developing technologies for removing and mitigating space debris and leading international rulemaking.

- 平成28年の基本計画において、スペース・デブリは、宇宙政策を巡る環境認識として言及。工程表に具体的な項目なし。
- Space debris was merely mentioned as one of surrounding issues for space policy in 2016 version of the plan and there was no mention in the road map.

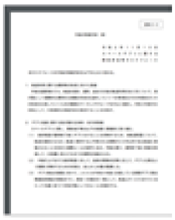
- 令和2年度版においては、スペース・デブリは、宇宙政策の目標と具体的なアプローチの一つとなり、工程表においてもスペース・デブリ対策が項目として建てられた
- In the 2020 version, the space debris issues are identified as one of the policy goals and approaches. The new section on space debris issues are added in the roadmap.

- 環境省における、GOSATの事業主体として、適切な運用と適正な処分を行う責任を持つため省内検討チームの設立と中間取りまとめの発表。
- Ministry of Environment has launched own initiative to discuss proper operation and disposal of GOSAT and its mid-term report on the internal discussion.

Souce: CAO website;
出典　内閣府宇宙開発戦略推進本部ウェブサイト

日本の事例 The case study Japan

第4回 スペースデブリに関する関係府省等タスクフォース大臣会合 （2020年11月10日開催）
The 4th meeting of the Task Force by related ministries on space debris (Nov 11, 2020)



今後の方針として、関係省庁に対して、以下の措置について積極的に取組むよう求める

- 政府衛星の運用終了後のデブリ化抑制。
- 今後打ち上げる政府衛星について、予めデブリ化を抑制するための対策を講じる。

The related ministries are requested to take proactive measures on the following

- Post mission disposal of government satellites to restrain them becoming space debris
- Take measure to prevent government satellites becoming space debris for future launches.

Souce: CAO website;
出典 内閣府宇宙開発戦略推進本部ウェブササイトhttps://www8.cao.go.jp/space/taskforce/debris/dai4/gijisidai.html

環境省：スペースデブリ問題に関する省内検討チーム設置と中間報告の発表
MOE: the establishment of study group on space debris issues and releasing the mid-term report on GOSAT

中間報告書のポイント

- 平成30年の宇宙活動法施工前に打上げられた衛星について、環境省が率先してデブリ化防止に向けた方向性を整理Satellites launched before 2018, MOE take initiative to study measures to prevent those satellites becoming debris.
- GOSATのデブリ化のリスク低減のためには、衛星が利用可能な状態であっても、後継機へのミッションの継続性がかくんんされた段階での運用終了が望ましい。It is desirable to terminate the mission when the continuation to the successing satellite is confirmed though the satellite itself is functioning.
- 検討結果の国内外への発信によるデブリ防止対策の機運の向上。To increase awareness on the issue both in Japan and abroad by disseminating the result of the study.

（出典：環境省ウェブサイト https://www.env.go.jp/press/108494.html）

9

産業界の取組 The case study- industry

The space industry has been actively raising own voice: inputs their opinion on the reviews conducted by USG.

The USG listens intently to the U.S. commercial space community to hear industry's best practices and standards.

The Satellite Industry Association

米国のtrade association。The Satellite Industry Association (SIA) is a U.S.-based trade association
デブリ低減を含む宇宙活動に係る原則を公表。It publishes the space safety principles on its website.
https://sia.org/policy/space-debris-mitigation-sustainability/

Space Safety Coalition (SSC)

- SSCは、宇宙関連企業、関連団体などの４０の参加主体からなるアドホックの組織。The Space Safety Coalition (SSC) is an *ad hoc* coalition of companies, organizations, and other government and industry stakeholders. There are 40 endorsees as of Nov. 2020.
- 2019年９月に「Best Practices for the Sustainability of Space Operations」を公表。既存の宇宙ガバナンスのギャップを明らかにし、よりよいプラクティスを促すことを目的とする。The SSC published "Best Practices for the Sustainability of Space Operations" in 2019 to address gaps in current space governance and promote better spacecraft design, operations and disposal practices aligned with long term space operations sustainability.
- スペースデブリについて、運用終了から5年以内のでオービット終了を呼びかけ。There is one provision calls on satellite operators to complete the deorbiting of their satellites at the end of their lives within five year.

◆ 民間企業の間では、25年ルールを含め、既存のデブリ低減策では十分ではないとの認識が存在していることの現れ。また、既存の規制を超える内容のベストプラクティスを民間企業が提案していることは注目に値する。This shows that there is a general recognition among commercial space operators that existing mitigation guidelines are not sufficient including the so called 25 years rule.

 出典 source https://spacesafety.org/ https://spacenews.com/new-coalition-seeks-to-improve-space-safety/

10

2 Space Traffic management (STM)
STM関連の動向

はじめに　to begin with… What is STM?

STMについて国際社会のコンセンサスのある定義やスコープはない。
しかし、宇宙活動の安全に関するものであることは共通。

No shared definition of STM. The Goal of STM is to enhance safety operation in space

IAA "Cosmic Study on Space traffic management"(2006)

"...the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference."

→ スコープとしては、開発・製造段階、打上げ、運用、EOL、大気圏再突入まで。スペクトラム含む。
有害な干渉なく宇宙活動を実施するための適当な手段

Space Policy Directive-3, National Space Traffic Management Policy of the U.S. (2018)

"the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.
→宇宙活動の調整に焦点か。

はじめに　to begin with… What is STM?

STMはコンセプト。人により範囲、内容、レベルなどの違いに留意→明確に

国際的なレベルなのか、国内のレベルの話なのか
Global level or national level？

技術的なシステムのことなのか、レジーム（ルールや規制）の話なのか。**Technical System(e.g. SSA) or rule/regime/regulation?**

トップダウンかボトムアップのアプローチを想定しているのか
Top Down or Bottom up?

包括的かビルディング・ブロックか？
Comprehensive approach or building blocks?

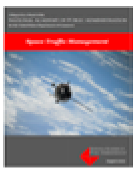
管理か調整か、強制か
Management or Coordination or Enforcement?

国ごとの実施の積み上げ、各国の措置の積み上げ→国際的なharmonization・均てん化というボトムアップが一番現実的
Focuses on incremental the bottom up approach with wider participation

米国の事例　Case Study- The U.S

Organizational: Civil SSA/STM agency　STM/SSAに係る国内の組織とシステムの整理

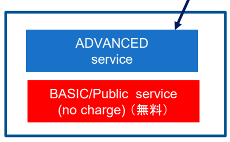
SPD-3
- Civil SSA/STMの役割を国防総省（DOD）からcivil agency（商務省（DOC））に移管するよう指示。（議会の承認待ち）
- Tasks the civil SSA/STM agency's role from DOD to DOC so that DOD can focus on SDA and national security.



National Academy of Public Administration 報告書 (NAPA report) (August 2020)

- 米議会の要請により、安全保障分野以外でのSTMの機能を担うのに適当な当局を検討。
→米商務省がlead agencyとなることが適当
At the request of the Congress, the report identifies Office of Space Commerce, DOC as best suited to lead STM function outside of the national security sphere.

民間SSAサービス・プロバイダーを活用（有料を想定。）
報告書では、定義は敢えて行わず。

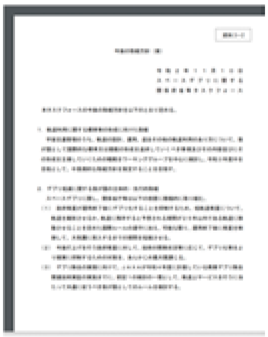


FAA Streamlined Launch and Reentry Licensing Requirements (SLR2) (Oct, 2020)

- FAA（連邦航空局）が、打上げ・再突入関する許可の要求をより簡素化・柔軟なものとするべく改訂。全ての商業的な宇宙機の打ち上げと再突入について共通のライセンスや安全規則が適用される、一つのライセンスで複数回の打上げが可能となる（異なる射場含め）。パフォーマンスベースの規制。

日本の事例 The case study Japan slowly but surely

第4回 スペースデブリに関する関係府省等タスクフォース大臣会合 （2020年11月10日開催）
The 4th meeting of the Task Force by related ministries on space debris (Nov 11, 2020)



Souce: CAO website;
出典　内閣府宇宙開発戦略推進本部ウェブサイト
https://www8.cao.go.jp/space/taskforce/debris/dai4/gijisidai.html

- 宇宙交通管理として、軌道設計、運用、退去その他の軌道利用のあり方について、我 が国として国際的な標準又は規範の形成を追求していくべき事項及びその内容並びにそ の形成を主導していくための戦略をワーキンググループを中心に検討し、令和3年度中を 目処として、中長期的な取組方針を策定することを目指す。
- JAXAが令和４年度に計画している商業デブリ除去関連技術の実証までに、軌道上サービスを行うにあたっての日本としてのルールを検討。

→ 日本政府として、省庁横断的に宇宙交通管理を公式に議論するのは初の取組。(STMの概念に該当するものは、活動法上部分的に存在するも、STMとして議論するのは初。）

- To develop mid to long term guidelines on issues related STM as orbit planning operation, de-orbiting, that includes setting up a working group to discuss them.
- To discuss domestic rules relating OOS prior to the launch of phase 1 of CRD2 project by JAXA.

It is the first time for GOJ to discuss on rules on STM with related ministries.

欧州の例　The Case of EU Horizon 2020

SPACEWAY

- 18ヶ月間にわたる１５０万ユーロのプロジェクト。EUにとってのSTMの概念を構築するために必要となるガイドライン・標準についての共通の認識の形成を行う。STMの要件に関連する能力（SSA/STM技術）の評価し、**EUの利益に合致する**STMに関するベスト・プラクティスの提供も目的とする（これらには、宇宙環境の安全保全、安全保障及び持続可能性の保全とEUの主権と競争力の強化も含む。

to create a common understanding of the guidelines and standards necessary to develop a Space Traffic Management (STM) concept for the European Union (EU). It also aims to assess European technical available and required capabilities (notably in the field of SSA/SST technologies) with respect to STM requirements; and to provide a set of STM best practices and recommendations in line with EU interests. This includes the preservation of a safe, secure and sustainable space environment as well as the reinforcement of European sovereignty and competiveness.

(source: https://cordis.europa.eu/project/id/101004208)

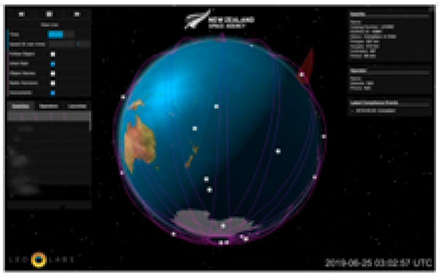
- 二つの委託調査　two feasibility studies

PERASPERA: Space Robotics Technologies

- 2014年からHorizon2020の一部として欧州委員会が拠出。ESAがコーディネーターで、ASI, CDTI, CNES, DLR, POLSA, UKSAが参加。
- 宇宙のロボティックス技術が欧州の宇宙セクターの競争力の鍵となる技術であると特定されたことを受けて、the “Space Robotic Technologies” Strategic Research Cluster (SRC)が設立。

NZの事例　軌道上の活動の監督への動きになるか？
The Case of NZ – new trend for oversight on orbit?

Regulatory Platform for Low Earth Orbit



- NZ宇宙庁（NZSA)とLeoLabs社が2020年7月に発表
- LeoLabs社から提供されるデータに基づいて、NZSAがラインセンスを付与したLEO上の物体の監督（宇宙法の遵守状況を監視）を行う。
- 本プラットフォームを通じて、NZSAは、物体の位置、将来の位置・軌道、過去の軌道歴、軌道変更の情報の入手、ライセンス条件を遵守しない場合のアラートを入手可能。
- 将来的には、衝突予測や大気圏再突入位置の予測なども行われる予定。

"The mission of the NZSA is to provide leadership and regulatory oversight for our rapidly expanding space sector. Critical to achieving this mission is putting in place the tools and capability to monitor and ensure responsible and sustainable behavior. "
- Peter Crabtree, general manager of New Zealand's Ministry of Business, Innovation and Employment

（出典）LeoLabs社プレスリリース https://www.prnewswire.com/news-releases/leolabs-and-new-zealand-space-agency-unveil-regulatory-platform-for-low-earth-orbit-300874417.html,

LeoLabs and New Zealand announce tool to monitor low Earth orbit activity
by Debra Werner — June 25, 2019, Spacenews https://spacenews.com/leolabs-and-new-zealand-announce-tool-to-monitor-low-earth-orbit-activity/

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産業界等の取組　The case study- others

Best Practices ベストプラクティス

産業界から、よりproactiveな規制やルールを求める声。自主的にベストプラクティスを作成

The Space Safety Coalition

The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS)

■ 概要
軌道上サービス（OOS)とランデブー接近運用（RPO)に関する、法的拘束力のないコンセンサスベースでの技術的・運用上の標準を研究・作成・公表を政府や産業界に促すことを目的とする。
CONFERS is the iindustry-led initiative with initial seed funding provided by the Defense Advanced Research Projects Agency (DARPA) that aims to leverage best practices from government and industry to research, develop, and publish non-binding, consensus-derived technical and operations standards for OOS and RPO
■ 各種ガイドラインを作成し、公表。 The CONFERS published related guidelines.

- Guiding Principles for RPO and OOS (published Nov 2018)
- Design and Operating Practices (updated Oct 2019)
- On-orbit Satellite Servicing Mission Phases (published Oct 2019)

https://www.satelliteconfers.org/about-us/

IAF- IISL-IAA MOU

データ共有　Data Sharing

宇宙データ協会（Space Data Association)

■ 衛星運用者の間でデータ共有を行うために2009年に設立された国際的な産業界の団体。主要な通信衛星企業をメンバーとする。

Formed in 2009, the SDA aims to enhance safety of flight via sharing of operational data and promotion of best practices across the industry. The SDA is also working to improve the accuracy and timeliness of collision warning notifications, as well as working with all interested entities to help define the next generation of STM systems and capabilities.
https://www.space-data.org/sda/about/sda-overview/

 18

3 summary and What’s next?

まとめ　summary

米国　US

- SDP-3を受け、米国政府はデブリ低減規制・ガイドラインの見直し実施中。
  The USG is in the middle of process of updating regulations/guidelines on space debris mitigation.

- OSMDPについては、他国政府も自国のデブリ低減規制のベースラインとして採用されることを米国としては期待。
  As for OSMDP, the USG expects the international community to adopt by other states as a baseline for domestic operator regulation.

- 現在引き続きパブリック/コメントが行われているFCCのデブリ低減ガイドラインの見直しでは、特定の技術的な要求を求めるのではなく、パフォーマンスをベースとした規制が志向されている。また、衛星運用者に対して、衛星システム、運用計画、廃棄計画などの情報提供を求め、これらをベースに当該衛星運用者のデブリ低減策を判断するために使われる。
  As for FCC, The U.S. tends to focus on performance-based regulation, not technical requirements. The recently updated FCC guideline would require applicants to disclose more information about their systems, operations plans, and disposal plans which will be used to scrutinize their orbital debris mitigation intentions.

- 産業界の成長力や競争力を損なうことが目的ではないため、これらの見直し過程において産業界の意見も聴取。
  The USG is attentive to industry’s concerns and opinion over updating regulations so that the updates is not overtly impede the growth of satellite industry.

日本 Japan

- 全体的に前向き・積極的な傾向。ただし、具体的な基準の議論はまだなされていない。There is a positive move but no concrete discussion in terms of specific measure.
- 宇宙活動法に基づくデブリ低減策について、政府衛星・民間企業について打上げ以降の実施の確認、遵守率などは不明。Not clear of compliance rate of debris mitigation measures based on the Space Activities Law. There is no means to observe/ oversite the compliance by the government except reporting.

今後の課題 What’s next?

■ 現状のガイドラインの実施・遵守の確実な確保のための強いイニシアティブ
Need for the Strong initiative to make sure the compliance of the existing guidelines

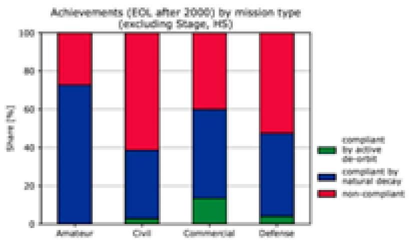


Figure 6.2: Share of compliance in terms of clearing the LEO protected region by mission type.

ESA’s Annual Space Environment Report (ESA, 2020)

■ 例えば、宇宙デブリの既存のガイドラインについても、遵守率は半分程度というのが現状。The compliance rate is about 50% even with the current guidelines and regulation on space debris mitigation although there is an increase of general compliance rate.

■ 新規のルールに加えて、遵守・実施率を確実にすることも重要。Not only with the update of existing guidelines and regulations, it is equally important to raise the implementation/compliance rate.

■ 既存の規制で十分でないものは？
Where is the gap in the existing guidelines enough?

■ 日本については、FCCデブリ低減ガイドラインの議論など国際的な議論・規制をフォローしていく必要あり。 For Japan, need to follow the major international regulations.

今後の課題 What’s next?

■ 産業界のベストプラクティスを国内の法規制・グローバルなルールの議論にどう取り込んでいくか。

The importance of how to incorporate the industry’s best practices into domestic and global standards/guidelines.

■ 新規参入の国や企業をどう巻き込んでいくか

How to make sure the engagement with new entrants; states or companies to share same goal and experiences.


ASTROSCALE
SPACE SWEEPERS
SINCE 2013
www.astroscale.com

B08

低軌道デブリ光学観測システム
Optical Observation System for LEO Objects

○柳沢 俊史, 神谷 浩紀, 黒崎 裕久（JAXA）
○YANAGISAWA Toshifumi, KAMIYA Kohki,
KUROSAKI Hirohisa (JAXA)

JAXA では豪州に遠隔観測施設を整備し、低軌道デブリを観測するための研究開発を実施している。小型望遠鏡に大型 CMOS センサを設置、センサから得られる大量の画像データを独自の手法で解析することにより 10 cm程度の多数の未カタログ物体をほぼリアルタイムで検出することが可能である。本講演では最新の研究状況及び検討している将来の低軌道デブリ監視システムについて紹介する。

The remote observation site for LEO debris was establish at Siding The optical remote observation system using small telescopes and large CMOS sensors was established in Australia. By analyzing a lot of data from the CMOS sensors with the image-processing technologies developed at JAXA, number of un-cataloged LEO objects are detectable. The system will contribute to the space situation awareness in the future.

The quadruple telescope for LEO objects observation. It consists of 4 18cm-telescopes and 4 large CMOS sensors.

9th Space Debris Workshop Feb 25th 2021

Optical observation system for LEO objects

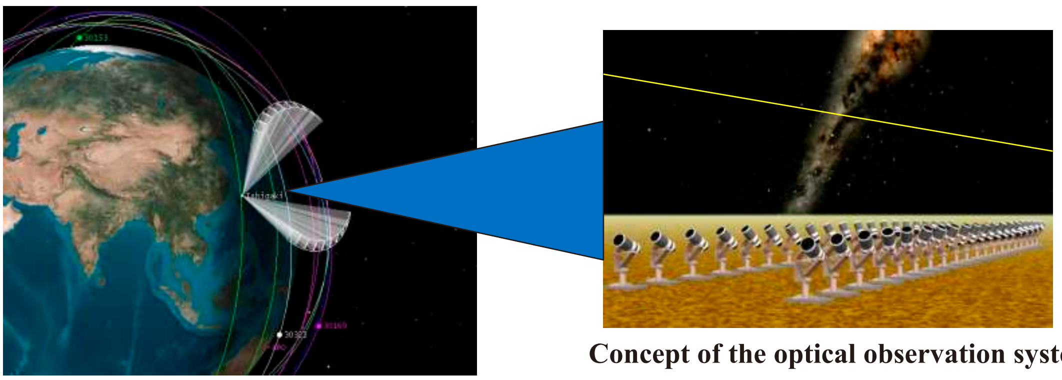
Japan Aerospace Exploration Agency(JAXA)
Research and Development Directorate

T.Yanagisawa, K.Kamiya, and H.Kurosaki

1

Abstract

We are considering optical observation system for LEO objects. Although the lighting condition and the bad weather limit the observable time, the system will be constructed with extremely low cost. In addition, optical sensors like CMOS become large, highly sensitive and less noisy. Combining these sensors with high-speed data analysis using FPGA and/or GPGPU enable us to establish the system which will complement the current space surveillance network and contribute to the SSA in the future.



Concept of the optical observation system

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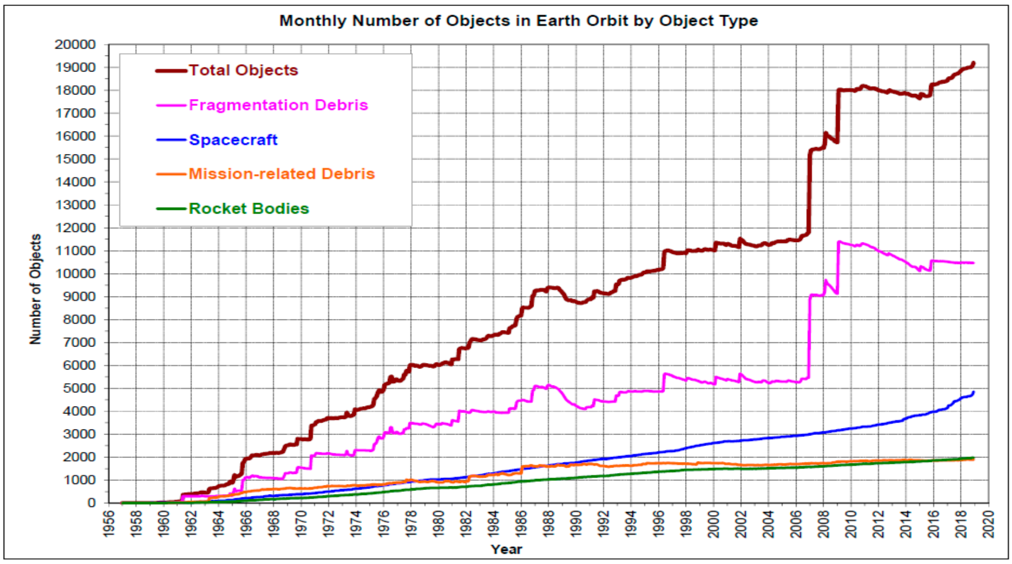
Background



- 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.

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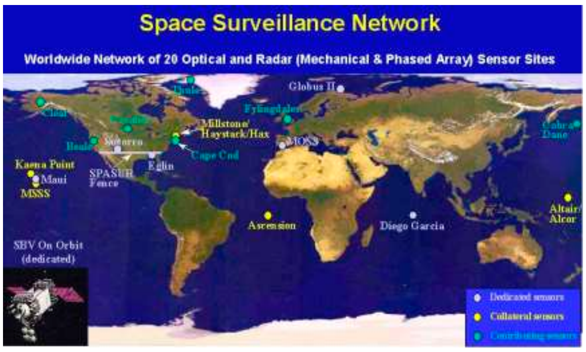
Background



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.

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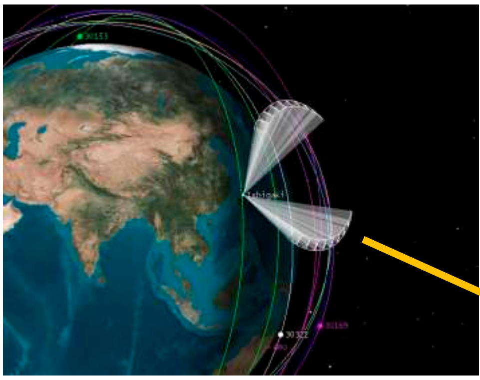
LEO survey system using the optical fence

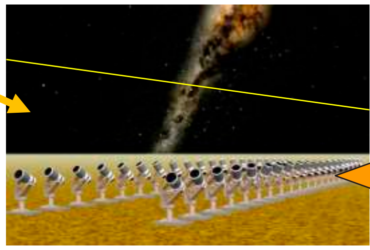


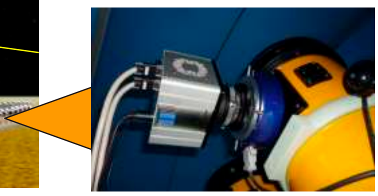
Optical fence for LEO survey

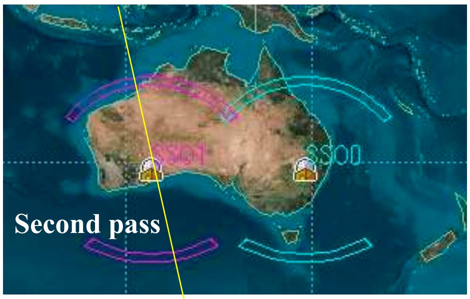
About 40 optical sensors are installed to one site.

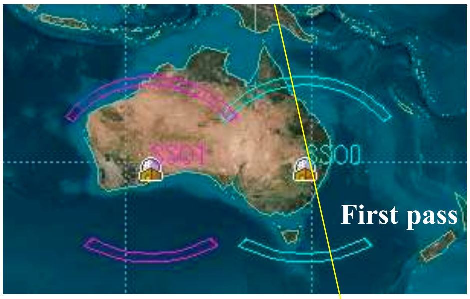
Two regions of the sky are monitored to get long arc.

Two consecutive passes should be observed for accurate orbital determination. For this reason, two longitudinally separated sites are considered.









2 observation sites in Australia for two consecutive pass observations

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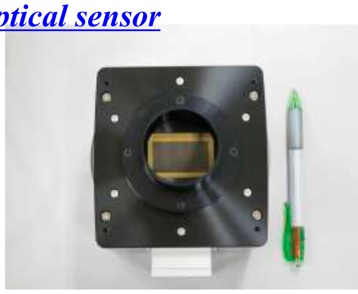
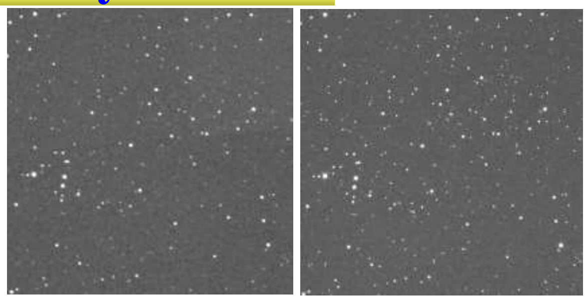
JAXA

Component of the system

Optical sensor

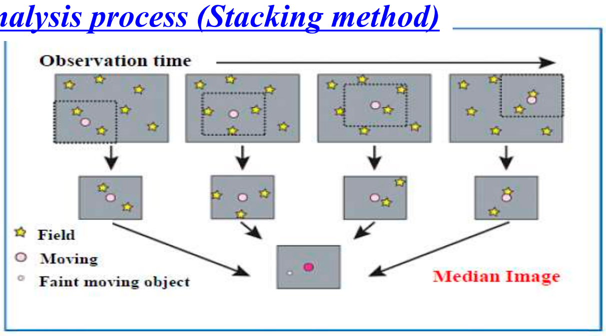


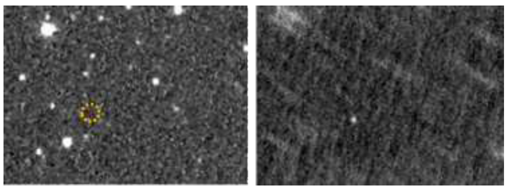
Large CMOS camera developed for LEO objects. The readout speed is 60 times faster that CCD.



Difference between CCD frame(left) and CMOS frame(right) under the same condition

Analysis process (Stacking method)





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

- ●Optical sensor: small telescope＋large CMOS camera
- ●Analysis process: Multi-core PC + FPGA based image-processing technique

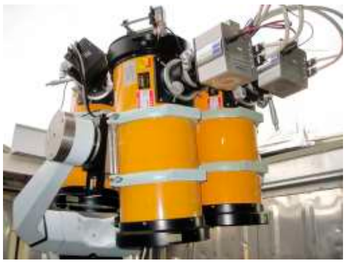
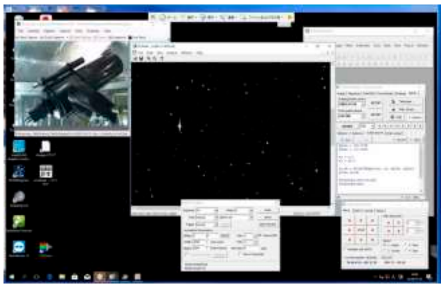
Real time detection of LEO objects of 10cm

FPGA developed for the method

JAXA

Observational environment

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.

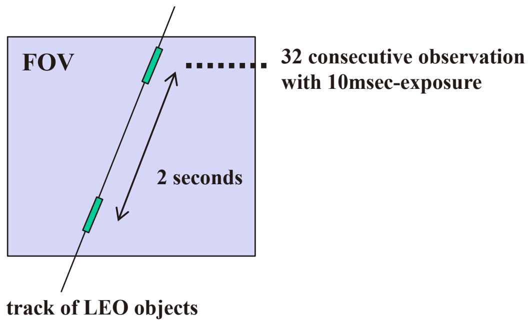
Test scene in Japan

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

LEO survey using CMOS sensor

To investigate the usefulness of the CMOS sensor, LEO survey observations were carried out using two sets of 18cm telescope and the CMOS sensors.
To avoid the overflow of the memory, interval observation was carried out. Data was analyzed with the FPGA-based stacking method offline.

Concept of the interval observation



Observation time:	**90minutes after the dusk on Dec 9th 2019.**
Observation site:	**The remote observation site at Siding Spring Observatory**
Observation equipment:	**Takahashi 18cm telescope, and Bitran CMOS sensor**
Data acquisition:	**32 consecutive frames with 10msec exposure (2-second interval)**
Data analysis:	**FPGA-based stacking method**

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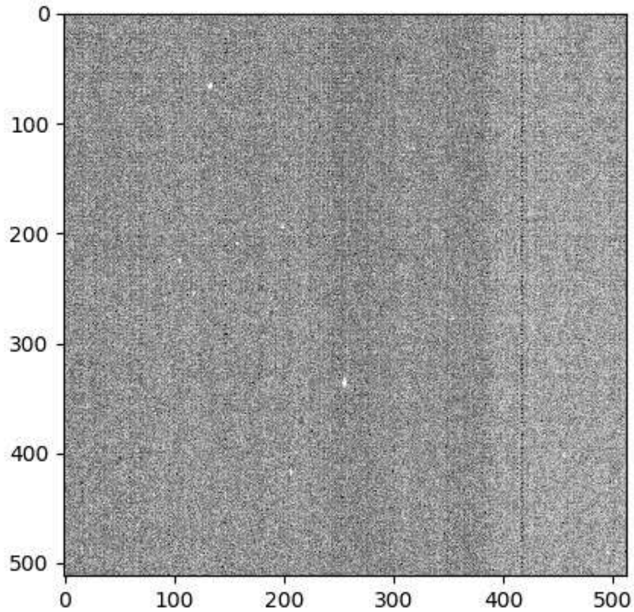
LEO survey using CMOS sensor



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

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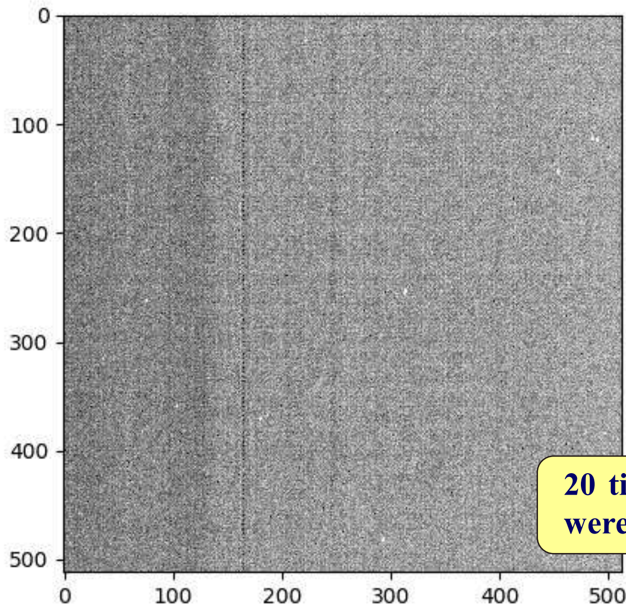
LEO survey using CMOS sensor



20 times fainter objects were detectable.

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

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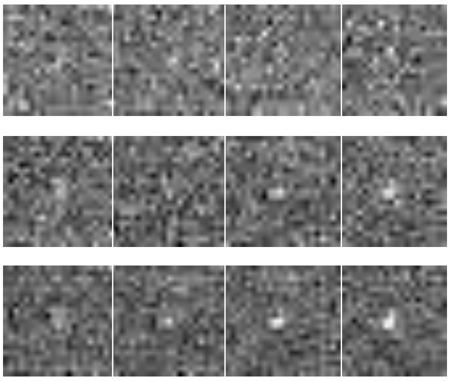
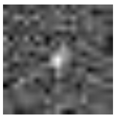
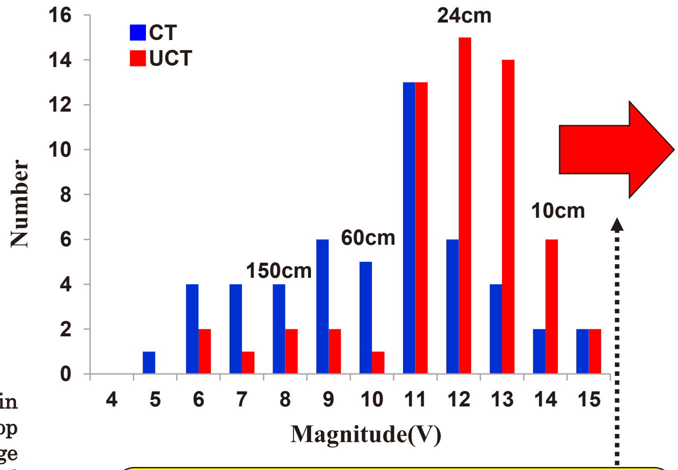
LEO survey using CMOS sensor

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 .



Aim to detect smaller objects with improvements of observation method and analysis process

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

The technology may contribute to SSA in the future

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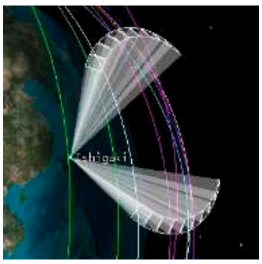
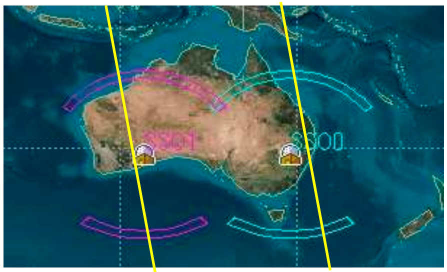
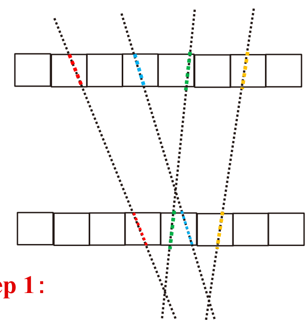
Orbit Determination

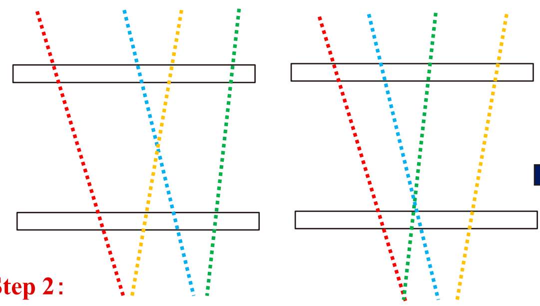






Step 1 :

One-to-one correspondence in one site data



Step 2 :

One to one correspondence in two site data

Precise orbit determination

One-to-one correspondence for each object is needed for precise orbit determination. Four sets from two sites observation data must be collected.

Circular orbit is calculated using the data taken with each sensor. One-to-one correspondences are possible for almost all the objects comparing the circular orbital elements.

Orbit Determination

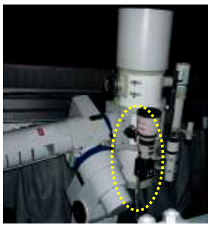
Observation sites:

Ishigakijima Morita Observatory (Okinawa)

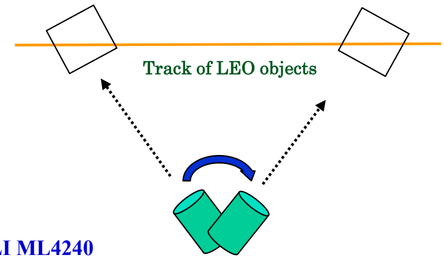
Rikubetsu Observatory (Hokkaido)

Observation equipments:

Canon 200mm F2 + FLI ML23042



Canon 300mm F2.8 + FLI ML4240

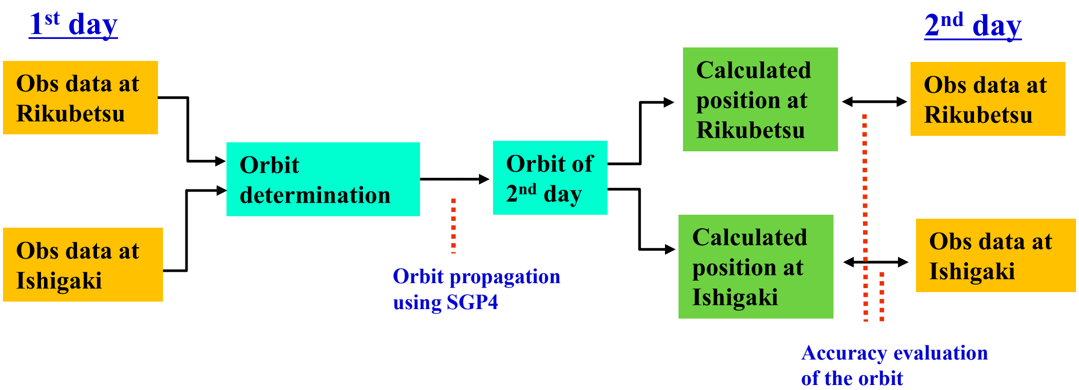


Observation date and time: Jul/27-28　after dusk and before dawn

Targets: 4 TLE-objects (14521, 13589, 20720, 21574)

In order to mimic the observation using the optical fence system described before, some cataloged objects were observed from 2 longitudinally separate sites, assuming one of the sensor of the system detects those objects with no orbital information. Each object was observed at 2 separate sky regions on each site. The first day's data was used for orbit determination and the second day's one was for evaluation of the accuracy of the orbit determination.

Orbit Determination



Result of the accuracy evaluation

SSC number of objects	14521	13589	20720	21574
Rikubetsu dRA(arcsec)	181.19	34.99	19.62	199.27
Rikubetsu dDec(arcsec)	186.08	33.06	11.08	246.91
Ishigaki dRA(arcsec)	96.23	10.84	N/A	195.52
Ishigaki dDec(arcsec)	339.20	14.22	N/A	491.74

The result shows the orbit determinations are accurate enough to track objects next day in spite of quite limited observation data. In the case of the objects of 13589 and 20720, the differences are less than 0.01-degree. These facts indicate the proposed optical observation system is quite useful for orbit determination of un-cataloged LEO objects.

Detection ability of the system

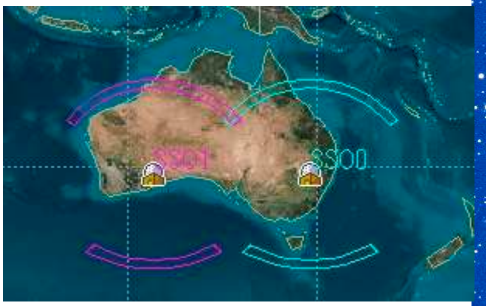
Number of detected and orbit-determined objects was estimated using STK. Objects of 10cm and larger are assumed to be detected with the system.

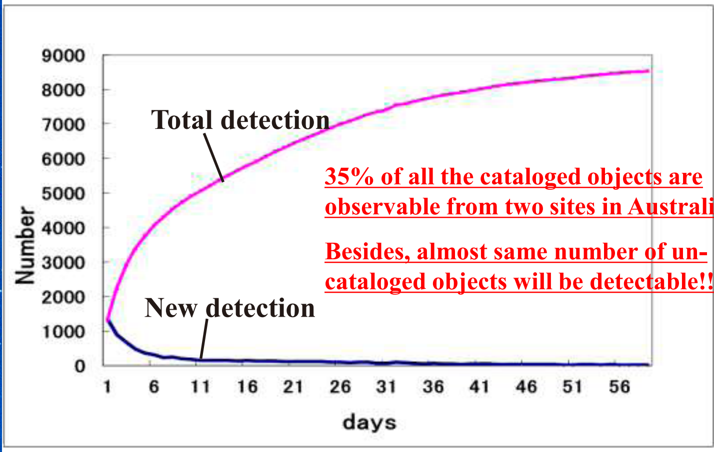
Sites: Siding Springs Observatory in Australia and one imaginary observatory located at western side to the Siding Spring Observatory by 25-degree.

Devices: 40 sets of the 18cm telescope and the CMOS sensor for each site.

Targets : Cataloged objects

period: Four months from Jan 1st of 2020





About 9100 objects (35% of all the objects) were detected and orbit-determined after 4 mouths observation using the system.

Weather conditions were not considered.

As shown in the next slide, orbital planes of the objects are rotating around the globe.

The sites for follow-up observation are needed

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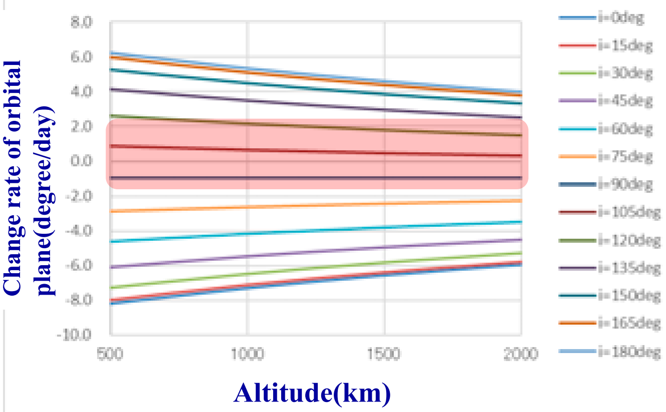
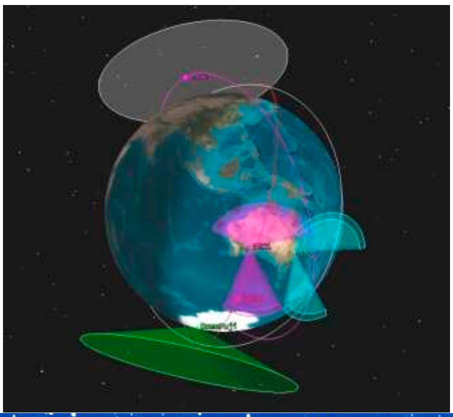
Observation Ability

The system can detect the targets under the condition of lighting for targets and umbra for the sites. Change rate of orbital plane contributes to detect all the targets. The objects of the small change rate are difficult to re-observe after the first observable period. Follow-up site for polar region can observe these targets.





Follow-up observation

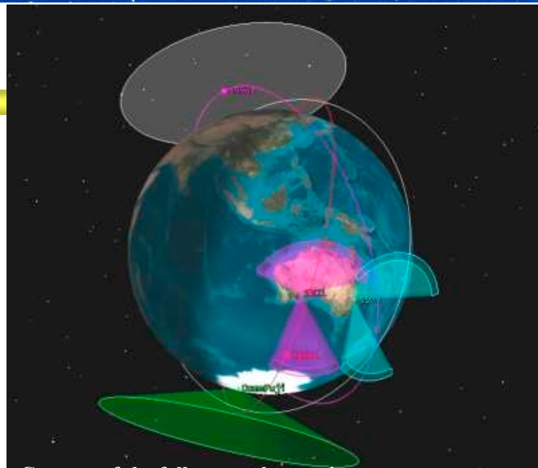
Observabilities of 7 typical objects from the sites near both polar regions are investigated using STK.

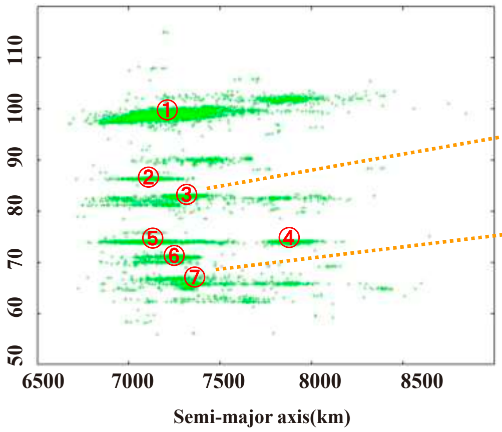
Sites : Dome Fuji of the South Pole and Svalbard islands near the North Pole

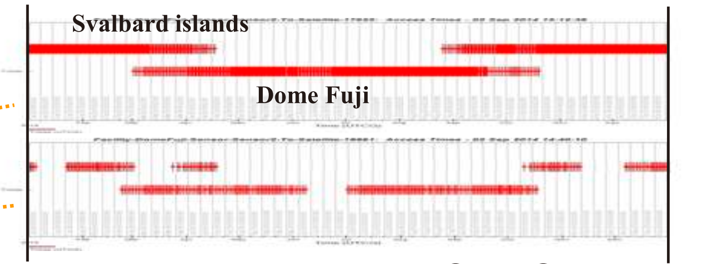
Devices : 8 sets of the 18cm telescope and the CMOS sensor for each site.

Targets : 7 typical objects detected by the system.

Period : One year from Jan 1st of 2020


Concept of the follow-up observation





Observabilities of object③ and ⑦.

Objects ① to ④ are observable from the South Pole and/or the North Pole. Objects ⑤ to ⑦ have un-observable period from both sites.

Summary

We are considering optical observation system for LEO objects. Although the lighting condition and the bad weather limit the observable time, the system will be constructed with extremely low cost. In addition, optical sensors like CMOS become large, highly sensitive and less noisy. Combining these sensors with high-speed data analysis using FPGA and/or GPGPU enable us to establish the system which will complement the current space surveillance network and contribute to the SSA in the future. We confirmed that LEO objects of around 10 to 20cm were detectable using the basic observation and analysis unit established in Australia.

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Acknowledgement

This work was supported by Innovative Science and Technology Initiative for Security (Grant Number JPJ004596), ATLA, Japan.

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B09

日豪 2 地点からの低軌道物体光学観測実証

Optical Observation Demonstration of LEO Objects from Japan and Australia

○中道 達也，篠原 流，泉山 卓（IHI），
柳沢 俊史，神谷 浩紀，黒崎 裕久（JAXA）
○NAKAMICHI Tatsuya, SHINOHARA Ryu, IZUMIYAMA Taku (IHI), YANAGISAWA Toshifumi,
KAMIYA Kohki, KUROSAKI Hirohisa (JAXA)

近年，低軌道物体の数が増加している。宇宙空間の安定利用のためには，低軌道物体の位置・軌道把握が不可欠である。 低軌道物体の位置・軌道を精度よく把握するには，複数地点での観測データを用いた軌道決定が有効である。さらに，同一パスの観測データを用いて軌道決定することで，より早く，精度の高い軌道把握が実現できる。このことにより，レーダを用いたスペース・フェンスと同様の宇宙状況監視を光学観測により実現できる。 本研究では，複数地点観測による低軌道物体検出，追尾の実証を実施した。地球上の遠隔にある 2 地点で同一パスの観測データを光学的に取得し軌道決定精度を確認した。観測地点としては，太陽同期軌道の軌道傾斜角に沿った，豪州にある JAXA サイディング・スプリング観測所と日本の IHI 相生観測所の 2 地点を利用した。本講演では，実証の第 1 ステップとして既知物体の観測および軌道決定精度評価の結果を報告する。

In recent years, the number of low-earth orbit (LEO) objects has been increasing. For stable use of outer space, it is essential to grasp the position of LEO objects. In order to accurately grasp the position and orbit of those LEO orbit objects, it is effective to determine the orbit by using observation data from multiple observatories. Furthermore, it is possible to realize a faster and more accurate orbit determination by using the same path observation data. Thus, it is possible to realize space situational awareness similar to a space fence using radar by optical observation. In this study, we will demonstrate optical observation of LEO objects from multiple observatories. Addition, we realize improvement of orbit determination accuracy by using data of the same path that observed from multiple observatories. Two observatories, JAXA Siding Spring Observatory and IHI Aioi Observatory, were used for this study. Those observatories are placed along the angle of sun-synchronous orbit. In this paper, we will report the observation results of known objects and the results of their orbit determination accuracy evaluation.

9th Space Debri Workshop

Optical observation demonstration of LEO objects from Japan and Australia

IHI

25th Feb. 2021

Tatsuya Nakamichi, Ryu Shinohara, Taku Izumiyama (IHI Corporation, Space Development Dept.)
Toshifumi Yanagisawa, Kohki Kamiya, Hirohisa Kurosaki (JAXA, Research and Development Directorate)

Contents

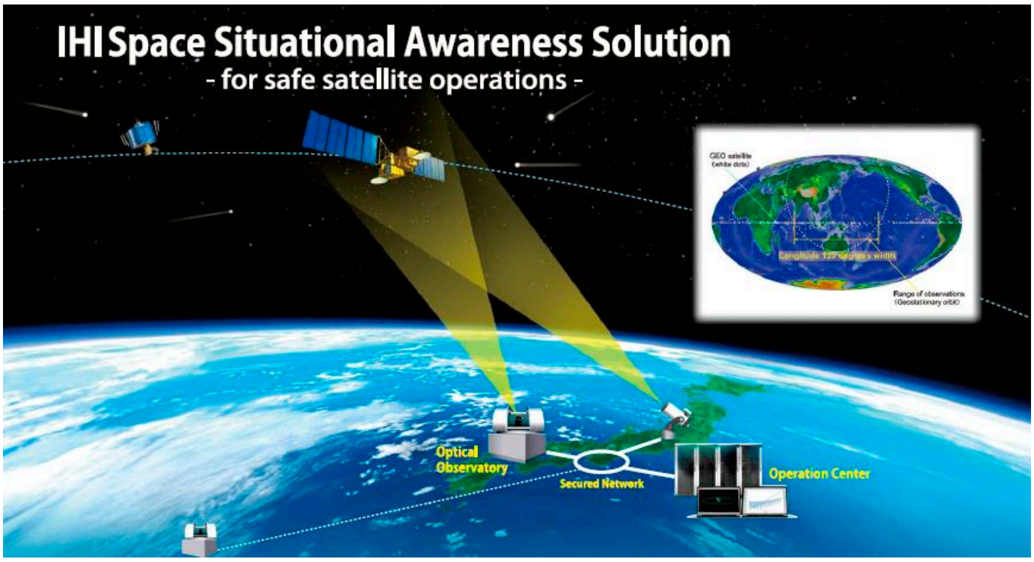
IHI

1. Background

IHI

Space situational awareness (SSA), to understanding orbit of object in space, is essential for space utilization. Especially in low earth orbit (LEO), the demand for understanding orbit of satellite and debris is increasing.

IHI have been developing optical observation technology for SSA.



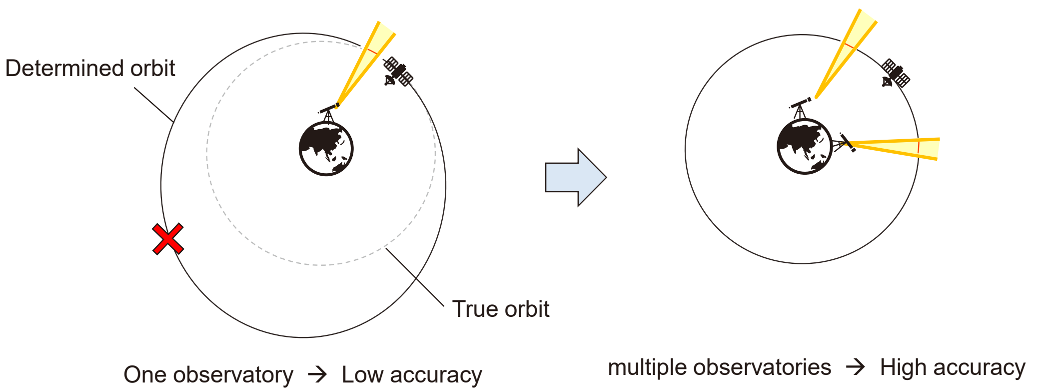
2. Objective

IHI

To improve optical observation accuracy, it is effective to determine the orbit by using observation data from multiple observatories.

Furthermore, it is possible to realize a faster and more accurate orbit determination by using the same path observation data.

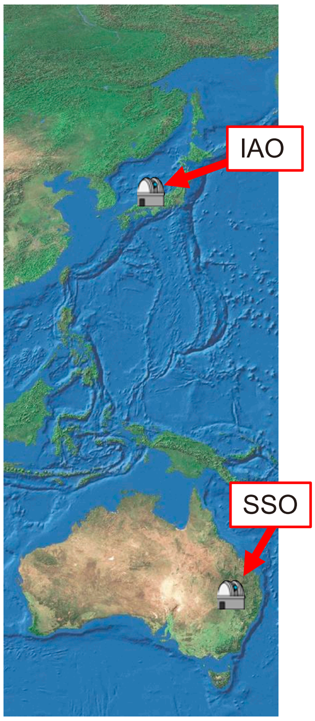
In this presentation, we report the orbit determination result which is based on same path data from two observatories
(JAXA Siding Spring Observatory in Australia and IHI Aioi Observatory in Japan).



3. Observatory

IHI

(1) IHI Aioi Optical Observatory (IAO)
- Location
  - Latitude: 34.7901 [deg]
  - Longitude: 134.457 [deg]
  - Altitude: 33.0 [m]
- Specification
  - 40 cm telescope,
  - CCD camera
  - Field of view: 1.0 x 1.0 [deg]

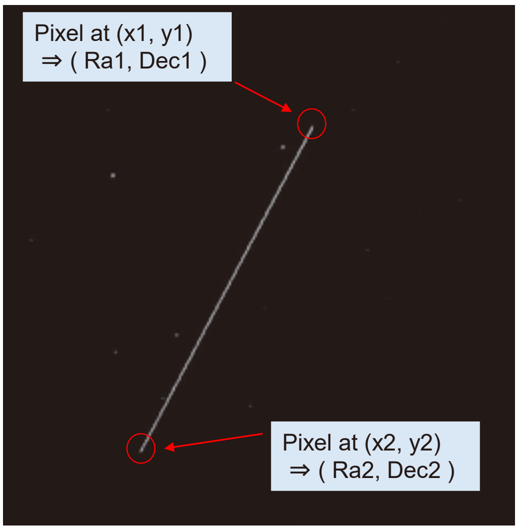


(2) JAXA Siding Spring Observatory (SSO)
- Location
  - Latitude: -31.2735 [deg]
  - Longitude: 149.064 [deg]
  - Altitude: 1153.02 [m]
- Specification
  - Four 18 cm telescopes,
  - CMOS camera
  - Field of view: 4.3 x 2.4 [deg]

4. Data Processing

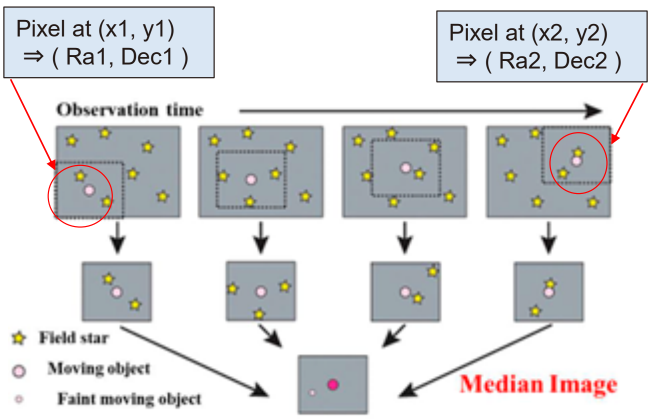
IHI

●IAO
Convert the end points of bright line in image to the position of the object on the celestial sphere.



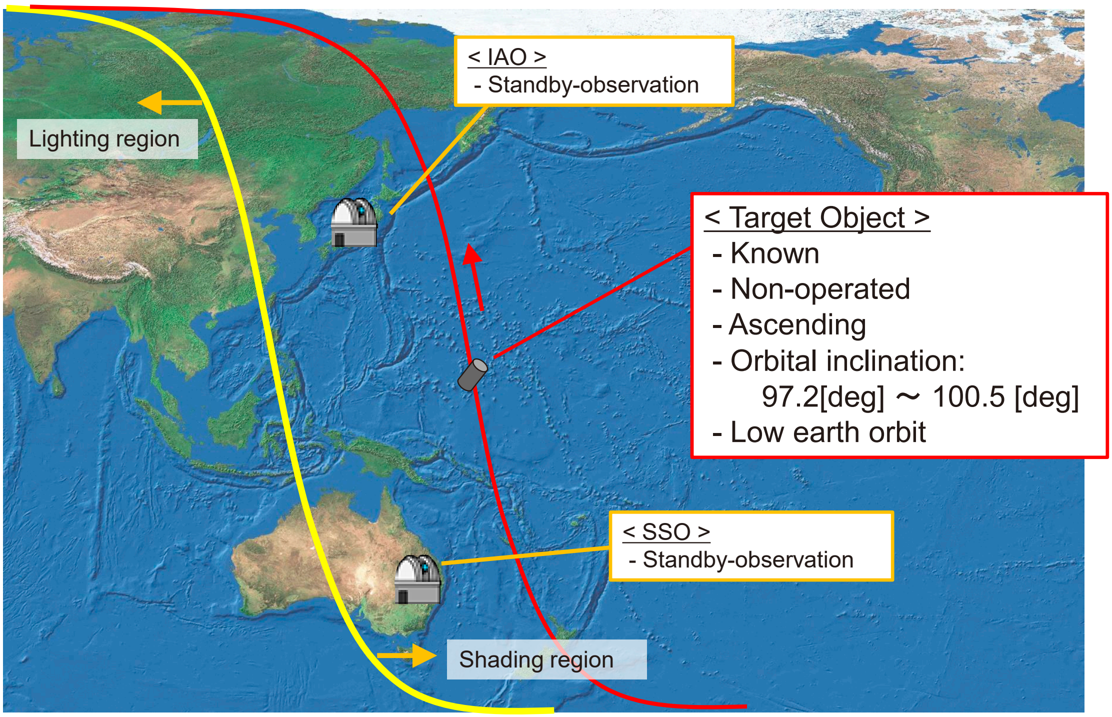
(Observed image with 1.0 [sec] exposure)

●SSO
Extract the position on the celestial sphere from the object on the first and last image of the observation.



5. Observation

IHI



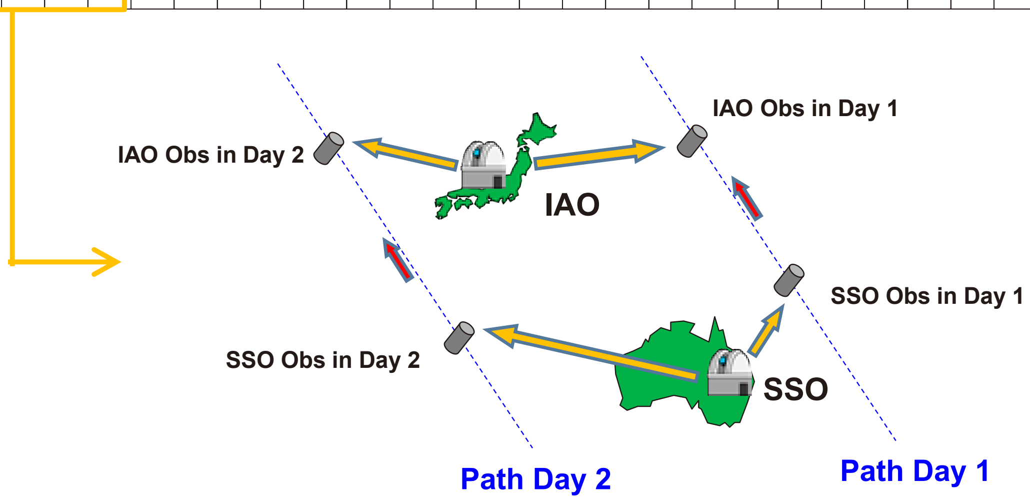
5. Observation

IHI

< Case_1 > Observation from 2 observatories for 2 days
- Object : CZ-2C R/B
- NORAD ID : 28480

● : observed

	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8		Day 9		Day 10		Day 11		Day 12		Day 13	
	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO
Case_1	●	●	●	●	●						●	●	●	●			●			●						●



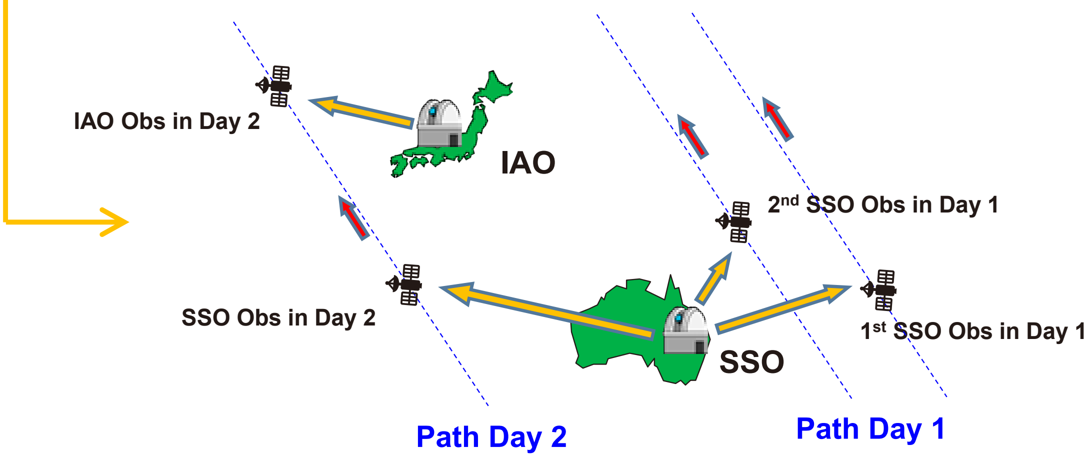
5. Observation

IHI

< Case_2 > 2 Paths Observation in 1 day and 1 path observation
- Object : SERT 2
- NORAD ID : 04327

● : observed

	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8		Day 9		Day 10		Day 11		Day 12	
	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO	SSO	IAO
Case_2	●● (2paths)		●	●			●			●								●				●	●	●

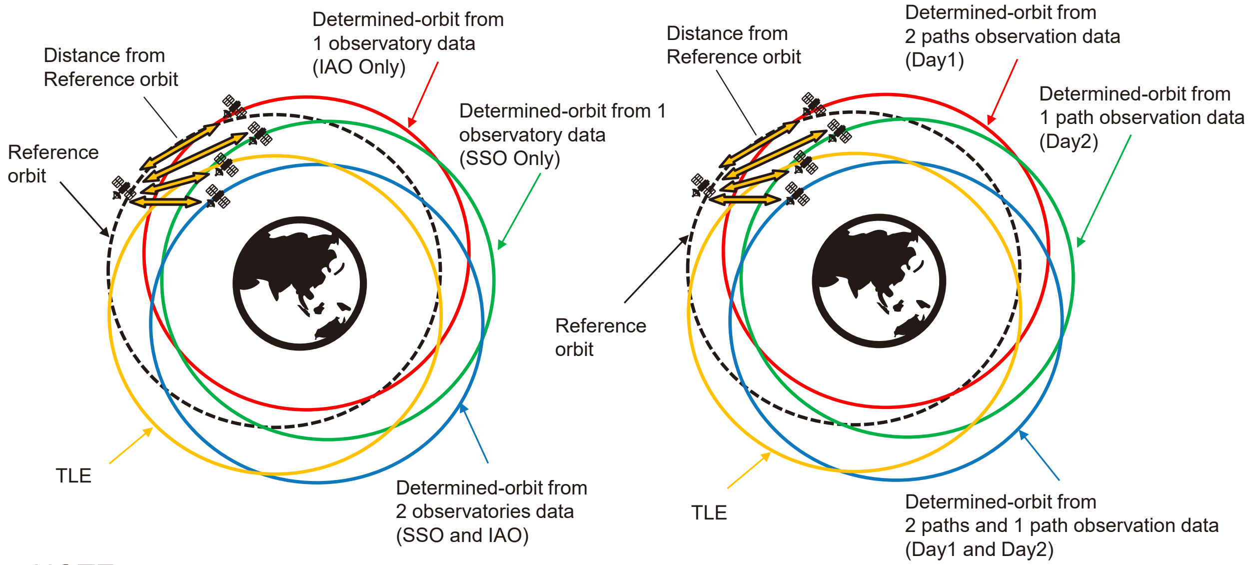


6. Evaluation

IHI

(1) Effect of the number of observatory

(2) Effect of 2 paths observation in 1 day



NOTE:
(1) In all cases, we evaluated change over time of the difference from "Reference orbit" and determined-orbit or TLE.
(2) "Reference orbit" which is calculated from all observation data, is regarded as the "most probable orbit".6

6. Evaluation

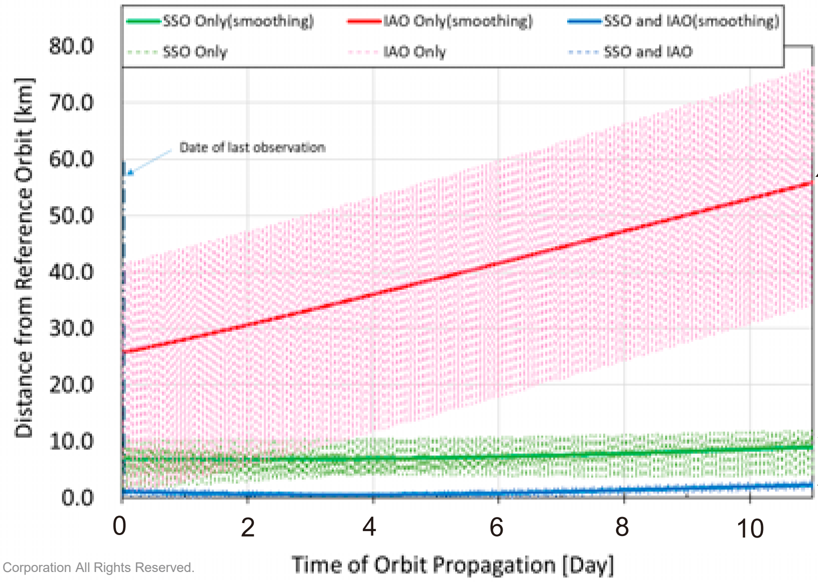
IHI

(1) Effect of the number of observatory

<Comparison orbit>

<Case_1> CZ-2C NORAD ID: 28480	Data of Orbit Determination				Total time of observation [sec]
	Day 1		Day 2		
	SSO	IAO	SSO	IAO	
SSO Only	●		●		8.6
IAO Only		●		●	5.6
SSO and IAO	●	●	●	●	14.2

Orbit determination was improved by using 2 observatories data



IAO only

SSO only

SSO and IAO

6. Evaluation

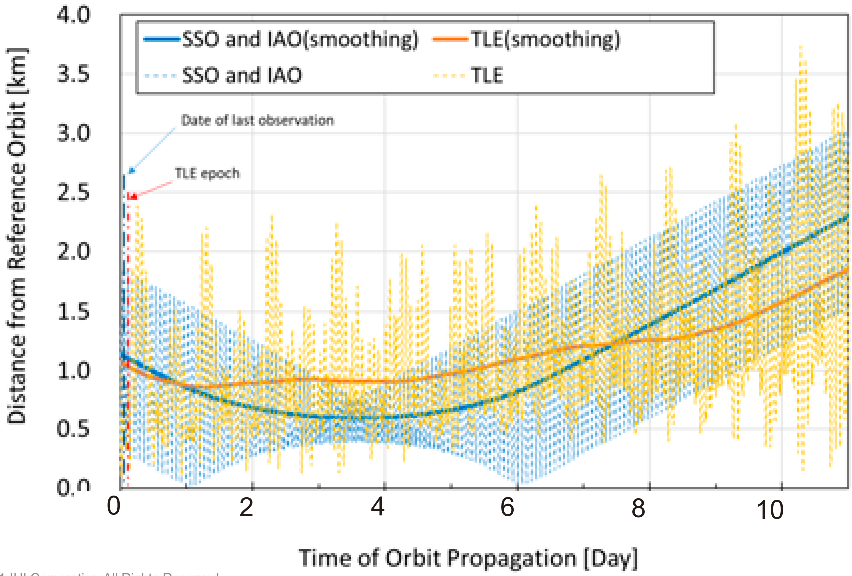
IHI

(1) Effect of the number of observatory

<Comparison orbit>

<Case_1> CZ-2C NORAD ID: 28480	Data of Orbit Determination				Total time of observation [sec]
	Day 1		Day 2		
	SSO	IAO	SSO	IAO	
SSO and IAO	●	●	●	●	14.2
TLE	N/A				N/A

With 2 observatories data, orbit determination accuracy will be equal or better than TLE.



SSO and IAO

TLE

6. Evaluation

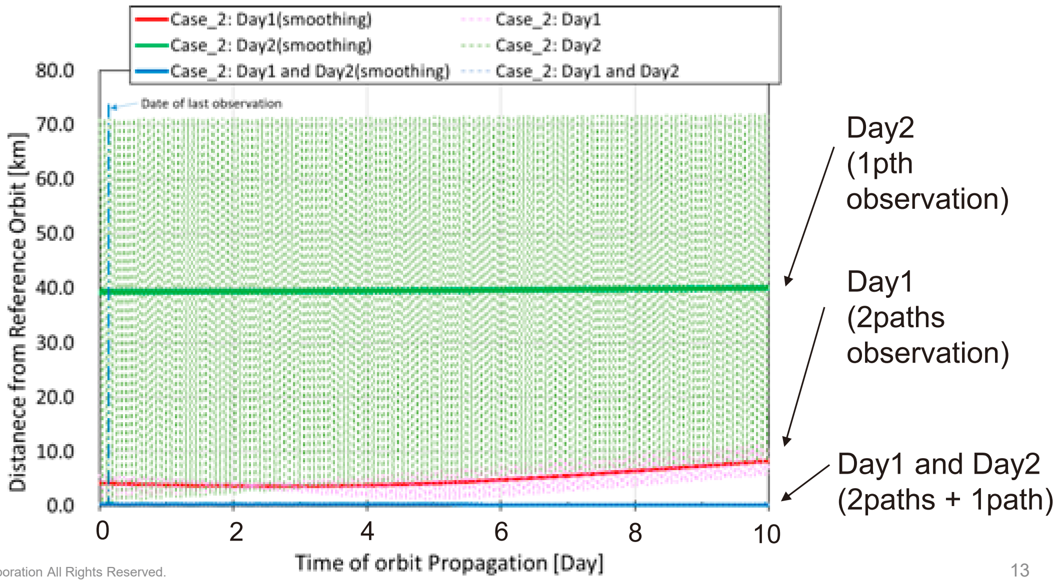
IHI

(2) Effect of 2 paths observation in 1 day

<Comparison orbit>

<Case_2> CZ-2C NORAD ID: 04327	Data of Orbit Determination				Total time of observation [sec]
	Day 1		Day 2		
	SSO	IAO	SSO	IAO	
Day1	●●				12.6
Day2			●	●	7.0
Day1 and Day2	●●		●	●	19.6

With 2 paths observation, orbit determination accuracy will be better than orbit from 2 observatories data.



6. Evaluation

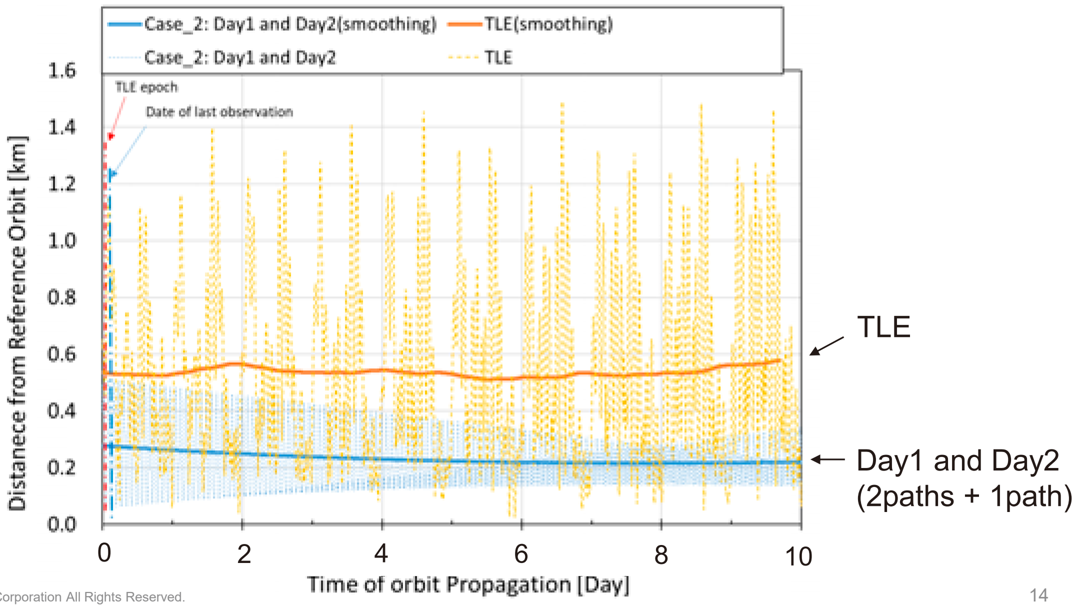
IHI

(2) Effect of 2 paths observation in 1 day

<Comparison orbit>

<Case_2> CZ-2C NORAD ID: 04327	Data of Orbit Determination				Total time of observation [sec]
	Day 1		Day 2		
	SSO	IAO	SSO	IAO	
Day1 and Day2	●●		●	●	19.6
TLE	N/A				N/A

Even though, total observation time is short (less than 20 [sec]), orbit determination accuracy will be equal or better than TLE.



7. Analysis

IHI

< Objective >
Investigated the deference between reference orbit and determined-orbit in the view of the orbital elements.

< Method >
Replace one of the orbit 6 elements of the reference orbit with that of the determined-orbit.

<Result>
Semi Major Axis (SMA) is the most predominant element for orbit accuracy.

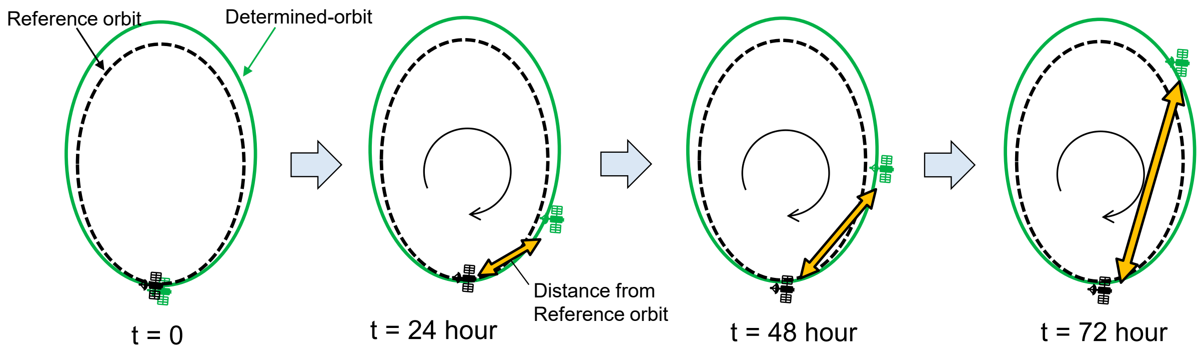
NORAD ID:28480

No.	Name	Epoch	SemiMajor Axis	Eccentricity	True Arg of Latitude	Inclination	RAAN	ArgofPerigee	Max Disitance from Reference orbit in 10 days
[-]	[-]	[-]	[km]	[-]	[deg]	[deg]	[deg]	[deg]	[km]
1	Reference Orbit	15 Oct 2020 13:46:31.466 UTCG	7174.543	0.01379	109.648	98.072	315.156	231.718	-
2	Obs Orbit	15 Oct 2020 13:46:31.466 UTCG	**7174.546**	**0.01380**	**109.648**	**98.072**	**315.157**	**231.822**	3.109
3	SemiMajorAxis	15 Oct 2020 13:46:31.466 UTCG	**7174.546**	0.01379	109.648	98.072	315.156	231.718	3.492
4	Eccentricity	15 Oct 2020 13:46:31.466 UTCG	7174.543	**0.01380**	109.648	98.072	315.156	231.718	0.268
5	TruArgofLatitude	15 Oct 2020 13:46:31.466 UTCG	7174.543	0.01379	**109.648**	98.072	315.156	231.718	0.169
6	Inclination	15 Oct 2020 13:46:31.466 UTCG	7174.543	0.01379	109.648	**98.072**	315.156	231.718	0.031
7	RAAN	15 Oct 2020 13:46:31.466 UTCG	7174.543	0.01379	109.648	98.072	**315.157**	231.718	0.047
8	ArgofPerigee	15 Oct 2020 13:46:31.466 UTCG	7174.543	0.01379	109.648	98.072	315.156	**231.822**	0.983

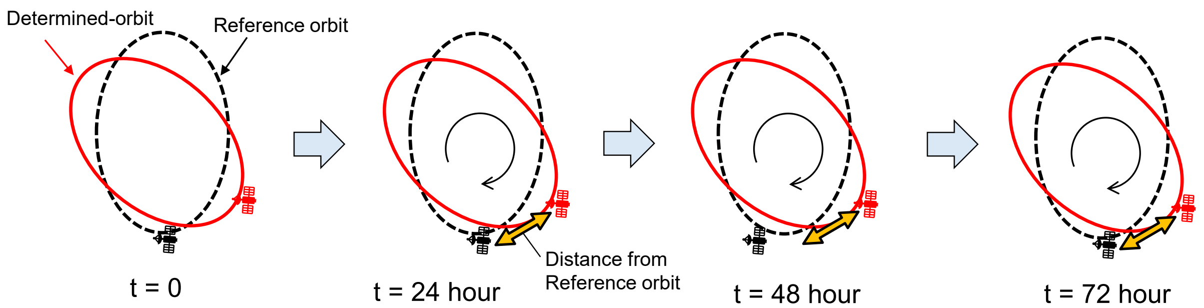
7. Analysis

IHI

Even though, Difference of SMA is small value, distance from reference orbit will increase after few period.



If only difference is the angle of the orbit, the distance from reference orbit will not increase.



8. Conclusion

IHI

< Conclusion >

(1) Orbit determination accuracy was improved by using 2 observatories data.

(2) Even though, total observation time is short (less than 20 [sec]), orbit determination accuracy with 2 paths observation will be equal or better than TLE.

(3) Semi Major Axis (SMA) is the most predominant element for orbit accuracy.

< Future Work >

(1) Acquire highly accurate orbit determination technology that can be used for SSA/STM services

(2) Orbit determination of unknown object.

IHI
Realize your dreams

B10

静止衛星の測光・分光（同時）観測

Simultaneous Photometry and Spectroscopy of GEO Satellites

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（日本スペースガード協会）
○FUJIWARA Tomoko, NISHIYAMA Kota, OKUMURA Shin-ichiro, NIMURA Tokuhiro
(Japan Spaceguard Association)

未知のスペースデブリの特性を知る手法を確立するためには、まず運用中の静止衛星を対象とした光学観測を行い、ライトカーブやスペクトルについての基礎的データを収集することが有効である。ライトカーブから衛星の形状や運動状態が推測でき、スペクトルは衛星の材質を反映している。 我々は静止衛星を対象に、美星スペースガードセンターの 1.0m 望遠鏡と 0.5m 望遠鏡で測光観測を、隣接する美星天文台の 101cm 望遠鏡で低分散分光観測を同時に行った。観測対象としたのは静止軌道上の東経 140° 付近にある、気象衛星ひまわり 8 号 (国際標識番号: 2014-060A)、ひまわり 9 号 (同 2016-064A)、オーストラリアの通信衛星 SKY MUSTER(同 2015-054A)の 3 機である。 本講演では、各衛星のライトカーブやスペクトルの特徴とその時間変化について報告する。また 9 月末にみちびき 3 号(QZS-3, 2017-048A) の観測も予定しており、良質なデータが取得できれば併せて報告する予定である。

The basic study of optical light curves and spectra of active satellites in geostationary Earth orbit (GEO) is quite useful to construct some methods to understand characteristics of unresolved space debris. Analysis of the light curves helps to estimate the shape and motion of each object and spectral measurements enable to discuss surface materials. We have made simultaneous observations at adjacent observatories. Bisei Spaceguard Center (BSGC) has 1.0-m/0.5-m telescopes to acquire light curves and the 101cm telescope with a low-resolution spectrograph has been used at Bisei Astronomical Observatory (BAO) located 100m from BSGC. The target objects are three GEO satellites located at around 140o E.: Japanese meteorological satellites HIMAWARI-8/9 (International Designator 2014-060A/2016-064A) and an Australian communication satellite SKY MUSTER (2015-054A). In this paper, we discuss photometric and spectroscopic characteristics and their temporal changes. Additionally, observations of another satellite QZS-3 (2017-048A) are scheduled in late September and it is possible to present supplemental data.


the 9th Space Debris Workshop (24-26 Feb, 2021)
(Simultaneous) Photometry and Spectroscopy of GEO Satellites
静止衛星の測光・分光（同時）観測
Tomoko Fujiwara, Kota Nishiyama,
Shin'ichiro Okumura, Tokuhiro Nimura
(Japan Spaceguard Association)
tomokof@spaceguard.or.jp


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1. Introduction
2. Observations and Data Analysis
• Photometry
• Spectroscopy
3. Results and Discussion
4. Conclusions

1.Introduction

Aims:

basic study of optical light curves and spectra of active satellites in geostationary Earth orbit (GEO) in order to construct some methods to understand characteristics of unresolved space debris

Methods:

- Photometry
  light curves→ information of the shape and the motion
- Spectroscopy
  spectra → information of surface materials

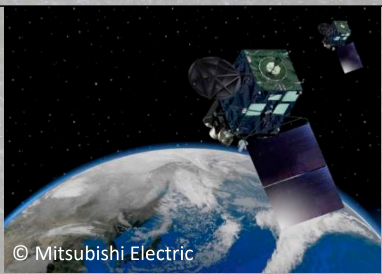
Target Objects

Quasi-Zenith Satellite

SAT NAME	HIMAWARI-8	HIMAWARI-9	SKY MUSTER	QZS-3 (MICHIBIKI-3)
Int'l Designator (COSPAR ID)	**2014-060A**	**2016-064A**	**2015-054A**	**2017-048A**
NORAD ID	40267	41836	40940	42917
Launch	2014-10-07	2016-11-02	2015-09-30	2017-08-19
Orbit	GEO (140.65°E)	GEO (140.75°E)	GEO (140°E)	GEO (127°E)
Operator	Japan Meteorological Agency (JPN)		NBN Co Limited (AUS)	Cabinet Office (JPN)
Mission Type	Weather		Communication	Navigation
Manufacturer	Mitsubishi Electric		Space Systems/Loral	Mitsubishi Electric
Bus	DS2000		SSL 1300	DS2000

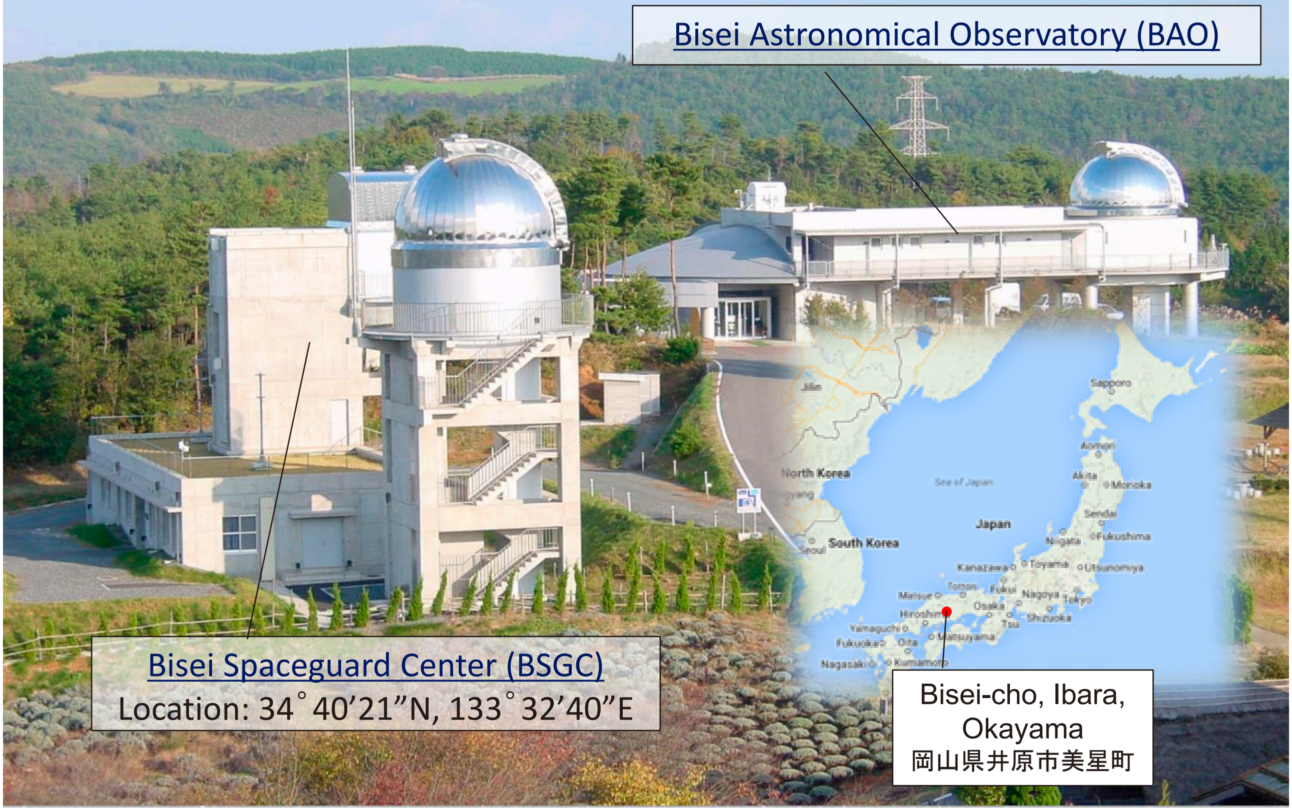
Target Objects

Quasi-Zenith Satellite

SAT NAME	HIMAWARI-8	HIMAWARI-9	SKY MUSTER	QZS-3 (MICHIBIKI-3)
Int'l Designator (COSPAR ID)	2014-060A	2016-064A	2015-054A	2017-048A
Dimensions (in-orbit) (stowed)	5.1mx8.0mx5.3m 2.2mx2.1mx2.9m		12m × 26m × 9m 3m × 3.5m × 8.5m	7.1mx19.0mx5.4m ?
Launch mass Dry mass	3,450kg 1,300kg		6,440 kg ?	4.3 t 1.7 t
Power generation (End-of-Life)	2.2kW		16.4kW	6kW
	 © Mitsubishi Electric		 © Gunter Dirk Krebs	 © Cabinet Office

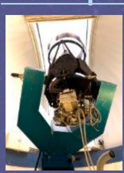
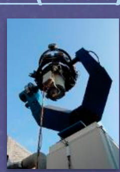
ref: Meteorological Satellite Center (2018), Takahara, T. et al (2014) & Cabinet Office (2019)
https://spaceflight101.com/ariane-5-va231/sky-muster-ii/

2. Observations and Data Analysis



Instrument Specifications

ref: https://www.bao.city.ibara.okayama.jp/

Site	Bisei Spaceguard Center (BSGC)		Bisei Astronomical Observatory (BAO)
			
Observation Type	**Photometry**		**Spectroscopy**
Telescope	**1.0-m Reflector**	**0.5-m Reflector**	**101-cm Reflector**
Focal Ratio Optical Configuration Mounting	F/3.0 Cassegrain Equatorial, Open fork	F/2.0 Cassegrain Equatorial, Open fork	F/2.8 (composite F/12) Folded Cassegrain South Equatorial, Open fork
CCD Camera	Special order	Apogee Alta U42 (partly SBIG ST-10)	ANDOR DU-440BV
Chip Array Size (pixels) Pixel Size (μm) Pixel Scale	*2k-4k* back-illuminated, fully-depleted CCDs x 4 2048 x 1104 /CCD --- 2.1"/pixel with binning	EV2 CCD42-40 2048 x 2048 13.5 x 13.5 2.93"/pix	 2048 x 512 13.5 x 13.5 ---
Others	• Filter: W(4900-9100 Å) • Field of View(R.A.x decl): 72' x 148' • Limiting magnitude: 18.7 (2 min exposure)	• Filter: W(4900-9100 Å) • Field of View(R.A.x decl): 100' x 100' • Limiting magnitude: 17 (2 min exposure)	• Spectrograph (Low-dispersion) - Gratings: 300 lines/mm (R~1500@6500 Å) - Dispersion: 162 Å/mm - Wavelength: 3600-8000 Å - Slit Length: 25mm (7') - Slit Width: 120μm (2")

Observation Schedule (Photometry & Spectroscopy)

Date	Weather	BSGC (Photometry)		BAO (Spectroscopy)	
		Time (UTC)	Number of shots	Time (UTC) including exposures for Flat, Comp & standard stars	Target
2018 19 May		15:47〜16:22	159	14:55〜16:34	HIMAWARI 8 HIMAWARI 9 Sky Muster
13 Oct		N/A		14:51〜19:14	HIMAWARI 8 HIMAWARI 9 Sky Muster
2019 16 Feb	/	17:46〜19:10 (intermittently)	98	14:38〜18:50	HIMAWARI 8
04 May		11:44〜11:56 15:39〜18:07	573	15:03〜18:42	HIMAWARI 8
2020 18 Jan		N/A		14:17〜18:40	Sky Muster
17-18 Apr		N/A		N/A	QZS-3
27 Sep		10:07〜14:50	334	14:36〜19:34	QZS-3 +α
25 Dec	→	9:38〜19:33	1071	13:25〜18:50	QZS-3 +α

characteristics of spectra by satellite

temporal changes of spectra

Observation Schedule (Photometry & Spectroscopy)

Date	Weather	BSGC (Photometry) Time (UTC)	BSGC (Photometry) Number of shots	BAO (Spectroscopy) Time (UTC) including exposures for Flat, Comp & standard stars	BAO (Spectroscopy) Target
2018 19 May	☀	15:47～16:22	159	14:55～16:34	HIMAWARI 8 HIMAWARI 9 Sky Muster
13 Oct	☀💧	N/A		14:51～19:14	HIMAWARI 8 HIMAWARI 9 Sky Muster
2019 16 Feb	☀/☁	17:46～19:10 (intermittently) bad data (for unknown reasons)	98	14:38～18:50	HIMAWARI 8
04 May	☀|☁	11:44～11:56 15:39～18:07	573	15:03～18:42 bad data (due to clouds)	HIMAWARI 8
2020 18 Jan	☀	N/A		14:17～18:40	Sky Muster
17-18 Apr	☂ ☁	N/A		N/A	QZS-3
27 Sep	☀💧	10:07～14:50	334	14:36～[illegible] device failure	QZS-3 +α
25 Dec	☀→☁	9:38～19:33	1071	13:25～18:50 missing standard star spectrum (due to bad weather)	QZS-3 +α

Simultaneous Observations (by a miracle) [2018 19 May]

Image of the BSGC 1.0m Telescope

designed for survey and tracking of:

- **Space Debris** in orbit
- Minor Planets especially **Near Earth Objects (NEOs)**

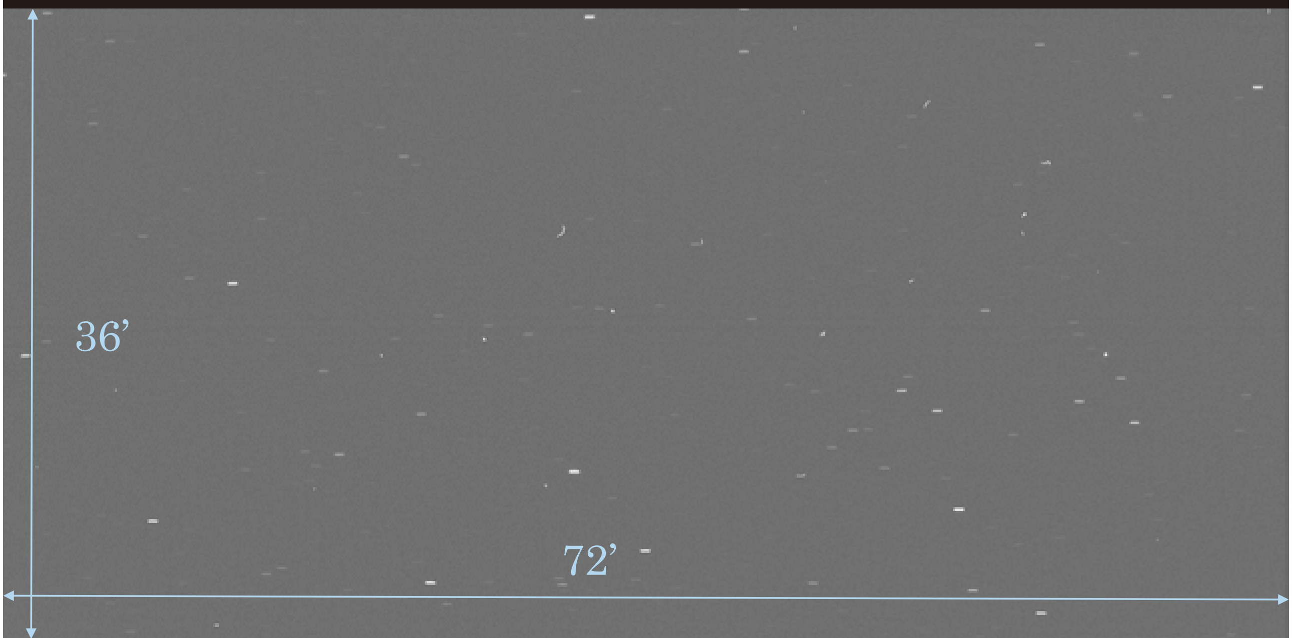


Image of the BSGC 1.0m Telescope

designed for survey and tracking of:

- **Space Debris** in orbit
- Minor Planets especially **Near Earth Objects (NEOs)**

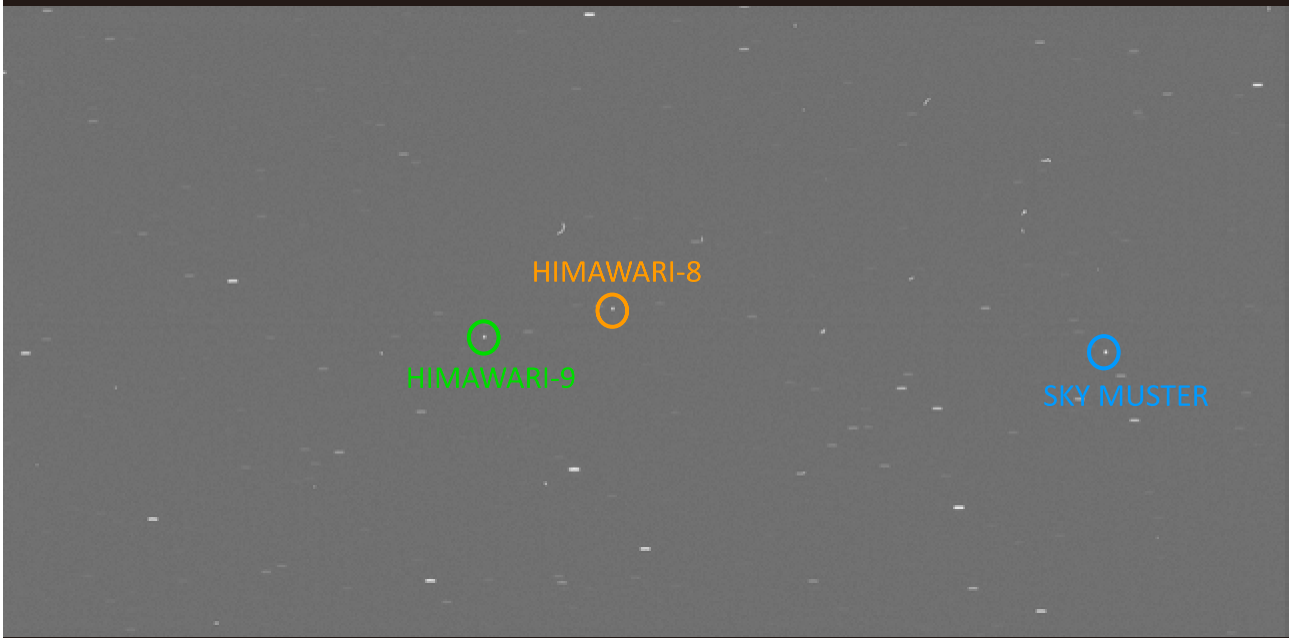
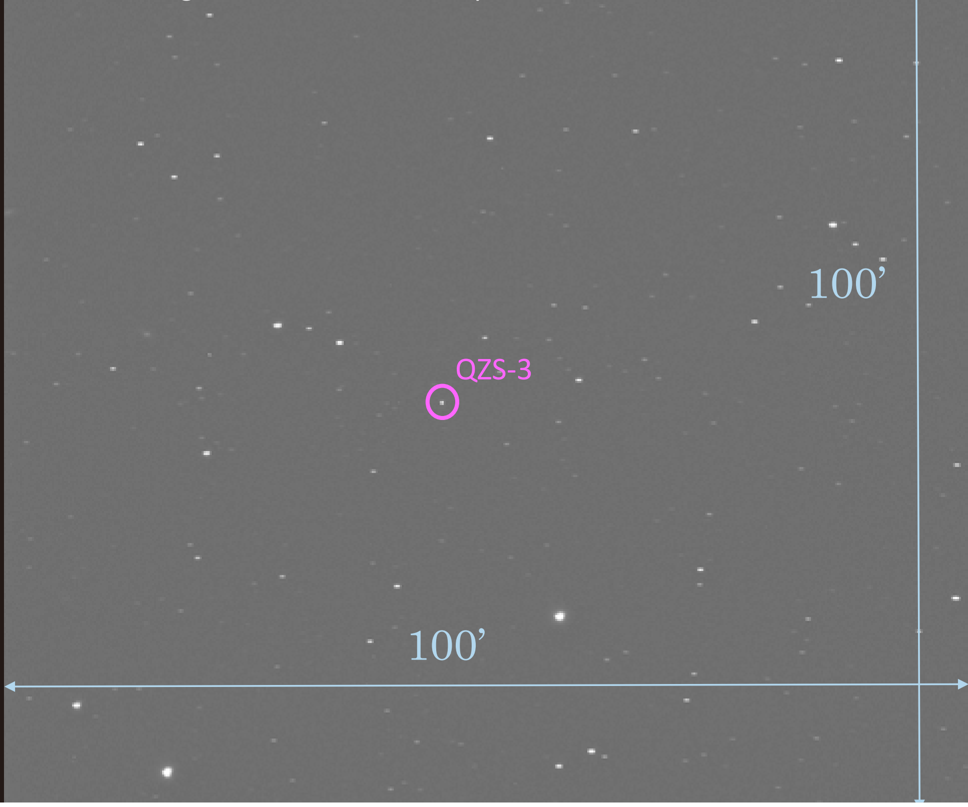


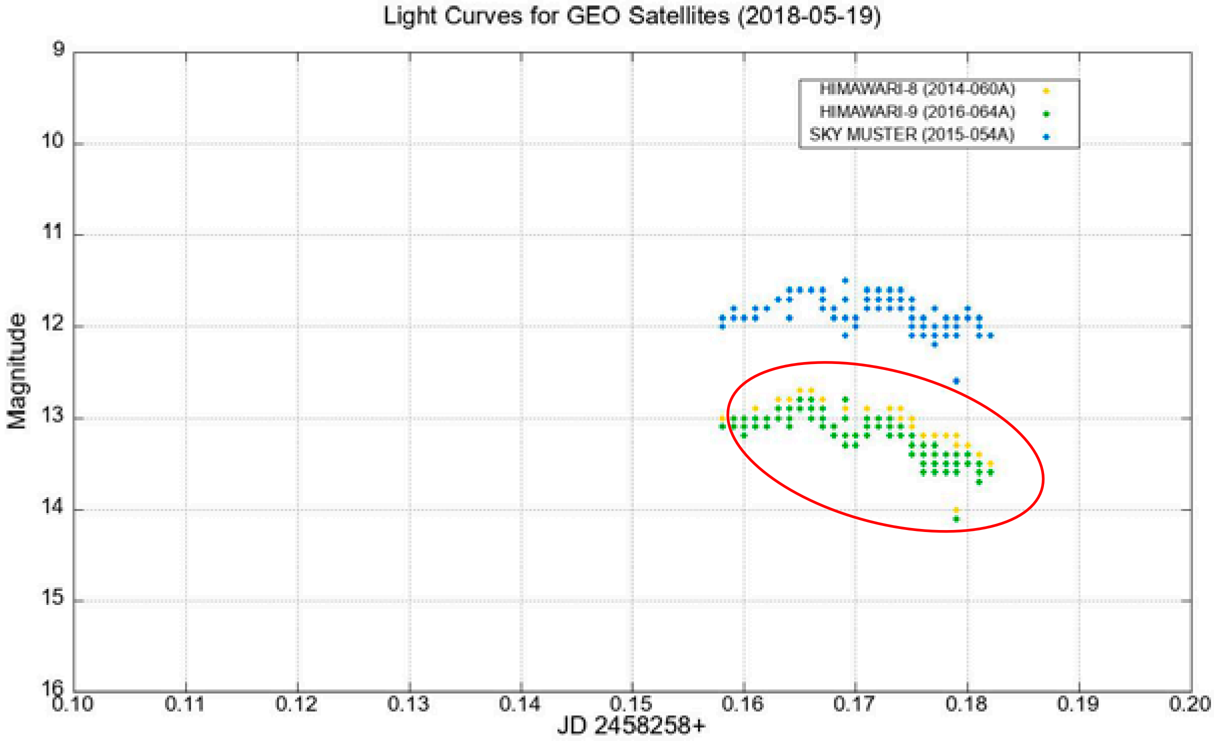
Image of the BSGC 0.5m Telescope

with the same design as the 1.0m Telescope

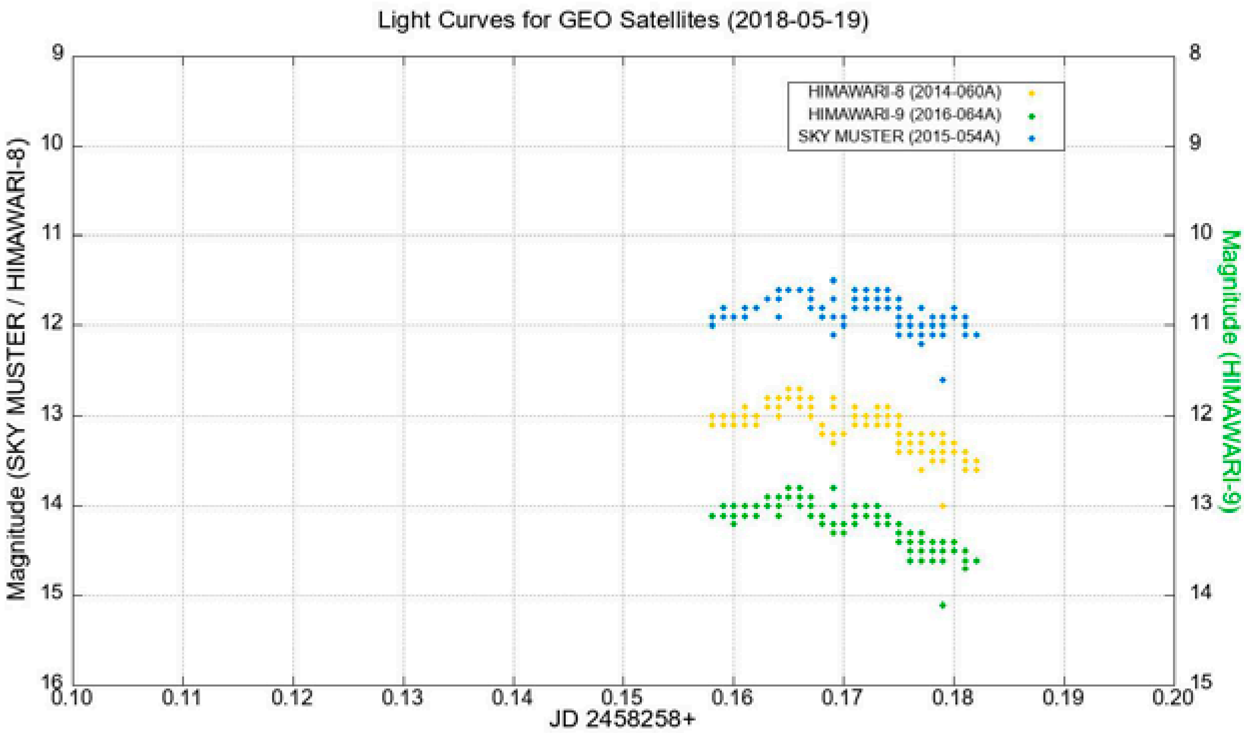


3. Results and Discussion

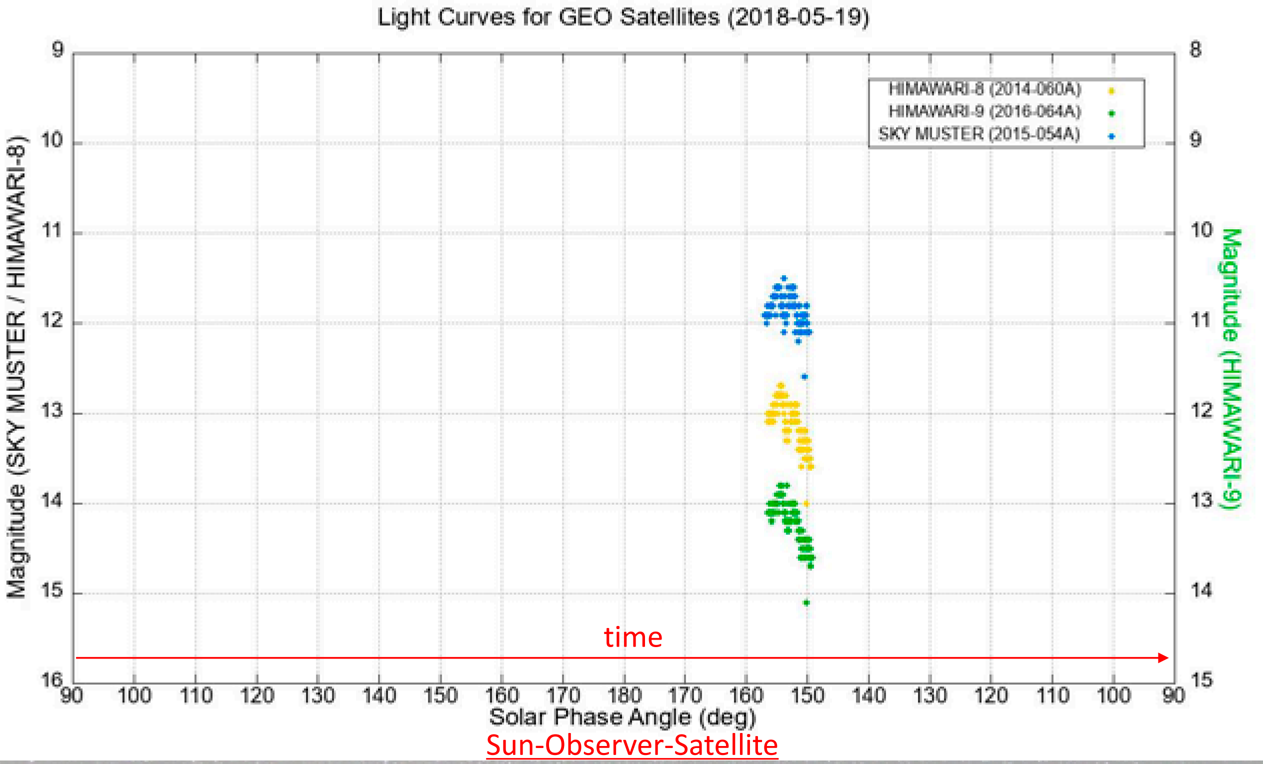
Light Curves (Time-Magnitude) for HIMAWARI-8/9 & SKY MUSTER



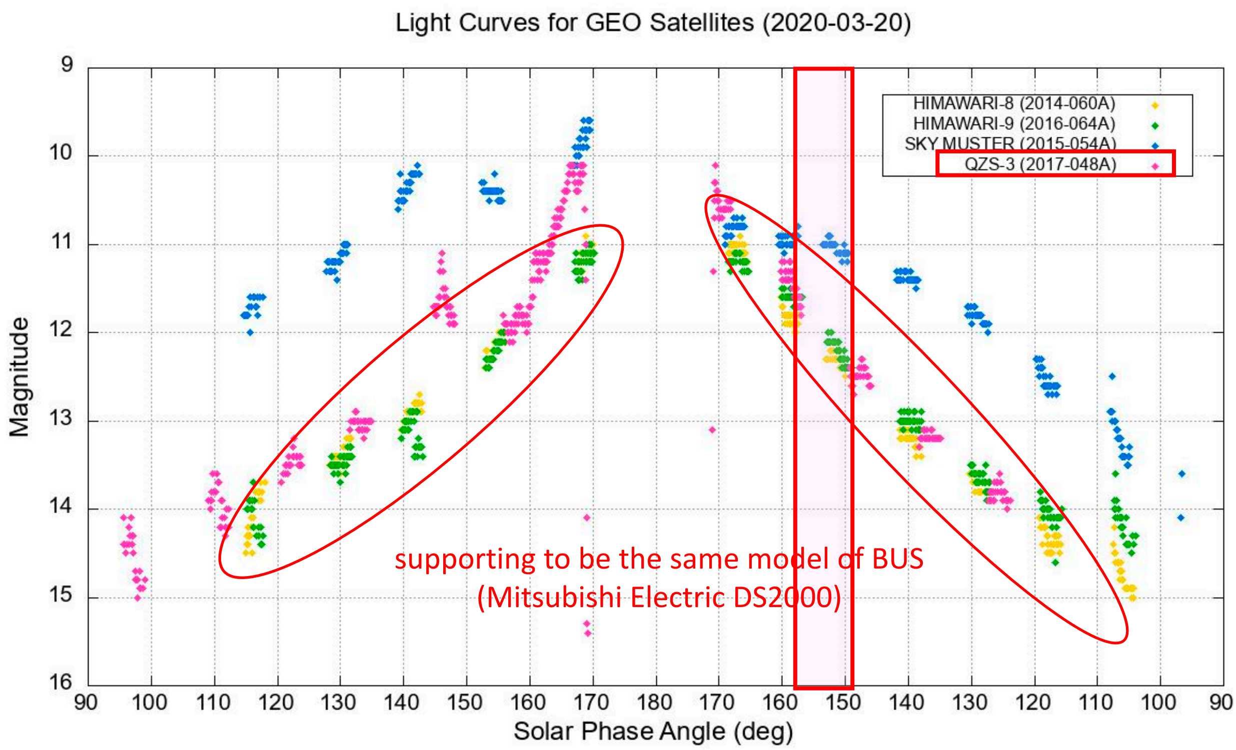
Light Curves (Time-Magnitude) for HIMAWARI-8/9 & SKY MUSTER

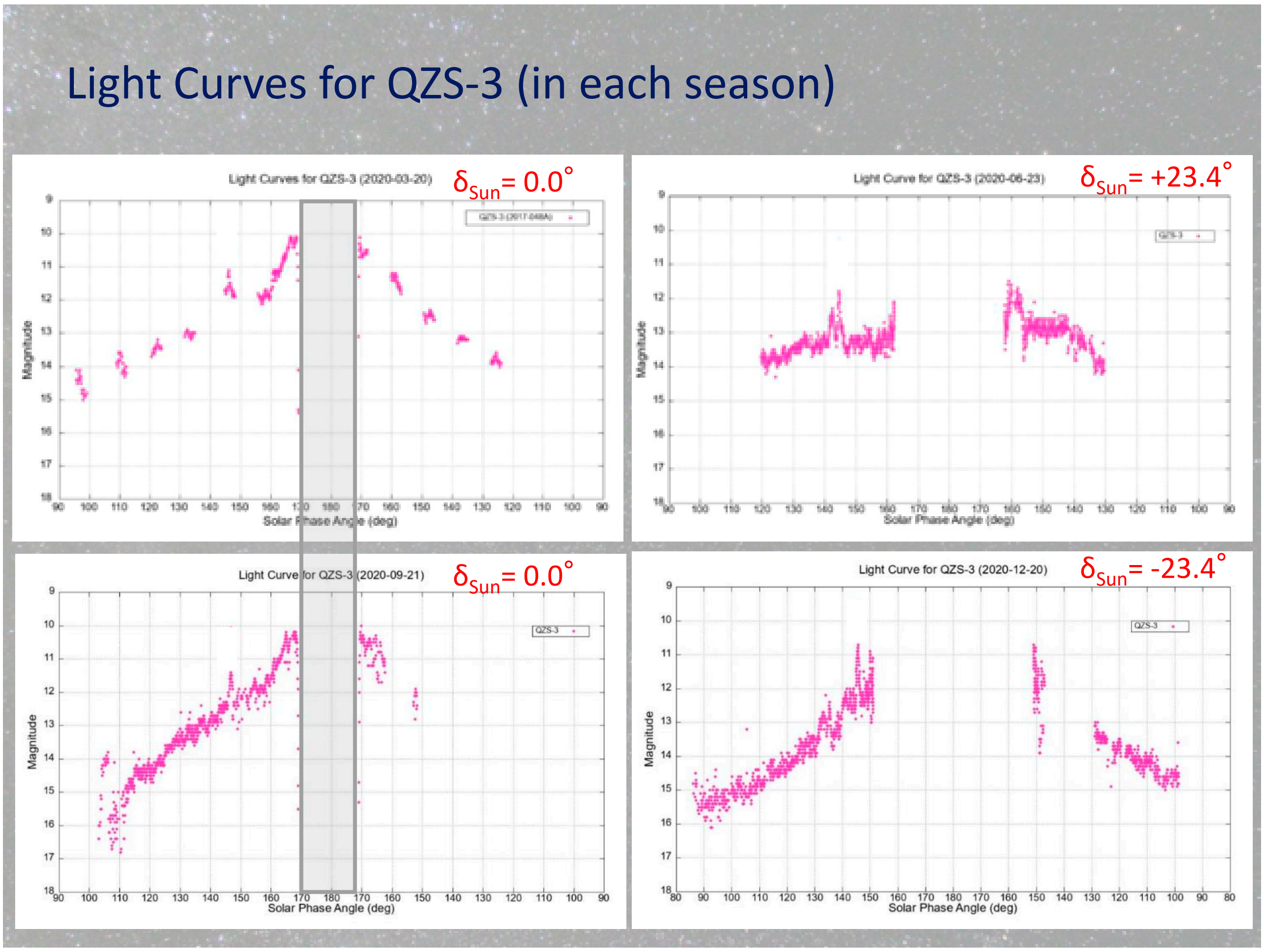


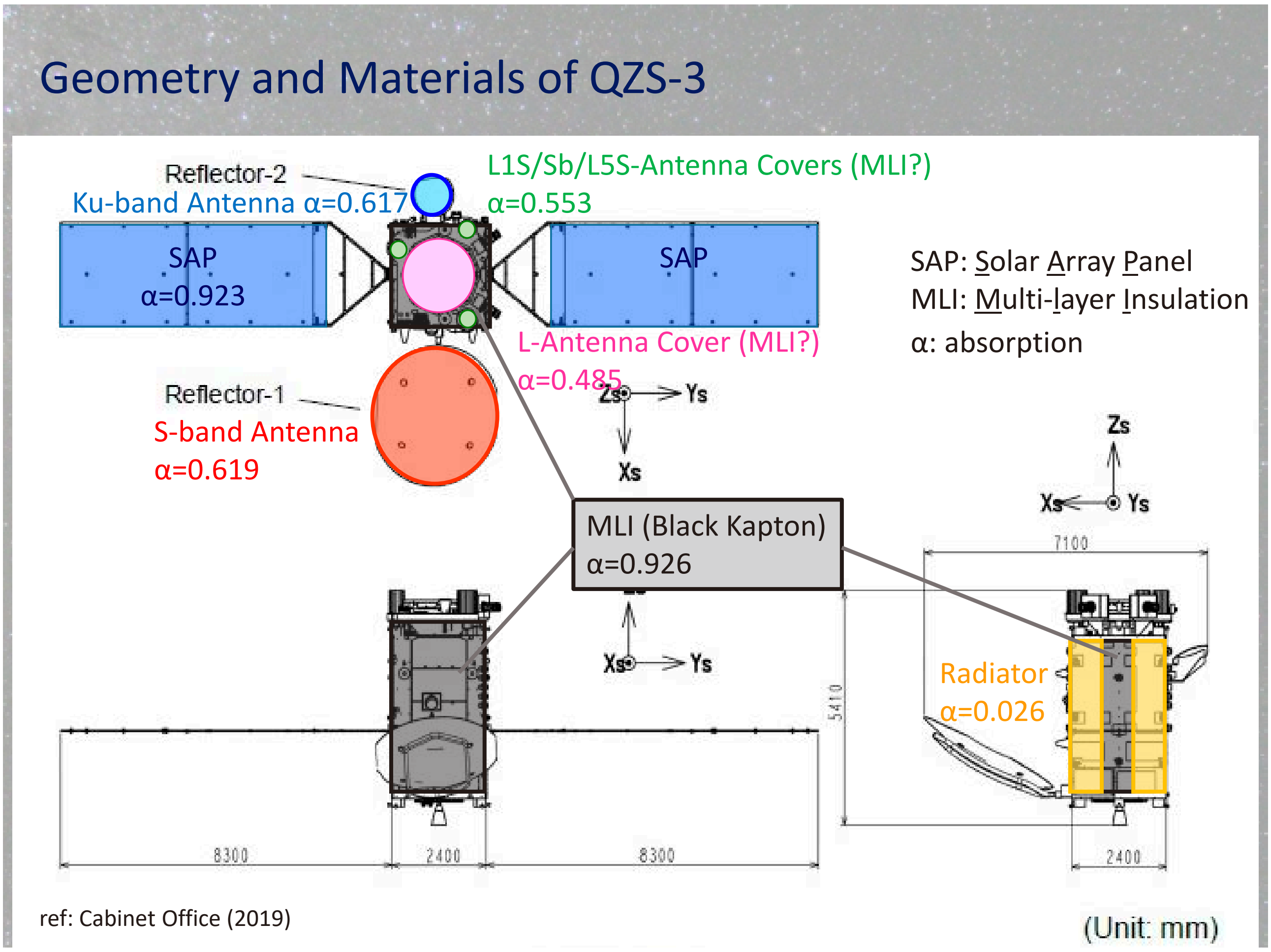
Light Curves (Solar Phase Angle-Magnitude) for HIMAWARI-8/9 & SKY MUSTER



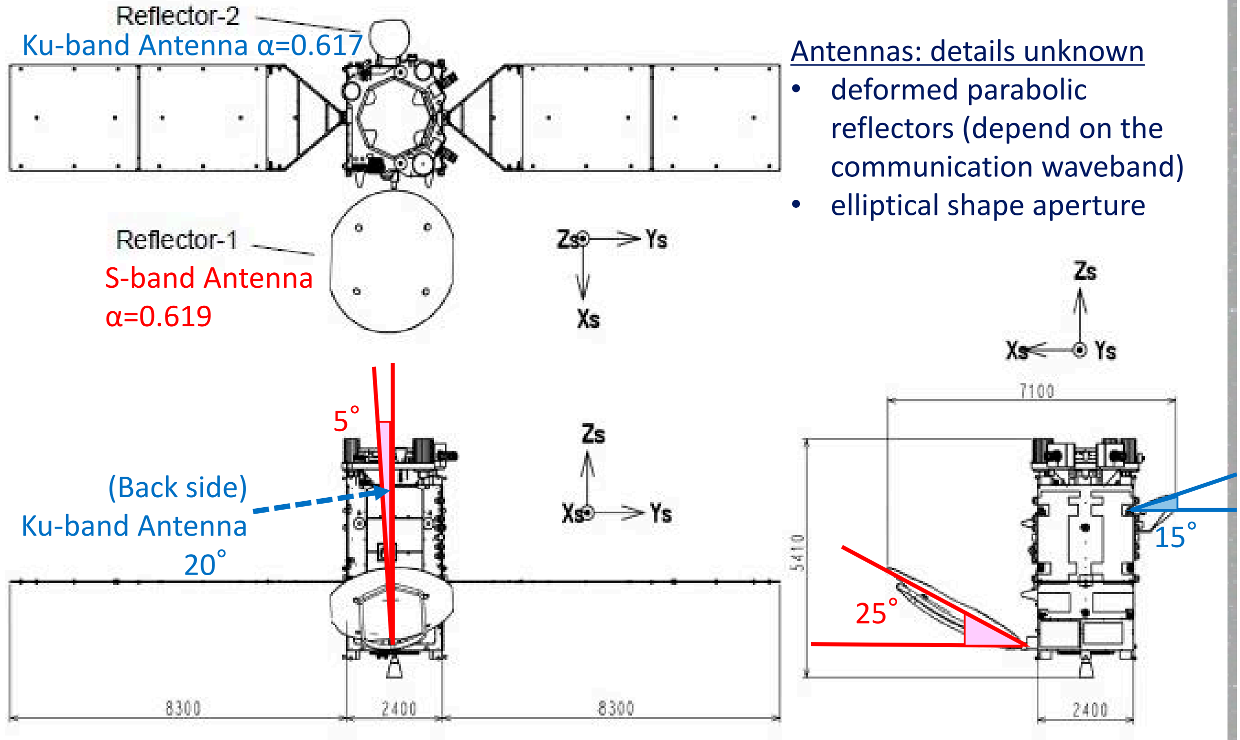
Light Curves for GEO Satellites with the 0.5m Telescope during the Vernal Equinox (2020-03-20)




Light Curves for QZS-3 (in each season)
Light Curves for QZS-3 (2020-03-20)
δ_{Sun}= 0.0°
Light Curve for QZS-3 (2020-06-23)
δ_{Sun}= +23.4°
Light Curve for QZS-3 (2020-09-21)
δ_{Sun}= 0.0°
Light Curve for QZS-3 (2020-12-20)
δ_{Sun}= -23.4°
Magnitude
Solar Phase Angle (deg)
QZS-3


Geometry and Materials of QZS-3
Reflector-2
Ku-band Antenna α=0.617
L1S/Sb/L5S-Antenna Covers (MLI?)
α=0.553
SAP
α=0.923
SAP
SAP: Solar Array Panel
MLI: Multi-layer Insulation
α: absorption
L-Antenna Cover (MLI?)
α=0.485
Reflector-1
S-band Antenna
α=0.619
Zs
Ys
Xs
MLI (Black Kapton)
α=0.926
Radiator
α=0.026
7100
5410
8300
2400
8300
2400
ref: Cabinet Office (2019)
(Unit: mm)

Geometry and Materials of QZS-3



Antennas: details unknown

- deformed parabolic reflectors (depend on the communication waveband)
- elliptical shape aperture

ref: Cabinet Office (2019)

(Unit: mm)

Conditions for a Light Curve Simulation

- The shape of antennas

  →assumed planar antennas

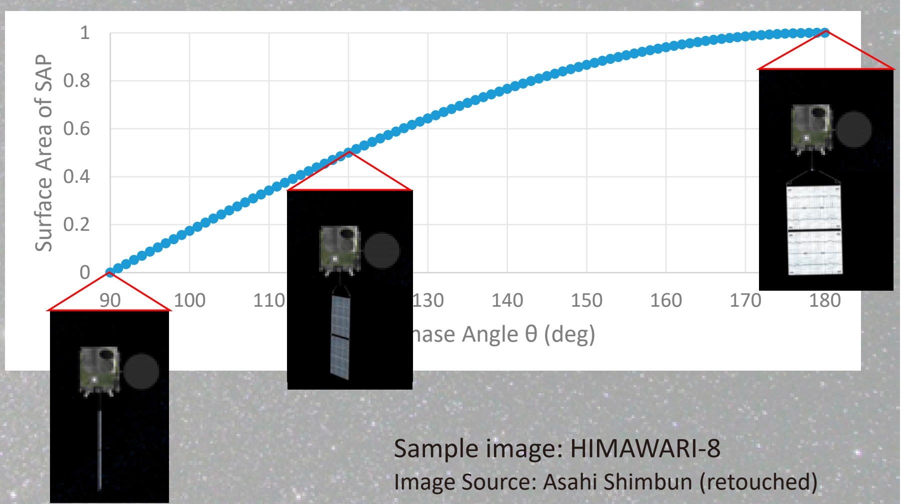
- Variations in absorption rates due to long-term deterioration

  →ignored

- Surface areas of each material

  SAP ∝ cos (180°－θ) (θ: Solar Phase Angle)

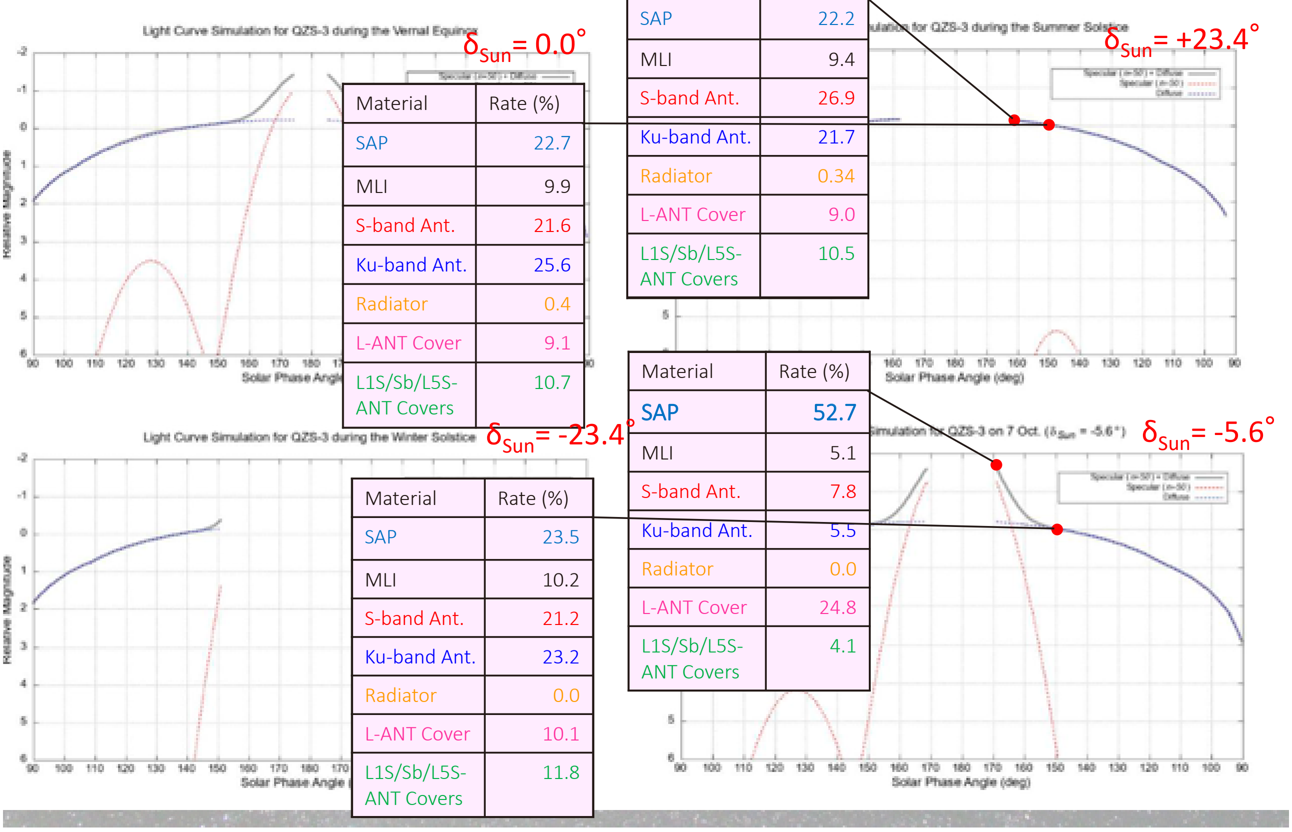
  The others = const.



Sample image: HIMAWARI-8

Image Source: Asahi Shimbun (retouched)

Light Curve Simulations for QZS-3 (in each season)



Vernal Equinox (δ_{Sun} = 0.0°)

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

Summer Solstice (δ_{Sun} = +23.4°)

Material	Rate (%)
SAP	22.2
MLI	9.4
S-band Ant.	26.9
Ku-band Ant.	21.7
Radiator	0.34
L-ANT Cover	9.0
L1S/Sb/L5S-ANT Covers	10.5

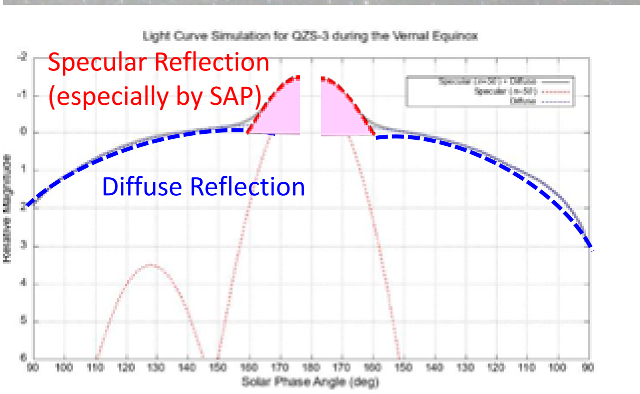
Winter Solstice (δ_{Sun} = -23.4°)

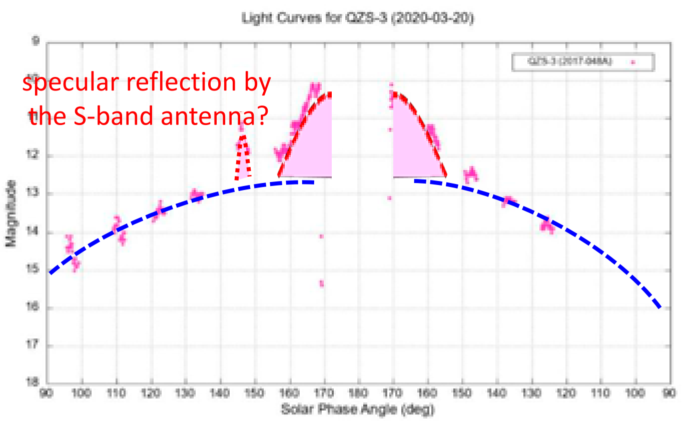
Material	Rate (%)
SAP	23.5
MLI	10.2
S-band Ant.	21.2
Ku-band Ant.	23.2
Radiator	0.0
L-ANT Cover	10.1
L1S/Sb/L5S-ANT Covers	11.8

7 Oct. (δ_{Sun} = -5.6°)

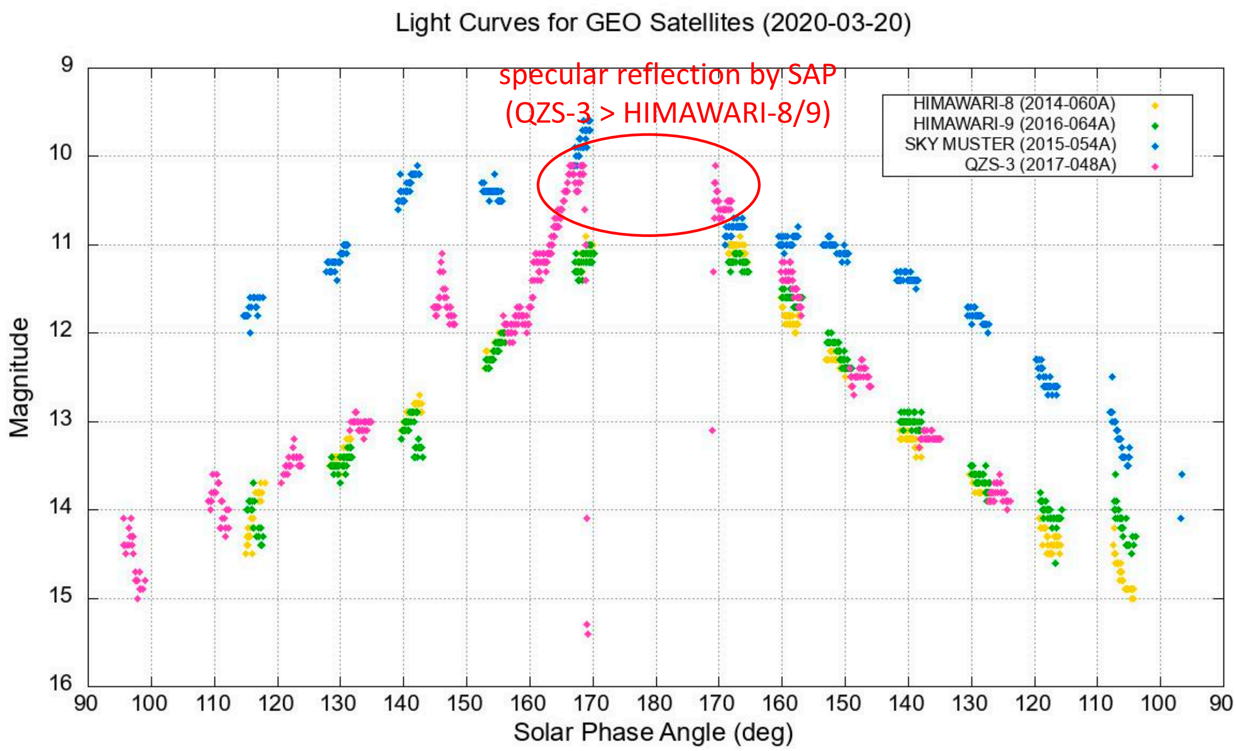
Material	Rate (%)
SAP	52.7
MLI	5.1
S-band Ant.	7.8
Ku-band Ant.	5.5
Radiator	0.0
L-ANT Cover	24.8
L1S/Sb/L5S-ANT Covers	4.1

Light Curve Simulations for QZS-3

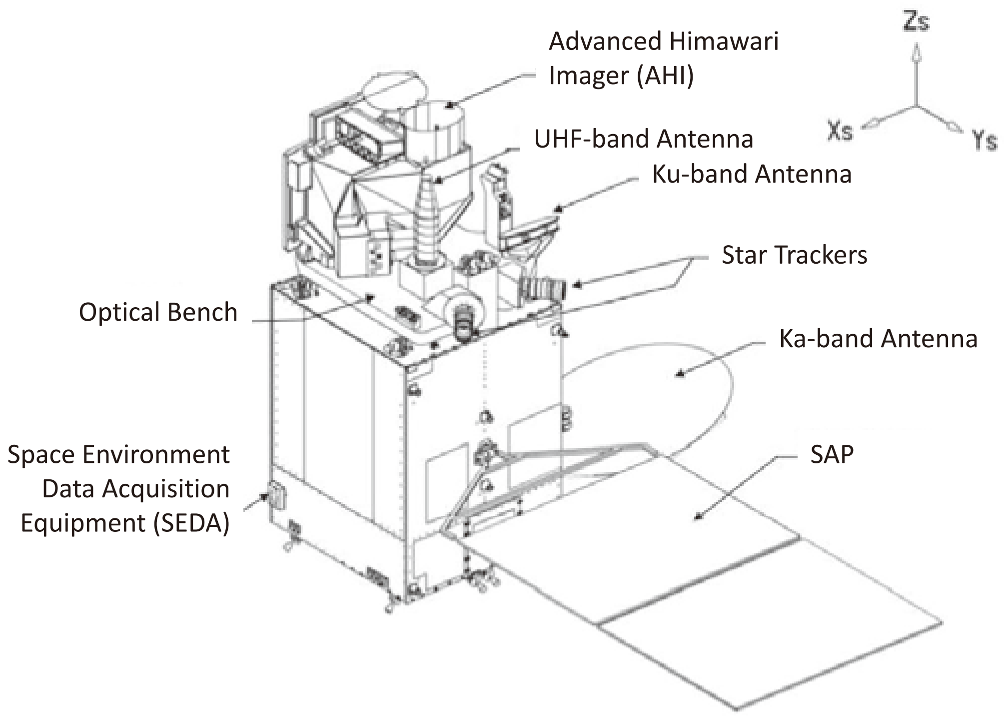




Light Curves for GEO Satellites (2020-03-20)

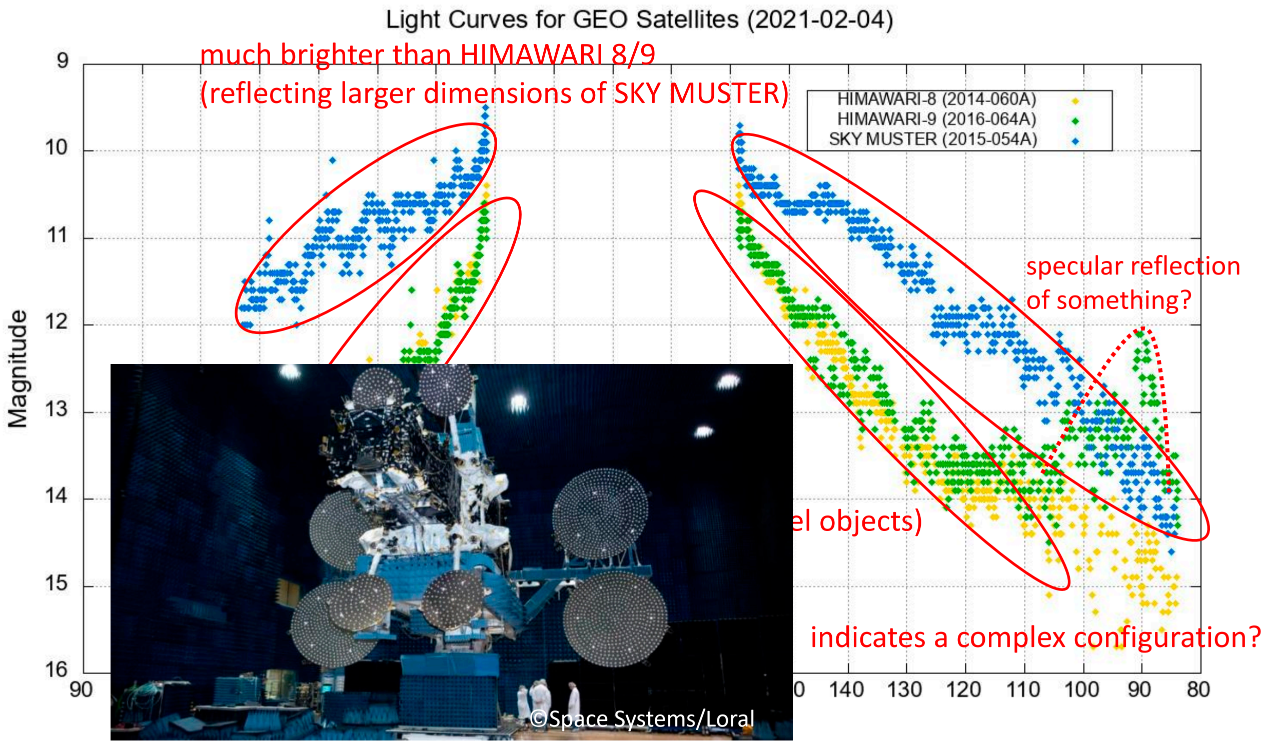


Configuration of HIMAWARI-8/9

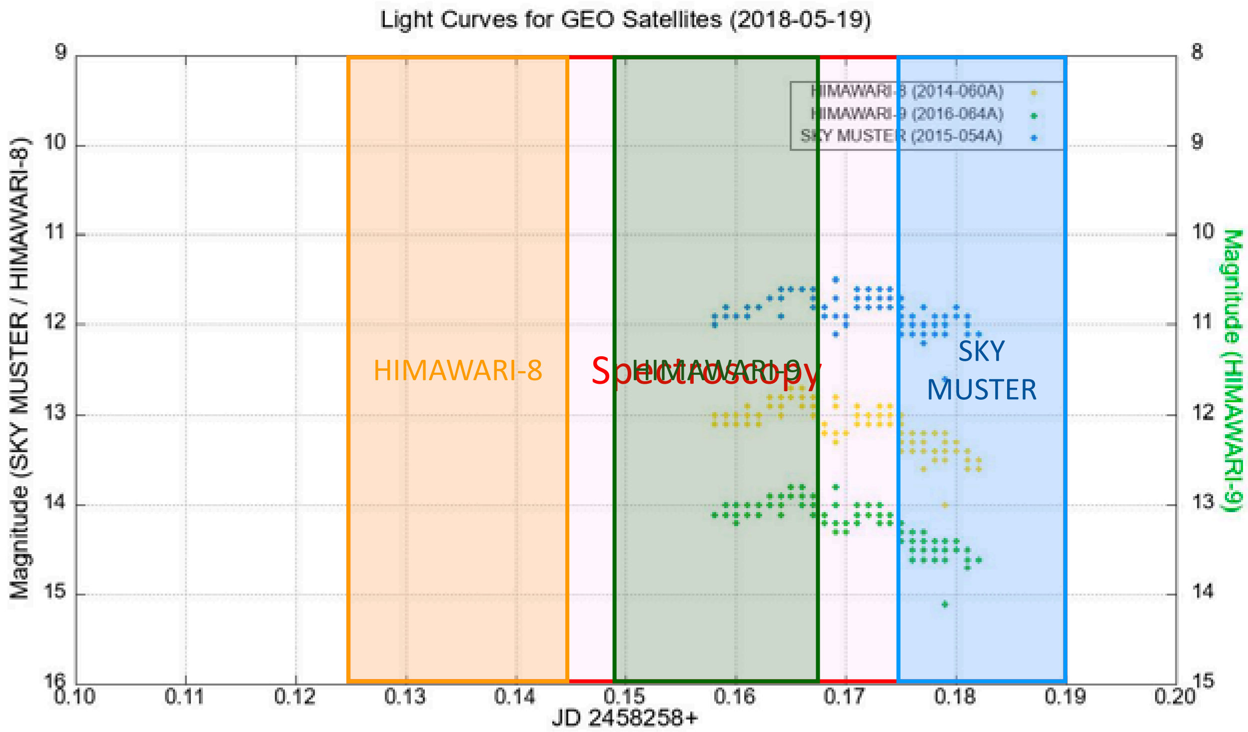


Meteorological Satellite Center (2018)

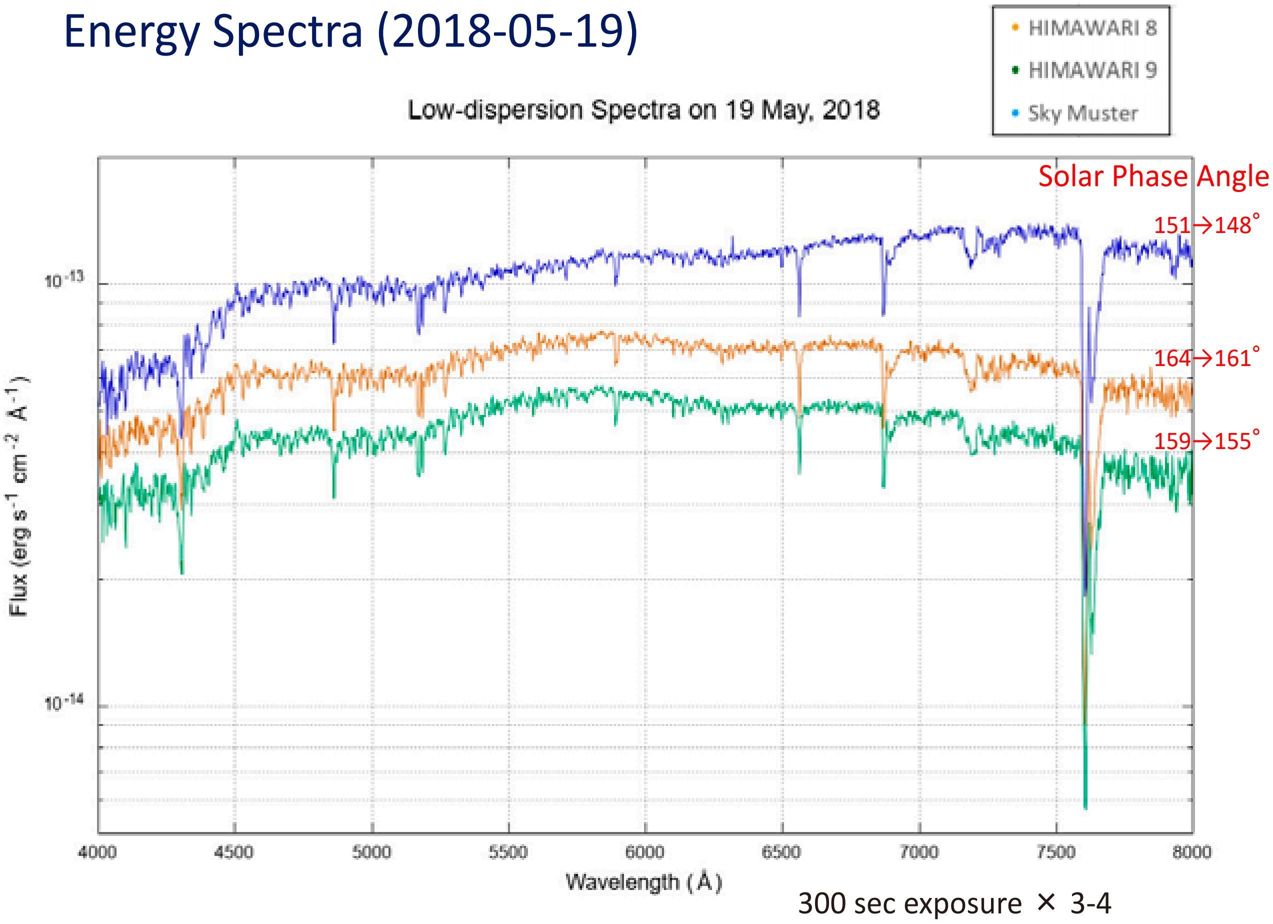
Light Curves for HIMAWARI-8/9 & SKY MUSTER (2021-02-04)



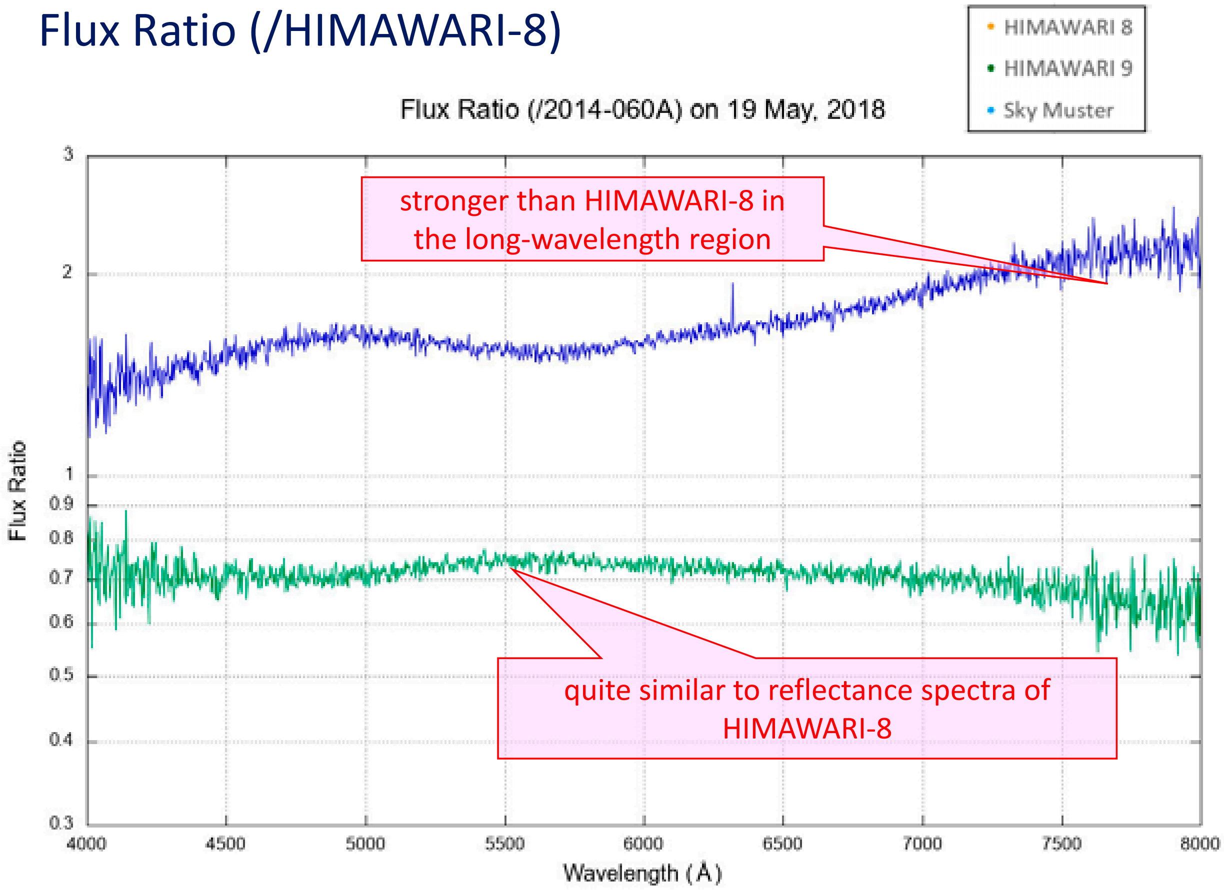
Simultaneous Observation Schedule (2018-05-19)



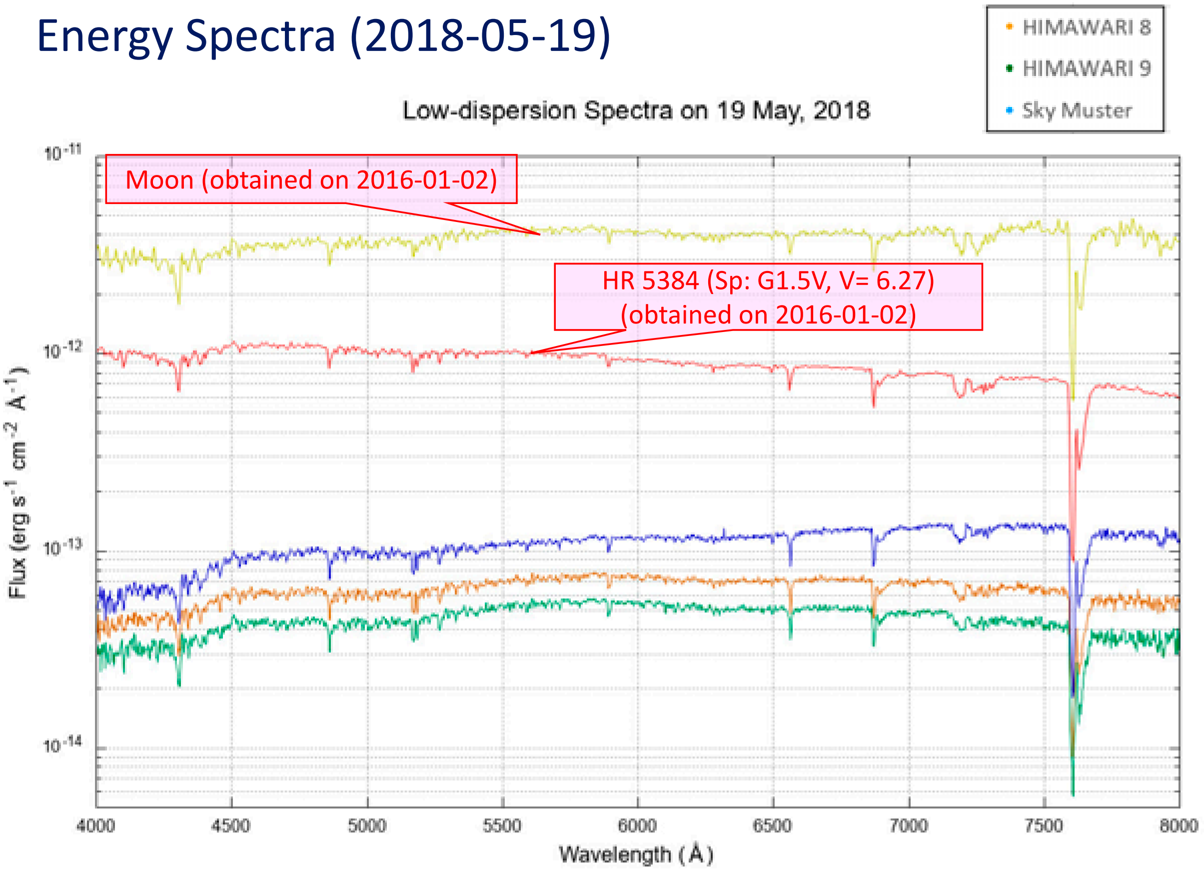
Energy Spectra (2018-05-19)



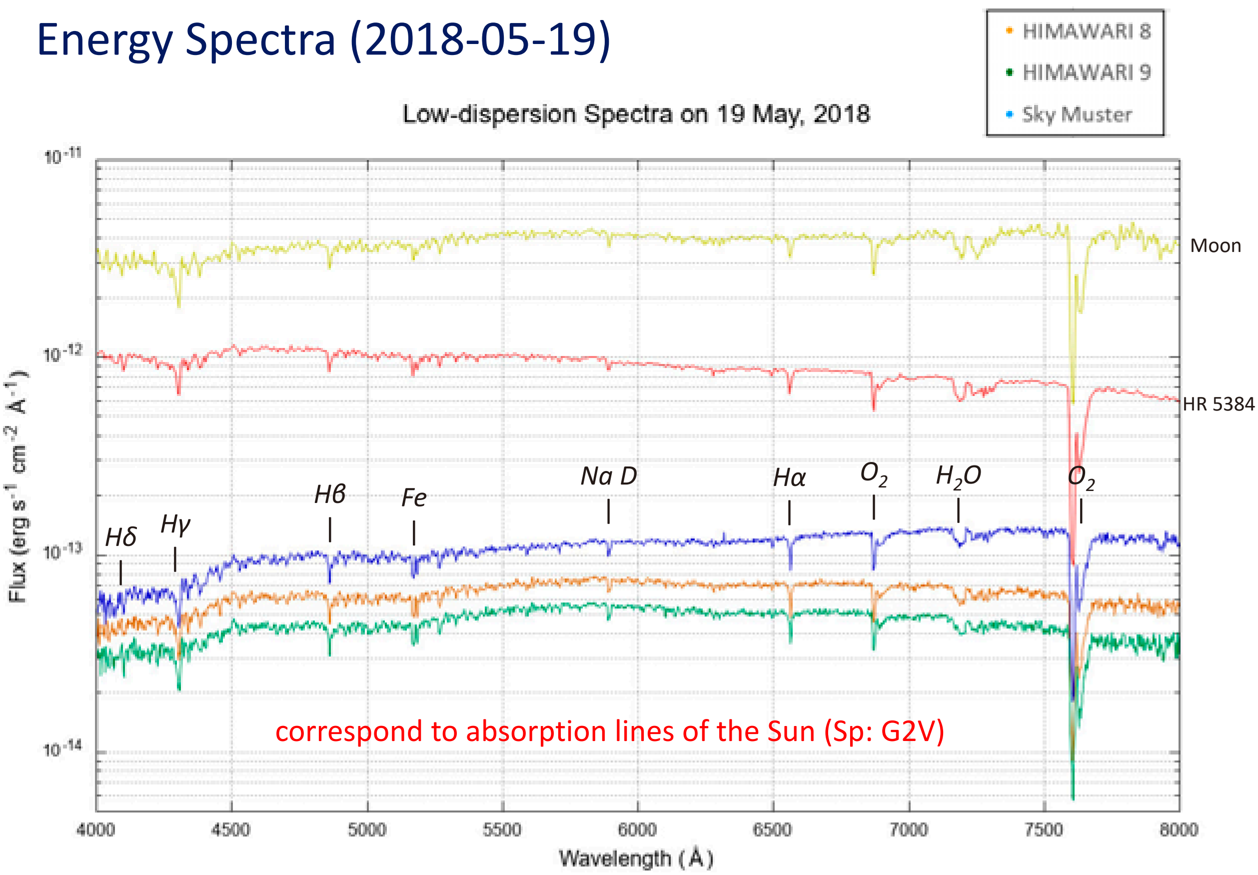
Flux Ratio (/HIMAWARI-8)



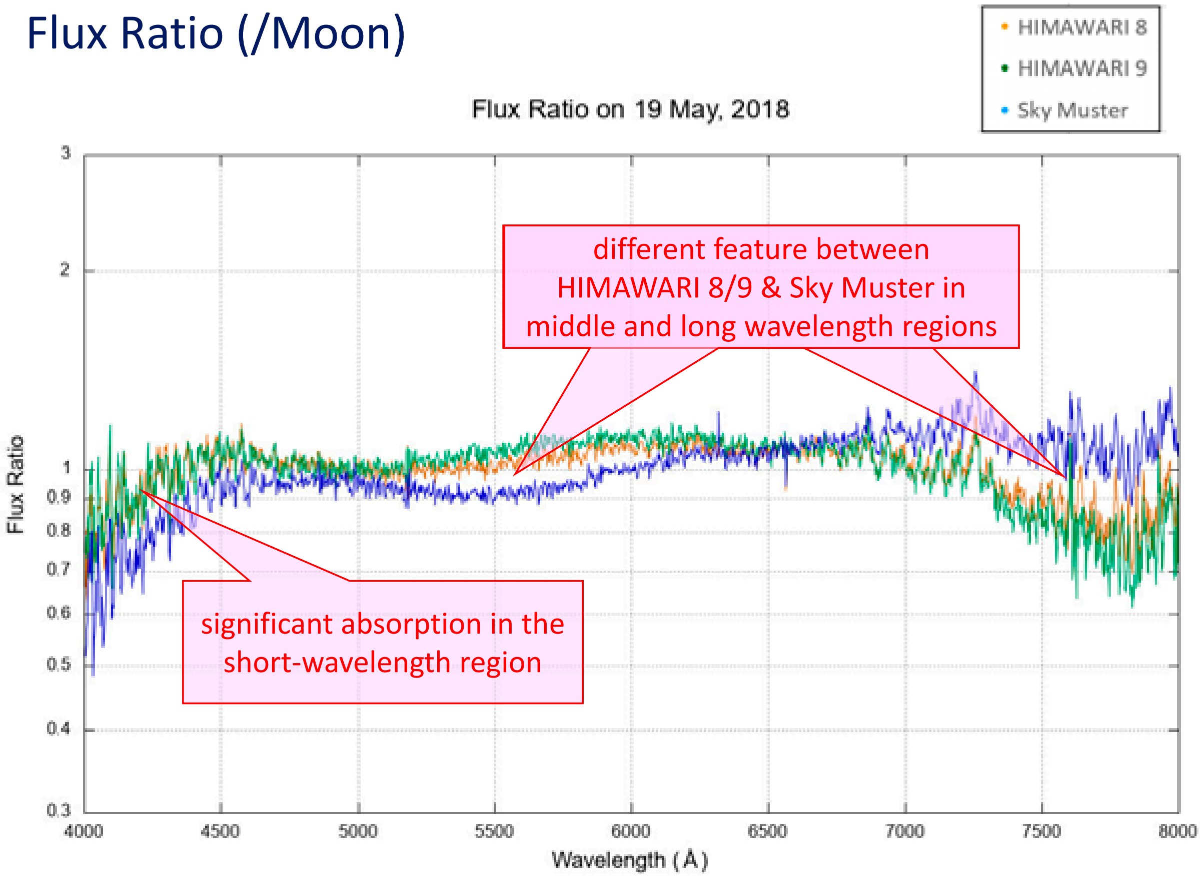
Energy Spectra (2018-05-19)



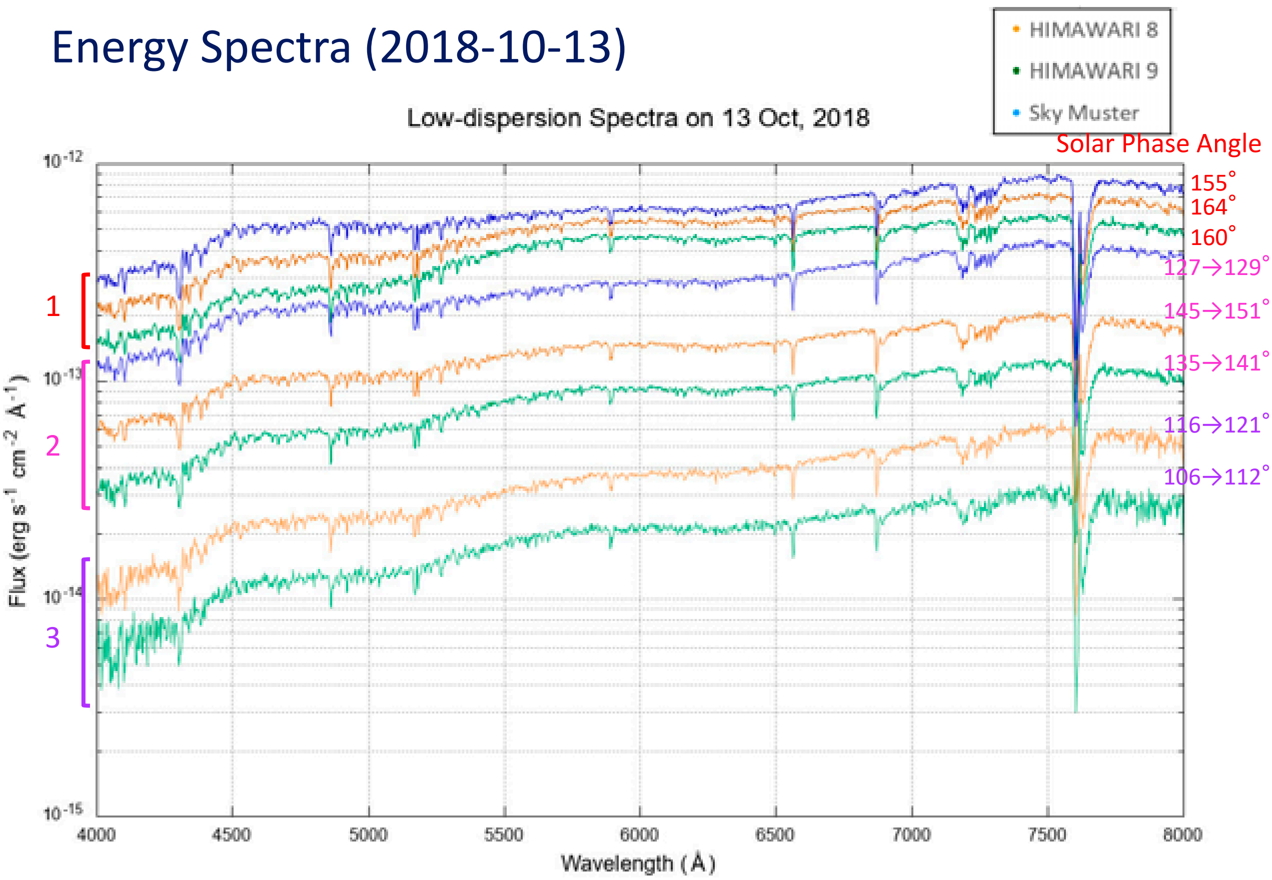
Energy Spectra (2018-05-19)



Flux Ratio (/Moon)

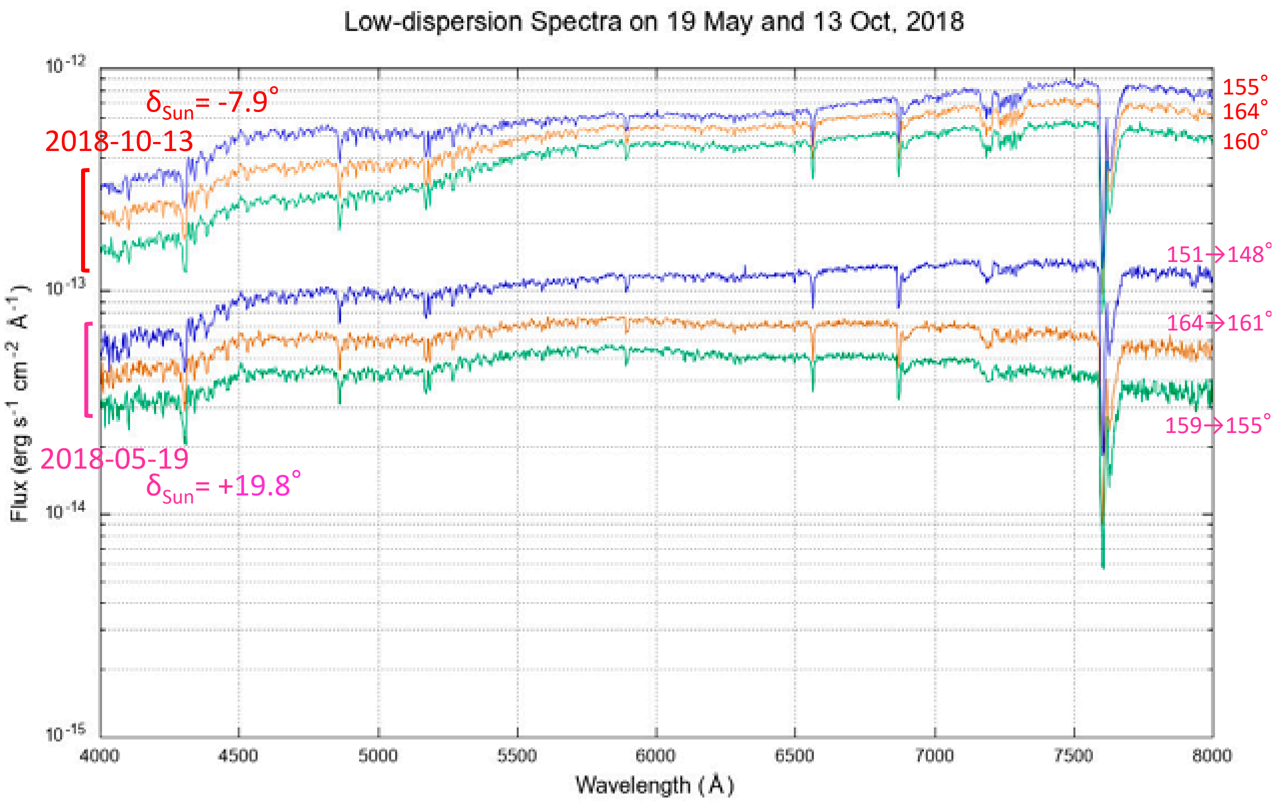


Energy Spectra (2018-10-13)

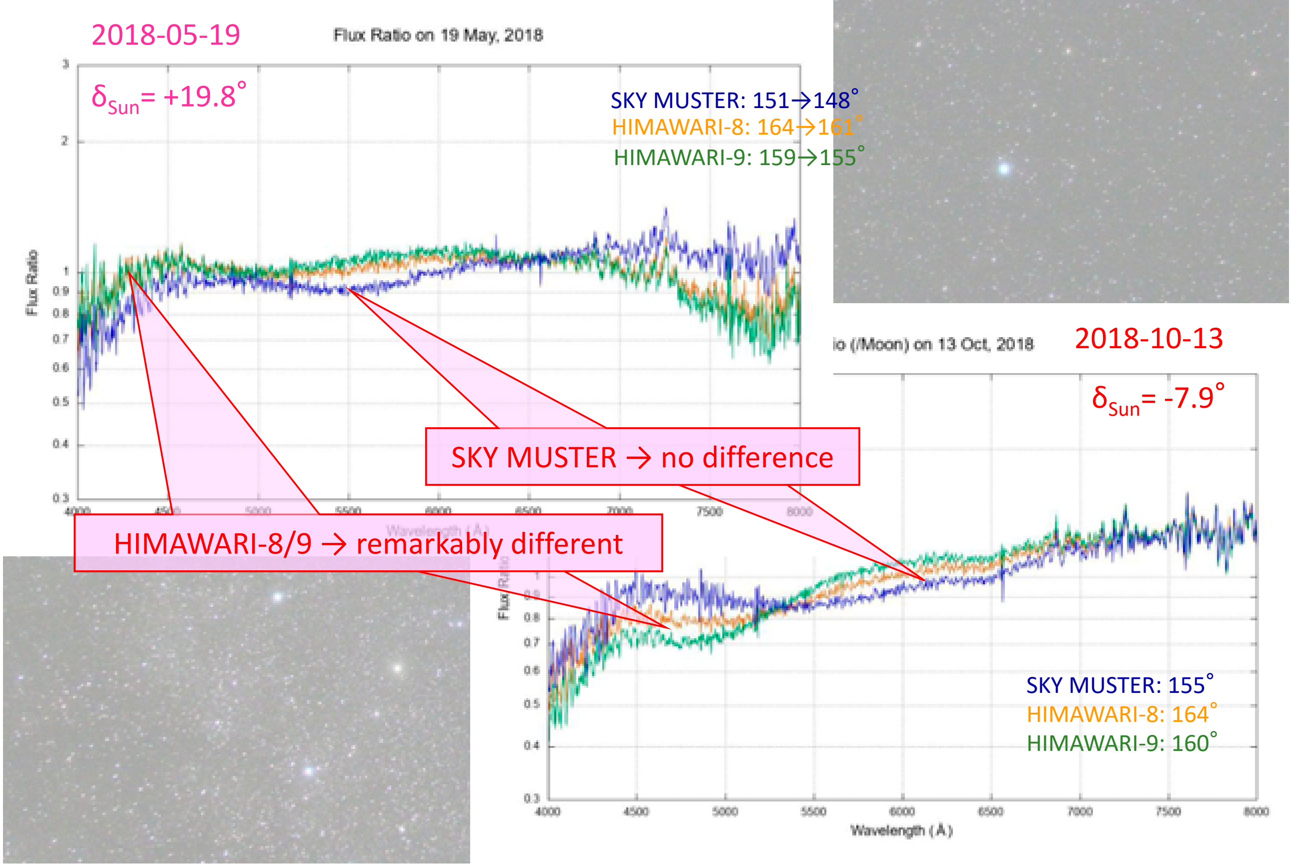


300 sec exposure × 2-5

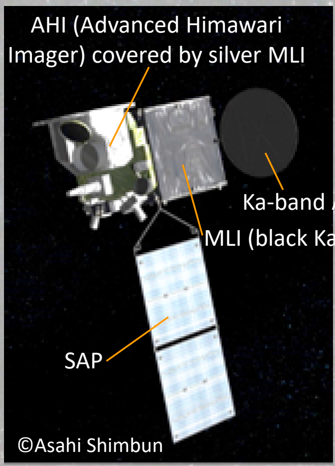
Comparison of Spectra (2018-05-19 vs 2018-10-13)

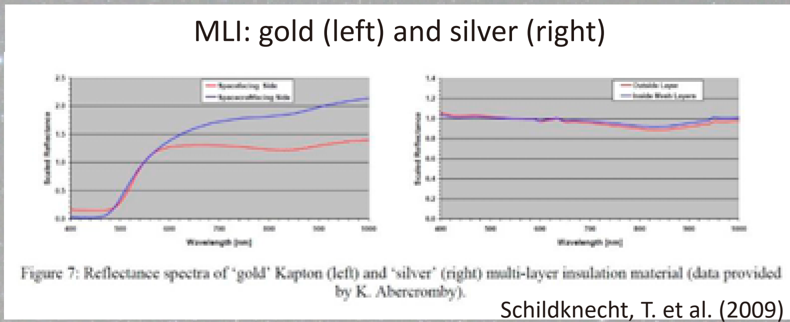


Comparison of Flux Ratio (/Moon)



Reflectance Spectra of each Material





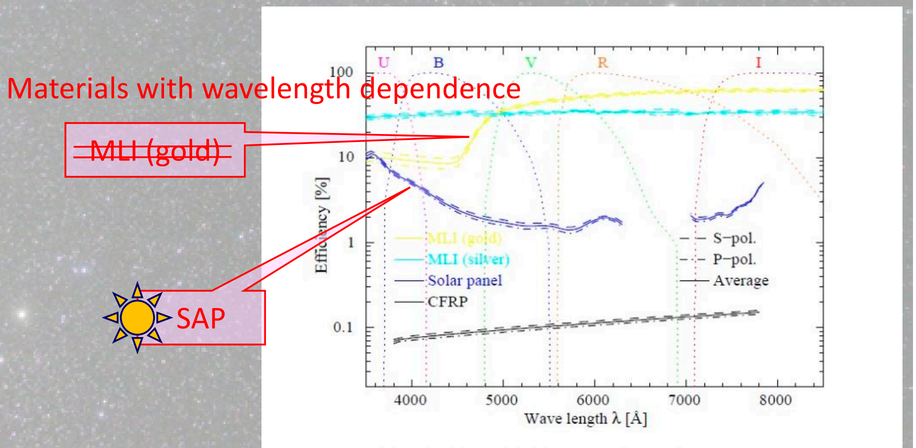
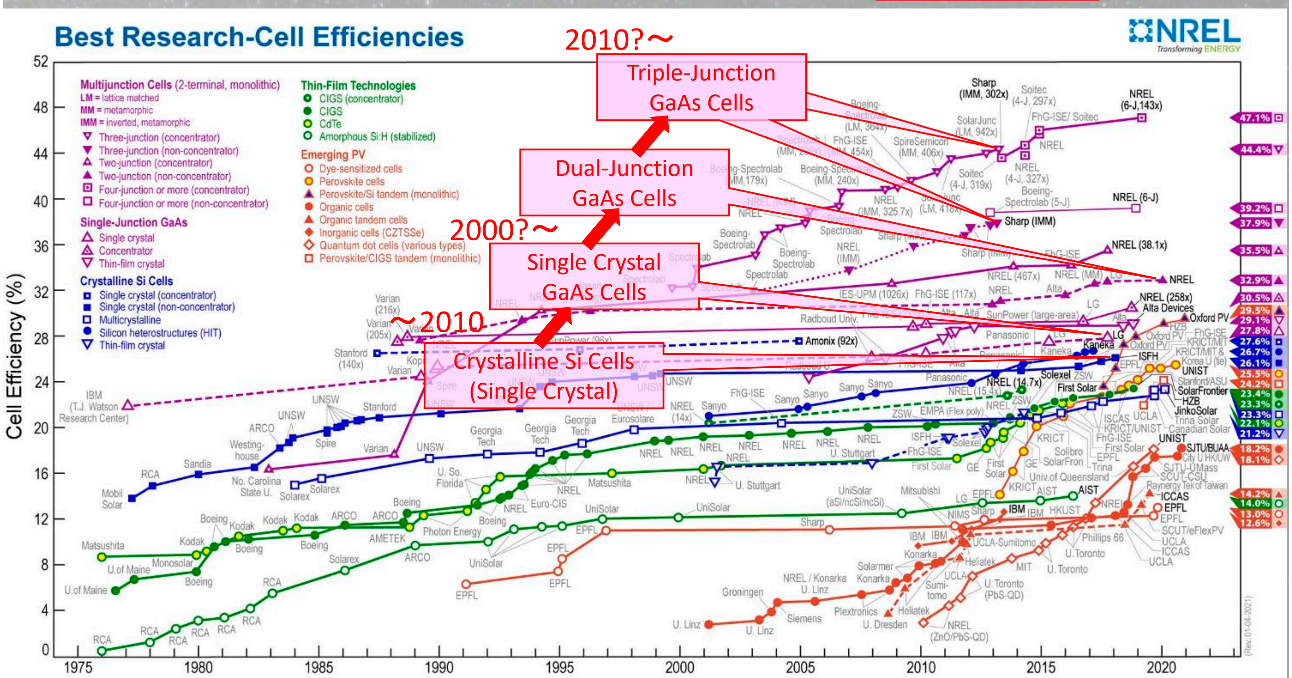


Fig. 3. Spectral reflectance of typical materials.

Endo, T. et al. (2017)

Best Research-Cell Efficiency Chart

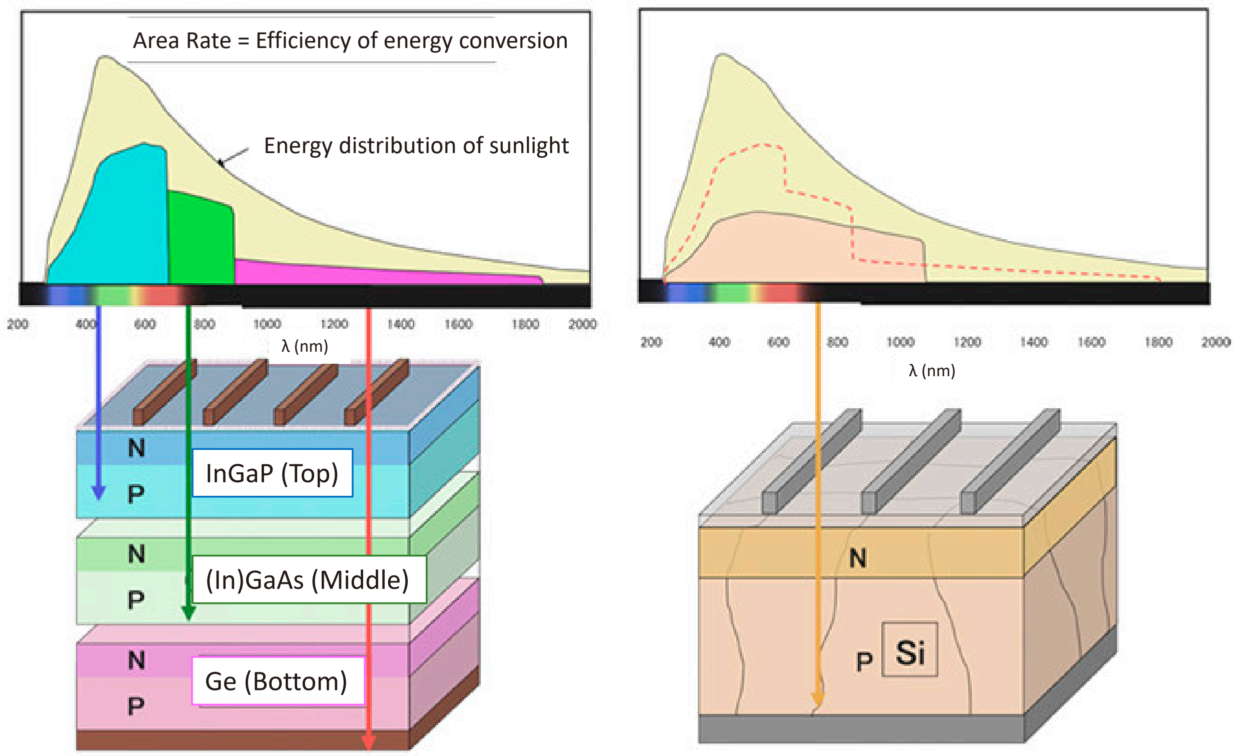
for Spacecrafts



ref：National Renewable Energy Laboratory

Some information on SAP enables us to estimate the rough age of a satellite!

Structure and Efficiency for Solar Energy Utilization of Triple-Junction InGaP/GaAs/Ge and Crystalline Si Cells



ref: https://www.nedo.go.jp/hyoukabu/articles/201111sharp/index.html

Reflectance Spectra of Crystalline Si and Triple-Junction Cells

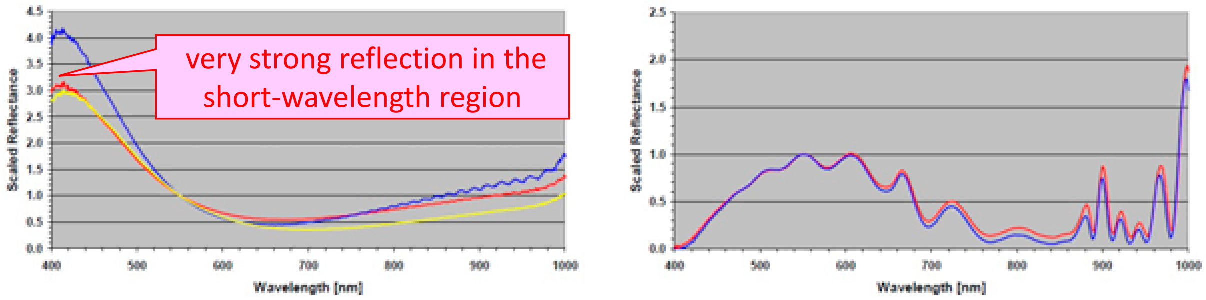
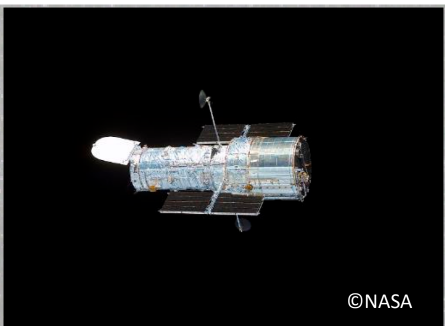


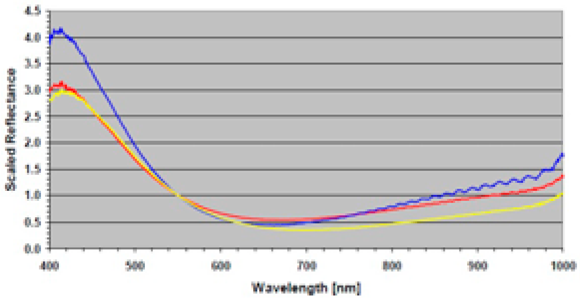
Figure 6: Reflectance spectra of two laboratory samples of solar cells. Left: solar cell sample from the Hubble space telescope solar array retrieved in March 2009 (~8.25 years in space); right: triple junction solar cell sample.

Schildknecht, T. et al. (2009)



Replacement of SAP from Si to GaAs cells in Service Mission 3B (March 2002)

Reflectance Spectra of Crystalline Si and Triple-Junction Cells



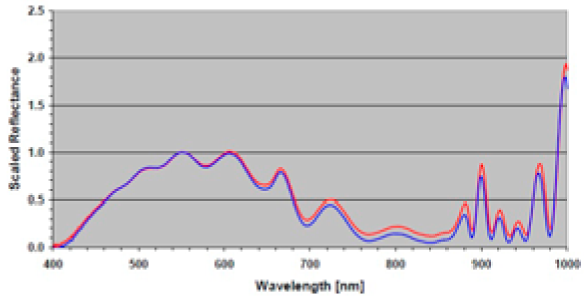
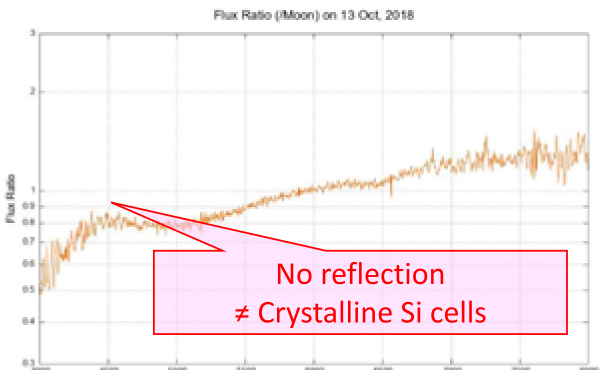
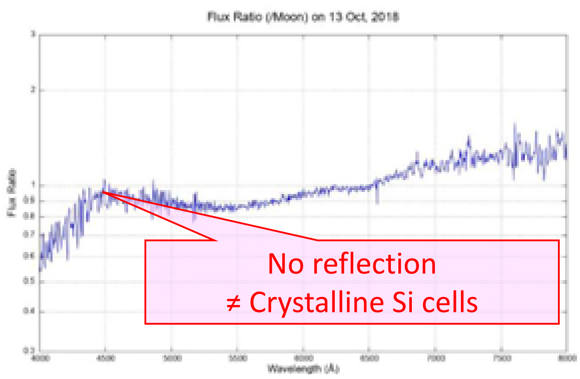


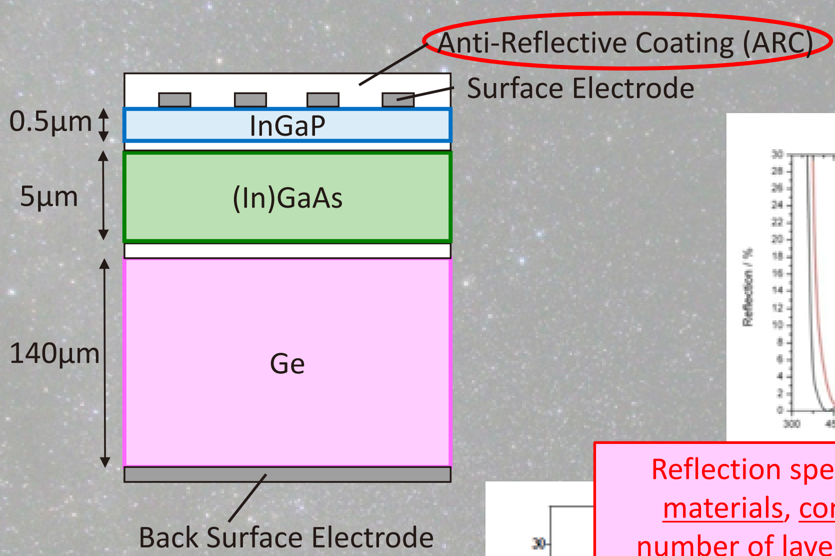
Figure 6: Reflectance spectra of two laboratory samples of solar cells. Left: solar cell sample from the Hubble space telescope solar array retrieved in March 2009 (~8.25 years in space); right: triple junction solar cell sample.

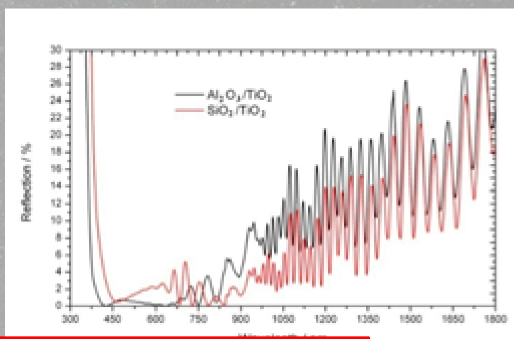
Schildknecht, T. et al. (2009)





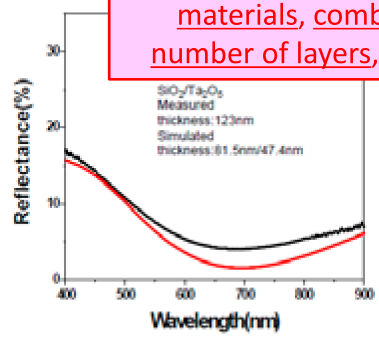
Cross Sectional View of InGaP/GaAs/Ge Cells

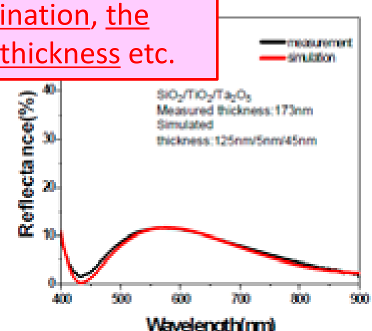




. et al. (2013)

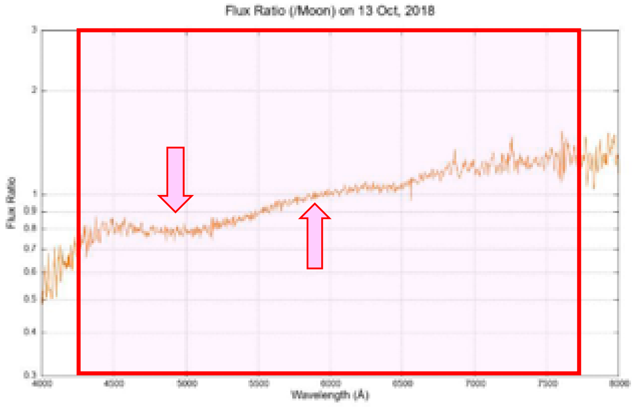
Reflection spectra depend on materials, combination, the number of layers, thickness etc.

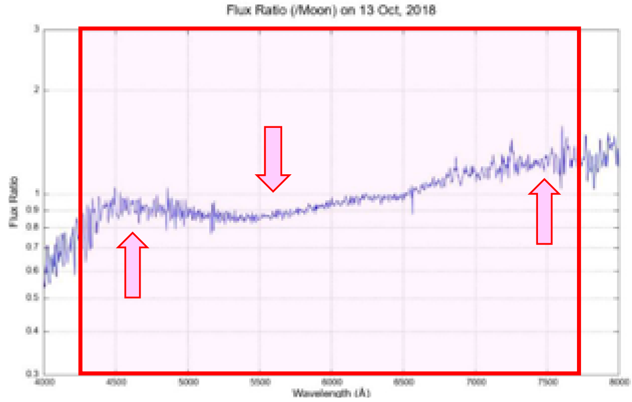




Chang, L-B. et al. (2010)

Identification of Anti-Reflective Coatings





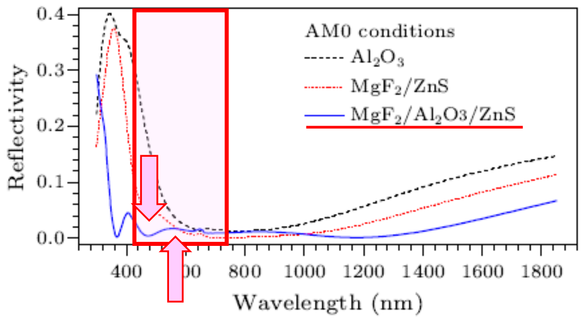
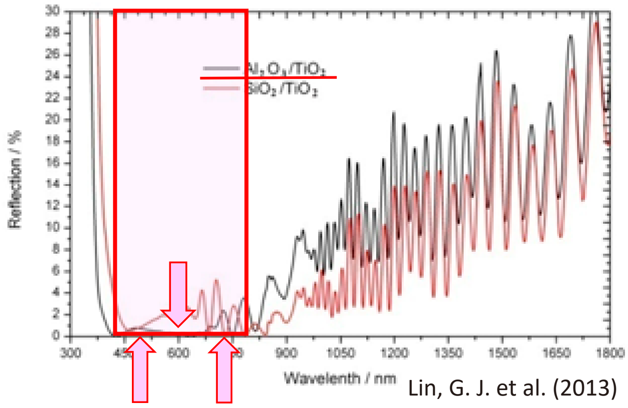


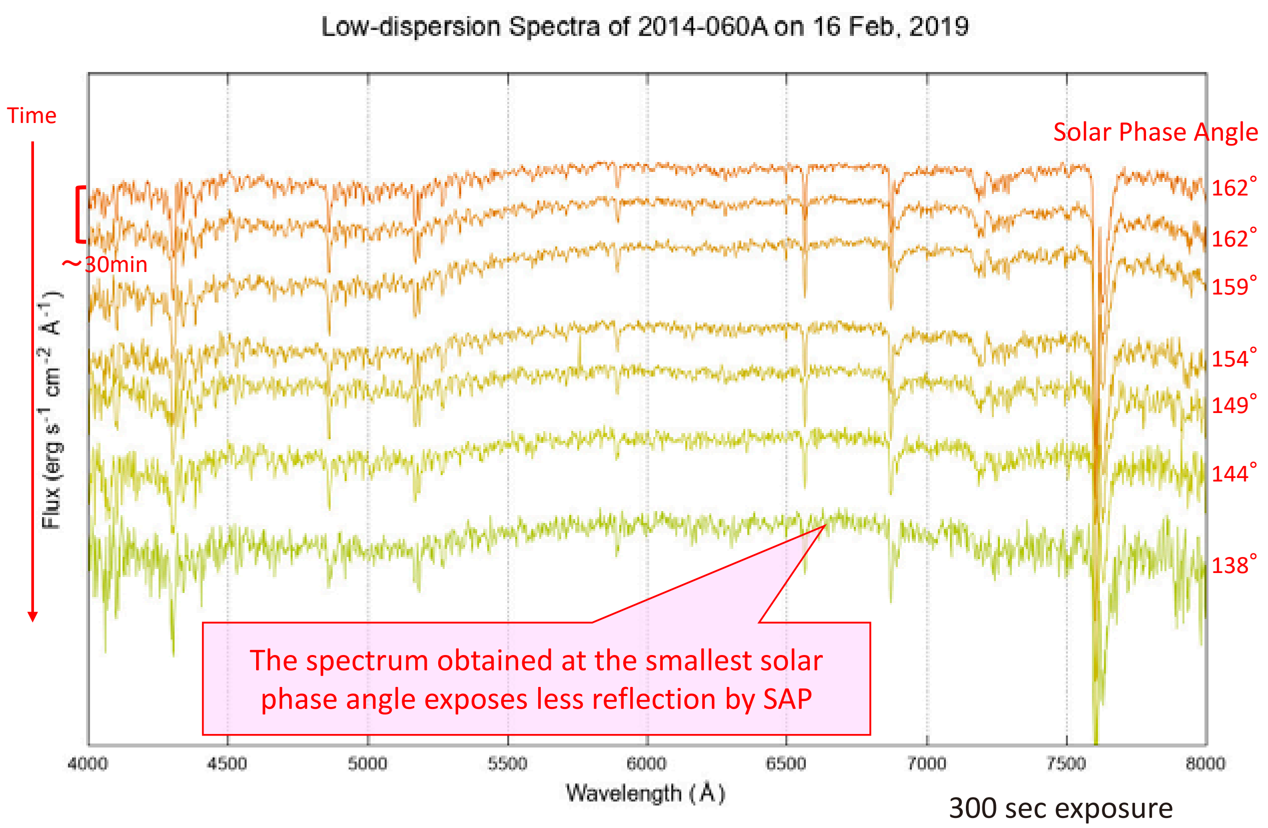
Fig. 9. ARC reflectivity vs wavelength under the AM0 condition.

Zhan, F. et al. (2011)



Lin, G. J. et al. (2013)

Temporal Changes of Spectra for HIMAWARI-8



300 sec exposure

Normalized Spectra by the Last Data (with the Smallest Solar Phase Angle)

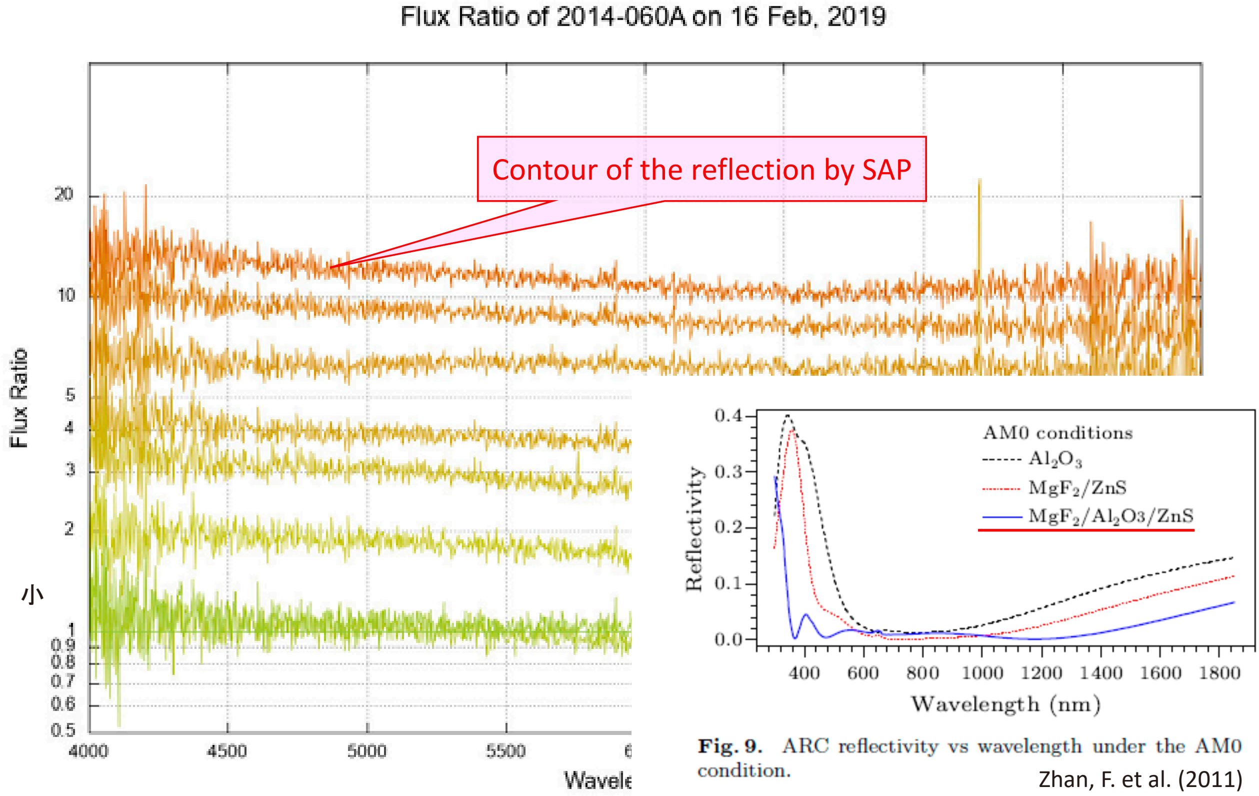
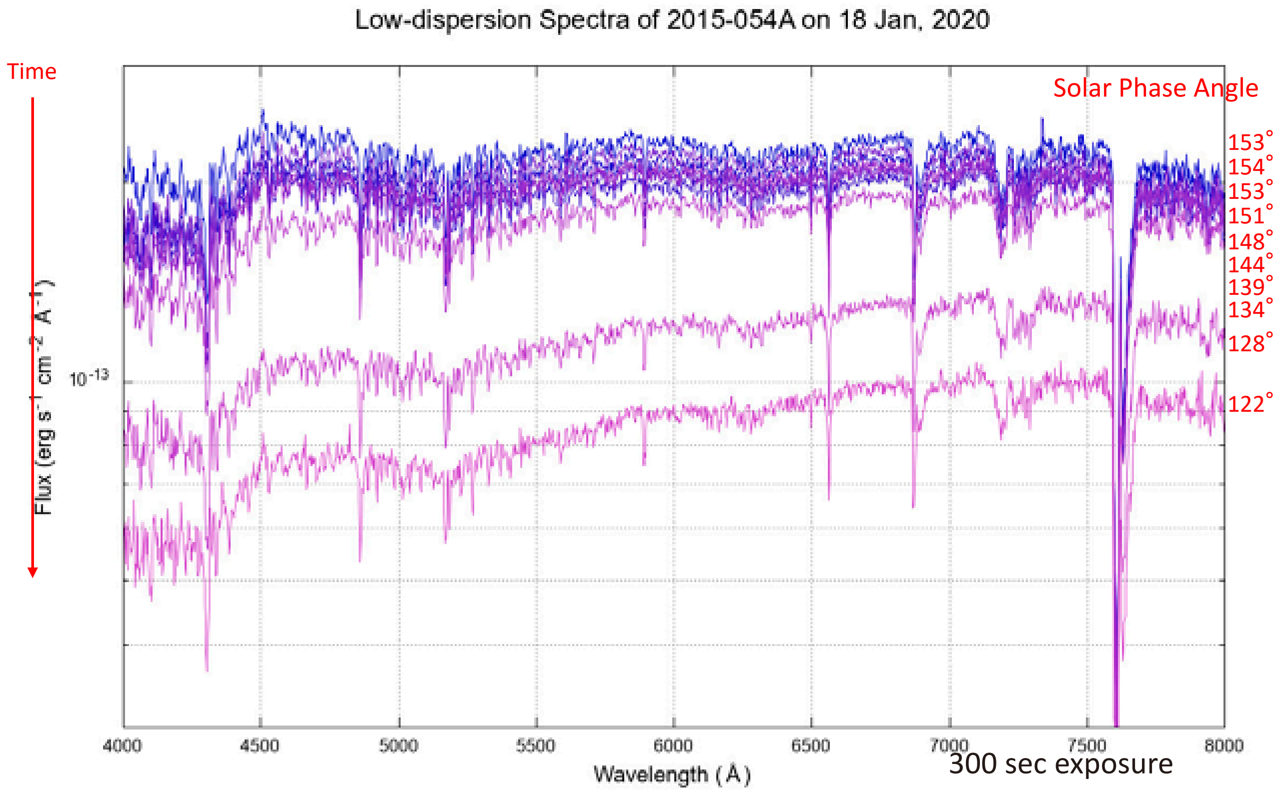


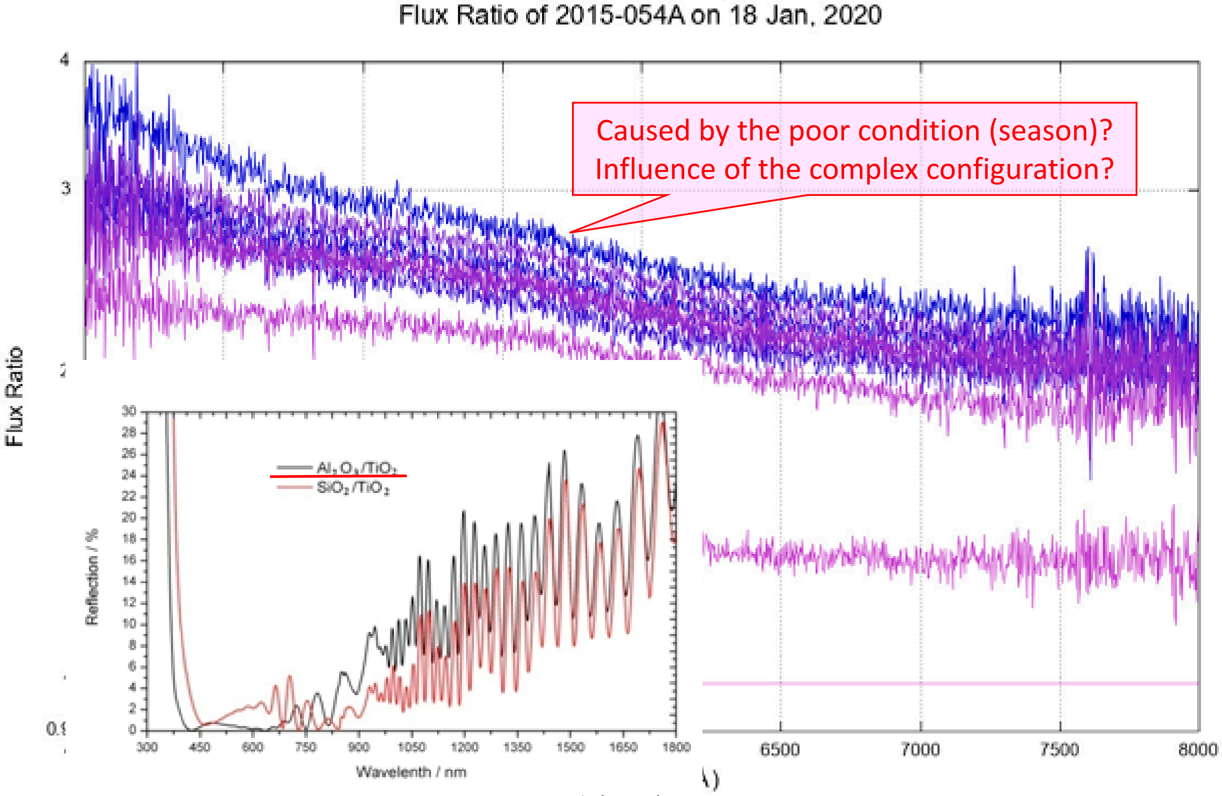
Fig. 9. ARC reflectivity vs wavelength under the AM0 condition.

Zhan, F. et al. (2011)

Temporal Changes of Spectra for SKY MUSTER



Normalized Spectra by the Last Data (with the Smallest Solar Phase Angle)



Lin, G. J. et al. (2013)

4. Conclusions

1. Light curves for GEO satellites yield information about their own dimensions and configurations
   - HIMAWARI-8/9 have very similar light curves
   - SKY MUSTER has a brighter light curve profile than HIMAWARI-8/9
2. The brightness / intensity of spectra of a satellite varies with the solar phase angle and with the season (the declination of the Sun)
   - (brighter) large solar phase angle ⇔ small solar phase angle (dimmer)
   - (brighter) δ_{Sun}=-5.6 ⇔ summer solstice: δ_{Sun}=+23.4 (dimmer)
3. The contour of each spectrum shows characteristics of SAP including ARC and also varies with the solar phase angle and with the season

Future Works

1. Application of the light curve simulation model for QZS-3 to other satellites (HIMAWARI-8/9, SKY MUSTER…)
2. Follow-up photometric / spectroscopic observations to know temporal changes of light curves / spectra
3. Additional spectroscopic observations for satellites (including QZS-3) especially with other types of SAP cells

Thank you for your attention!

★Acknowledgements★

We are grateful to the following people / institutions:

- Dr. Ryouta Maeno (Bisei Astronomical Observatory) for supports of spectroscopic observations
- Dr. Osamu Hashimoto (Gunma Astronomical Observatory) for fruitful discussion on spectra
- 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

Corresponding author: Tomoko FUJIWARA 藤原智子
(E-mail: tomokof@spaceguard.or.jp)

Any comments or suggestions are welcome!

B11

ライトカーブ観測と H-2A R/B モデルを用いた再現実験

Light Curve Observation and Reproduction Experiment Using Model of H-2A R/B

○黒崎 裕久, 柳沢 俊史, 林 正人, 河本 聡美（JAXA）
○KUROSAKI Hirohisa, YANAGISAWA Toshifumi, HAYASHI Masato, KAWAMOTO Satomi (JAXA)

積極的デブリ除去（Active Debris Removal, ADR）は、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。そのためターゲットのライトカーブのみを使用してターゲットの姿勢や運動に関する情報を得られれば、デブリ除去ミッション実現に向け前進となる。そこで 60cm 望遠鏡と CMOS センサを使用して、ADR 対象候補の一つである、日本の H-2A ロケットの 2 段目のライトカーブ観測を開始した。また、観測したライトカーブを模擬するために、光学シミュレーターと呼ばれる実験設備で実験を実施した。光学シミュレーターでは、H-2A R/B のスケールモデルを使用し、軌道上での物体の姿勢や運動、太陽方向を考慮して、地上望遠鏡で観測した場合のライトカーブを再現できる。また、ライトカーブの網羅的な傾向を検討するために、CG を使用したライトカーブシミュレーションツールを開発した。これにより、光学シミュレーターを使用してライトカーブを取得するための実験時間が大幅に短縮できると期待される。

Active debris removal (ADR) is one of the most promising methods for ensuring safe space activities, free from the danger of debris. In order to carry out an ADR mission, the attitude and motion of the target must be determined precisely in advance. Developing methodology to extract these values using only the target's light curve would be a great step forward. We started the light curve observations of the ADR candidates, 2nd stages of Japanese H-2A rockets using the 60cm telescope and the CMOS sensor. In addition, we developed an optical simulator in the laboratory to mimic observed light curves. The simulator can reproduce the exact light curve that considers the attitude, movement, and lighting conditions using a scale model of the H-2A R/B. We also developed a light curve simulation tool using CGs that can estimate the overall tendency of the light curve, which will dramatically reduce experimental times for simulating light curve using the optical simulator.

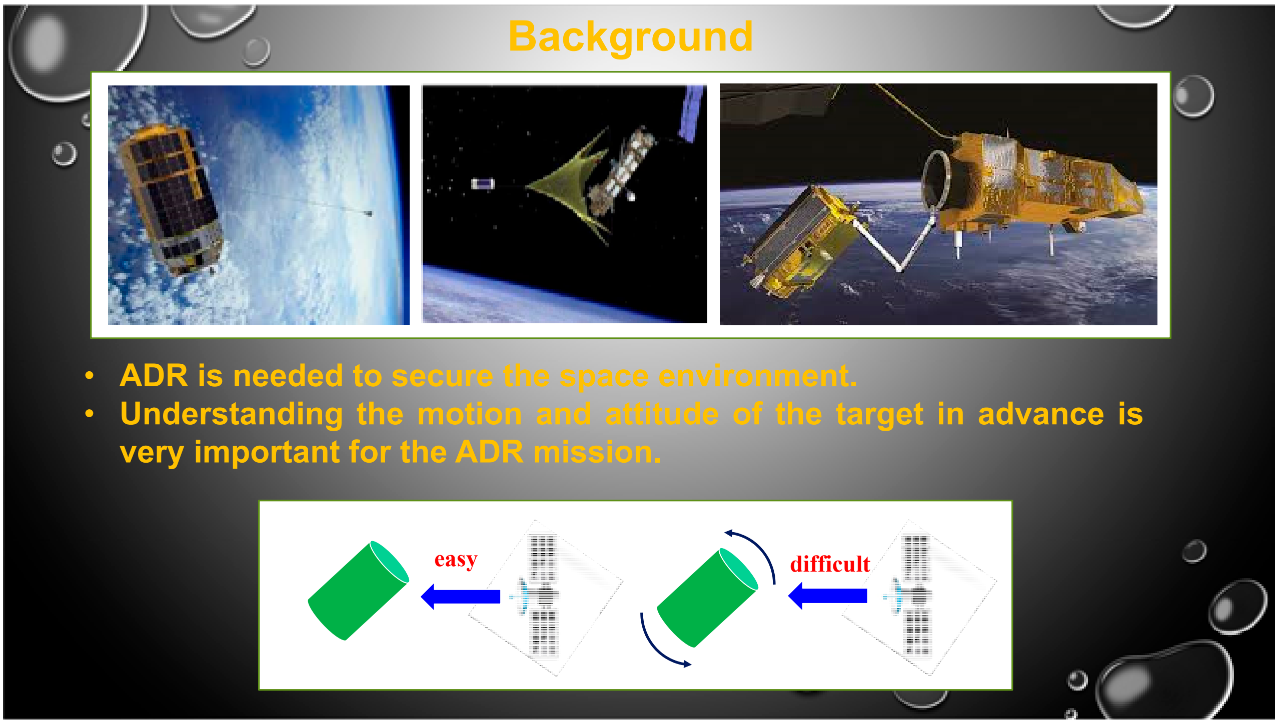
LIGHT CURVE OBSERVATION AND REPRODUCTION EXPERIMENT USING MODEL OF H-2A R/B

ライトカーブ観測とH-2A R/Bモデルを用いた再現実験

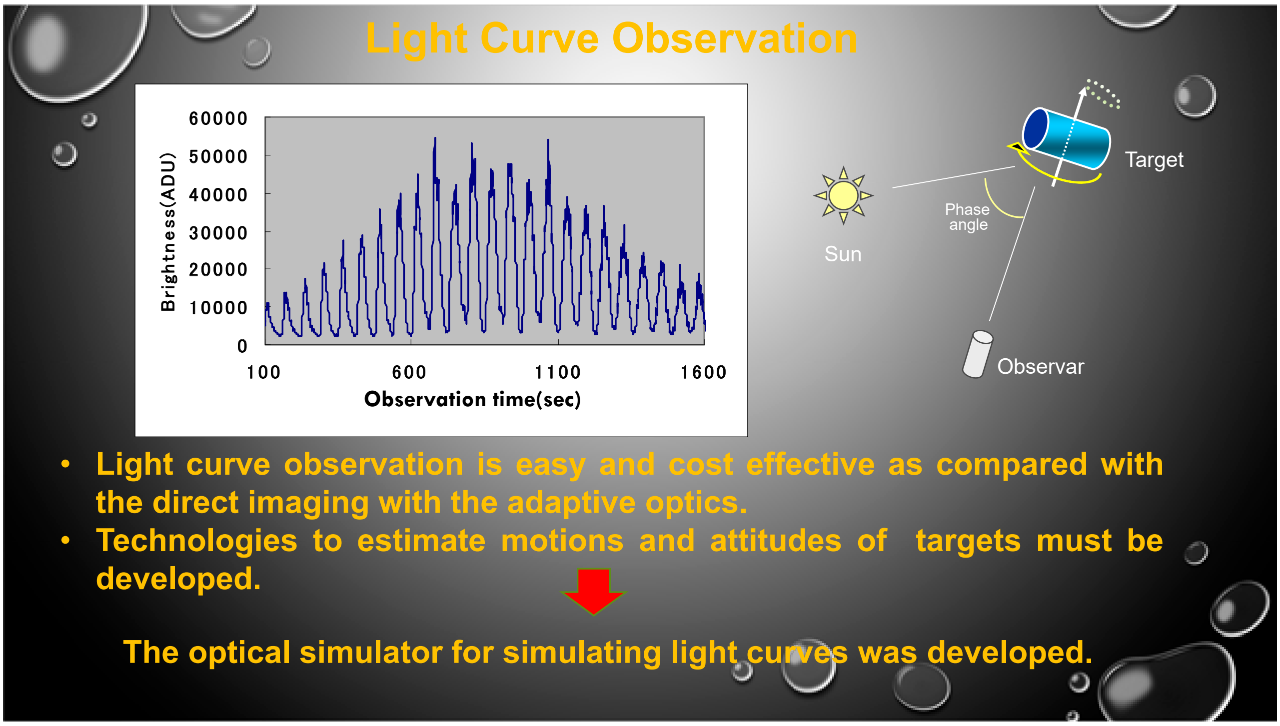
○KUROSAKI Hirohisa, YANAGISAWA Toshifumi, HAYASHI Masato, KAWAMOTO Satomi
Japan Aerospace Exploration Agency (JAXA)
○黒崎裕久，柳沢俊史，林正人，河本聡美（JAXA）

Abstract

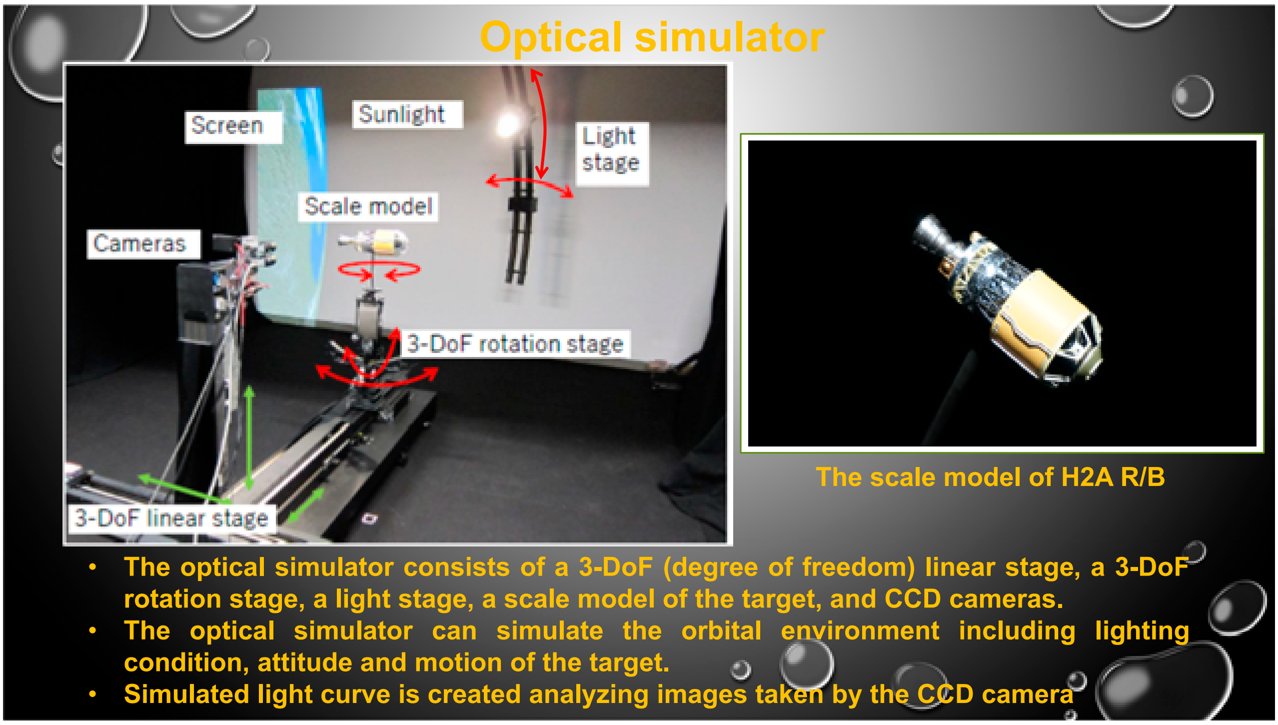
Active debris removal (ADR) is one of the most promising methods for ensuring safe space activities, free from the danger of debris. In order to carry out an ADR mission, the attitude and motion of the target must be determined precisely in advance. Developing methodology to extract these values using only the target's light curve would be a great step forward. We started the light curve observations of the ADR candidates, 2nd stages of Japanese H-2A rockets using the 60cm telescope and the CMOS sensor. In addition, we developed an optical simulator in the laboratory to mimic observed light curves. The simulator can reproduce the exact light curve that considers the attitude, movement, and lighting conditions using a scale model of the H-2A R/B. We also developed a light curve simulation tool using CGs that can estimate the overall tendency of the light curve, which will dramatically reduce experimental times for simulating light curve using the optical simulator.

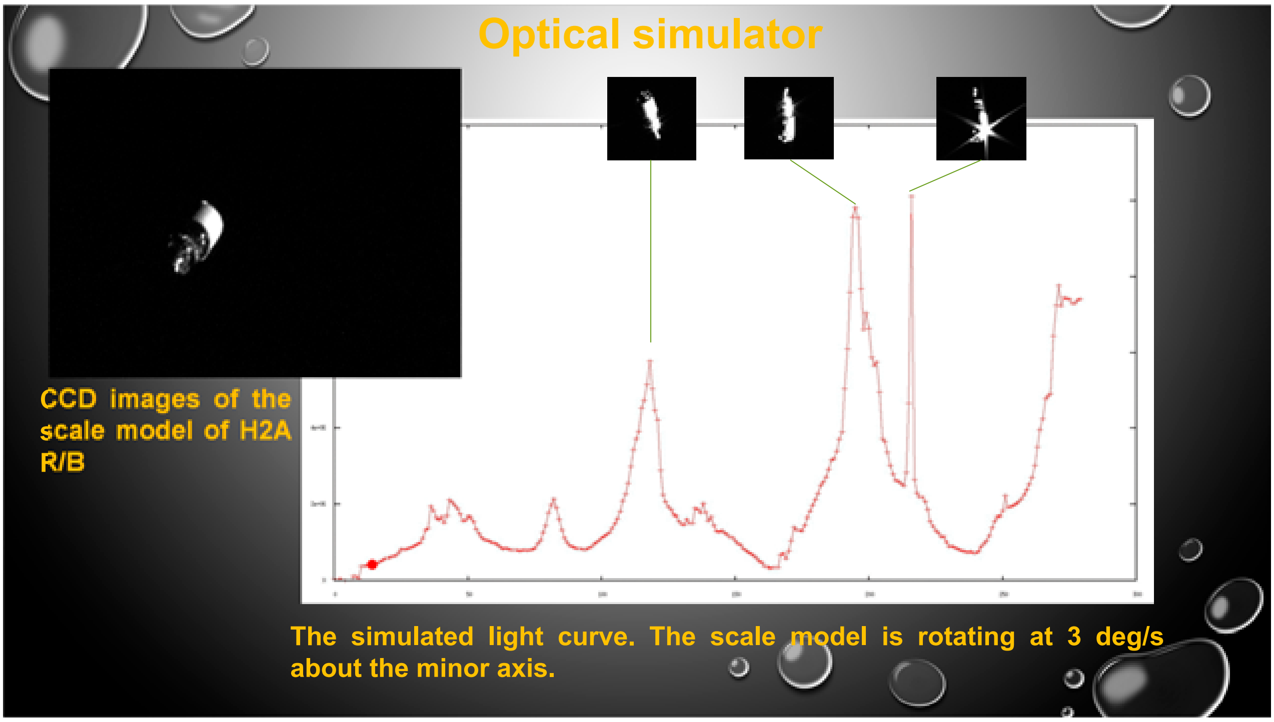


Background
ADR is needed to secure the space environment.
Understanding the motion and attitude of the target in advance is very important for the ADR mission.
easy
difficult

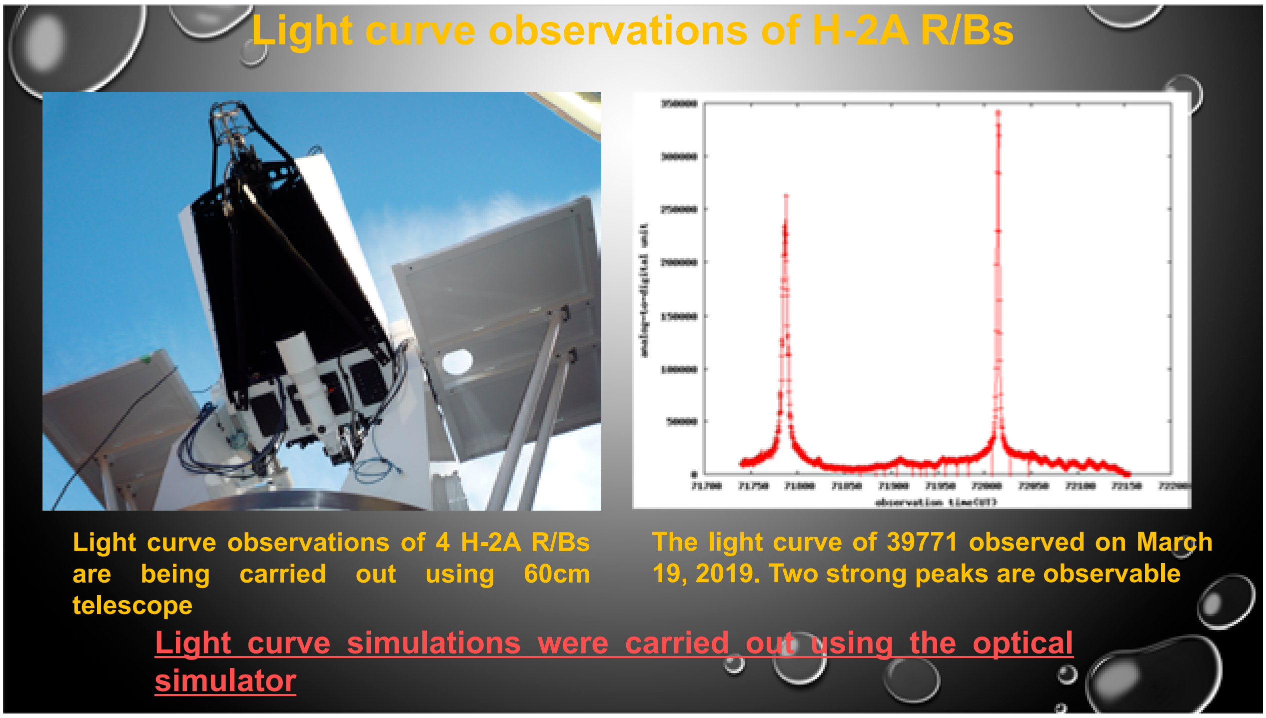


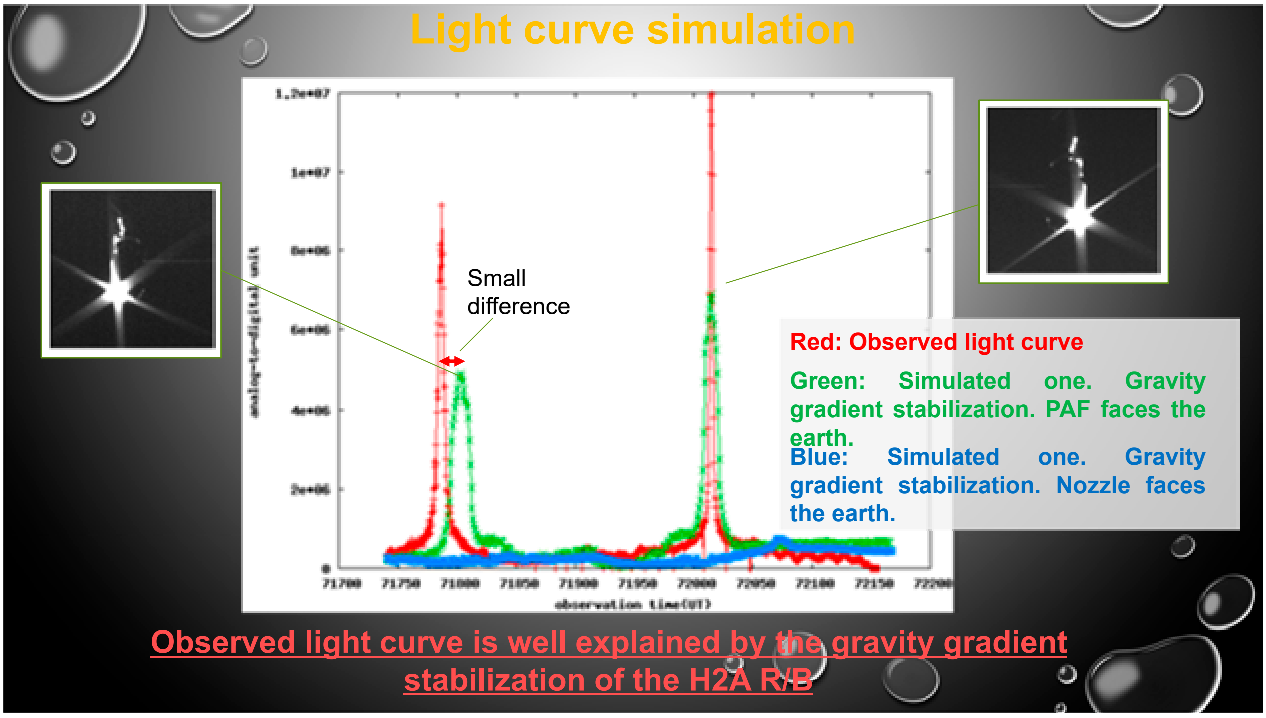
Light Curve Observation
60000
50000
40000
30000
20000
10000
0
Brightness(ADU)
100
600
1100
1600
Observation time(sec)
Target
Phase angle
Sun
Observar
Light curve observation is easy and cost effective as compared with the direct imaging with the adaptive optics.
Technologies to estimate motions and attitudes of targets must be developed.
The optical simulator for simulating light curves was developed.

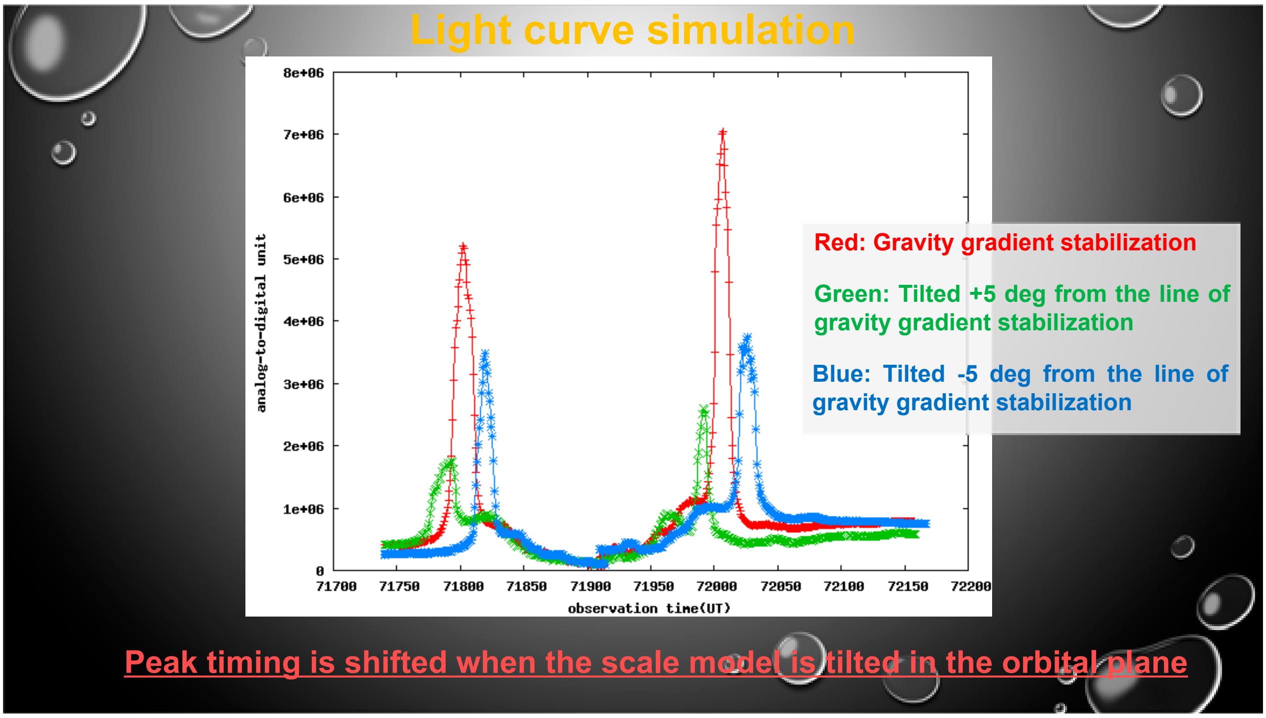

Optical simulator
Screen
Sunlight
Light stage
Scale model
Cameras
3-DoF rotation stage
3-DoF linear stage
The scale model of H2A R/B
• The optical simulator consists of a 3-DoF (degree of freedom) linear stage, a 3-DoF rotation stage, a light stage, a scale model of the target, and CCD cameras.
• The 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.

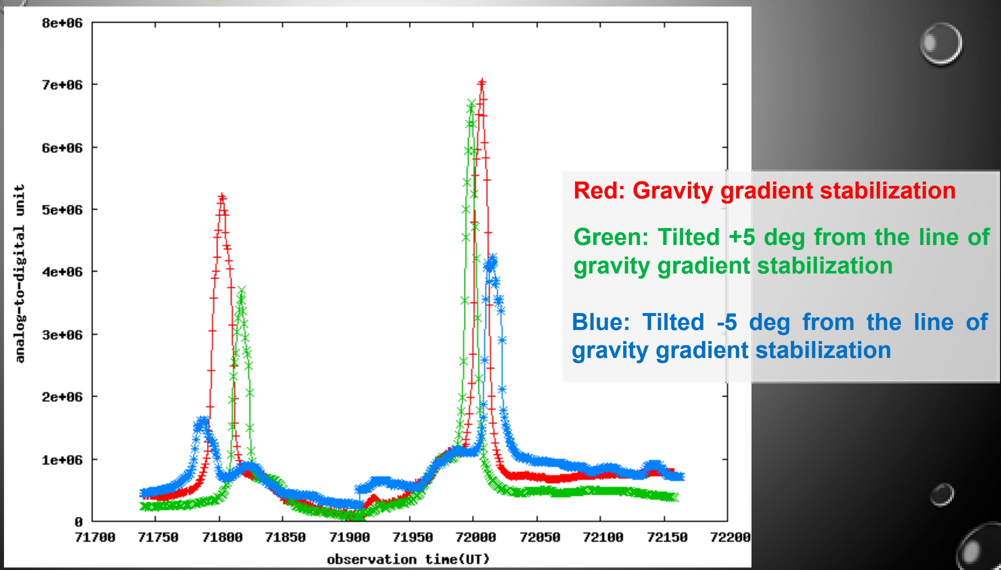

Mt. Nyukasa Optical Observatory
N 35˚54’05”, E 138˚10’18”, Altitude 1,870m
Mt. Nyukasa in Nagano prefecture, Japan


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


Light curve simulation
Small difference
analog-to-digital unit
observation time(UT)
Red: Observed light curve
Green: Simulated one. Gravity gradient stabilization. PAF faces the earth.
Blue: Simulated one. Gravity gradient stabilization. Nozzle faces the earth.
Observed light curve is well explained by the gravity gradient stabilization of the H2A R/B


Light curve simulation
8e+06
7e+06
6e+06
5e+06
4e+06
3e+06
2e+06
1e+06
0
analog-to-digital unit
71700 71750 71800 71850 71900 71950 72000 72050 72100 72150 72200
observation time(UT)
Red: Gravity gradient stabilization
Green: Tilted +5 deg from the line of gravity gradient stabilization
Blue: Tilted -5 deg from the line of gravity gradient stabilization
Peak timing is shifted when the scale model is tilted in the orbital plane

Light curve simulation

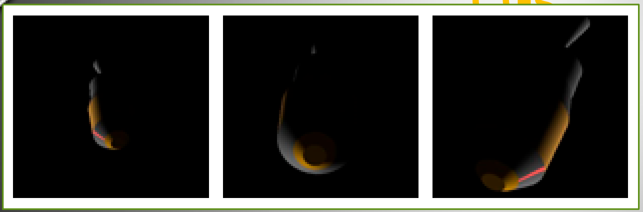


Peak interval is changed when the scale model is tilted outside the orbital plane

Light curve simulation

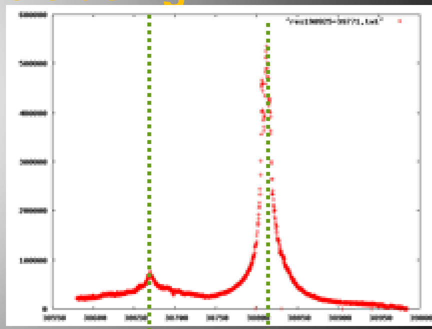
- Observed light curve of H2A R/B is well explained by the gravity gradient stabilization of the target.
- Peak timing changes as the attitude of the target changes.
- Peak timing enable us to understand the attitude of the targets.
- The result explained here is just one example.
- A lot of observation and simulation are needed for total understanding.

Light curve simulation tools using CGs



① ② ③

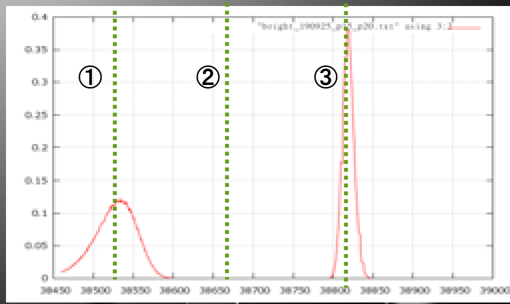
CGs of each timing



A light curve simulation tool using CGs is being developed to reduce actual experimental time for simulations.

The tool creates light curves of each component considering its reflective properties, attitude, and lighting condition.

Simulated light curve of PSS



Conclusions

The experiments using the optical simulator showed that the light curve of the H2A R/B (SSC#: 39771) observed on March 19, 2019 is explained by the attitude of the gravity gradient stabilization where the payload attach fitting of the H2A R/B was directing to the earth. It was also established that a few degrees of tilt of the target shifts peak timing. This means the attitude of the target may be determined using the times of the peaks in some cases. Although this is one case out of countless situations, simulating exactly the same light curve is the one step toward the total understanding of the ADR targets from light curves. Many more light curve observations and the simulations under the various conditions are needed to extract additional information on the H2A R/B for actual ADR.

B12

微小デブリ軌道上観測データの統計的解析手法

Statistical Analysis on In-situ Measurements of Small Space Debris

○古本 政博, 佐原 宏典(東京都立大学)
○FURUMOTO Masahiro, SAHARA Hironori (Tokyo Metropolitan University)

大きさが 2 mm に満たないような微小なスペースデブリは地上からの観測が不可能であるが，電源ハーネスを切断するなどして衛星を機能喪失させ得る．この問題に対し現在，衝突センサを搭載した衛星により微小デブリを軌道上で観測する計画が各国で進められており，その観測データの効果的な利活用が期待される．そこで本発表では，空間的・時間的に高解像度が期待される軌道上観測データに対し統計的手法を活用することで様々な解析が可能であることを示す．まず，空間的分布に関しては，逐次モンテカルロフィルタを適用して微小デブリの軌道面分布を逐次的に推定する手法について，概略とシミュレーション結果を示す．また，時間的分布について，環境変動の有無を数学的根拠を伴って判断しその規模を推定するための手法としてカイ二乗検定と赤池情報量基準を導入し，シミュレーションにより検証する．将来の微小デブリの軌道上観測におけるこれらの手法の活用により，宇宙開発の安全と持続可能性の向上が期待される．

The impact of small pieces of space debris (less than 2 mm in size) that ground-based observations are unable to detect can cause fatal damage to a spacecraft. Accordingly, to monitor the environment of these small pieces, in-situ measurements that utilize on-orbit impact sensors capable of detecting small objects are being advanced. This study proposes statistical methods to analyze the in-situ data of small debris, which has high spacial and temporal resolution. First, the sequential Monte Carlo filter is applied to estimate the spacial distribution of small debris. Second, this presentation describes that temporal changes of the debris environment can be detected and assessed utilizing the Chi-squared testing and Akaike Information Criterion. These proposed methods are evaluated by simulations with an engineering models to simulate impacts with small debris. The methods proposed by this study can contribute the sustainable space development and utilization by providing better knowledge of small debris utilizing the in-situ measurements.

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9th Space Debris Workshop
B12

Statistical Analysis on In-situ Measurements of Small Space Debris
微小デブリ軌道上観測データの統計的解析手法

Masahiro Furumoto
Hironori Sahara
(Tokyo Metropolitan University, Japan)

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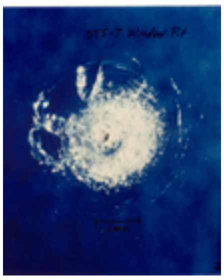
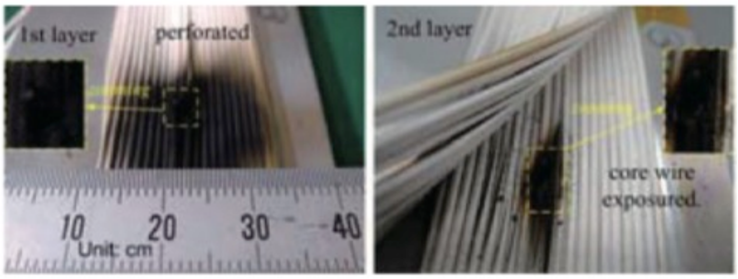
Background

Sub-millimeter-size Debris

- Small debris (< 2 mm) can neither be tracked nor detected by the ground-based observations
- There is a difference between the existing models (MASTER / ORDEM)
- Impact of small debris can cause a fatal damage on a spacecraft



Small debris impact
on shuttle window (NASA)



Cables severed by an impact with simulated debris (0.3 mm)
Nitta et. al., 2010

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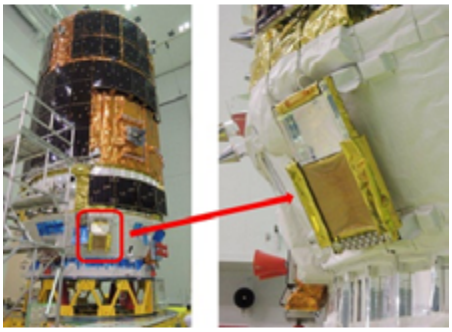
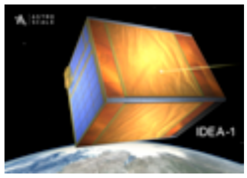
Background
In-situ Measurement



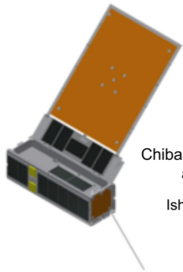
Space Debris Monitor on HTV-5
(image credit: JAXA)

Space Debris Sensor on ISS
(image credit: NASA)

Small Satellites



▲ IDEA by Kyushu Univ. and Astroscale (Launch Failed)



◀ ASTERISC by Chiba Institute of Tech. and Tohoku Univ.

Ishimaru et al., 2020

Advantages of in-situ measurements:

High resolution of time and location of impacts

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Objectives

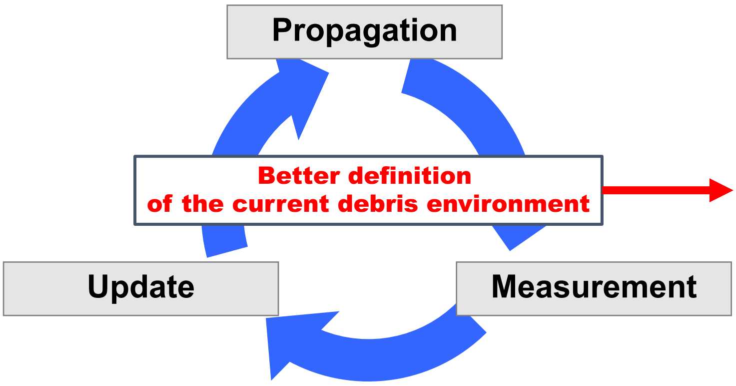
Data from in-situ measurements
- Location Identification
- High Temporal Resolution

\+ **Statistical Analysis**

1. Dynamic environmental estimation
   Distribution model of debris that can be updated sequentialy based on latest data
2. Detection of environmental change
   Quantitative identification of environmental changes posed by breakups or influence of the solar activity

Dynamic Environmental Estimation

Concept of the dynamic modeling



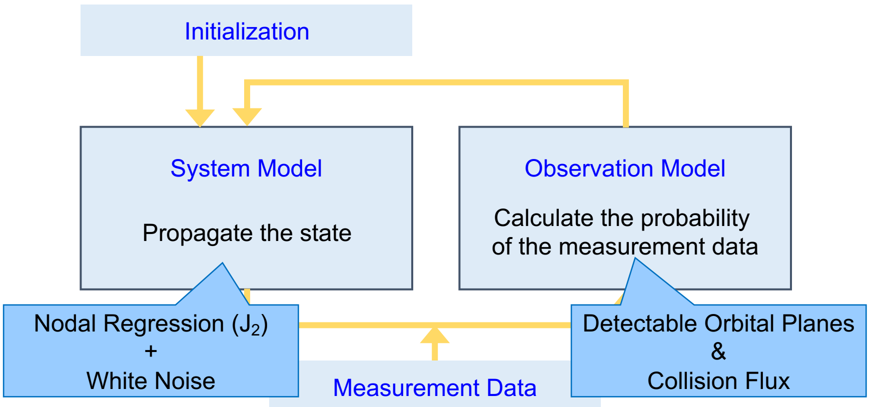
- ➢ **Optimal Protection Design**
- ➢ **"Collision Alleviation"**

Dynamic Environmental Estimation

Estimation Algorithm

(Furumoto, M. and Hanada, T., Advances in Space Research, Vol. 62, No. 3, Pages 533-541, 2018.)

❖ Sequential Monte Carlo (SMC) filter
: A statistical method to estimate the state incorporating simulation and measurement data



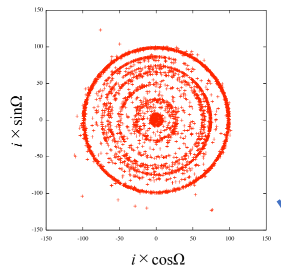
Dynamic Environmental Estimation
System Model

◆ State Vector

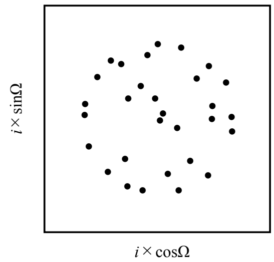
- Represents the orbital plane distribution of small debris in circular orbits at same altitude of the detector
- Approximate the environment by an ensemble of orbits that represent a huge number of debris

$$\boldsymbol{x}^{(i)} = (N_d, \Omega_1, i_1, \Omega_2, i_2, \ldots, \Omega_n, i_n)$$

N_d : Number of debris that each orbit includes
n : Number of orbital planes



Actual Distribution



Ensemble Approximation

◆ Propagation

- Nodal regression (J_2)
- Random Noize

$$N_d(t+\Delta t) = N_d(t) + \Delta t v_N$$
$$\Omega(t+\Delta t) = \Omega(t) + \Delta t\left(-\frac{3}{2}\frac{J_2 a_e^2}{p^2} n \cos i + v_\Omega\right)$$
$$i(t+\Delta t) = i(t) + \Delta t v_i$$

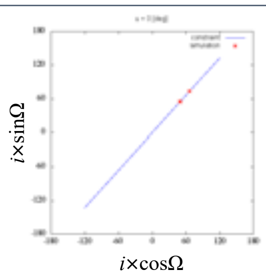
Dynamic Environmental Estimation
Observation Model

$$\log l(\boldsymbol{y}_1, \ldots, \boldsymbol{y}_n) = \sum_{i=1}^{n} \log \lambda(\boldsymbol{y}_i) - \int_A \lambda(\boldsymbol{y}) d\boldsymbol{y}$$: Likelihood based on Inhomogeneous-Poisson process

◆Orbital plane constraint

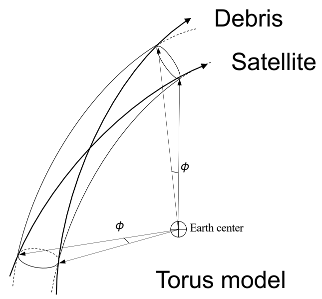
The orbital plane on which debris is detected by the satellite is constrained by the position of the satellite

$$\frac{x}{r}\sin\Omega'\sin i' - \frac{y}{r}\cos\Omega'\sin i' + \frac{z}{r}\cos i' = 0$$



◆Collision Flux

The collision flux **λ** between two circular orbits is approximately determined by the torus model



Torus model

Dynamic Environmental Estimation

Simulation

MASTER 2009

↓

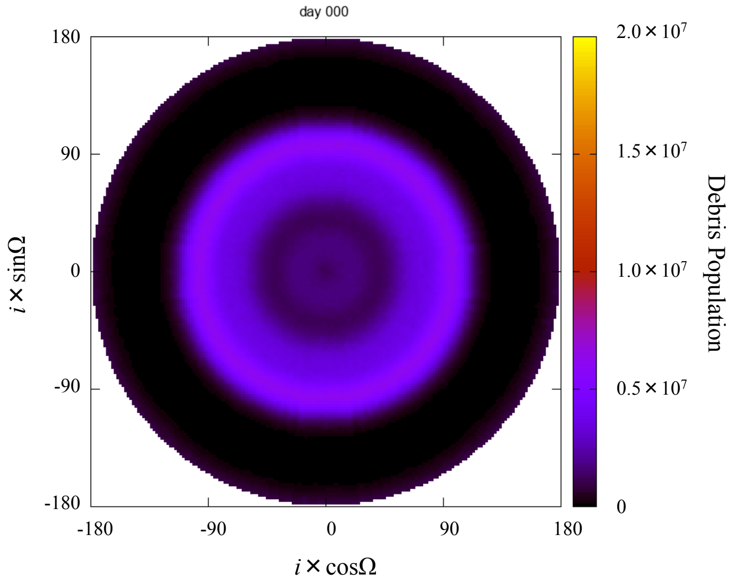
Simulated impact data

↓

Estimation Model

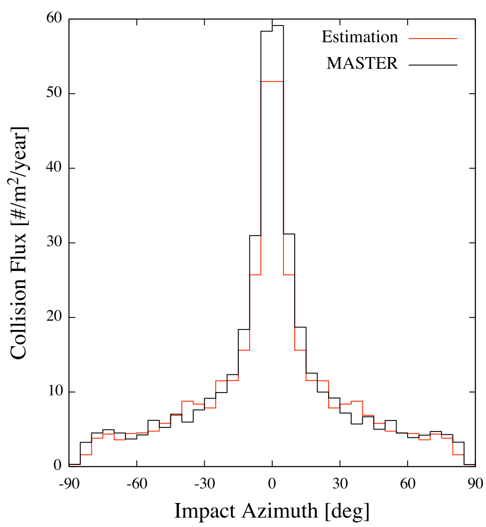
↓

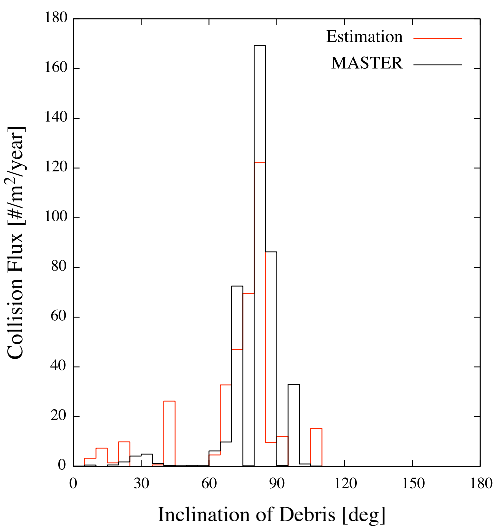
Estimated Distribution



Dynamic Environmental Estimation

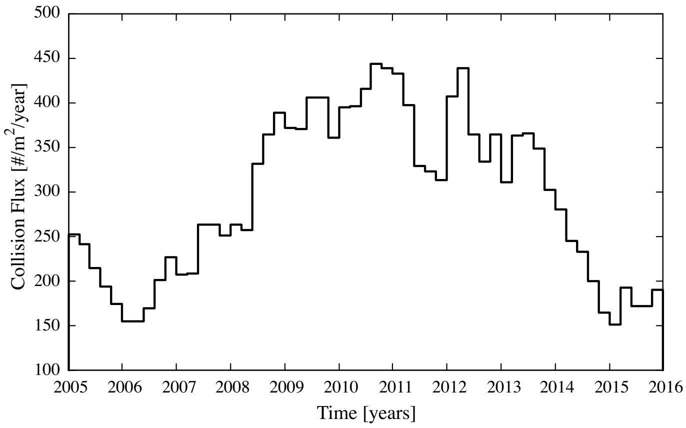
Simulation Results





Detection of Environmental Change

(Furumoto, M. and Sahara, H., Acta Astronautica, Vol. 177, Pages 666-672, 2020.)

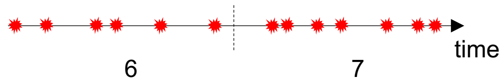


Collision Flux History in MASTER-8 at 865 km SSO

- Debris environment changes continuously / drastically

  influenced by
  - Solar activity
  - Ejection
  - Breakup

- Sampled data must include randomness

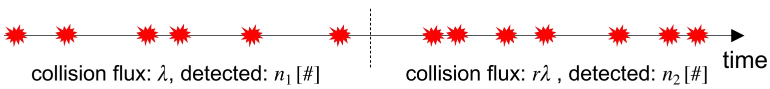


→ Statistical evaluation is important

Detection of Environmental Change

Methods 1/2

- Chi-Squared Testing



Null hypothesis: The density of the Poisson process, which is followed by the impact of fragments, is constant throughout the entire period of measurement.

Alternative hypothesis: The Poisson process with a uniform density cannot explain the measured quantity of impacts.

Based on Chi-squared testing, the null hypothesis is rejected when $\chi^2 = \frac{(n_1 - n_2)^2}{n_1 + n_2} \geq 3.84$ (significance level 5%)

(= change confirmed)

Substitute $n_1 = \frac{\lambda}{2}, n_2 = \frac{r\lambda}{2}$ (Ideal measurement data) → $r = 1 + \frac{\chi^2}{\lambda} \pm \sqrt{\frac{\chi^2}{\lambda}\left(\frac{\chi^2}{\lambda} + 4\right)}$ Detectability Equation

(χ^2 = 3.84)

Detection of Environmental Change

Methods 2/2

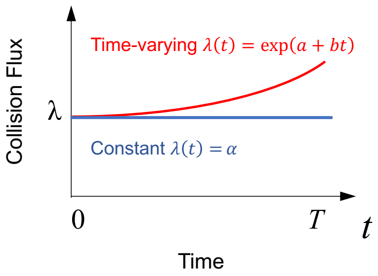
- AIC Comparison

AIC (Akaike Information Criterion): Criterion to select the model that explains the data (smaller is better)

$$\mathrm{AIC} = -2\left(\log \hat{L} - N_{param}\right)$$

Number of unknown parameters in the model

Maximum likelihood



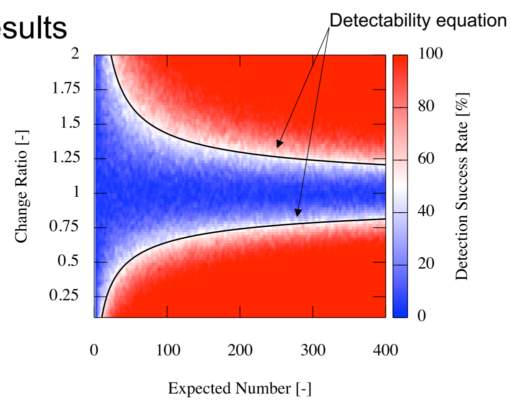
1. Calculate maximum likelihood and AIC
2. Environmental change is confirmed
   if the AIC of the time-varying model is smaller
   (also extent of the change can be estimated)

Detection of Environmental Change

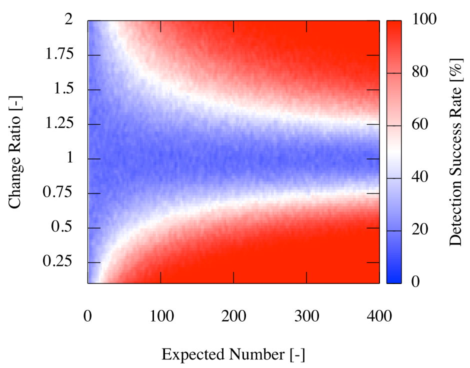
Simplified Simulation

1. Randomly generate impacts following Poisson process
   with an expected number of impact and its change ratio
2. Detect the environmental change using proposed methods
3. Repeat 1. and 2. in 200 times and calculate the percentage of successfully detected case

Results



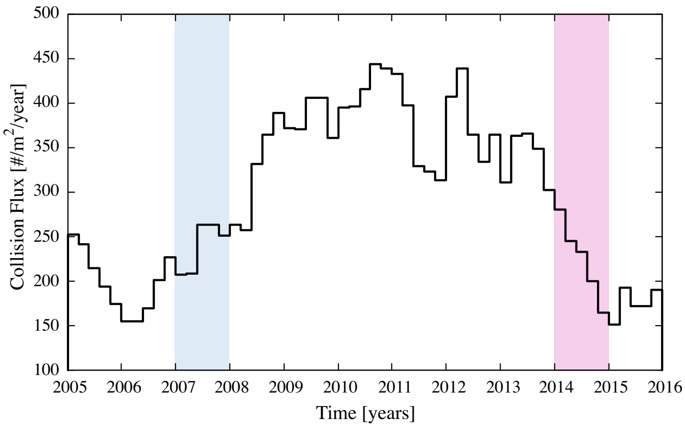
Chi-squared testing



AIC comparison

Detection of Environmental Change

Precise Simulation



Start epoch	Collision flux [#/m²/year] Initial	Final	Change Ratio (r)
Jan 2007	207.2	263.4	1.271
Jan 2014	280.1	152.0	0.542

- Generate impacts following MASTER-8 definition
- 100 MC cases
- 4 cases of measurement system (with sensor area of A [m^2])
  - Microsatellite, $A = 0.25$
  - Legacy satellite, $A = 1$
  - Constellation of microsatellites, $A = 2.5$
  - Constellation of legacy satellites, $A = 10$

Detection of Environmental Change

Precise Simulation

Detection Results (Limit of r: result of detectability equation)

in 2007 (actual change ratio r = 1.271)

A [m²]	λ_0 [#]	Limit of r	Success Rate [%] Chi-squared	AIC
0.25	51.8	1.62	8	1
1	207.2	1.29	19	39
2.5	518	1.18	55	81
10	2072	1.09	99	100

in 2014 (actual change ratio r = 0.542)

A [m²]	λ_0 [#]	Limit of r	Success Rate [%] Chi-squared	AIC
0.25	70.0	0.58	25	18
1	280.1	0.78	67	74
2.5	700.2	0.85	91	100
10	2801	0.92	100	100

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Detection of Environmental Change

Precise Simulation

Estimated extent of environmental change

in 2007 (actual change ratio r = 1.271)

A [m^2]	Average	Median	Standard Deviation
0.25	5.08	5.08	N/A
1	1.61	1.51	0.29
2.5	1.40	1.40	0.14
10	1.37	1.38	0.08

in 2014 (actual change ratio r = 0.542)

A [m^2]	Average	Median	Standard Deviation
0.25	0.36	0.38	0.09
1	0.44	0.44	0.09
2.5	0.55	0.55	0.07
10	0.55	0.55	0.04

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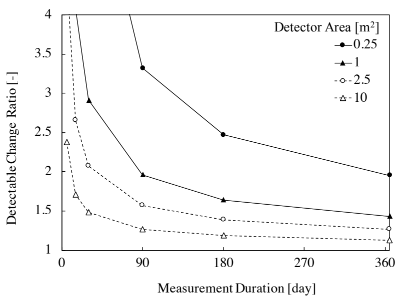
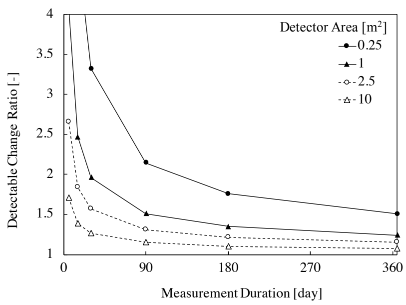
Detection of Environmental Change

Requirements on In-situ Measurement

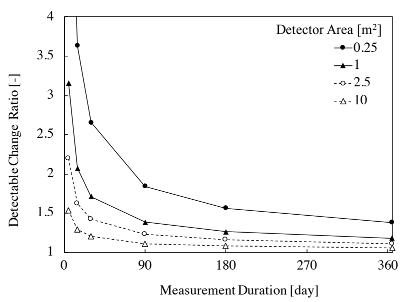
Required mission duration to detect environmental changes
(Calculated by detectability equation)



initial collision flux = 100 [#/m^2/year]



initial collision flux = 300 [#/m^2/year]



initial collision flux = 500 [#/m^2/year]

Conclusion

Statistical analysis for in-situ measurements provides better understanding of the environment of small debris

- Dynamic Environmental Estimation
  - Sequential model based on SMC filter can estimate distribution of sub-millimeter-sized debris utilizing in-situ measurements
- Detection of Environmental change
  - Statistical methods to identify environmental changes were developed
    - Chi-squared testing: Low computation cost, benefit to on-board detection
    - AIC comparison: More reliable and capable to estimate the change extent
  - Detectability equation determines the limit of change ratio of environment
  - Requirement on in-situ measurement systems to detect environmental changes were presented

B13

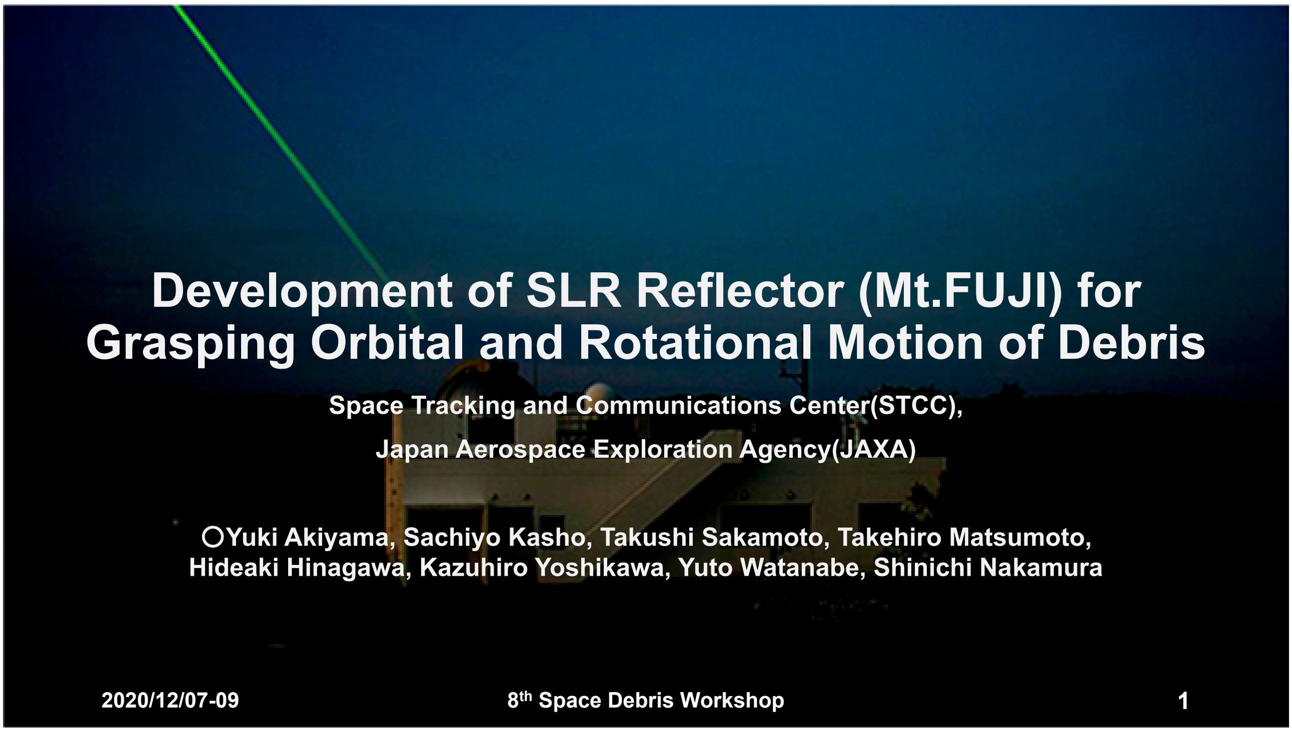
デブリの軌道・回転運動把握のための SLR 反射器(Mt.FUJI)の開発

Development of SLR Reflector (Mt.FUJI) for Grasping Orbital and Rotational Motion of Debris

○秋山 祐貴，嘉生 幸代，坂本 拓史，松本 岳大，
日南川 英明，吉川 和宏，渡邊 優人，中村 信一（JAXA）
○AKIYAMA Yuki, KASHO Sachiyo, SAKAMOTO Takushi, MATSUMOTO Takehiro, HINAGAWA Hideaki, YOSHIKAWA Kazuhiro, WATANABE Yuto, NAKAMURA Shinichi (JAXA)

近年，宇宙環境の急激な混雑化が進んでおり，宇宙状況把握(SSA)が国際的な課題となっている．通常宇宙ゴミ(デブリ)は，レーダ観測や光学観測により軌道把握がなされるが，地上からの視認性の悪さや機器的制約などにより，位置決定精度はせいぜい数十 m オーダである．近年ではデブリへのランデブー・捕獲を行う能動的デブリ除去(ADR)も盛んに検討されている．ADR では予めデブリの軌道・回転運動を把握している必要がある一方で，地上からデブリの回転運動を把握する技術は未確立である． 飛翔体が反射器を搭載していれば，衛星レーザ測距(SLR)により数 cm オーダで軌道決定，さらに軌道決定残さから回転運動の推定が可能である．従来，反射器は特注品であり大型・高価であった．しかし，反射器が安価な市販品となれば，将来デブリとなる物体に搭載でき，軌道・回転運動の把握の一助となる．そこで，JAXA では小型・軽量・安価をコンセプトに汎用的な反射器(Mt.FUJI)の開発を 2018 年度より開始した．本発表では Mt.FUJI の概要について報告する．

The dawn of space engineering development brought the rapid pollution and congestion of the space environment due to orbital debris. Therefore, space situational awareness (SSA) has become an international issue. Conventionally, orbital debris can be tracked by radar and/or optical observations. However due to poorness of their visibility from the ground and constraints of observation systems, their positioning accuracy is on the order of tens of meters at most. In recent years, active debris removal (ADR), which performs rendezvous and capture of debris, has been actively studied. Although it is necessary to grasp the orbital and rotational motion of orbital debris in advance, the techniques for grasping the rotational motion of orbital debris from the ground has not been fully established yet. If the space vehicle is equipped with one or more reflectors, it is possible to determine its orbit on the order of several cm by satellite laser ranging (SLR), and to estimate the rotational motion from the orbit determination residuals. The reflectors developed and installed in Japan and overseas were custom-made, large, and expensive. If reflectors become inexpensive commercial products, they can be mounted on objects that will become orbital debris, it will help to grasp the orbital/rotational motion. Therefore, JAXA started development of a general-purpose reflector (called Mt.FUJI) in 2018 with the concept of small size, light weight, and low cost. In this presentation, we report the overview of Mt.FUJI.



Contents

1. Introduction
2. What is SLR?
3. HTV-X and Technology Demonstration Mission
4. What Is Mt.FUJI?
5. How to estimate attitude motion by SLR?
6. Validation of Method for HTV-X Mission
7. Summary

2

1. Introduction

- SSA(Space Situational Awareness) is an international issue. Debris can be tracked by radar and/or optical observations, however due to poorness of its visibility from the ground, its positioning accuracy is on the order of tens of meters at most.
- In ADR(Active Debris Removal), it is necessary to grasp the orbital and rotational motion of debris in advance. However, the techniques for grasping the rotational motion of debris from the ground has not been established yet.

Break through these issues by SLR (Satellite Laser Ranging) and LRA(Laser Reflector Array) !

Development purpose: Development of compact, lightweight, inexpensive general-purpose LRA(Mt. FUJI)	Research purpose: Demonstration of Mt.FUJI performance and evaluation of rotational motion estimation method by SLR

- Small space objects cannot mount LRAs
- Little benefit to universities and businesses at expense of increased weight and development costs.
- Poor visibility after becoming debris

Large, and Heavy / Custom -made / Expensive → former LRA ← OD / Rotation Estimation?

- Key device for high precision orbit determination
- Although attracted attention as a means of estimating rotational motion, not yet evaluated estimation accuracy since true rotational motion of target object is unknown,

Mt.FUJI: MulTiple reFlector Unit from Jaxa Investigation

- More space objects can mount LRAs
- Rich visibility after becoming debris.
- Possible to grasp the orbit with high accuracy.
- Contributes to SSA

Small and Light / general-purpose / Inexpensive → JAXA Developed LRA Mt.FUJI ← OD / Rotation Estimation

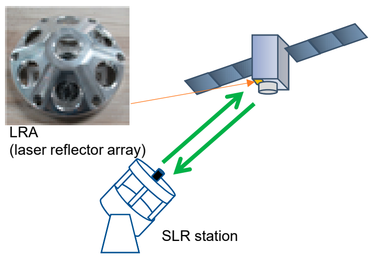
- Performance demonstration of Mt.FUJI can be performed by using HTV-X.
- The world's-first evaluation of rotation estimation accuracy by SLR and LRAs since true value of HTV-X's rotational motion are known.
- Contributes to ADR

2. What is SLR?

SLR : Satellite Laser Ranging
High precision ranging system that measures the distance between a SLR station and a target object by measuring time from shooting laser pulse from SLR station toward a target mounting LRA to detection the reflected pulse.

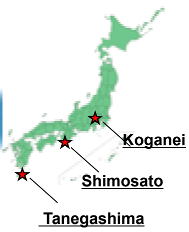
- High accuracy
- Verification of other orbit determination methods
- No electrical I/F for space object

- Sensitive to weather
- Interference with sensors mounted on space object



SLR

- About 40 SLR stations in the world (3 domestic stations)
- Laser ranging activities are organized under the International Laser Ranging Service (ILRS)
- Prediction data (CPF) and acquired SLR data (FR / NP) are uploaded to the public server which anyone can freely download and use it
- FR is a correction of raw observation data
- NP is a compressed version of FR in a specific period
- New SLR station is under construction in Tsukuba Space Center (operation starts in 2021).



SLR stations

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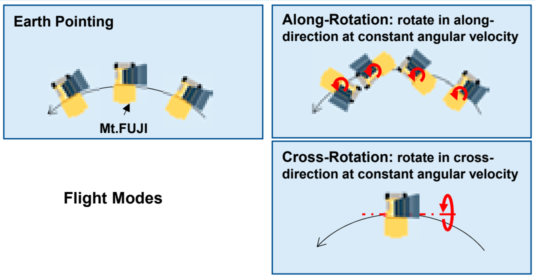
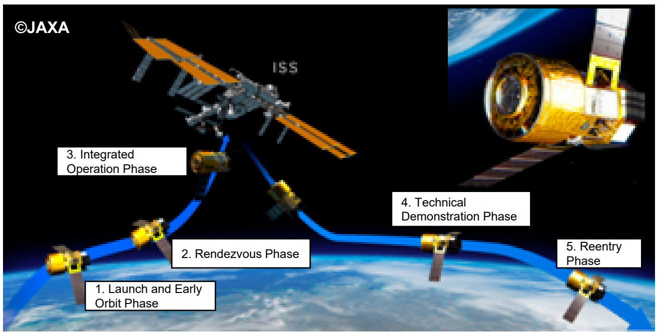
3. HTV-X and Technology Demonstration Mission

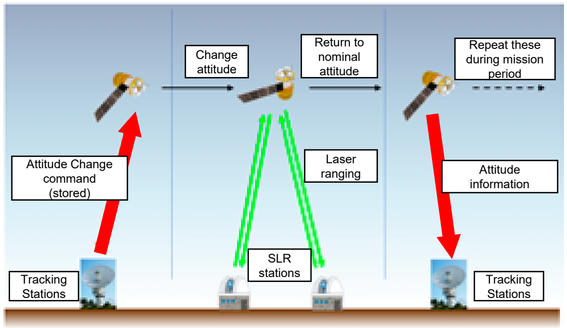
- HTV-X is the successor to HTV (Launch in FY2022 (planned))
- 3 Mt.FUJIs are mounted onto the back side of HTV-X
- HTV-X changes its attitude when SLR
- The period, duration(at least one week), and flight mode are currently being adjusted
- 3 different types of flight modes are under consideration
- Purpose of the SLR Technology Demonstration Mission
  - ① Performance demonstration of LRA (Mt.FUJI)
  - ② Evaluation of rotational motion (angular velocity) estimation method by SLR



Flight Modes



HTV-X



Operation overview

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4. What is Mt.FUJI?

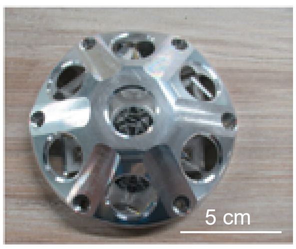
Mt.FUJI : MulTiple reFlector Unit from Jaxa Investigation

- ✓ Small, light, and inexpensive LRA for LEO space objects developed by JAXA from 2018
- ✓ Smaller and lighter LRA, Mini-Mt.FUJI, is also under development

- Equipped with 7 CCRs (Corner Cube Reflector; reflecting waves directly towards the source)
- 45 degrees half-cone angle of FOV(Field Of View)
- Palm size
- Less than 800 km for Mt.FUJI and 400 km for Mini-Mt.FUJI are target altitudes
- 3 Mt.FUJIs are mounted on the cone bumper panel of HTV-X at 120 degrees intervals, along with a pedestal for adjusting the angle so that each FOVs do not overlap

Specifications

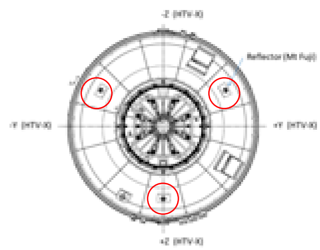
Item	Mt.FUJI	Mini-Mt.FUJI
Altitude	< 800 km	< 400 km
Diameter	112 mm	70 mm (TBD)
Height	32 mm	20 mm (TBD)
Mass	< 280 g	<120 g (TBD)
CCR size	1 inch	0.5 inch
Number of CCRs	7	
FOV	45 deg/Mt.FUJI (approx. 15deg/CCR)	
Material	Body: Aluminum CCR: Fused silica Cushion: PTFE, PFA	



Mt.FUJI

CCR

Mt.FUJI with pedestal



Location of Mt.FUJIs

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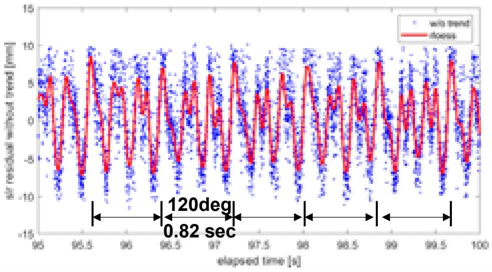
5. How to estimate attitude motion by SLR?

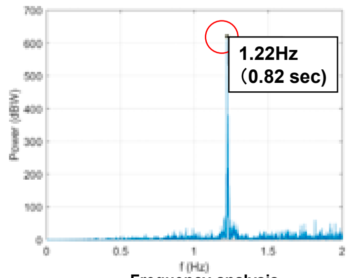
Basic idea: When a target object is in rotational motion, the CCRs that contributes to the laser reflection is switched to another by the rotational motion. Therefore SLR data should contain information on the CCR switching. If so, by analyzing the data somehow, we can grasp the rotational motion of the target?

Step1: Orbit determination	Orbit determination by SLR data or other sources (ex.GPS, RAAN, …)
Strep2: O-C(SLR residual)	Calculation of SLR residual (O-C) by using OD ephemeris and SLR data
Step3: angular velocity estimation	Estimate angular velocity by reading angular velocity directly from the waveform of SLR residual or by performing frequency analysis

Flow of estimation



SLR residual



Frequency analysis

Example
- Using AJISAI SLR data, SLR residual is calculated. Blue dot is SLR residual, and red is smoothing of SLR residual
- <Direct reading>: 1 peak→ 2 peaks → 2 peaks are repeated at intervals of about 0.82 seconds. Since AJISAI has a 120 degrees symmetric structure, it rotates 120 degrees in 0.82 seconds.
- <Frequency analysis>: When the intensity of the signal contained in the SLR data is calculated for each frequency, a sharp peak is at 1.22 Hz corresponding to 0.82 seconds.
- With either method, the angular velocity is estimated to be approximately 146 degrees / sec.

Although such high-speed rotation is impossible for HTV-X mission, is this method effective for attitude estimation of HTV-X?

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6. Validation of Method for HTV-X Mission

Purpose of this survey
- Check if angular velocity can be estimated from SLR residual with flight modes and angular velocities under consideration

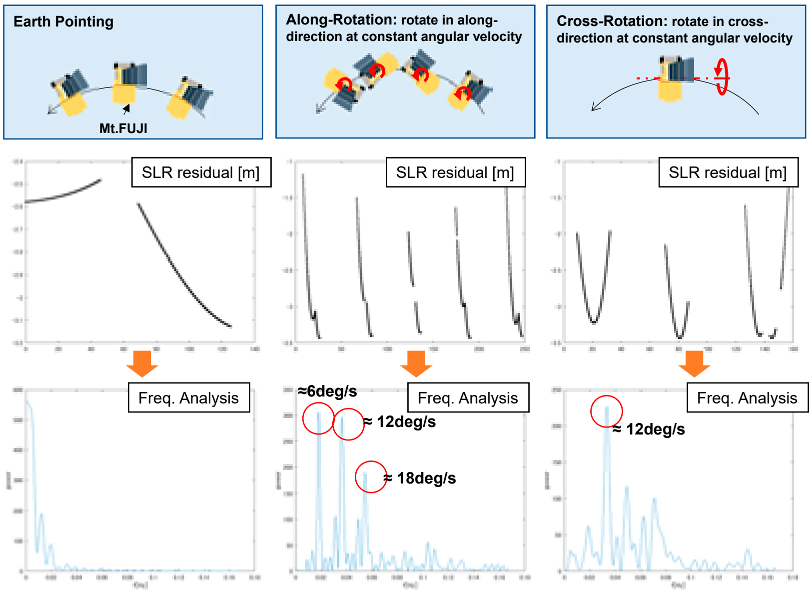
Survey method

SLR residual(t) = d(t)- r(t)
d(t): dist. b/w SLR station and CCR
r(t): dist. b/w SLR station and HTV-X center of gravity

- d(t) is NaN when SLR station is out of FOV of CCR
- Attitude motion is considered for orbit propagation
- Investigate whether angular velocity can be estimated from SLR residual

Result
- SLR station is CHAL, minimum elevation angle of SLR station 20 degrees, and the rotational angular velocity is 6 deg/s (which is higher than the actual experiment)
- The SLR residuals and frequency analysis results differ greatly depending on the flight modes

- Although more detailed examination is required, considered possible to estimate flight mode and angular velocity of HTV-X from the SLR residual



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7. Summary

- **Introduction**
  - Development of compact, lightweight, and inexpensive general-purpose SLR reflector (Mt.FUJI) → Contributes to SSA
  - Demonstration of Mt.FUJI performance and evaluation of rotational motion estimation method by SLR → Contributes to ADR
- **SLR**
  - High-precision ranging system using laser
  - On-board component is only a reflector that do not required electrical I/F
- **Mt.FUJI**
  - Compact, lightweight, and inexpensive SLR reflector being developed by JAXA
- **HTV-X and Technology Demonstration Mission**
  - Platform for technology demonstration
  - Performance demonstration of Mt.FUJI and the world's-first evaluation of rotation estimation accuracy by SLR and LRAs
- **Angular velocity estimation method based on SLR residual**
  - SLR residual contains information on CCR switching (equivalent to attitude motion information)
  - Angular velocity can be estimated by reading directly from the waveform of SLR residual or detecting peaks by frequency analysis
  - Confirmed applicability of the method to HTV-X technology demonstration mission
- **Future works**
  - Statistical evaluation of estimation method by pseudo data analysis and construction of estimation model by machine learning
  - Higher accuracy of estimation method (correction considering geometry for stations at the time of observation, construction of attitude estimation model, etc.)

C01

衛星用複合材推薬タンクの再突入安全性評価モデル

Re-entry Survivability Analysis Model of Spacecraft Composite Propellant Tank

○清水 隆三, 松本 純, 足立 寛和, 藤本 圭一郎, 池田 博英（JAXA）
○SHIMIZU Ryuzo, MATSUMOTO Jun, ADACHI Hirokazu, FUJIMOTO Keiichiro,
IKEDA Hirohide (JAXA)

ミッション終了後の低軌道周回衛星が自然落下して大気圏に再突入する際、チタン合金製の推進薬タンクは溶融せずに地上まで到達するため、安全上のリスクとなっている。地上の安全性向上のためには推進薬タンクが溶融するのが望ましく、JAXA では溶融させることを目指してアルミ合金製ライナの複合材推薬タンクの研究・開発を実施してきた。開発当時、複合材の樹脂が再突入時の加熱で熱分解し、気流の効果で炭素繊維が飛散して露出したライナが溶融すると想定していたが、溶融性については追加評価を実施している。JAXA では、アーク加熱風洞でのテストピース加熱試験結果に基づく熱物性のモデル化と、再突入時に実機形状タンクが受ける空力加熱環境の解析評価を進めており、両者を組み合わせた溶融性評価状況を報告する。

A propellant tank for spacecraft is usually made of titanium alloy, it would not demise during atmospheric re-entry of the LEO spacecraft and cause a risk to the ground. So, it is desirable that a propellant tank would demise. JAXA had conducted research to develop an aluminum-lined, carbon composite overwrapped tank for reducing impact risk to the ground. In the early phase, it expected that the resin of CFRP would decomposed by aerodynamic heat and residual carbon fibers were blown away by the effect of airflow. However, reevaluation of the survivability of this composite propellant tank has been conducted by JAXA. We report the re-entry survivability analysis model based on arc wind tunnel tests , and current reevaluation status.

Re-entry Survivability Analysis Model of Spacecraft Composite Propellant Tank

衛星用複合材推薬タンクの再突入安全性評価モデル

Ryuzo Shimizu, Jun Matsumoto, Hirokazu Adachi, Keiichiro Fujimoto, Hirohide Ikeda (JAXA)

清水隆三，松本純，足立寛和，藤本圭一郎，池田博英（JAXA）

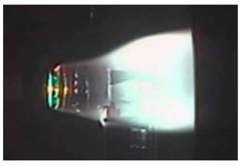
9th Space Debris Workshop
第9回スペースデブリワークショップ

（はじめに）
Introduction

A propellant tank for spacecraft is usually made of titanium alloy, it would not demise during atmospheric re-entry of the LEO spacecraft and cause a risk to the ground. So, it is desirable that a propellant tank would demise.
ミッション終了後の低軌道周回衛星が自然落下して大気圏に再突入する際、チタン合金製の推進薬タンクは溶融せずに地上まで到達するため、安全上のリスクとなっている。

JAXA had conducted research to develop an aluminum-lined, carbon composite overwrapped tank for reducing impact risk to the ground.
地上の安全性向上のためには推進薬タンクが溶融するのが望ましく、JAXA では溶融させることを目指してアルミ合金製ライナの複合材推薬タンクの研究・開発を実施してきた。

In the early phase, it expected that the resin of CFRP would decompose by aerodynamic heat and residual carbon fibers were blown away by the effect of airflow. However, to improve re-entry survivability analysis method, reevaluation of the survivability of this composite propellant tank has been conducted by JAXA.
開発当時、複合材の樹脂が再突入時の加熱で熱分解し、気流の効果で炭素繊維が飛散して露出したライナが溶融すると想定していた。しかしながら、再突入安全評価手法の向上のため、このタンクを具体的検討対象として追加評価を実施している。



We report the re-entry survivability analysis model based on arcjet wind tunnel tests, and current reevaluation status.
現在、アーク加熱風洞でのテストピース加熱試験結果に基づくタンク熱物性のモデル化を進めており、追加評価状況を報告する。

（検討対象）
Object: Composite Propellant Tank

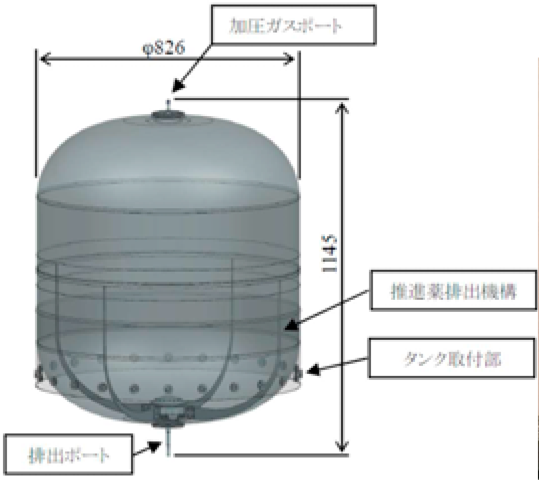
- **Composite Propellant Tank with Aluminum Alloy Liner**

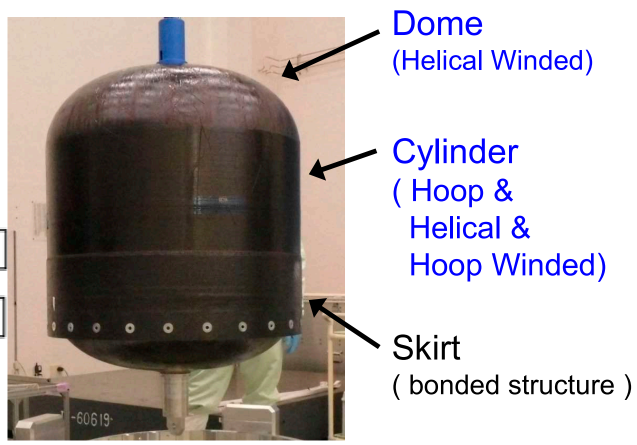
Target : Spacecraft

Merit : ① Low Cost and Short Supply Piriod チタンタンクより低コスト・短納期

② Light Weight (equivalent to Titanium Tank) チタンタンクと同等

③ (Demissablity) ⇨ Additional Study





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（報告内容）
Outline

Approach

Contents at this WS

① Preliminary estimation of heat flux during Re-entry
② Heating test for confirmation of probable damage
③ Heating test for construction of heat conduction model
④ Heat conduction analysis model
(one-dimensional → three-dimensional, anisotropic)
⑤ Transient heat conduction analysis (without recession of CFRP)

⇩

⑥ Heat flux estimation with 3D shape of tank
⑦ Transient heat conduction analysis

⇩

⑧ Detail study considering several effects.

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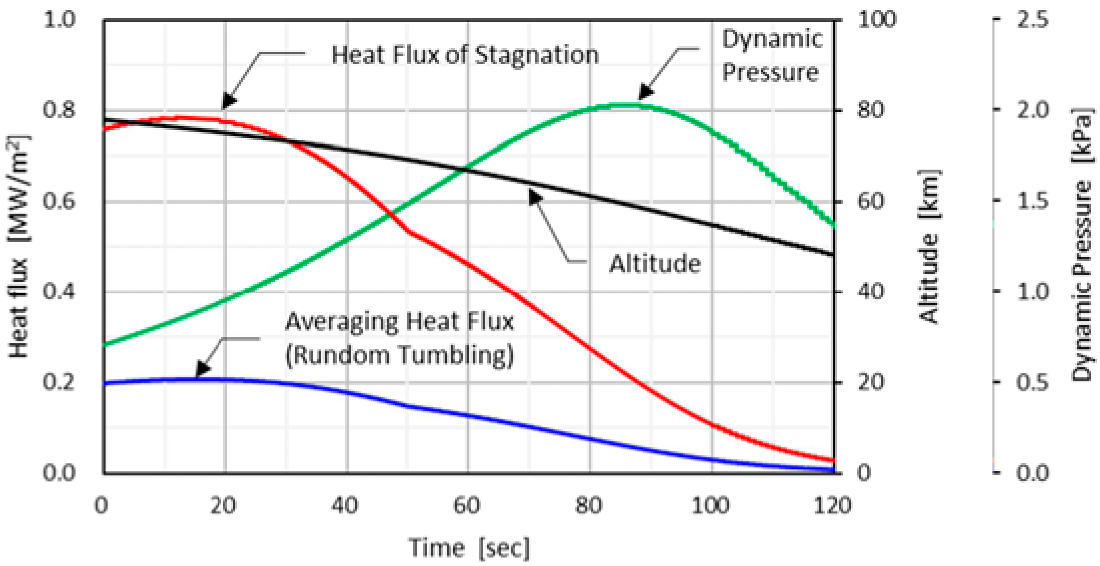
（再突入時加熱履歴の簡易推定）

Preliminary Estimation of Heat Flux

- Trajectory : Re-entry from SSO
  Tool : ORSAT-J (Shape of tank was substituted by “Sphere” .)
  Condition : Rundom Tumbling, Constant Mass



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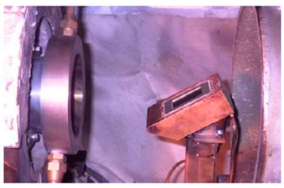
（想定加熱率下での損傷度確認試験）

Heating test for confirmation of probable damage

- Prupose: To obtain the knowledge about probable damage of this tank under the expected heating condition.
  （目的： 想定される加熱条件下において、実際のタンクと同じ材料・積層構成を有するテストピースに発生する損傷を確認する。）
- Facility: 750kW Arcjet Wind Tunnel in JAXA（Chofu）
  (Heating test with high enthalpy air flow)
- Specimens: The specimens were taken from a developing model of the composite propellant tank.
- Test Configuration:
  Specimens were declined to adjusting heat flux. The edge of specimen was protected by a titanium cover to prevent detachment of CFRP by delamination from the edge.
  （テストピース、試験形態： 実機大試作タンクの円筒部、ドーム部からテストピースを採取。テストピース端部からの剝れを防止・抑制するため、チタン合金製カバーで保護。）



（損傷度確認試験結果例）
Test Result – Example of Damage

- Test Result (Example of Specimen from Dome Section)

Constant Heat flux： 0.42MW/m²、 Pressure: 0.83 kPa （at Middle Area）

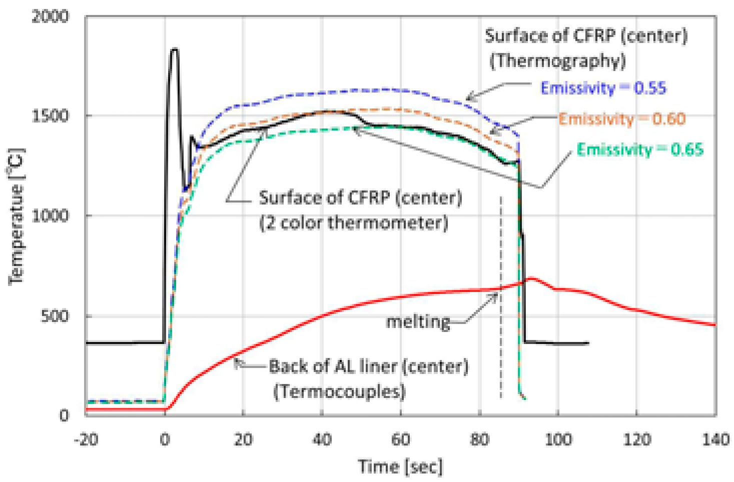
（Actuall heat flux was decreased by the bump of titanium cover.）

⇒ CFRP surface layer suffered damaged, but inner layers existing.

（ドーム部テストピース、中流部での加熱率0.42MW/m²、圧力0.83kPa。
CFRP層の表面側での損傷（消失）はあるものの、残存層が有る状態。）

（Before Test）

（After Test）



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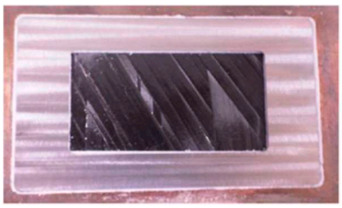
（損傷度確認試験結果例）
Test Result – Example of Damage

- Test Result (Example of Specimen from Dome Section)

Constant Heat flux： 0.17MW/m²、 Pressure: 0.58 kPa （at Middle Area）

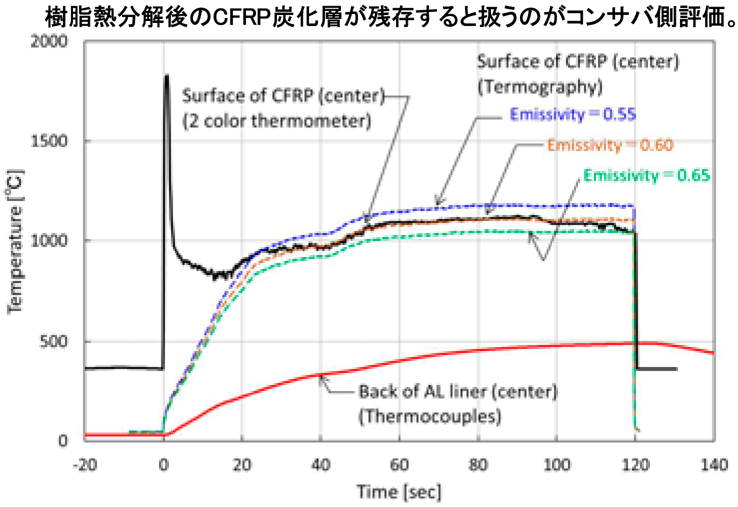
（Actuall heat flux was decreased by the bump of titanium cover.）

⇒ CFRP surface layer suffered slight damaged. For conservative evaluation, under the rundom tumbling condition, CFRP char layer will remain after the resin decomposed. （CFRP層の表面側での損傷は軽微。ランダムタンブリングの条件では樹脂熱分解後のCFRP炭化層が残存すると扱うのがコンサバ側評価。）



（Before Test）

（After Test）



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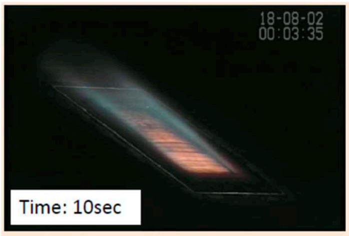
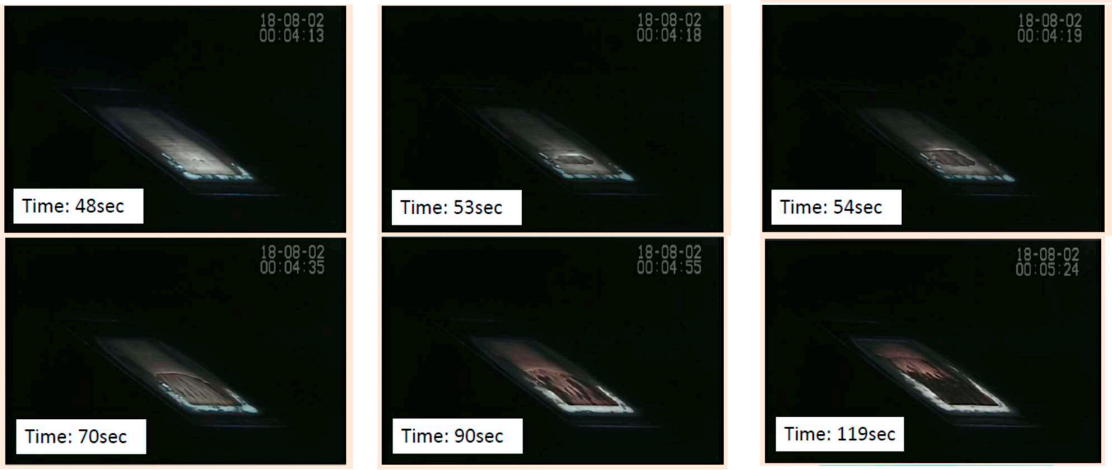
（損傷度確認試験結果例）

Test Result – Example of Damage

- Test Result (Example of Specimen from Cylinder Section)

Heat flux: 0.42MW/m^2 , Pressure: 0.83 kPa
(Actual heat flux was decreased by the bump of Ti cover.)
⇒ Recession occurred at CFRP surface layer (Hoop winded) after 48sec, but CFRP inner layer (Helical winded) remained. (表面のフープ巻き層は局所的な消失が層内で進行していく様子が確認された。ヘリカル巻き層では急速な進行は見られない。リセッションを期待しない方がコンサバ側。)





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（淀み点加熱による温度データ取得）

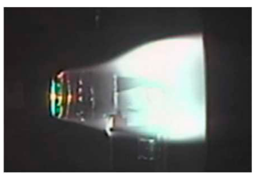
Heating test for construction of heat conduction model

- Prupose: To obtain temperature data for construction the heat conduction analysis model of this tank under stagnation heat flux.

（目的： 加熱率が比較的明確な（分布が小さい）淀み点加熱形態で試験を行い、熱伝導解析モデル構築に必要な温度データを取得する。）

- Facility: 750kW Arcjet Wind Tunnel in JAXA（Chofu） (Heating test with high enthalpy air flow)
- Specimens: The specimens were taken from a developing model of the composite propellant tank. For reference, SUS specimens were tested.

- Test Configuration:
Specimens were heated with stagnation heat flux. The edge of specimen was protected by a SUS cover to prevent detachment of CFRP by delamination from the edge.



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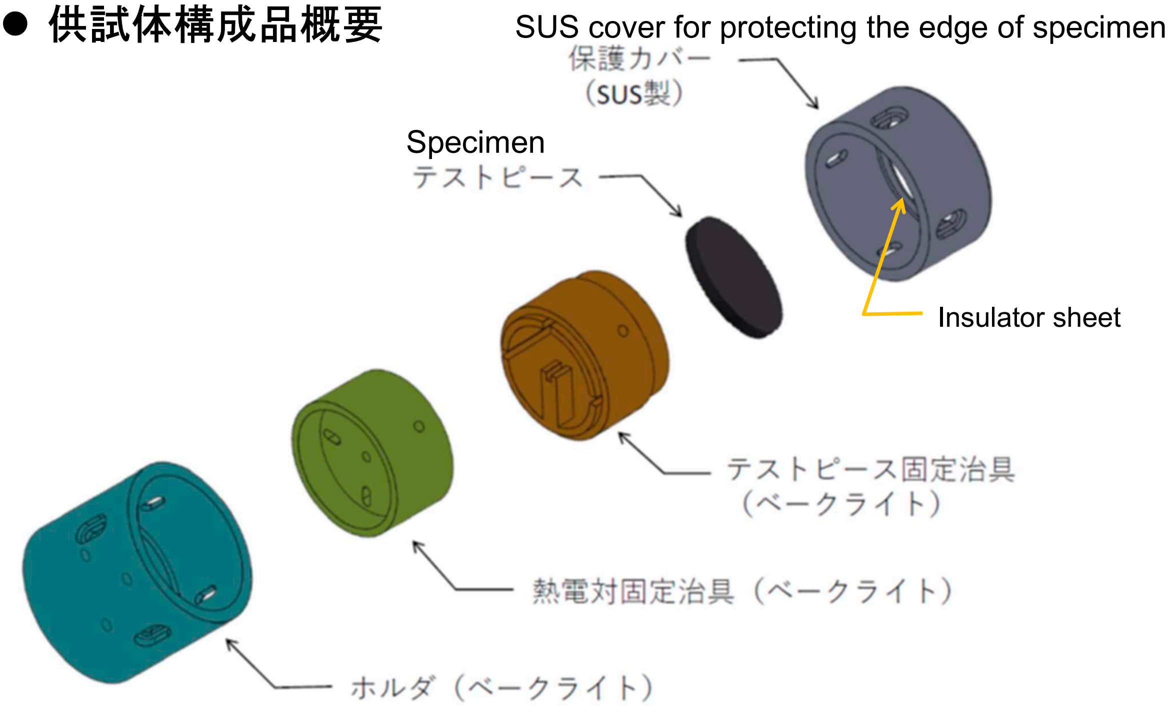
（淀み点加熱試験供試体）

Composition of Test Item

- **供試体構成品概要**



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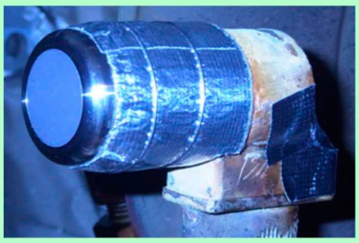
（淀み点加熱試験形態）

Heating Test Configuration

Probe of Facility
Sensor: Gardon gauge



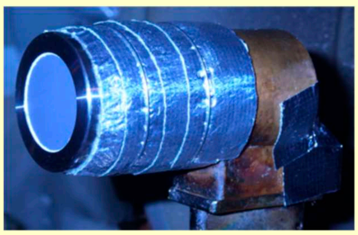
Shape: Probe of Facility
(without bump of cover)
TP: SUS (with Black Body Paint)

Flat Surface
(without bump)

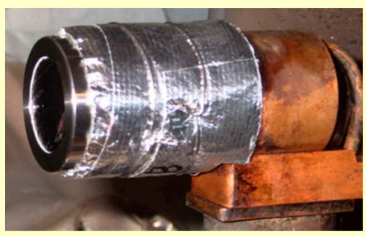
Edge Radius: 5mm

Surface with bump

Edge Radius: 1mm



Shape: Test Configuration
(with bump of cover)
TP: SUS (with Black Body Paint)



Test Configuration
Specimen from Tank
（CFRP／Aluminum Liner）

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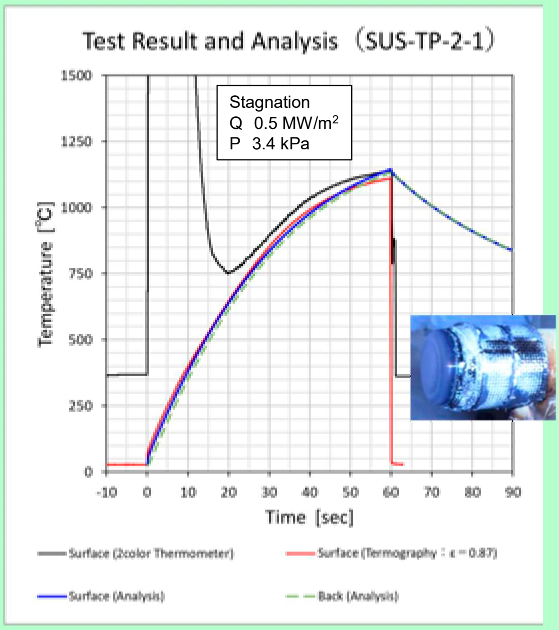
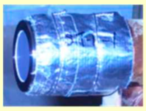
（試験結果－前面形状の影響）

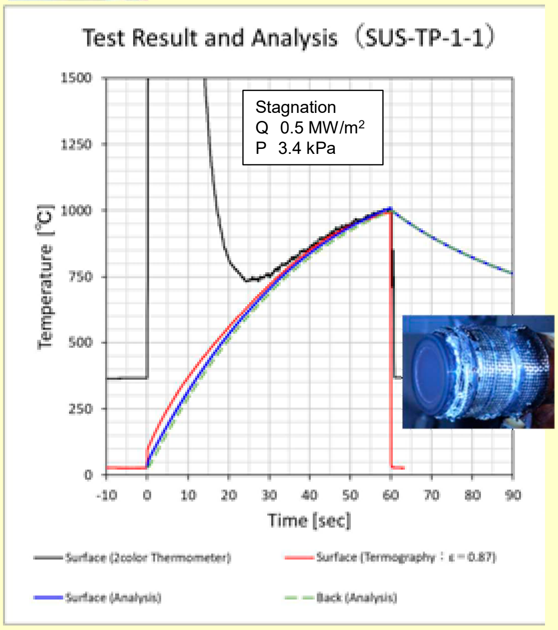
Test Result (Effect of Front Shape)

Shape: Probe of Facility
(without bump of cover)
TP: SUS (with Black Body Paint)





Shape: Test Configuration
(with bump of cover)
TP: SUS (with Black Body Paint)



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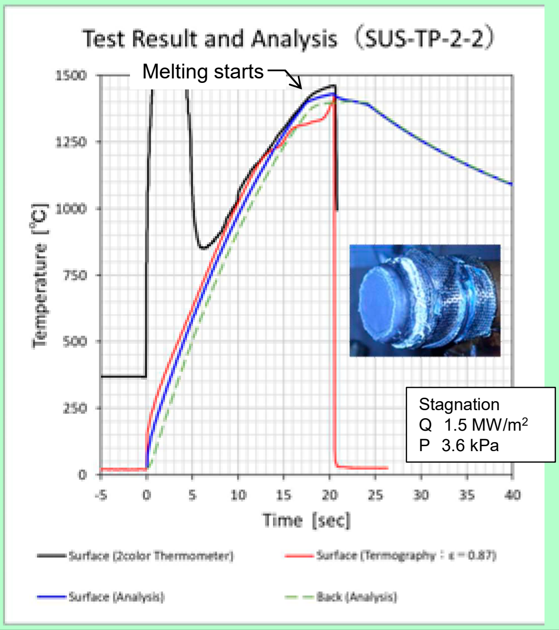
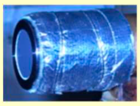
（試験結果－前面形状の影響）

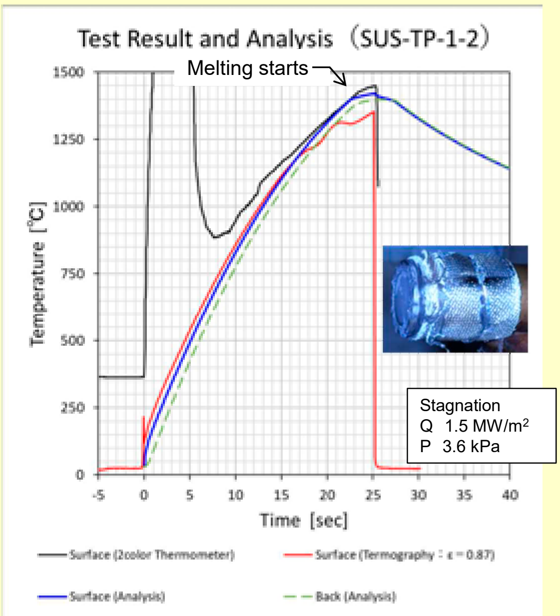
Test Result (Effect of Front Shape)

Shape: Probe of Facility
(without bump of cover)
TP: SUS (with Black Body Paint)





Shape: Test Configuration
(with bump of cover)
TP: SUS (with Black Body Paint)

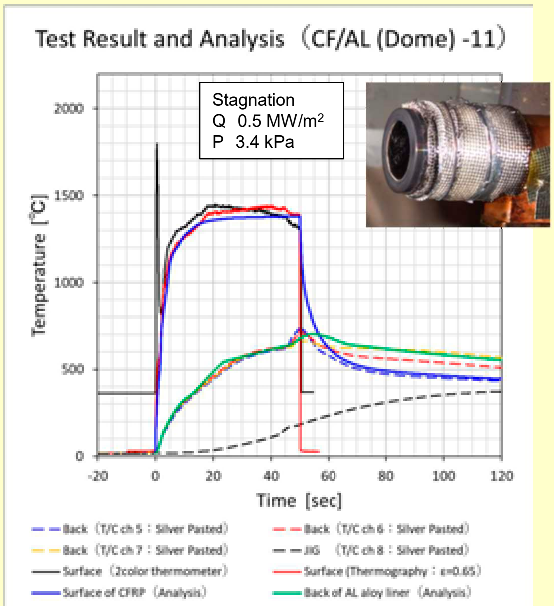


14

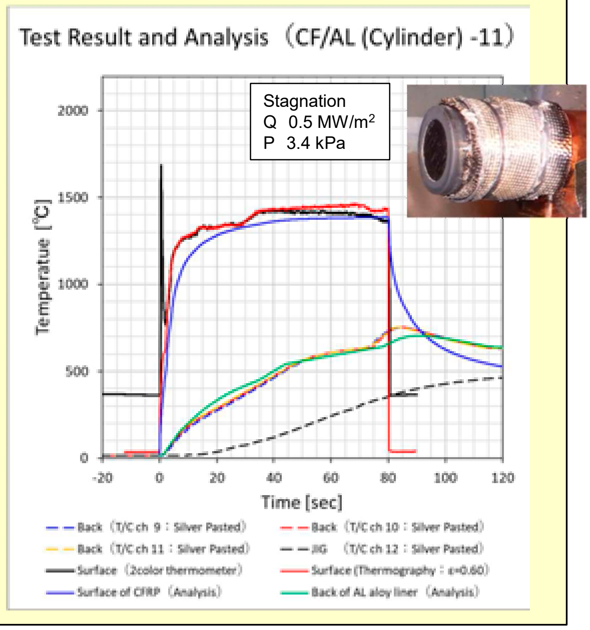
（淀み点加熱試験結果と再現解析）

Test Result and Analysis

Specimen from Tank Dome
（CFRP／Aluminum Liner)



Specimen from Tank Cylinder
（CFRP／Aluminum Liner)

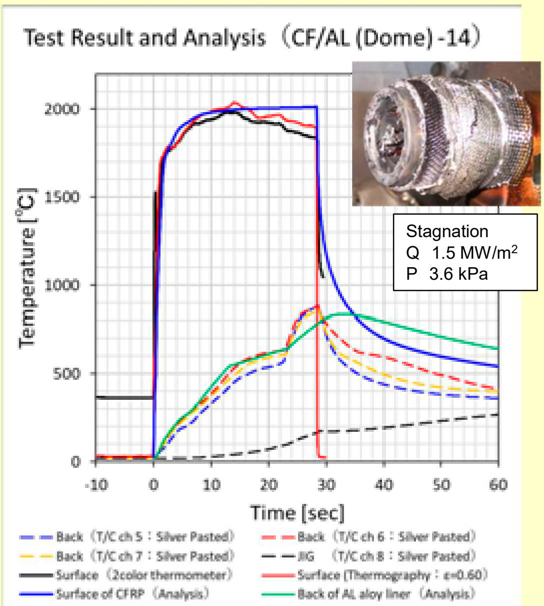


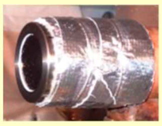
15

（淀み点加熱試験結果と再現解析）

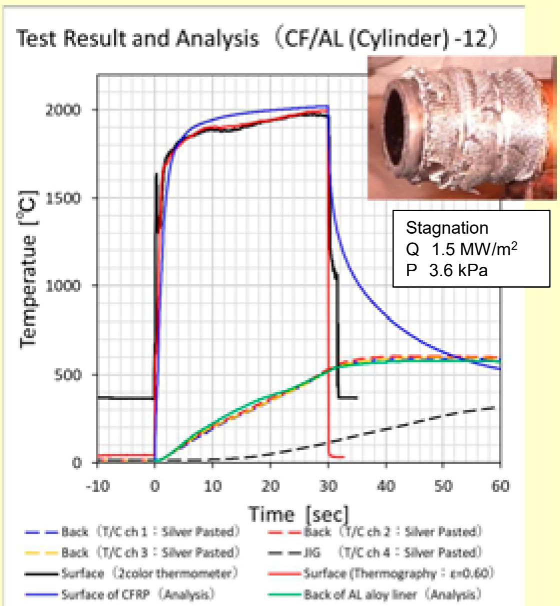
Test Result and Analysis

Specimen from Tank Dome
（CFRP／Aluminum Liner)





Specimen from Tank Cylinder
（CFRP／Aluminum Liner)



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（熱伝導解析モデル）

Heat Conduction Analysis Model

- **Improve one-dimensional heat conduction analysis model by fitting to test data.**

項目		モデル上の扱い
CFRP 熱物性	フープ巻き層 比熱 熱伝導率（面外）	ヴァージン層、炭化層ともUD積層材での取得データ（開発時）に基づいて設定。 急速な温度上昇を考慮し、樹脂熱分解の開始～終了温度をモディファイ。 （本来は各要素の温度履歴に応じて可変とすべきだが、現状は固定。） 樹脂熱分解の開始～終了でヴァージン層と炭化層の熱物性を合成（比例配分）。 樹脂熱分解に要する熱は熱分解開始～終了温度間で均等とモデル化。
	ヘリカル巻き層 比熱 熱伝導率（面外）	ヴァージン層、炭化層ともフープ層の熱伝導率から低減。 上記には樹脂熱分解後の熱伝導抵抗増加分を含む。 （アーク加熱風洞での加熱試験結果の合わせ込み結果による。）
	CFRP表面輻射率	0.60～0.65でモデル化。 アーク加熱風洞での加熱試験結果に基づいて設定。 （２色放射温度計の計測結果にサーモグラフィ処理結果が合うように設定。）
	CFRP／ライナ接着界面	接着剤の熱分解温度以上で熱伝導抵抗を増加。 （アーク加熱風洞での加熱試験結果の合わせ込み結果による。）
アルミライナ 熱物性	溶融・凝固潜熱	溶融潜熱は固相線温度～液層線温度で均等に吸収。 凝固時も液層線温度～固相線温度で均等に放出とモデル化。
試験条件（加熱率、境界条件）	高温壁加熱率（プローブ形状）	気流のエンタルピと空気比熱（300K、壁面温度）から算出。 SUS（プローブ模擬）の結果で補正係数設定。
	高温壁加熱率（タンクTP試験形態）	SUS（タンクTP供試体模擬）の結果で補正係数設定。 タンクTP（CFRP／アルミライナ）の表面温度合わせ込みでモディファイ。
	幾何補正	加熱面積／テストピース面積で加熱率を補正。
	治具への熱伝導	テストピース裏面と治具（近傍）の温度の差に比例とモデル化。 熱伝導抵抗は裏面温度（退避後）合わせ込みで設定。

- Extend to 3 dimensional thermal analysis model (anisotropic model)

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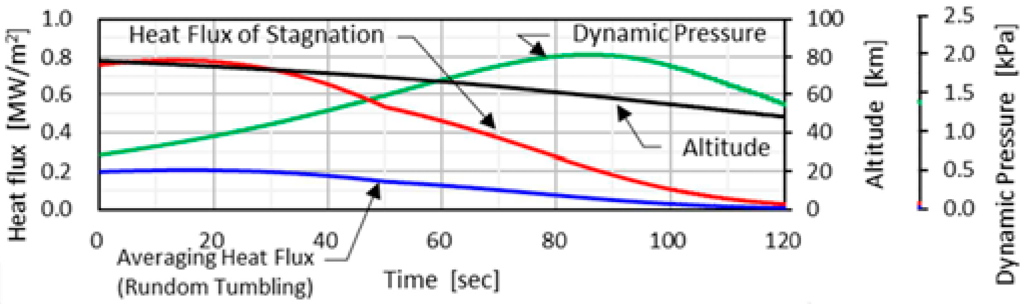
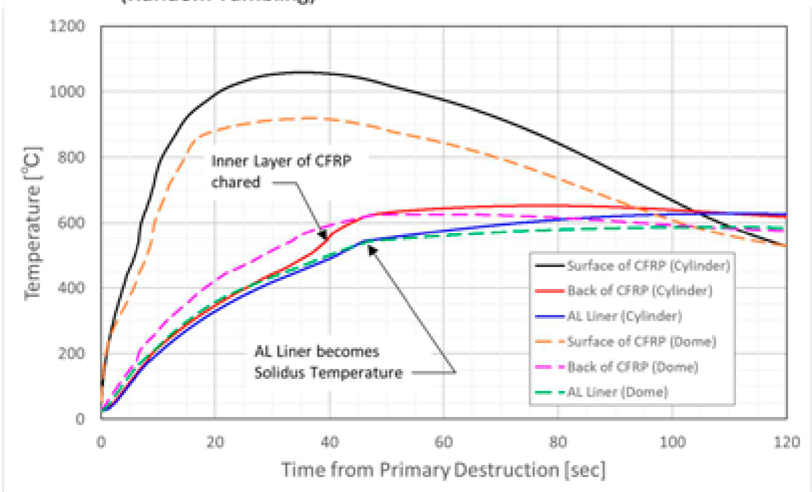
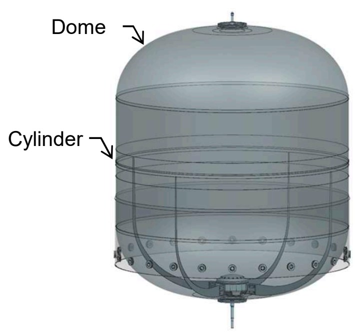
（再突入時の熱伝導解析）

Transient Heat Conduction Analysis







18

(今後の検討予定)

Further Study Plan

Approach

① Preliminary estimation of heat flux during Re-entry

② Heating test for confirmation of probable damage

Additional Test

③ Heating test for construction of heat conduction model

④ Heat conduction analysis model
(one-dimensional → three-dimensional, anisotropic)

⑤ Transient heat conduction analysis (without recession of CFRP)

⑥ Heat flux estimation with 3D shape of tank

⑦ Transient heat conduction analysis

⑧ Detail study considering several effects.
(Buckling of liner, deformation of tank, increase of heat flux, pressure distribution, etc.)

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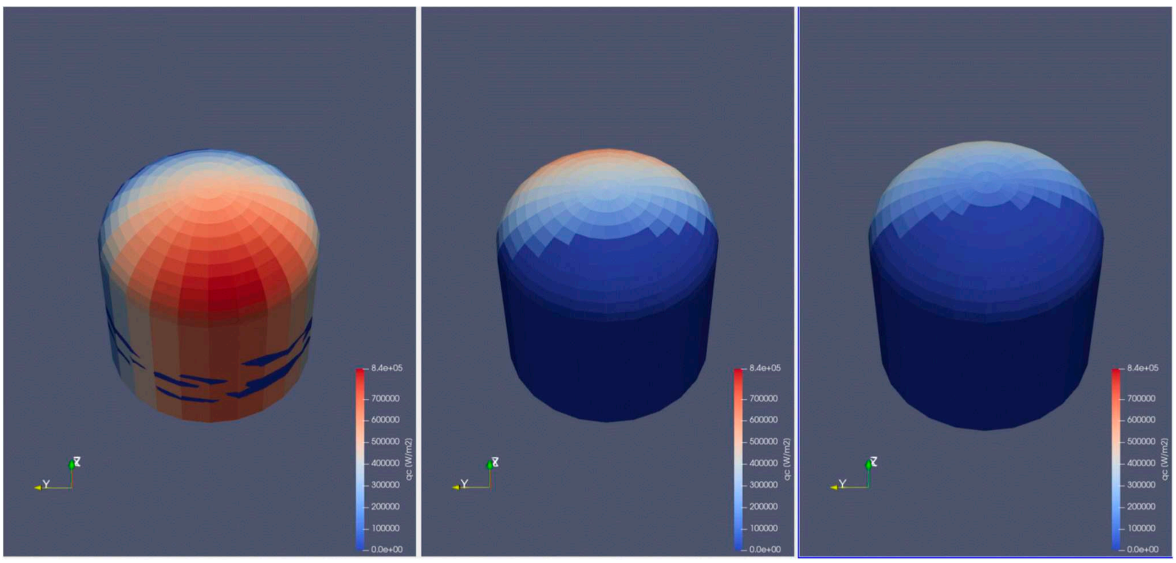
(実機タンク形状での再突入解析)

Re-entry Analysis by LS-DARC

Shape and mass properties : 3-dimensional Shape of Tank
Re-entry analysis by LS-DARC ⇒ Heat flux and pressure profile
(on-going)



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（まとめ）
Summary

- To improve survivability analysis method, additional study about re-entry survivability of the spacecraft composite propellant tank has been done.
  再突入安全評価手法の向上のため、アルミ合金製ライナを有する複合材推薬タンクを対象として再突入安全性の再評価を実施している。
- For this tank, it is conservative to expect no recession of CFRP layers, based on the test results by arcjet wind tunnel.
  アーク加熱風洞での損傷度確認結果から、CFRP層のリセッションを期待しないのが厳しい側の扱いである。
- Heat conduction analysis model was improved based on the heating tests by arcjet wind tunnel. Based on the analysis result in the case of re-entry from SSO, the temperature of aluminum liner rises to solidus temperature, but the absorption of latent heat does not be completed.
  試作タンクから採取したテストピースの淀み点加熱試験結果から熱伝導解析モデルを改良した。SSOからの再突入時の非定常熱伝導解析結果では、アルミライナが固相線温度には到達するが、潜熱吸収には至らない。
- To revise the Heat flux and pressure profile, we have started re-entry analysis with the 3-deimensional shape of this tank using LS-DARC.
  実機タンク形状での加熱率及び圧力分布の履歴を見直すため、LS-DARCを用いた解析を開始している。
- Further study will be conducted in consideration of several effects.
  今後、再解析結果を踏まえて、様々な現象を考慮して詳細検討を行う予定。

C02

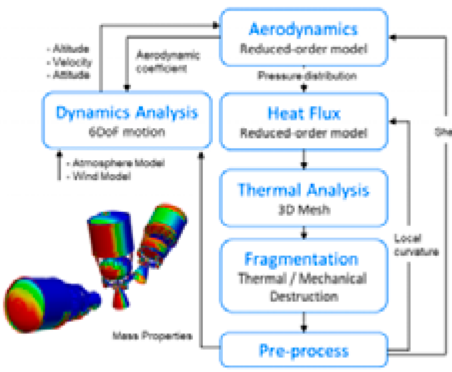
高忠実な物理モデルによるリエントリ安全評価法 LS-DARC の開発：第 2 報　熱流束モデル検証プロセス

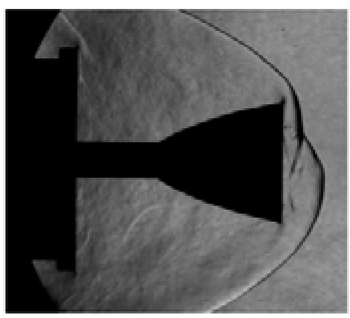
Development of High-Fidelity Model-based Re-entry Safety Analysis Tool LS-DARC: Part 2 Uncertainty Quantification Process for Heat-flux Model

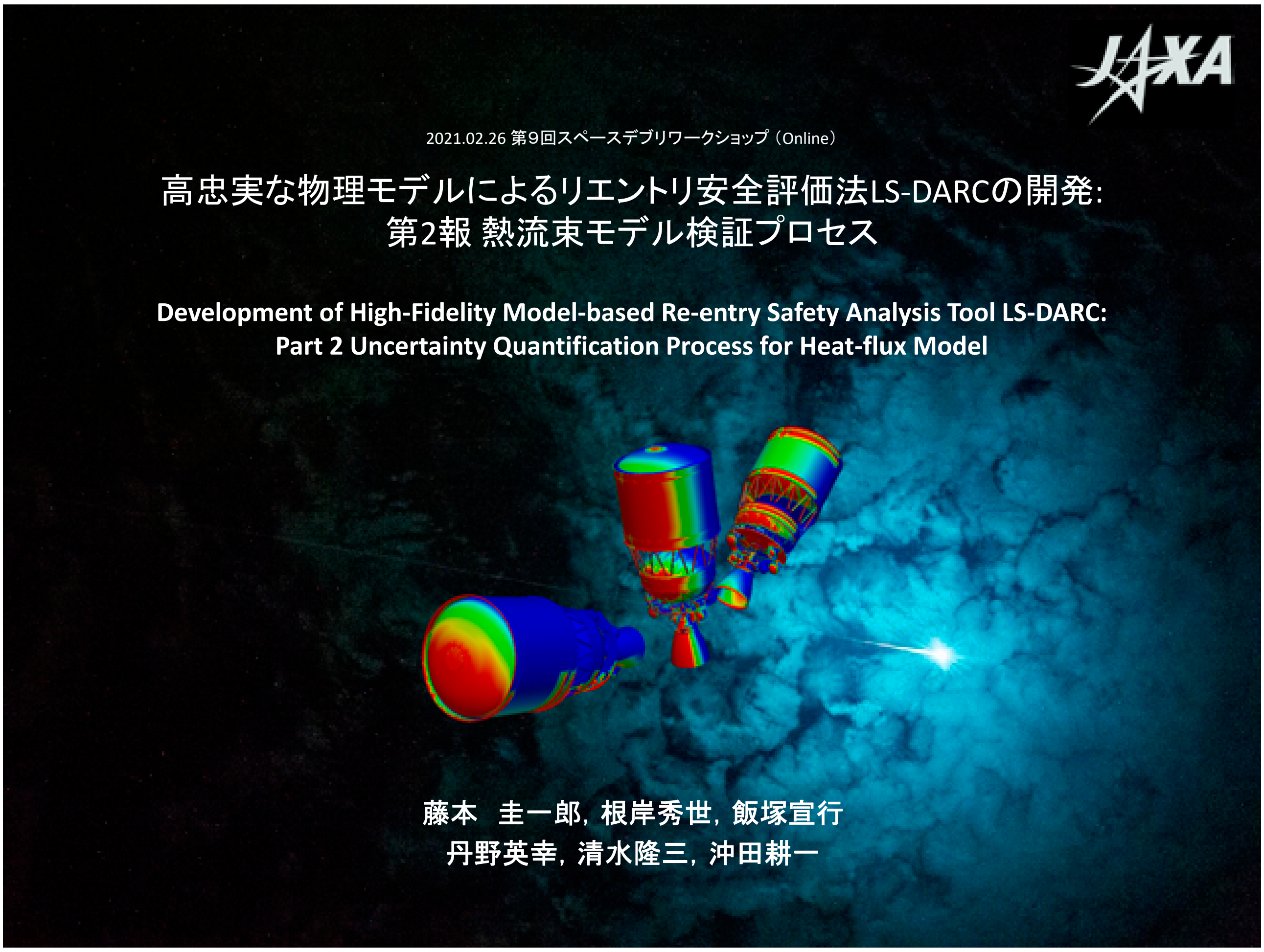
○藤本 圭一郎，根岸 秀世，飯塚 宣行，丹野 英幸，
清水 隆三，沖田 耕一（JAXA）
○FUJIMOTO Keiichiro, NEGISHI Hideyo, IIZUKA Nobuyuki, TANNO Hideyuki,
SHIMIZU Ryuzo, OKITA Koichi (JAXA)

宇宙開発はこの半世紀において科学や工学の両面において飛躍的な発展を遂げてきた．一方，宇宙開発を今後も持続可能なものにするためにはスペースデブリ問題の対策が重要である．本研究は新たなデブリ発生を抑える非デブリ化対策として，ロケット上段や宇宙機の大気圏突入後の溶融残存物による地上被害リスクの最小化を目指している．本研究では，とくに高忠実な物理モデルをベースとした複合物理連成解析法であるリエントリ安全評価法 LS-DARC（Destructive Atmospheric Re-entry Code）の開発に取組んでいる．設計パラメータ変更による安全性向上度を定量的に分析できるようにすることで，a) 上流設計段階からの溶融促進設計，b) 認知学的な不確かさの低減による高精度なリスク評価を実現することが目的である．LS-DARC により下図に示すようなロケット上段や衛星などの複雑形状に対して溶融残存物が生じるかどうかを評価することができるが，安全評価法として実用化するためには物理モデルの検証プロセスの確立が不可欠である．本報告ではとくに熱流束モデル検証方法を提案し，高エンタルピー風洞試験による検証データ取得をはじめとした検証状況について述べる．

Remarkable progress in space exploration both for science and engineering have been made in a half century. Space debris problem is a growing concern to be tackled internationally to keep our space activity sustainable. For the improvement in the ground safety related to the survived debris after the destructive re-entry of the rocket upper stages and the spacecrafts, the comprehensive considerations on the design and the disposal operation should be made. High-fidelity model-based re-entry safety analysis tool LS-DARC is under the development in JAXA. Purpose of this study is an establishment of quantitative assessment of the design and disposal operation change effect on the re-entry risk. Consequently, a) design for demise from the initial development phase, and b) accurate risk prediction by reducing epistemic uncertainty are realized. LS-DARC is multi-physics coupling analysis code including the aerodynamic and 6DoF trajectory analysis, surface heat flux distribution analysis, three-dimensional thermal transfer analysis. Establishment of the uncertainty quantification process of the LS-DARC models is essential in order to make it practical re-entry safety analysis tool. In this report, the uncertainty quantification process especially on the heat flux model is proposed and discussed. Research activities on the validation data acquisition by the high-enthalpy wind tunnel and the model validations are discussed.






2021.02.26 第9回スペースデブリワークショップ（Online）
高忠実な物理モデルによるリエントリ安全評価法LS-DARCの開発:
第2報 熱流束モデル検証プロセス
Development of High-Fidelity Model-based Re-entry Safety Analysis Tool LS-DARC:
Part 2 Uncertainty Quantification Process for Heat-flux Model
藤本 圭一郎, 根岸秀世, 飯塚宣行
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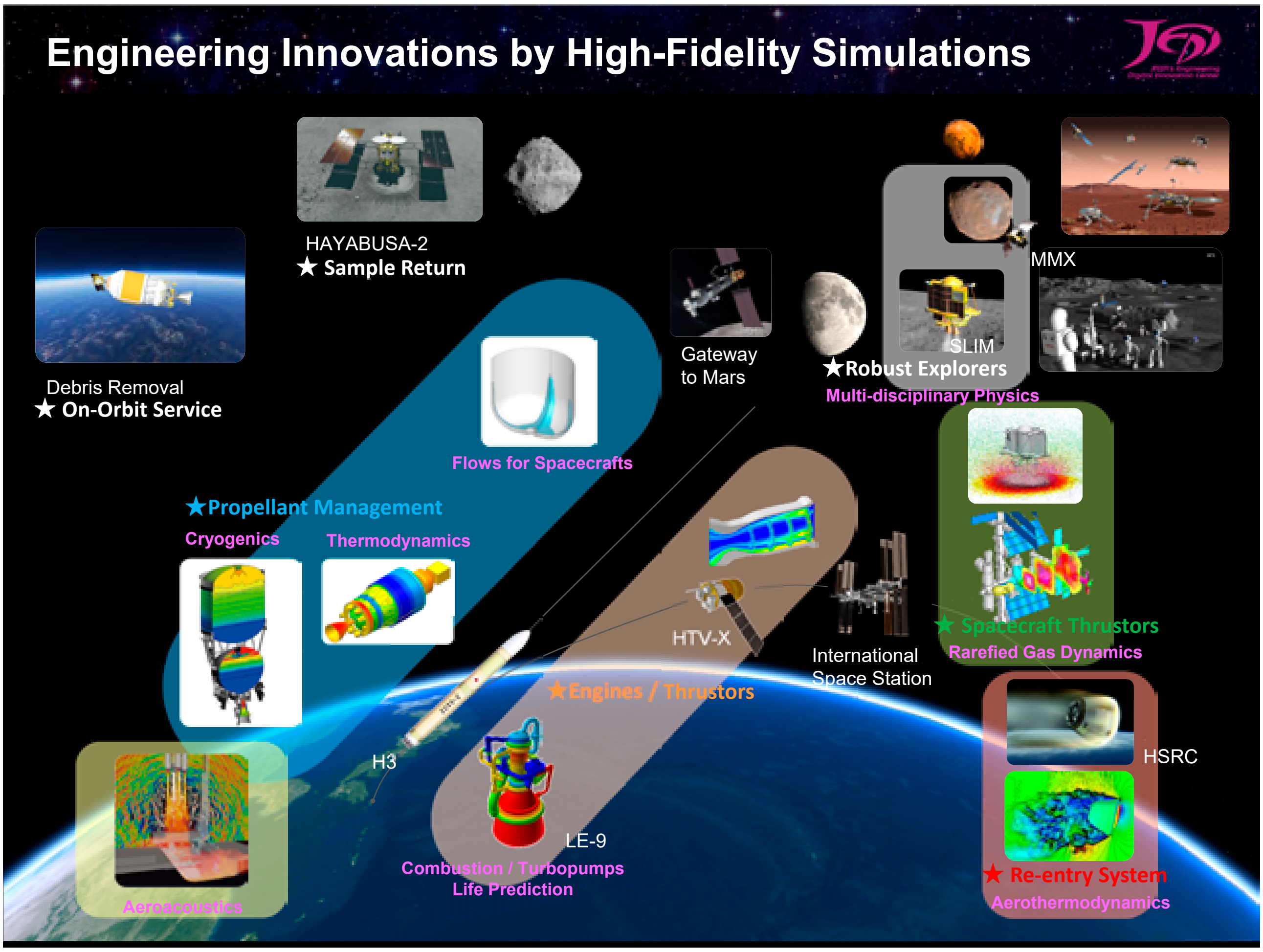
Engineering Innovations by High-Fidelity Simulations
HAYABUSA-2
★ Sample Return
Debris Removal
★ On-Orbit Service
Gateway
to Mars
MMX
SLIM
★Robust Explorers
Multi-disciplinary Physics
Flows for Spacecrafts
★Propellant Management
Cryogenics
Thermodynamics
HTV-X
International
Space Station
★ Spacecraft Thrustors
Rarefied Gas Dynamics
★Engines / Thrustors
H3
HSRC
LE-9
Combustion / Turbopumps
Life Prediction
Aeroacoustics
★ Re-entry System
Aerothermodynamics

Overview of Re-entry Safety Analysis

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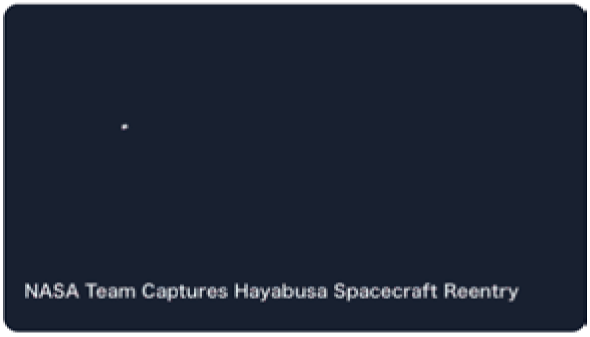
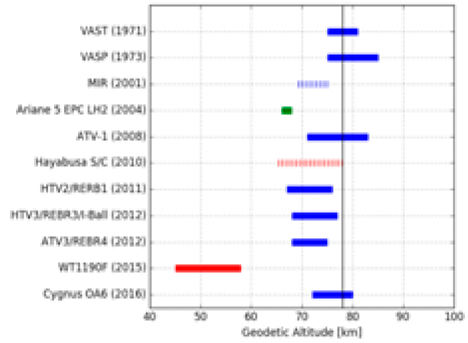
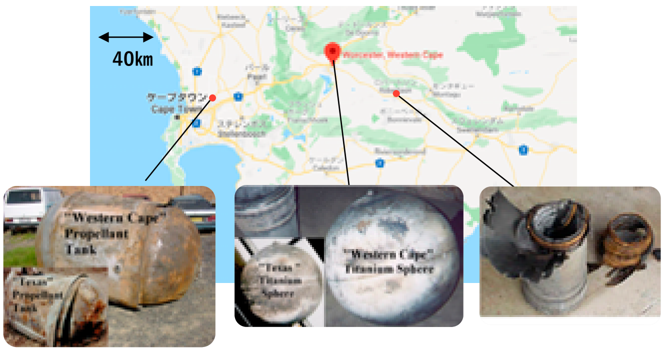
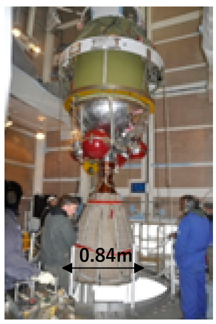
- ▹ Expected casualty (EC) value due to the survived debris of rocket upper stage and spacecrafts.
- ▹ If required, EC value is minimized by the controlled re-entry and the design-for-demise.
- ▹ Re-entry safety requirement is getting restricted internationally.





Survived debris dispersion area of Delta-II Rocket





AJ10 Engine(90~100kg)

Motivation to Develop High-fidelity Re-entry Safety Model

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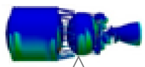
- ▹ Accurate EC analysis becomes available by reducing epistemic uncertainties.
  (e.g.) Heating surface area can be increased by considering the detailed geometries.
- ▹ Design-for-Demise becomes available by evaluating the design parameter sensitivity.

Object-oriented tool ORSAT-J

Shape: Basic Shapes
Attitude: Random Tumbling
Aerodynamics Heat-flux: Database, Formula

Spacecraft-oriented tool LS-DARC

Shape: Real Shape / Shape changes in time
Attitude: 6 DoF Analysis (e.g. Trim)
Aerodynamics Heat-flux: Local Panel Method
+ Larger heat flux at small curvature part



STEP1
Model Update
- Model Update of Heat flux and Aerodynamics
- New Base Shape
- Application of Detailed Models

Methods and Tool Development
- Model formulation and Implementation
- Integration of Tool
- GUI issues

STEP2
Model Update

Establishment for Practical Use
- Model Validation (Unit & Integrated)
- UQ
- Model Improvement

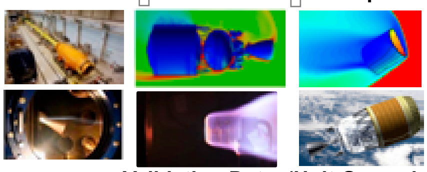
- Sensitivity Analysis on EC
- Comparisons

Accurate EC Analysis

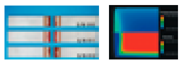
Design for Demise

Validation & Model Update

Versatile Physics Properties / Models



Validation Data (Unit Ground, Flight)



Material Data

Detailed Physics Model
(e.g., Ablator Effect Model for Heat flux)

Spacecraft-oriented Re-entry Risk Analysis Tool : LS-DARC

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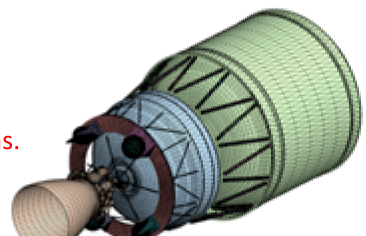
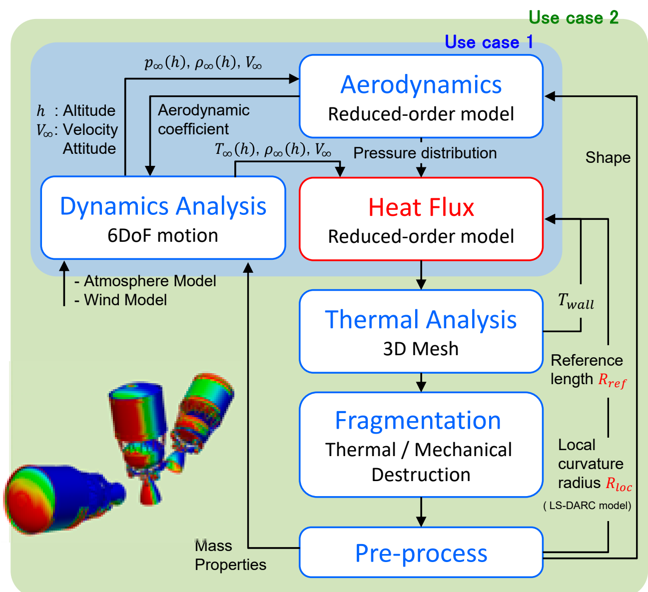
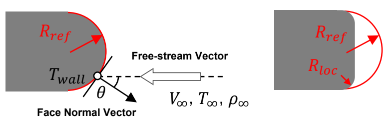
LS - Destructive Atmospheric Re-entry Code (LS-DARC)

- ▹ Development start from FY2015, completed 1st version in this fiscal year.
- ▹ Easy-to-use multi-disciplinary physics analysis.
- ▹ Heat flux models are originally formulated for the basic shape predictions.
- ▹ Heat flux model with considering local curvature effect.
- ▹ Fast MPI runs by super-computers.



Arbitrary Polyhedral Mesh





Trajectory	6DoF equations of motion – 4th order Runge–Kutta / Higher–order
Atmospheric properties	– US62/76 – NRL MSISE–00 / Earth GRAM
Aerodynamics	– Modified Newton Impact Theory – Nocilla correlation model
Heat flux	– LSDARC model – SCARAB 3.1 model (Radiative dissipation, oxidization, hot wall effect modification)
Thermal analysis	3D Thermal transfer equation
Destruction	– Thermal destruction – Mechanical destruction ＊under the development

Spacecraft-oriented Re-entry Risk Analysis Tool : LS-DARC

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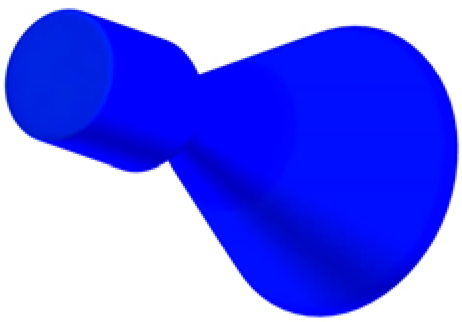
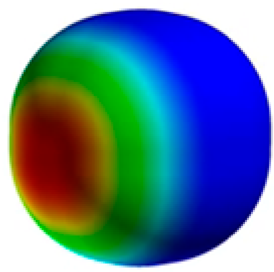
High-fidelity multidisciplinary analysis including 6-DoF motion and shape change effects.

Important considerations for the accurate EC predictions are,

▹ Fragment is aerodynamically stable or not ?
▹ How much attitude behavior and the deceleration rate are varied by the shape change ?
▹ How much are the heat flux level and the temperature increase rate changed during the re-entry ?



Melting Rocket Engines



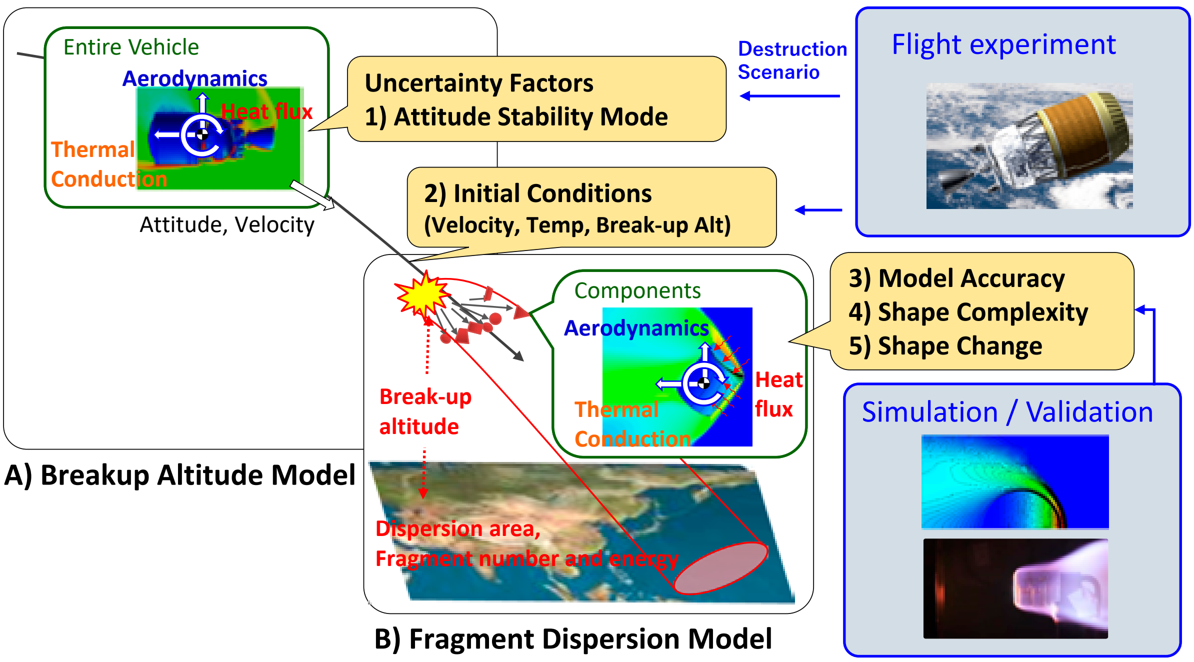
Gas Tanks

Ref (1): Fujimoto, K., Negishi, H., Shimizu, R., Daibo, T., Iizuka, N., Okita, K., "High-Fidelity Spacecraft-oriented Re-entry Safety Analysis Code of JAXA: LS-DARC", Proceedings of the 9th IAASS Conference, 2019.

Uncertainty Quantification Process – Key Uncertainty Factors

8

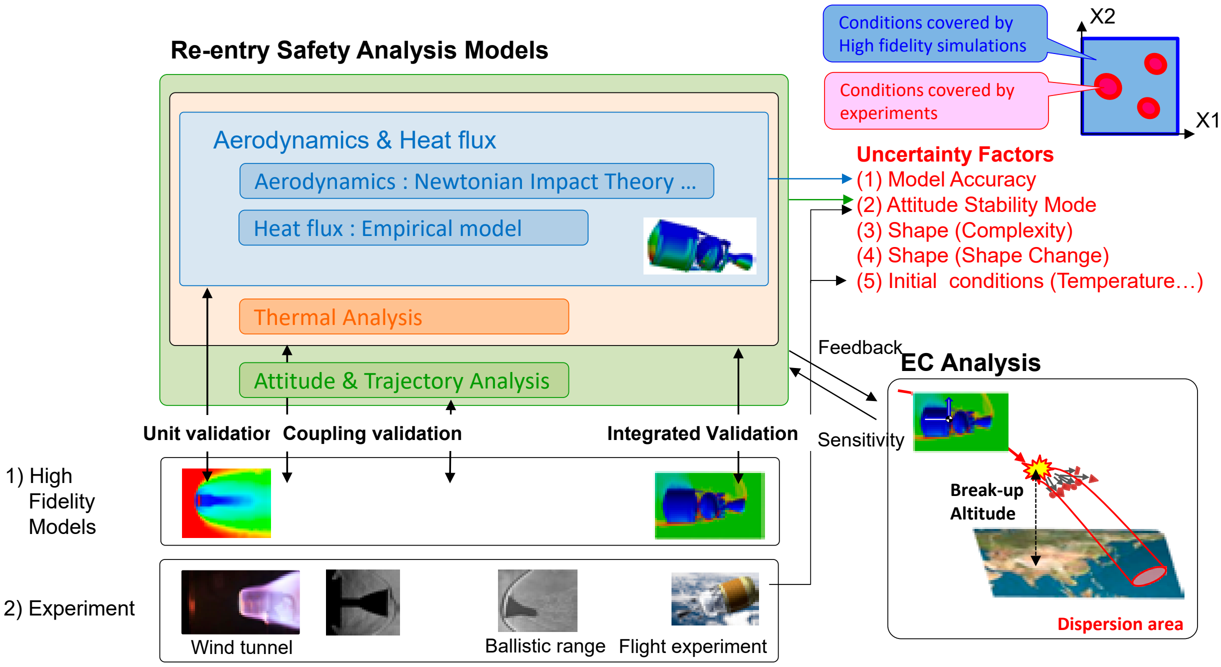
▹ Key uncertainty factors for re-entry risk analysis are identified, and the related uncertainties are quantified based on the flight experiment, high fidelity simulations, and ground test.



Ref (2): Fujimoto, K., Tani, H., Negishi, H., Saito, Y., Iizuka, N., Okita, K., Kato, A., "Uncertainty Quantification for Destructive Re-Entry Risk Analysis: JAXA Perspective," Stardust Final Conference, Conference, Springer book, pp.283-300, 2018.

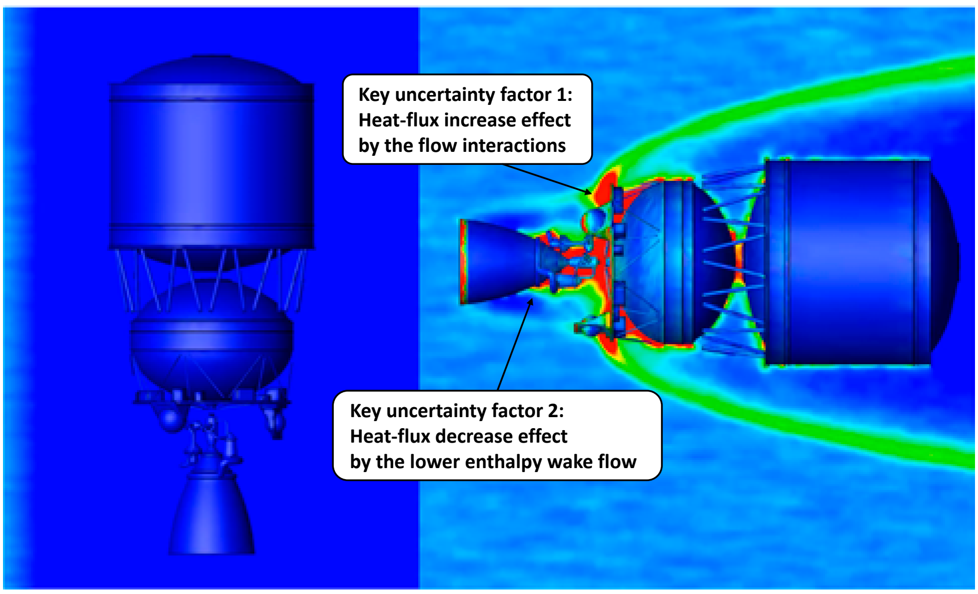
Uncertainty Quantification Process – Overview

- Destruction scenario investigation and key uncertainty factor identification by flight test in early phases.
- Started from low-cost unit validation, then expensive Integrated validation.
- Comparison with high-fidelity simulations to understand physics and cover parameter space globally.
- Comparison with experiments not to miss unknown physics under the carefully selected conditions.



Strategy for Heat-flux Model Validations

- Perfect prediction accuracy is not pursued, but its result should be the worst-case (e.g., lower heat-flux).
- Destruction scenario investigation and key uncertainty factor identification by flight test in early phases.
- Higher heat-flux area is always on the windward, thus the accurate prediction can be achieved even by the simple formulation of the heat-flux model.
- Heat-flux validations for basic shapes were carried out, then those for the realistic shape.

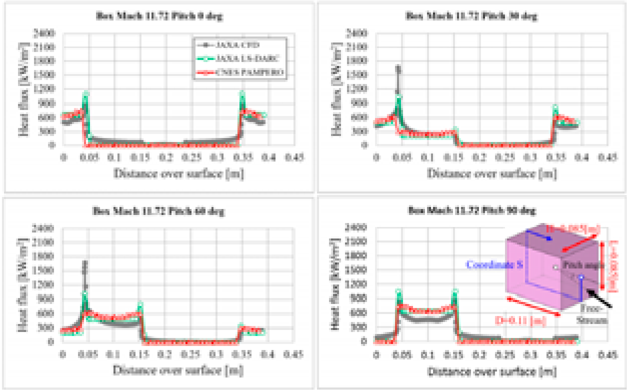


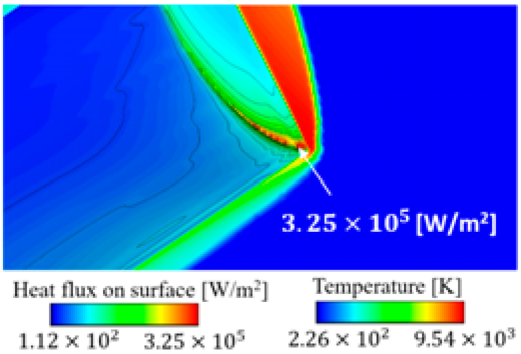
Demonstration 6DoF analysis by JAXA DSMC code (UNITED)

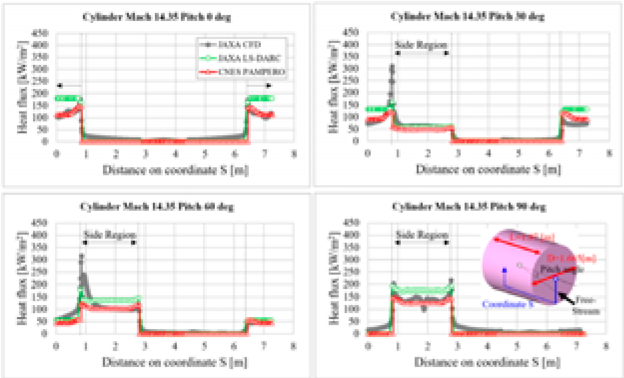
Unit Validation of Heat-flux Model for Basic Shapes

▹ Heat-flux model of LS-DARC were validated for basic shapes by the comparison with the results by CNES's PAMPERO under the joint research.

▹ LS-DARC and PAMPERO can quantitatively predict even at corners without changing the model parameter value.







Ref (3): Fujimoto, K., Negishi, H., Saito, Spel, M., Prigent, G., "Benchmark of JAXA and CNES Re-entry Safety Analysis Tools for Accurate Heat-flux Prediction ", Proceedings of the 9th IAASS Conference, 2017.

Unit Validation for Each Heat-flux Model Terms

▹ Uncertainty quantifications for each heat flux model terms are essential.

▹ Unit validation process was proposed based on the previous works, the heat flux formulations and the related material properties will be validated.

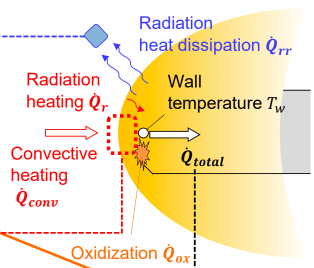
▹ Heat-flux induced by the recombination $\dot{Q}_{ox}$, the convective heating $\dot{Q}_{conv}$, the radiation heating $\dot{Q}_r$, and the radiation heat dissipation $\dot{Q}_{rr}$ can be obtained. It significantly contribute to the efficient uncertainty quantification and the model accuracy improvement.

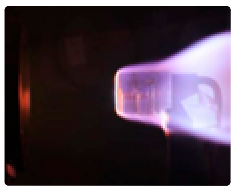
▹ Overview of the validation process are described bellow.

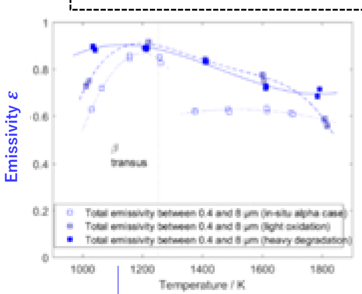
Measurement by sensor

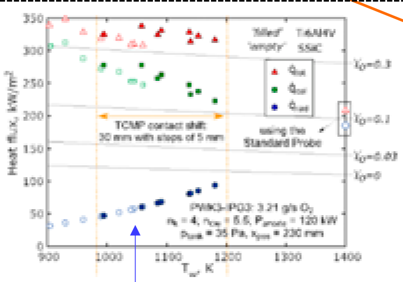
$$\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_r - \dot{Q}_{rr} + \dot{Q}_{ox}$$

Evaluated by CFD

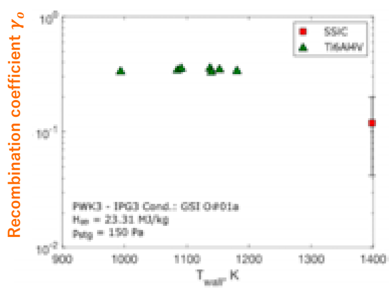








$$\dot{Q}_{rr} = \varepsilon \cdot \sigma \cdot T_w^4$$



**All plots are taken from the following literature.*
Ref (4): Massuti-Ballester, B., Pagan, A., Herdrich, G., "Oxidation and heterogeneous catalysis on titanium Ti-6Al-4V in high-enthalpy flows," IAC-18,C2,4,8,x46403, 2018.

Integrated Validation of Heat-flux Model for Realistic Shapes

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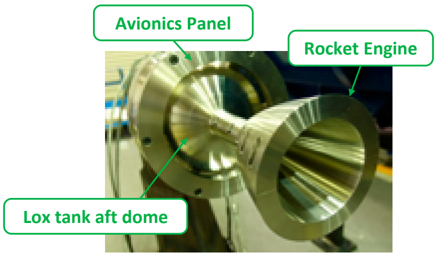
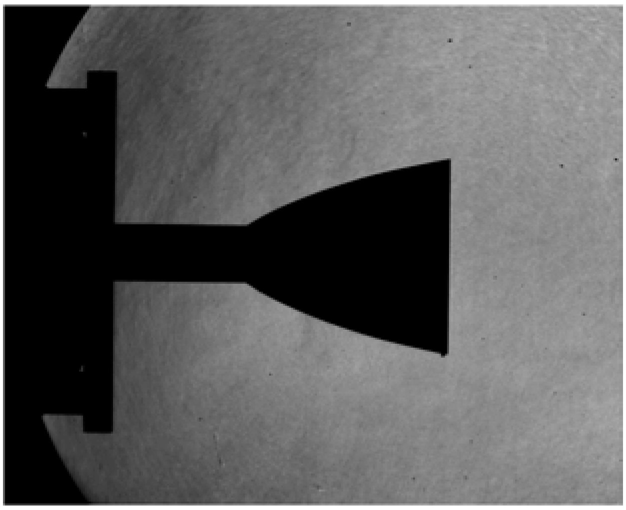
- ▹ Integrated validation of the heat-flux model for the engine of rocket upper stage is under the way.
- ▹ Complicated flow interactions such as the shock wave interactions and the unsteady wake flow were observed, those effects are not considered in the heat-flux model formulations.
- ▹ Unsteady recirculation and shock wave motions are observed, which is resulting in the unsteady aerodynamic heating.
- ▹ Measured heat-flux distributions are compared with the predictions, and the model parameter sensitivity study is under the way to achieve the lower predicted heat-flux level as comparing with the measurement.





High enthalpy shock tunnel : HIEST Max enthalpy 25MJ/kg, Max stagnation pressure 150MPa, 0.5m test article

Conclusion

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▹ High-fidelity spacecraft-oriented re-entry safety analysis code LS-DARC (Destructive Atmospheric Re-entry Code) has been developed for the epistemic uncertainty reduction on the expected casualty (EC) predictions and the design-for-demise to minimize the ground risk related to the survived debris.

▹ LS-DARC is the high-fidelity multidisciplinary coupling analysis code to predict the complicated off-nominal physics during the destructive re-entry of the rocket upper stages and the spacecrafts.

▹ Trajectory and attitude of the multiple complicated fragments, and those demising processes due to the severe aerodynamic heating can be predicted. Reduced-order models of the aerodynamic characteristics and the heat flux distributions are keys to handle complicated fragment shapes and to maximize analysis speed for the practical probabilistic analysis.

▹ Analysis capabilities and the current development status were shown. Uncertainty quantification strategies were discussed especially for the heat flux model.

▹ [Previous study] Predicted heat flux distributions were agreed well with the CFD result, and the prediction capability of the LS-DARC has been reached the same level with the ESA's SCARAB and the CNES's PAMPERO.

▹ Unit validation process was proposed by following same approach with the previous studies.

▹ Current status of the integrated validation for the rocket upper stage was summarized.


Learn together to go further !
JAXA
POC : fujimoto.keiichiro@jaxa.jp

C03

デブリ衝突損傷リスク解析ツール TURANDOT の現状と改修計画

Present Status and Improvement Plans of Tactical Utility for Rapid ANalysis of Debris on Orbit Terrestrial (TURANDOT)

○中渡瀬 竜二，上田 裕子，八田 真児（MUSCAT スペース・エンジニアリング）
河本 聡美（JAXA）
○NAKAWATASE Ryuji, UEDA O. Hiroko, HATTA Shinji (MUSCAT Space Engineering),
KAWAMOTO Satomi (JAXA)

本講演では，デブリ衝突損傷リスク解析ツール（TURANDOT）の概要と今後の改修計画を紹介する．TURANDOT は，JAXA で開発された宇宙機設計支援ソフトウェアである． 本ツールは宇宙機表面を詳細な格子に分割し，デブリに対する宇宙機自身の遮蔽を考慮した上で，各部位のデブリ衝突頻度を解析可能である．また，任意の宇宙機部位について，宇宙機表面材料と弾道方程式を設定することで，損傷リスクも評価可能である． さらに，メテオロイドのエンジニアリングモデルを用いることで，デブリと同様の解析が可能であり，ESA MASTER-2009 と NASA MEMR2 に対応している．現在，解析可能な軌道は GEO までの地球周回軌道に限られるが，MEMR2 は月周辺のメテオロイド環境を解析可能であるため，月面ならびに月周回軌道の解析を可能とする改修を検討中である． 加えて，対応しているエンジニアリングモデルをアップデート中である（NASA ORDEM 3.1，MEM 3）． 更に，原子状酸素の影響評価と月面における日照解析への応用を検討している．

We introduce overview and improvement plans of Tactical Utility for Rapid ANalysis of Debris on Orbit Terrestrial (TURANDOT). TURANDOT is developed by JAXA to assist the users for spacecraft design. The software is capable of prediction of probability of debris impact to a spacecraft including shielding effect of the spacecraft itself. In addition, corresponding damage risk can be evaluated by setting up the spacecraft surface materials and ballistic limit equations for a given spacecraft part. Furthermore, the software provides risk assessments not only for debris but also for meteoroids by applying engineering models of meteoroid and supports two models: ESA MASTER-2009 and NASA MEMR2. At present, TURANDOT can analyze the risks on the orbits around the Earth up to GEO, but we are planning to improve the software to enable analysis for the lunar surface and for the lunar orbits using MEMR2, which provides the meteoroid environment data around the Moon. In addition, an updating supporting engineering models is in progress: NASA ORDEM 3.1 for debris and NASA MEM3 for meteoroid. Moreover, an expansion of the application is being considered - analyzing the effect of atomic oxygen erosion on material and estimation of the solar irradiance that reaches objects on the Moon, for example.

C03

デブリ衝突損傷リスク解析ツールTURANDOTの現状と改修計画

Present status and improvement plans of Tactical Utility for Rapid ANalysis of Debris on Orbit Terrestrial (TURANDOT)

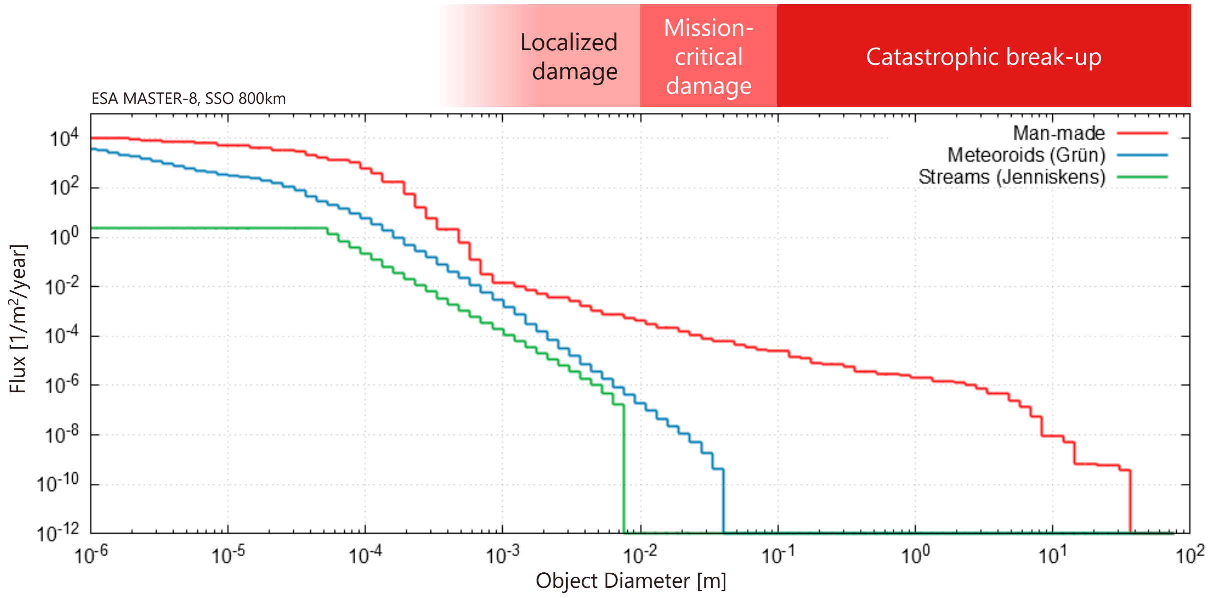
中渡瀬竜二，上田裕子，八田真児（MUSCATスペース・エンジニアリング株式会社），
河本聡美（JAXA研究開発部門）

NAKAWATASE Ryuji, UEDA O. Hiroko, HATTA Shinji (MUSCAT Space Engineering Co., Ltd.),
KAWAMOTO Satomi (JAXA Research and Development Directorate)

Contents

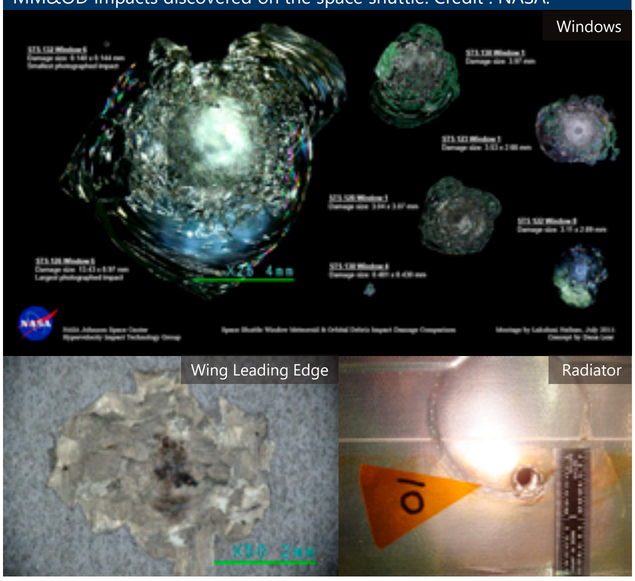
- Introduction
- Overview of TURANDOT
- What’s new on TURANDOT
- Planning enhancements
- Conclusion

Meteoroid/Orbital Debris Risk

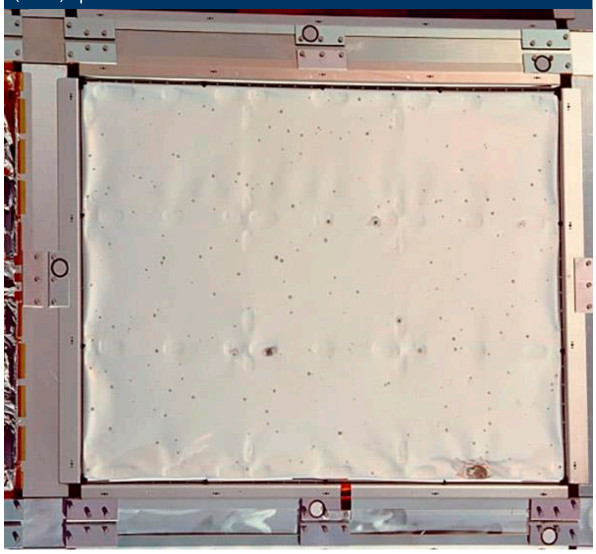


Meteoroid/Orbital Debris Risk

MM&OD impacts discovered on the space shuttle. Credit : NASA.



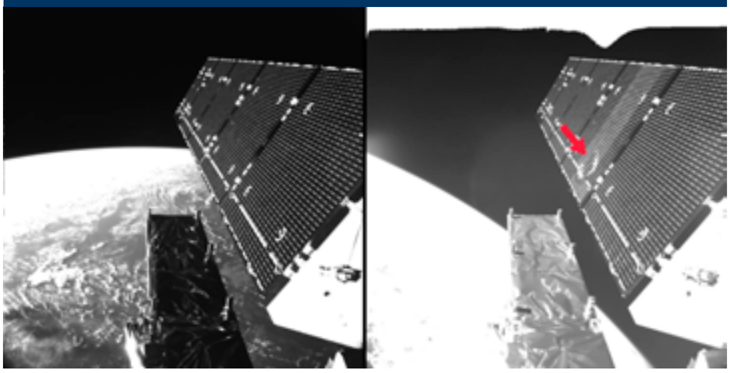
A close-up view of a panel from the Long Duration Exposure Facility (LDEF) spacecraft. Credit : NASA JSC.



Introduction

Meteoroid/Orbital Debris Risk

Sentinel-1 impact. Credit : ESA.



Impact-induced sustained discharge on power harness (ground experiment)

HIRAI Takayuki et al.,
The 7th Space Debris Workshop (2016)

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Introduction

Meteoroid/Orbital Debris Risk Assessment Tools

Tool	Space agency
BUMPER II	NASA
ESABASE2 / DEBRIS, PIRAT	ESA
COLLO, BUFFER	ROSCOSMOS
MDPANTO	DLR
SHIELD	BNSC
MODAOST	CAST
TURANDOT	**JAXA**

IADC Protection Manual(Version 7.1), IADC-04-03

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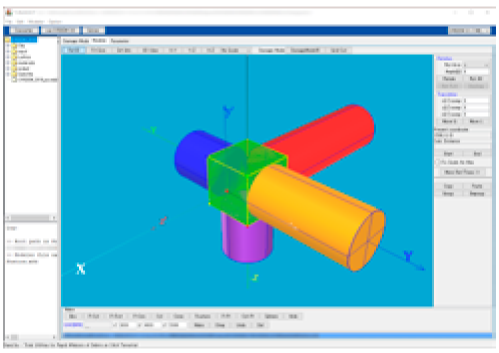
TURANDOT

- assesses Impact Flux, Impact Frequency and Impact Damage.
- takes shielding effect into account.
- supports ESA MASTER-2009, NASA ORDEM 3.0 and NASA MEMR2.

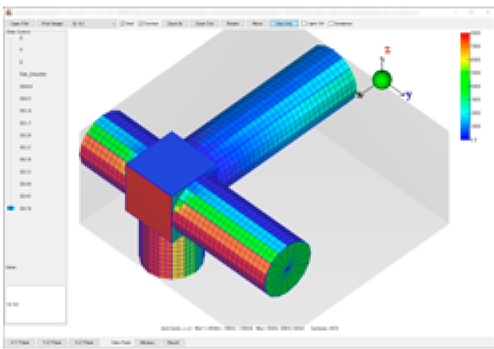
■ Layout of sensitive or critical equipment
■ Effectiveness of protection
■ Attitude of spacecraft
■ Inquiry of causes of failure

Integrated Analysis Environment

- Spacecraft modeling
- Grid generation
- Analysis condition setting



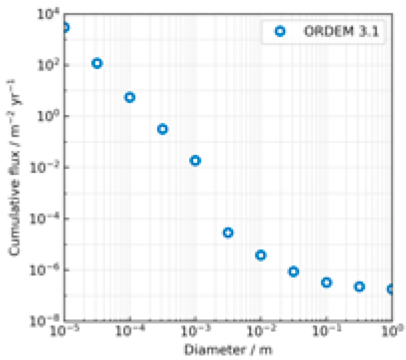
Modeling



Collision flux distribution

What's new on TURANDOT

- Engineering model
  - ESA MASTER-2009 (Debris / Meteoroid)
  - NASA ORDEM 3.0 (Debris)
  - NASA MEMR2 (Meteoroid)
- Central body
  - Earth
- Size thresholds for ORDEM
  - 11 size thresholds



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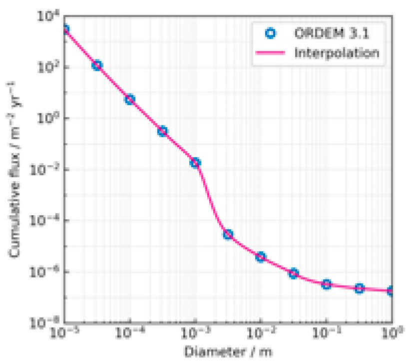
What's new on TURANDOT

What's new on TURANDOT

- Engineering model
  - ESA MASTER-2009 (Debris / Meteoroid) → **MASTER-8**
  - NASA ORDEM 3.0 (Debris) → **ORDEM 3.1**
  - NASA MEMR2 (Meteoroid) → **MEM 3**
- Central body
  - Earth + **Moon, Mars (Meteoroid)**
- Size thresholds for ORDEM
  - 11 size thresholds → **51**



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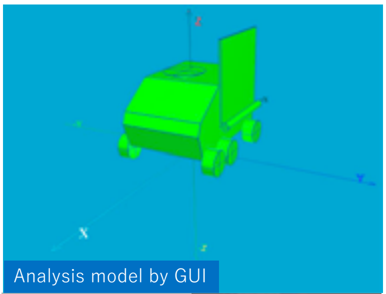
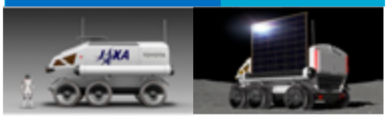
Planning enhancements

Application for Meteoroid around The Moon 1/2

Example:

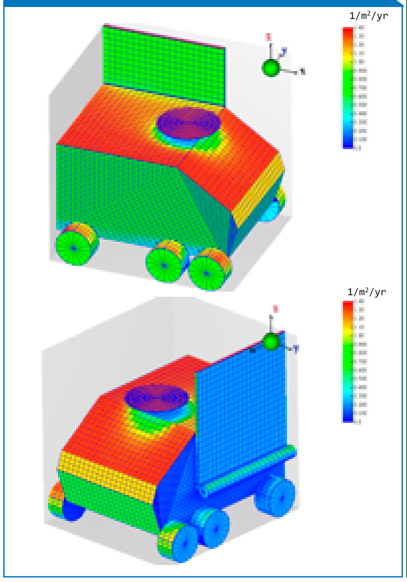
- A Moon rover
- Flux of MEMR2 by NASA
  - JD 2462502.5 (2030-01-01T00:00:00.0)
  - 0° lon., -89.5° lat. (15km apart from the pole)
  - 10^{-6} g $< m$ (124 μm $< d$)



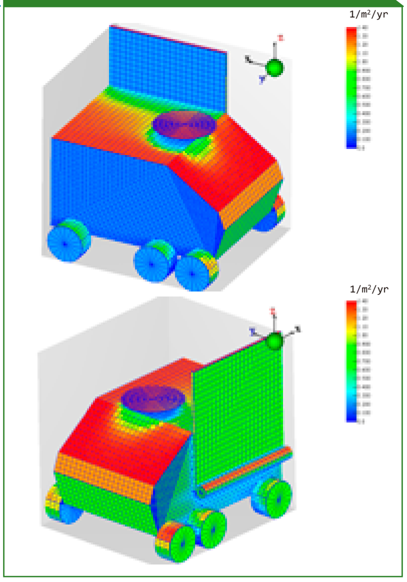


https://www.jaxa.jp/press/2019/03/20190312a_j.html

Advance direction: Sym-rotation



Advance direction: Anti-rotation



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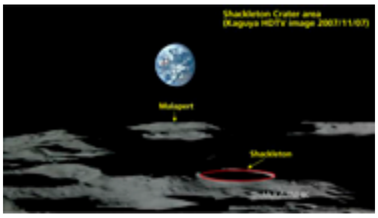
Planning enhancements

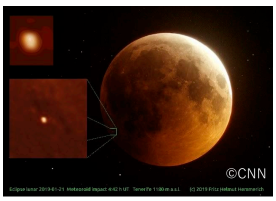
Application for Meteoroid around The Moon 2/2

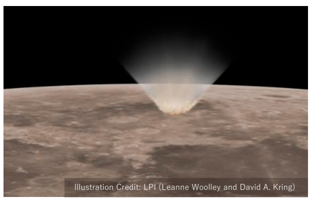
- Available for new materials as long as BLE is defined.
- The south pole of the Moon is rough terrain.
- Geographical shielding effect is to be introduced.



- Effect of ejecta by meteoroid can be analyzed, if corresponding flux is obtained.

Collison during total lunar eclipse
E = 1.5x10^9 J
≒TNT350kg





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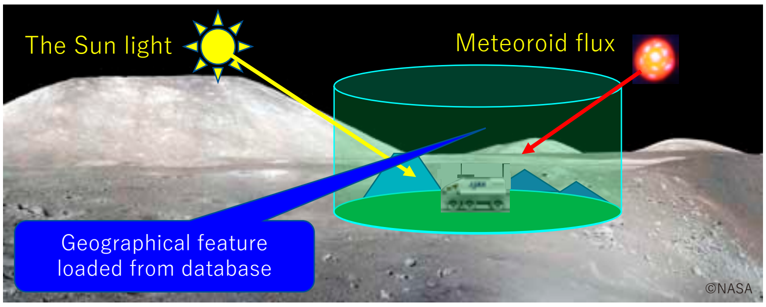
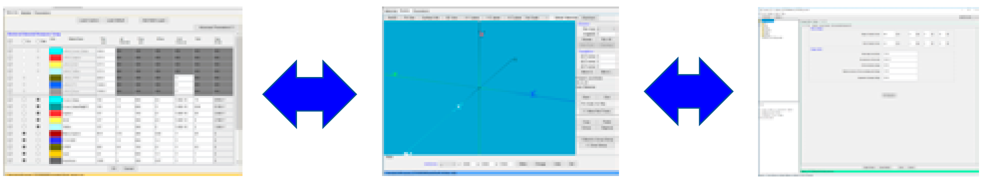
Analysis for the Sunshine or the Sunshade

- The Sunlight can be analyzed instead of meteoroid.
- Available for power generation.
- Reflection from the Moon surface may not be negligible because the solar elevation is very small around the south pole.



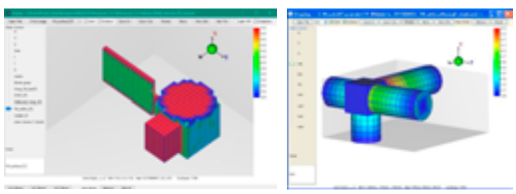
Application for AO Analysis –TURANDOT& MUSCAT-

- MUSCAT (charging analysis tool) was used in the past. [1]
- Common technology is used for both software. (Java® & Java3D®)
- GUIs are not common.



MUSCAT: charging property   Not same but similar GUI   TURANDOT: orbit/BLE

- Computation lattice is different
  - TURANDOT: along the surfaces
    - The collision angle can be exact.
  - MUSCAT: orthogonal lattice
    - The collision angle can be moderate.

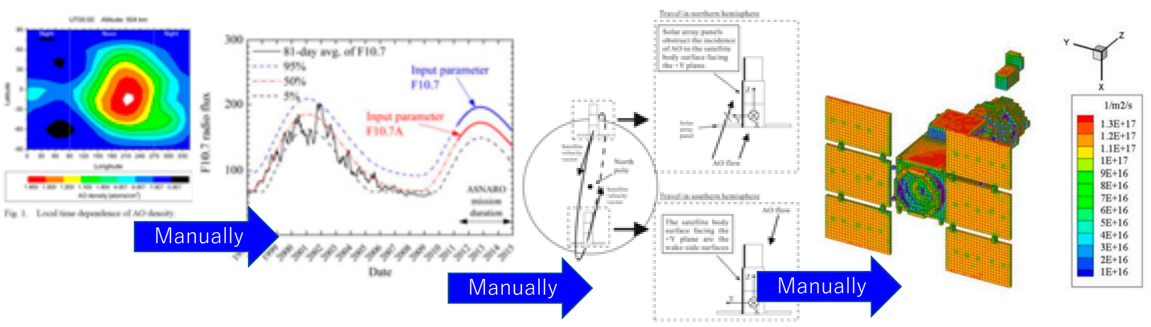


MUSCAT   TURANDOT

[1]Ref. Iwata., M, et. al, “Analysis of Atomic Oxygen Fluence Distribution on Satellite Surface,” Proceedings of ISTS2011 r-44/Trans. JSASS Aerospace Tech. Japan Vol. 10, pp. 5-9, 2012.

Application for AO Analysis

- An example of AO analysis by MUSCAT
- Technique of treating AO as ion of zero charge.
  - Introducing AO environment, application for MUSCAT were all manually conducted.
  - Limit by equally spaced orthogonal lattice. Small components was not simulated.



- Expansion of TURANDOT can reasonably provide analysis environment easy to use.

Conclusion

- An overview of TURANDOT and its improvement plans were presented.
- The potential for enhancement of TURANDOT were presented.
- Should you have any request, please feel free to contact us.

C04

次世代型宇宙用デブリモニタ BBM の開発

Development of JAXA Space Debris Monitor BBM

○松﨑 乃里子, 松本 晴久, 中西 大樹, 永松 愛子, 神谷 浩紀（JAXA）
○MATSUZAKI Noriko, MATSUMOTO Haruhisa, NAKANISHI Daiki,
NAGAMATSU Aiko, KAMIYA Koki (JAXA)

宇宙デブリセンサ SDM は、JAXA 研究開発部門で開発を行っている軌道上直接観測用のデブリセンサである。ターゲットである高度 600-1000km 上のサブミリサイズのデブリは、大きいものに比べて圧倒的に数が多く、今後も急増することが予測されている。その一方で、十分なデータが取得できておらず、データ取得は世界的に急務の課題となっている。この SDM の特徴は、シンプルな機構を持ち、特別な校正が必要ないという点である。この利点を活かして他のセンサーと組み合わせて利用することも可能であり、現在 NASA ODPO と協力の下、軌道上運用を目的としたデブリセンサの開発を行っている。SDM は検出エリアと回路部からなっており、検出エリアは極薄のポリイミドフィルム上に、数千本の 50 µm 幅の導線を細線加工したものである。ここにデブリが衝突することにより、100 µm~数 mm のデブリの直径が取得できる。本講演では、BBM の開発状況と今後の計画を紹介する。

The space debris monitor (SDM) is a flight experienced in-situ debris sensor focusing on micro to mill sized debris on 600 – 1000 km orbit. A continuous in-situ observation of those small debris at 600 to 1000 km has never been conducted. However, this information is essential to properly understand the current situation of vast amount of small debris orbiting near our earth because they are becoming a dominant risk factor on orbit. The unique point of the SDM is its simple detection system which does not need any special calibrations. Thanks to this advantage, the SDM has the potential to collaborate easily with other debris sensors. The SDM consists of a debris-detection area and circuit areas. The debris-detection area is made of very thin polyimide film and there are thousands of 50 µm-wide conductive grid lines capable of detecting the diameter of collided debris sized from 100 µm to millimeters. On this presentation, the current status of developing the SDM BBM and our future plan will be shared with audiences.

次世代型宇宙用デブリモニタBBMの開発

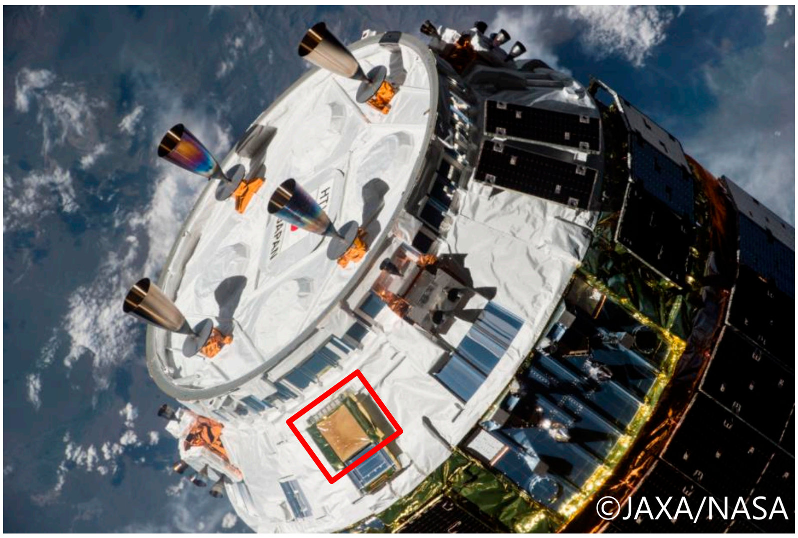
Development of JAXA Space Debris Monitor BBM

○松﨑乃里子, 松本晴久, 中西大樹, 永松愛子, 神谷浩紀 (JAXA)

○Noriko Matsuzaki, Haruhisa Matsumoto, Daiki Nakanishi, Aiko Nagamatsu, Koki Kamiya
(JAXA R&D)

Space Debris Monitor (SDM)

- ✓ In-situ debris detector
- ✓ Focusing on submillimeter-size debris under 1000km

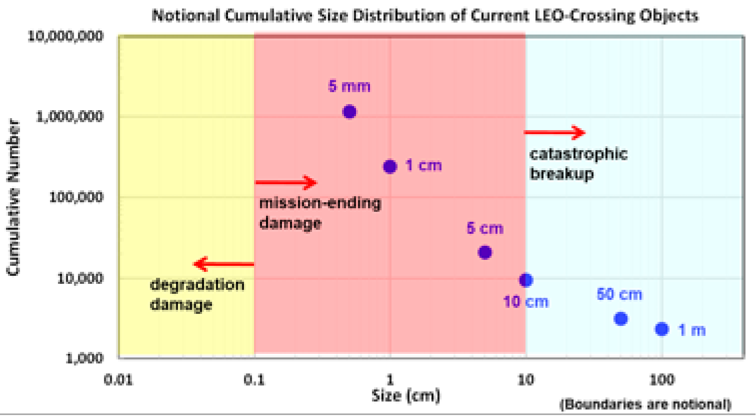


SDM on HTV-5

Background

Why focusing on <u>submillimeter-size debris</u>?

- ➢ Smaller debris is much more dominant on total number of orbital debris
- ➢ Small debris (mm to cm) is the main risk of mission-ending damage



Hyper Velocity Shock Test

- Particle size : 0.3 mm
- Collision Speed: 4 km/s

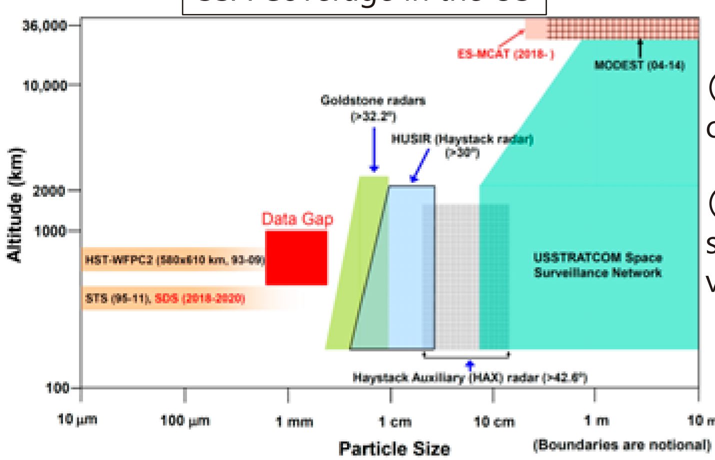
Orbital Debris Mitigation in Support of Space Situational Awareness and Space Traffic Management, J.C. Liou, International Symposium on Ensuring Stable Use of Outer Space http://www.jsforum.or.jp/stableuse/2019/pdf/2%20OD%20Mitigation,%20SSA,%20and%20STM%20rev%202%20(Liou).pdf

- 3 -

Background

- ➢ Space debris problem is getting worse
- ➢ Data gap still exists on distribution map of space debris → <u>**600 to 1000km**</u>

SSA Coverage in the US



☹Submillimeter-sized debris(<3 mm) can't be detected from the ground

☹Available data of submillimeter-sized debris at 600 -1000 km orbit is very limited.

U.S. Space Debris Environment, Operations, and Research Updates
J.-C. Liou, https://www.unoosa.org/documents/pdf/copuos/stsc/2018/tech-14E.pdf

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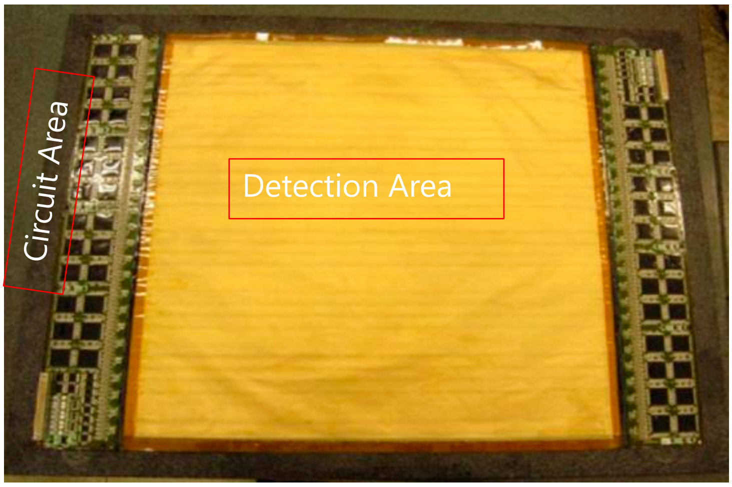
Development SDM So Far



- Flight Experiences: 2 (1 successful, 1 launch failure)
- Detection method: by 50um-wide conductive grids
- Detection area per sheet: ~40 x 40 cm
- Disconnection Detector: FPGA
- Material: Polyimide based (FPC manufacturing method used)

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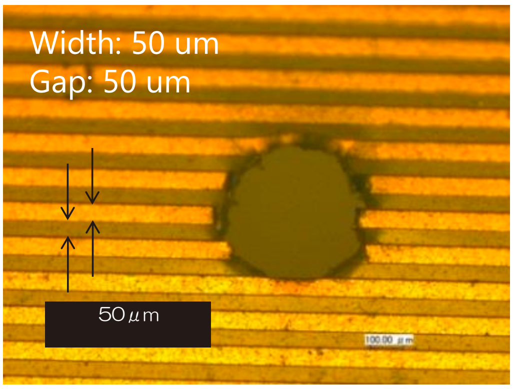
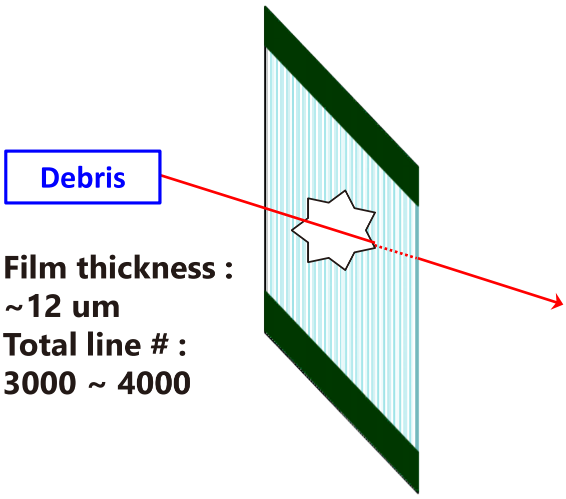
Basic Specification on SDM

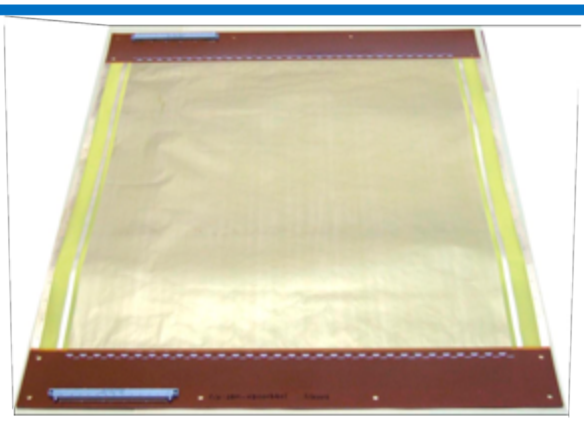




- Detectable from 100 um size debris
- Debris diameter and detection time can be determined from the information of disconnecting conducive grids
- No need for calibration → very simple detection system

- 6 -

New SDM: FPC Type



Data Measurement Equipment (DME)

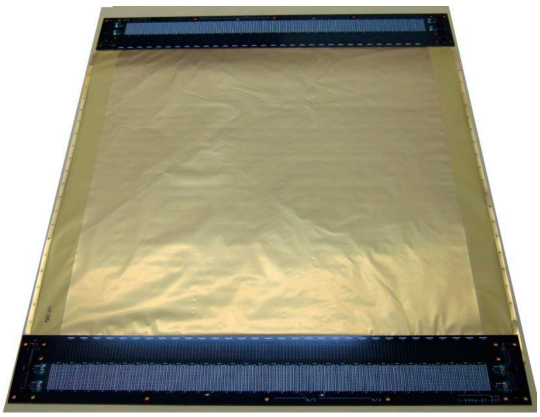
Specification of FPC Type	
Size	~50 x 50 cm
Weight	~ 100 g
Cu laminated film thickness	21 um
Line width	50 um
Line gap	50 um
No of total lines	4096 / sheet

Basic design does not change from old one, but…

- ✓ 52 FPGAs are replaced with one CPU and small diodes + α.
- ✓ Diodes are mounted on the outer space side. (the other hand of adhesive type)
- ✓ I/F can be integrated in one place by attaching DME.

- 7 -

New SDM: Adhesive Type



DME 

Specification of Adhesive Type	
Size	57 x 48 cm
Weight	~ 200 g
Cu laminated film thickness	18.5 um
Line width	50 um
Line gap	50 um
No of total lines	4096 / sheet

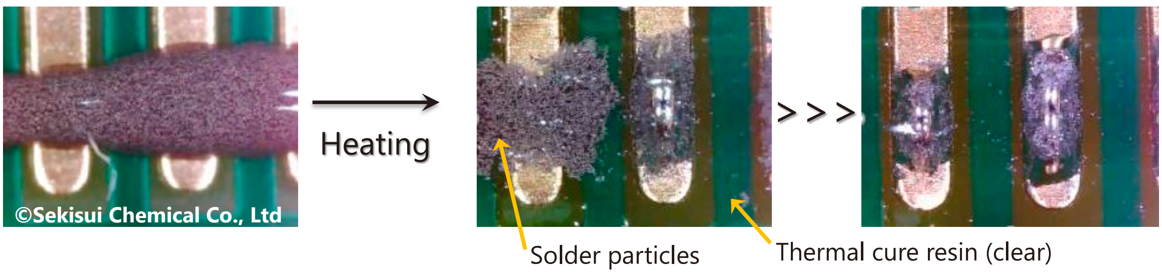
There are two big changes on the adhesive type SDM

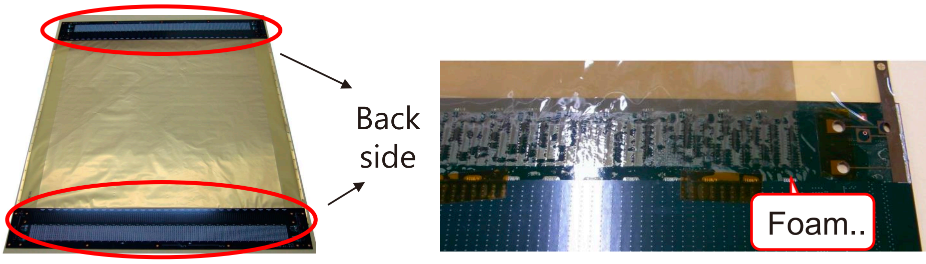
- ✓ 52 FPGA are replaced with one CPU and small diodes + α.
- ✓ I/F can be integrated in one place by attaching DME.
- ✓ The Self Assembly Paste is applied to connect components with different materials (PCB and polyimide film)

- 8 -

Changes on the Adhesive Type

Self Assembly Anisotropic Conductive Paste (SAP)

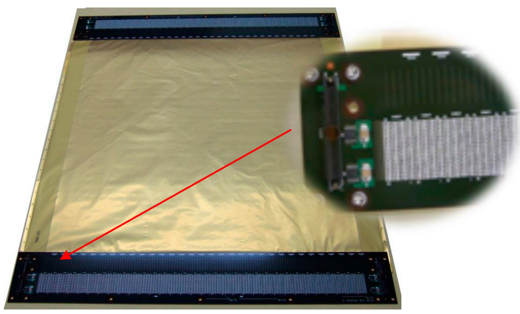




☺ PCB and polyimide film can be adhered with SAP
☹ Foams came out at the connecting area because resin was too little

Changes on the Adhesive Type

Many FPGAs were replaced by a CPU and diodes

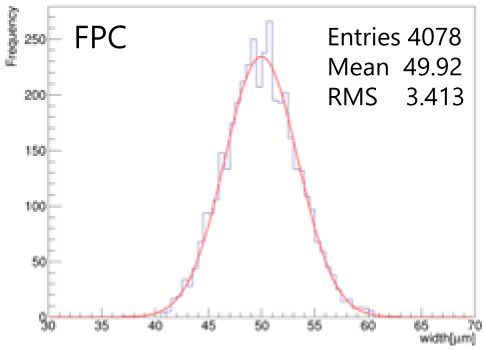


FPC (old)	SDM Type	Adhesive
52 custom-made FPGA	**Processor**	1 CPU
-	**Additional Electronics**	4096 diodes, capacitors, analog multiplexers

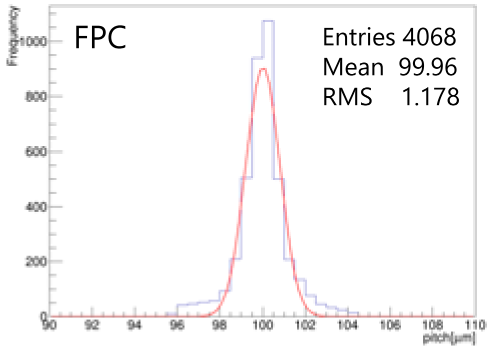
☺ The cost of electronics can be reduced on the adhesive type
☹ Issues remain in selection and mounting method of diodes

Sensor Pattern L/S measurement

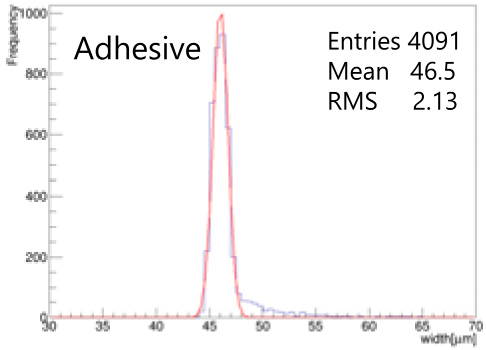
L/S are measured by video measuring system (Nikon NEXIV)

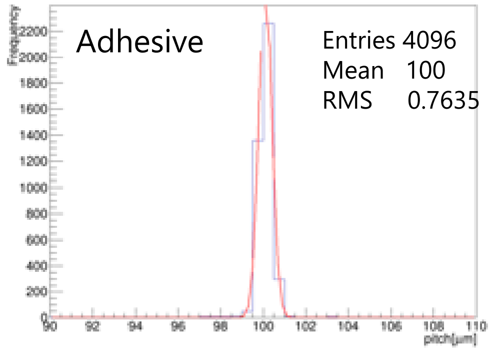


Cu line width



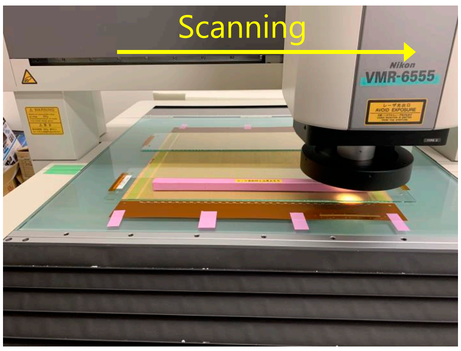
Pitch width (L+S)

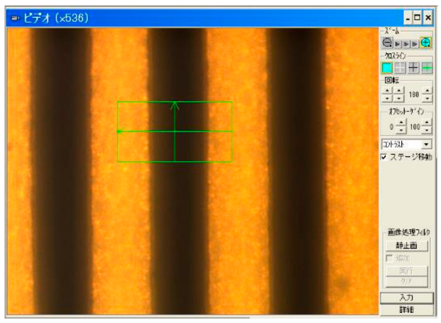




Sensor Pattern L/S measurement

L/S are measured by video measuring system (Nikon NEXIV)





- ✓ Line width and spacing of the Adhesive type are better controlled.
- ✓ The film of the FPC type looked little wavy and it caused scanning error.
- ✓ Controlling of pitch (=line width + spacing) is more important than controlling of line width.

Thermal Shock Test Results

Number of disconnection lines

	Before	After
Adhesive	0	122
FPC (new)	7	approx. 3000

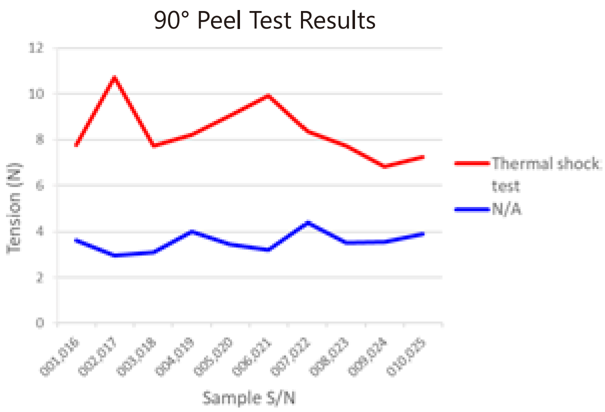
Test condition	
Temp.	-30 /+100 ℃
Hold time/cycle	30 min
Cycle	500

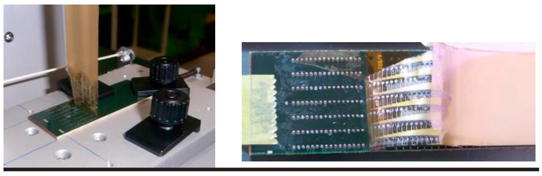
Adhesive type seems to show good durability for thermal shock !
However, there is doubt about the results…

- ✓ Thermal wind was too strong (30~40km/h) and might damage the samples.
- ✓ Lots of diodes fell out from the circuit board after the test, especially on the FPC type because this type has diodes on the back (shelf) side.
- ✓ Circuit board of FPC type is thinner than Adhesive type.
- ✓ Corrosion was founded on the electrode of diodes. It possibly caused soldering defects.

→Need for thermal shock test again with a no-air-type equipment

Tensile test on Adhesive type





Sample preprocess	No of samples	Design value	Ave. value
N/A	10	3.84 N	3.56 N
Thermal shock test	10	-	8.35 N

- ✓ Strength of the adhesion is sufficient (it is same as the design value)
- ✓ The sample after thermal shock test shows more strength because of baking of the thermal cure resin.
- ✓ Strength of SAP's adhesion does not deteriorate and get to be strong by heat.
- ✓ Ratio of resin in the SAP should be increased.

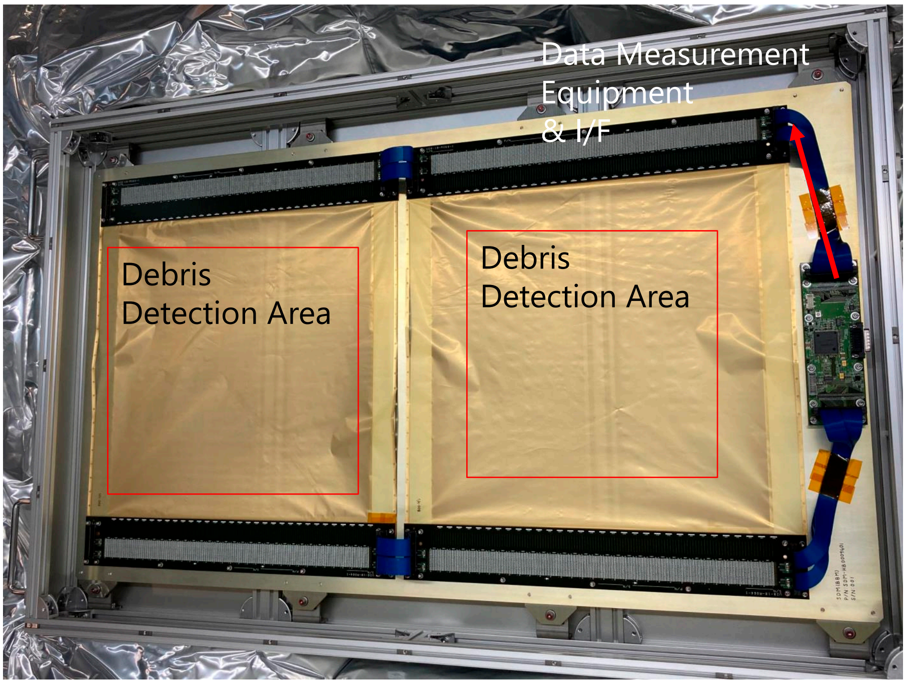
Conclusion & Future Plan

✓Adhesive type shows good performance.
✓The blending ratio of SAP needs to be changed. (ratio of solder and resin)
✓Connecting method of film and PCB on the Adhesive type needs improvement.
✓Need for reselection of diode.

Collaboration with NASA ODPO

✓JAXA and NASA ODPO now work together for a new in-situ debris monitor targeted submillimeter size debris.
✓Our BBM is ready for hyper velocity test in the US.

Our New BBM



C05

耐AOコーティングによるCFRPからのイジェクタの低減
Reduction in Ejecta from CFRP by Atomic Oxygen Protective Coating

○西田 政弘，高原 秀征（名古屋工業大学），古田 尚正，
岩瀬 賢明（東亞合成），東出 真澄，石田 雄一（JAXA）
○NISHIDA Masahiro, TAKAHARA Hideyuki (Nagoya Institute of Technology), FURUTA Naomasa,
IWASE Yoshiaki (Toagosei), HIGASHIDE Masumi, ISHIDA Yuichi (JAXA)

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，飛翔体が超高速衝突すると，多くの破片（イジェクタ）が飛散する．耐原子状酸素（AO）コーティングを塗布することで，イジェクタを低減しつつ，バンパーとしての性能は同等もしくは向上するようなデブリバンパーを目指して，研究している．その結果を報告する．

Carbon fiber reinforced plastic (CFRP) plates are widely used in spacecraft. When projectiles strike them at very high velocities, many fragments (ejecta) were scattered. Our group proposed AO coating/CFRP to reduce ejecta from CFRP and to keep or improve bumper performance. We would like to report some results of AO coating/CFRP.

第9回 スペースデブリワークショップ
2021年2月24日～26日オンライン

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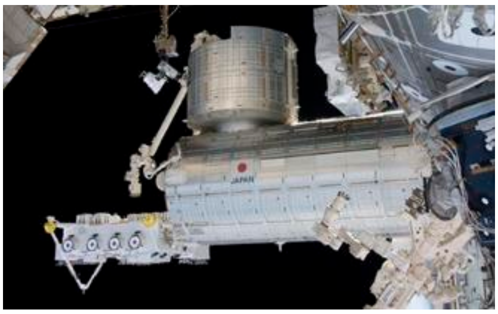
○西田政弘，高原秀征（名古屋工業大学）
古田尚正，岩瀬賢明（東亞合成株式会社）
東出真澄，石田雄一（宇宙航空研究開発機構）
Masahiro Nishida, Hideyuki Takahara (Nagoya Institute of Technology)
Naomasa Furuta, Yoshiaki Iwase (Toagosei Co., Ltd.)
Masumi Higashide, Yuichi Ishida (JAXA)

1

International Space Station

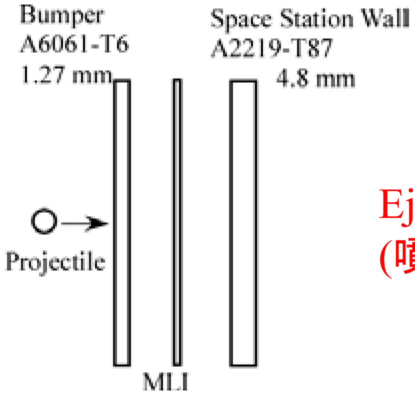
Courtesy of NASA
http://spaceflight.nasa.gov/gallery/images/shuttle/sts-127/html/s127e011212.html

JEM "KIBOU"

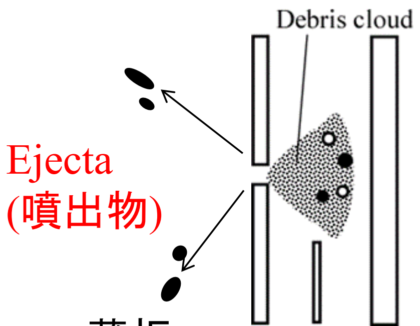


Courtesy of JAXA
http://www.jaxa.jp/projects/iss_human/kibo/index_j.html

Bumper shield



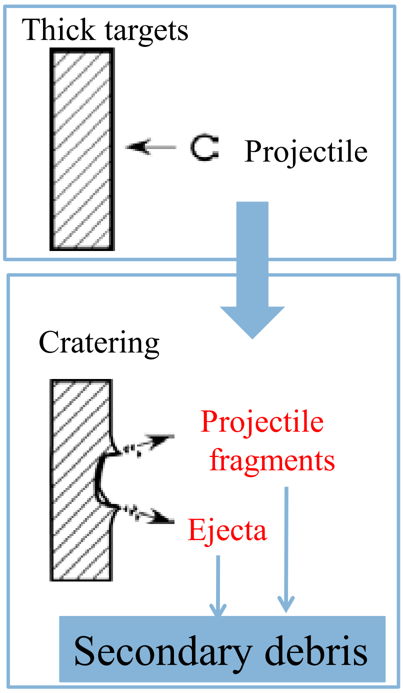
Whipple shields



Thin plate perforation

2

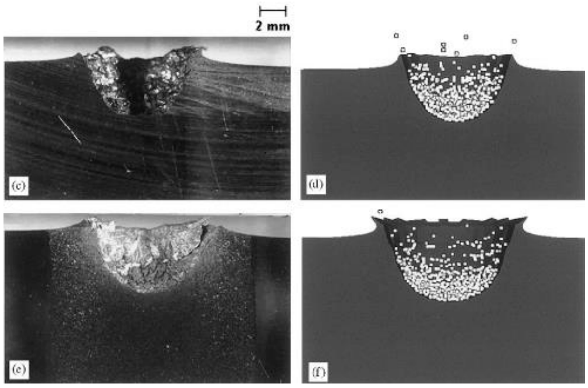
Penetration into Thick Plates



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.

Flux of Space Debris

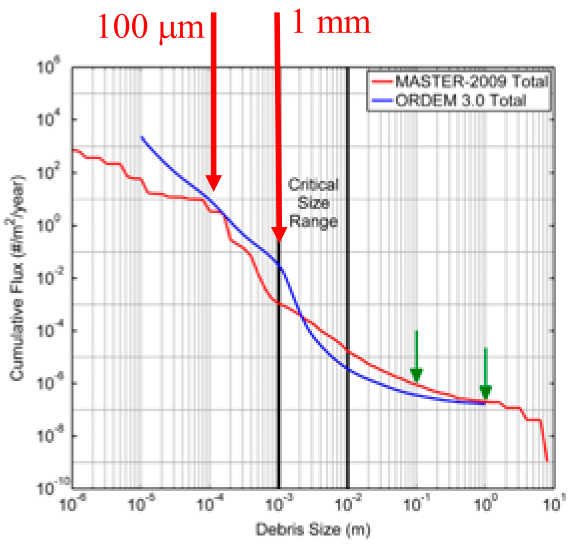


Fig. 1. ORDEM 3.0 and MASTER-2009 orbital debris fluxes for the ISS orbit in 2014.

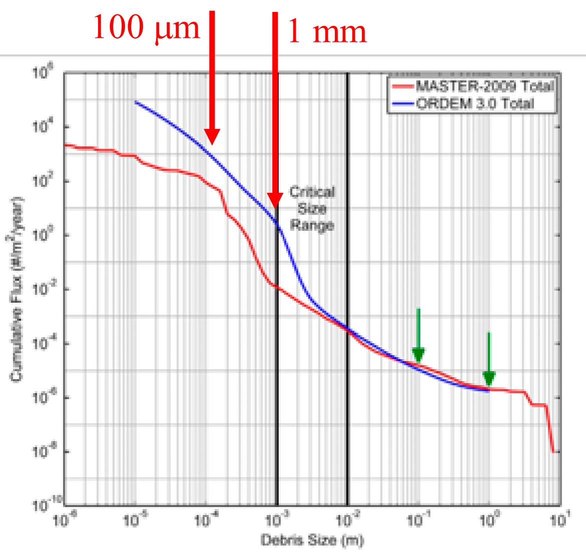


Fig. 4. ORDEM 3.0 and MASTER-2009 orbital debris fluxes for the SSO orbit in 2014.

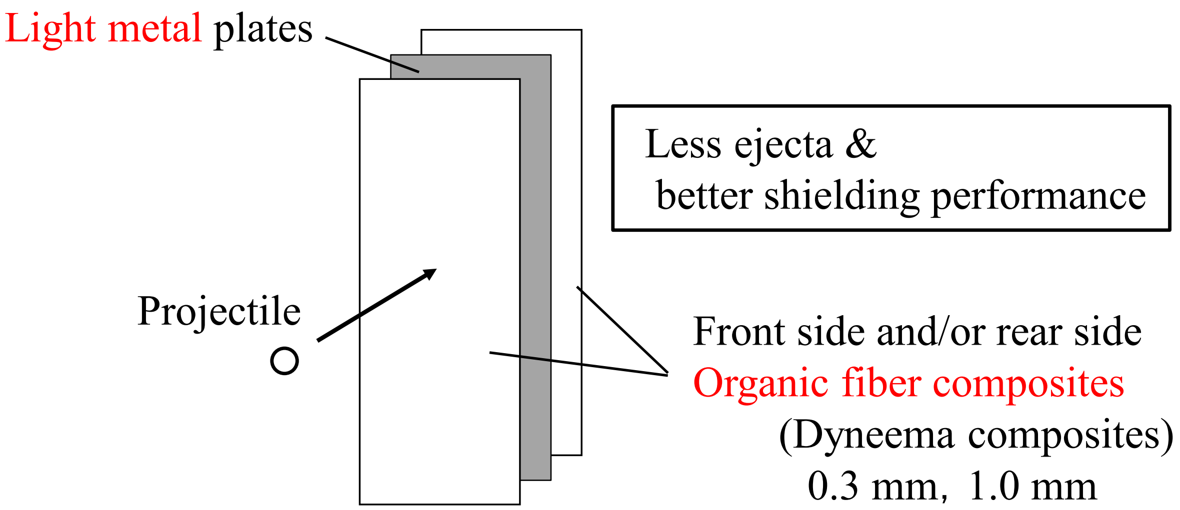
P. H. Krisko, S. Flegel, M. J. Matney, D. R. Jarkey, V. Braun, ORDEM 3.0 and MASTER-2009 modeled debris population comparison, Acta Astronautica, Vol. 113, 2015, pp. 204-211.

Purpose：Reduction of Ejecta（イジェクタの低減）

1) Coating / CFRP plates（コーティング / CFRP板）
（宇宙科学に関する室内実験シンポジウム2020，材料学会講演会2020電通大）

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2019，M&M2019材料力学カンファレンス九大，第8回スペースデブリワークショップ2018）

=> Poster presentation



Earlier Studies of Debris Shielding (1/2)

PBI coating/CFRP

Polybenzimidazole (PBI):
Atomic Oxygen Protective Coating

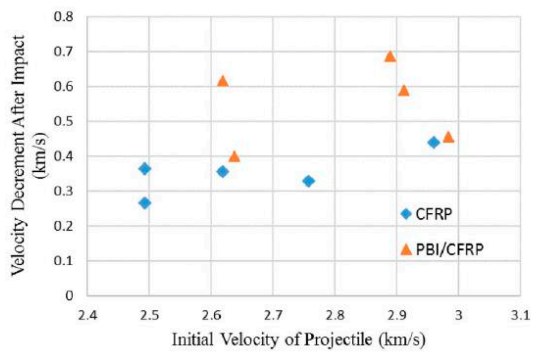
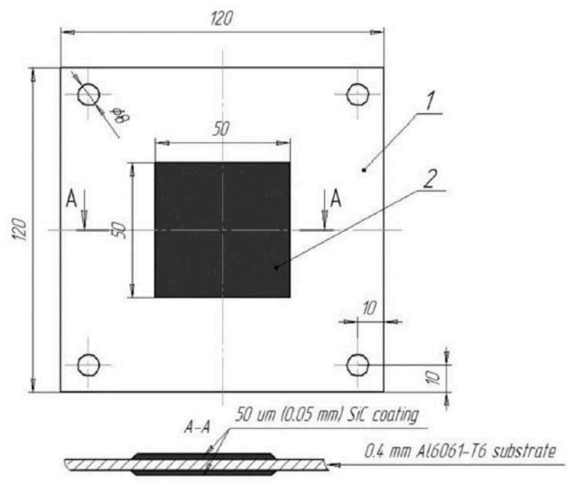


Fig. 5. Velocity decrement of the projectile after impact with CFRP and PBI/CFRP.

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 (2/2)

Ti-Al nylon impedance-graded materials

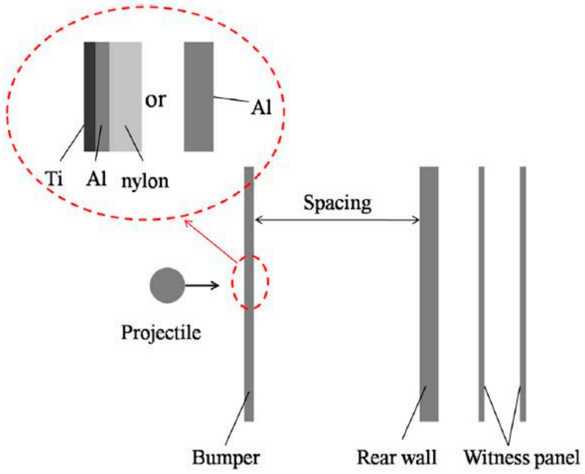


Fig. 1. Experiment schematic diagram.

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

Kevlar/ FRP

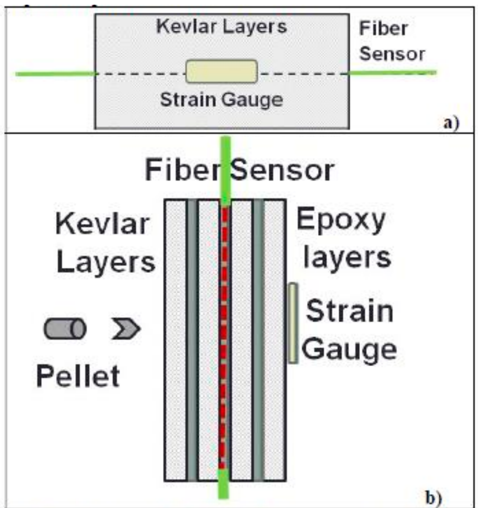


Figure 6, Four layers Kevlar/Epoxy, a) Top Front View; b) Cross Section Side View Strain Gauge and FBG (example Shot #79)

Emile Haddad, et al., Mitigating the effect of space small debris on COPV in space with fiber sensors and self repairing materials, Proc. ECSSMET (2018)

7

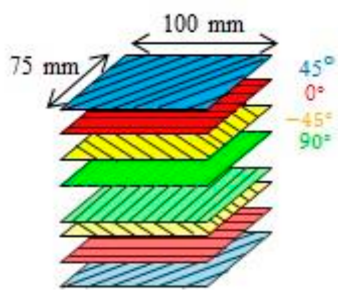
Atomic oxygen（AO）protective coating / CFRP plates

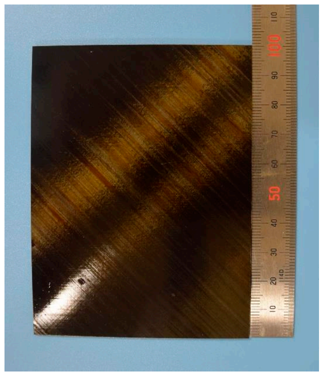
（耐原子状酸素コーティング/CFRP板）

9

Polyimide CFRP

Polyimide CFRP（Prepreg from JAXA*）
Size：75 mm×100 mm
Thickness：1.0 mm（8 ply）
Quasi-isotropic [45°/0°/−45°/90°]s
（擬似等方性）





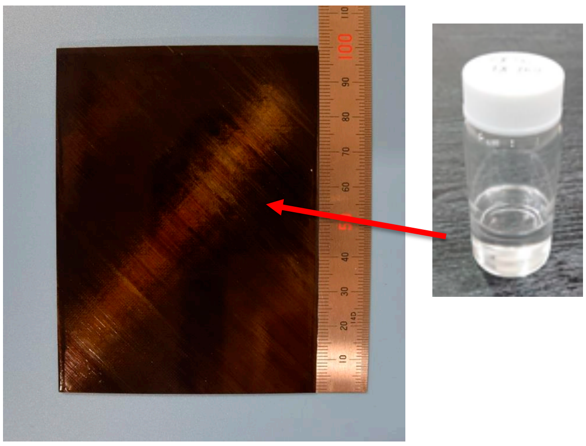
* 石田雄一，耐熱高分子基複合材（耐熱 CFRP）の適用技術研究，日本航空宇宙学会誌，68(2), 2020, pp. 38-42.
Miyauchi, M., Ishida, Y., Ogasawara, T. and Yokota, R., Highly soluble phenylethynyl-terminated imide oligomers based on KAPTON-type backbone structures for carbon fiber-reinforced composites with high heat resistance, Polymer J., 45, 2013, 594-600.

10

Atomic Oxygen（AO）Protective Coating

Coating
Sil-sesqui-oxane derivative
（シルセスキオキサン誘導体）
（Toagosei）
Thickness 5 μm, 20 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 20 μm
=> Areal density 1.58% up

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Sil-sesqui-oxane Derivative

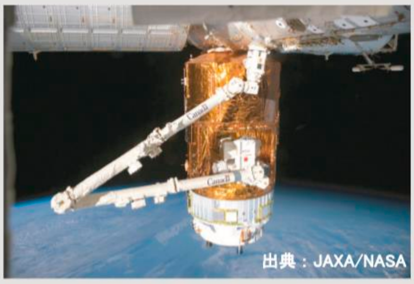


写真１　ポリイミドフィルム使用例（写真中央琥珀色光沢部）
ISSに取り付けられた「こうのとり」３号機

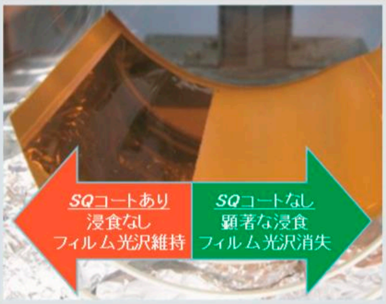


写真３　ポリイミドフィルムに対するプラズマアッシャー試験
簡易耐AO試験、15時間照射後

古田尚正，北村昭憲，鈴木浩，石澤淳一郎，木本雄吾，田村高志，シルセスキオキサン誘導体「光硬化型SQ シリーズ」の宇宙用材料への応用～耐原子状酸素コーティングの開発～，東亞合成．研究年報TREND (2013)

SQ series (1 - 2 μm)/ polyimide film (50 μm)

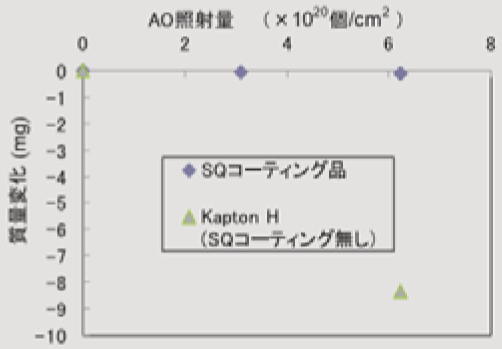


図２　AO照射による質量変化

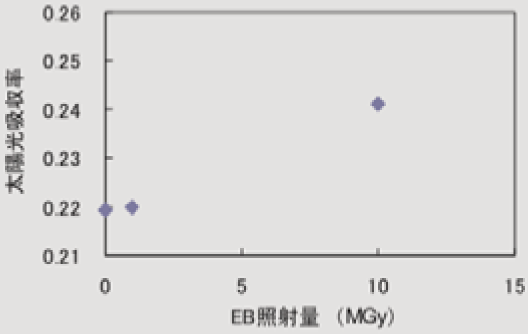


図３　EB照射による太陽光吸収率変化

Experimental Condition

Shot No.	Impact velocity [km/s]	Coating thickness [μm]	Areal density [g/cm²]
J-417	3.24		0.1705
J-413	3.17	5	0.1712
J-414	3.11	20	0.1732

Thickness 20 μm
=> Areal density 1.58% up

Experimental Setup (1/2)

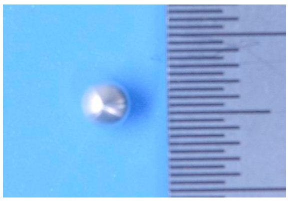
Two stage gas gun

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）



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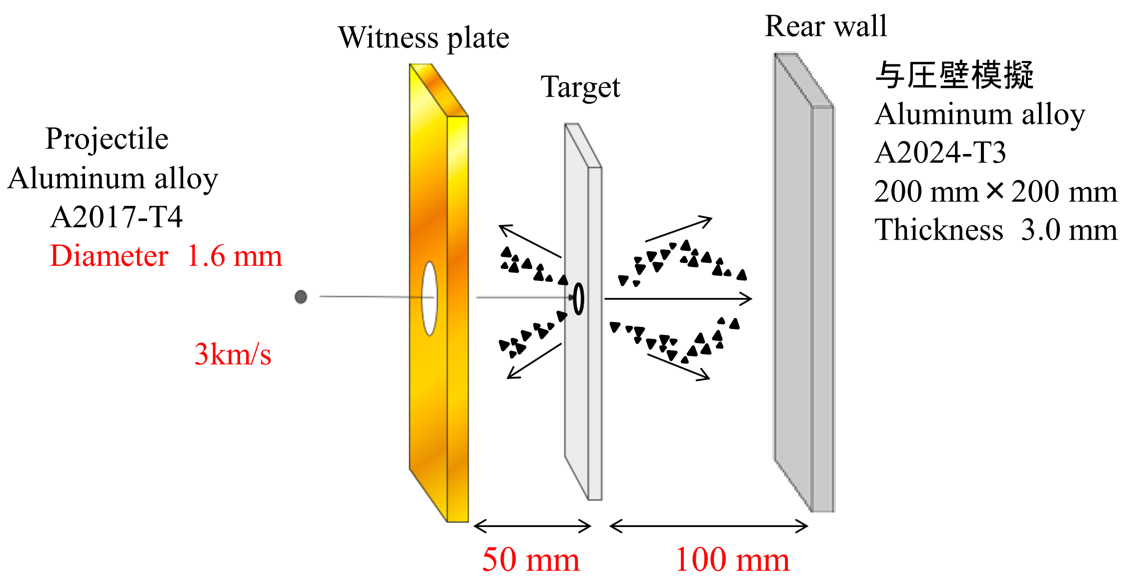
Experimental Setup (2/2)



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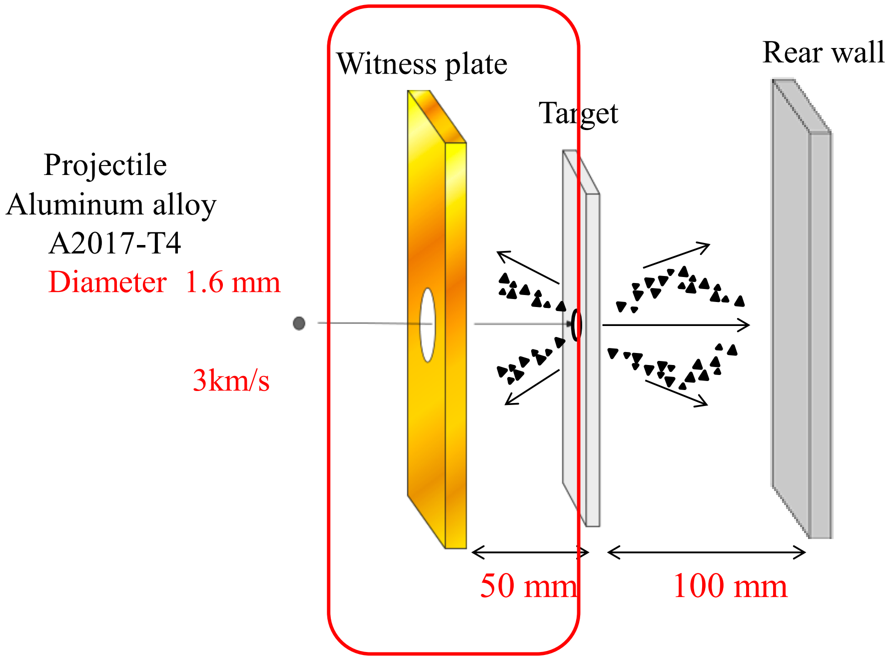
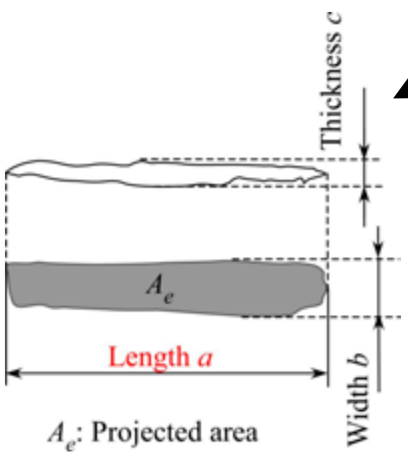
Results of Ejecta



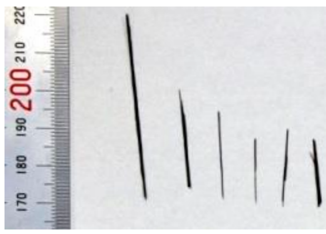
Evaluation of Ejecta (Direct method)

Image analysis software
ImageJ



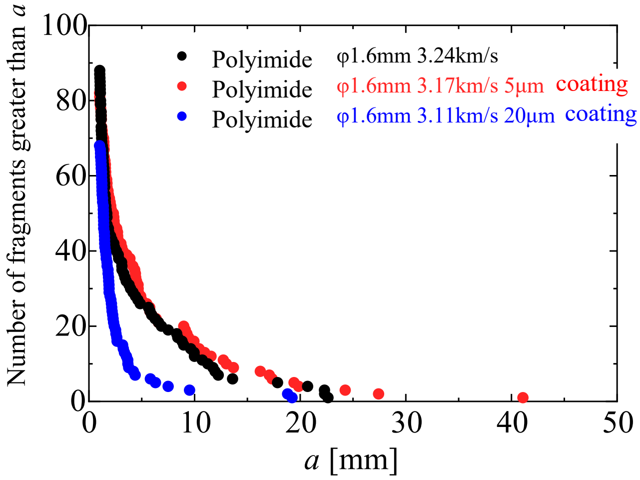
$a \geqq b \geqq c$

Fragments from CFRP plates



Main target: $a \geqq 1$ mm

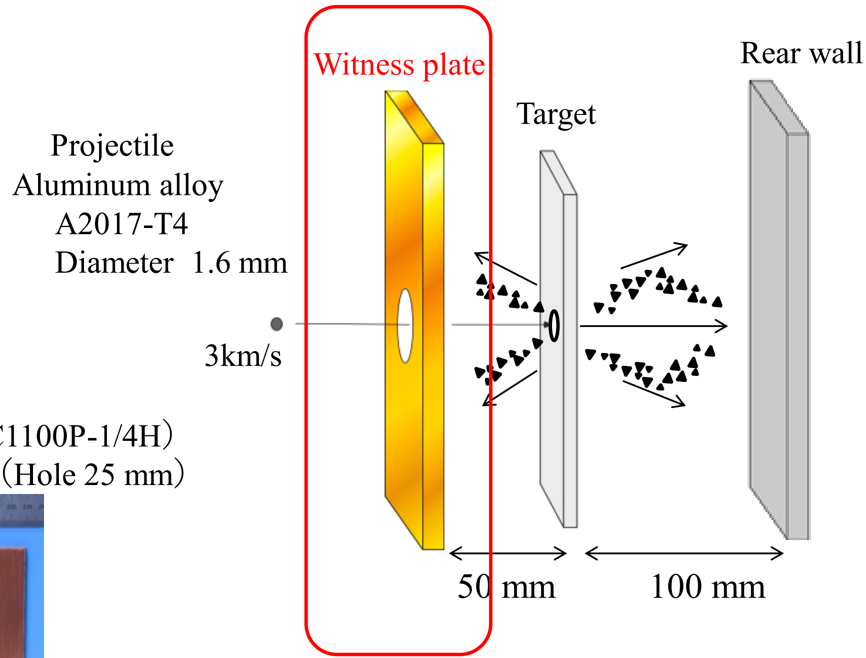
Results by Direct Method (Cumulative number distribution of ejecta)



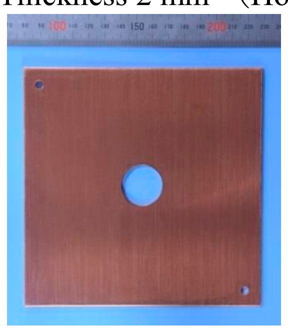
No.	Impact velocity [km/s]	Coating thickness [μm]	Areal density [g/cm²]	Number of ejecta over 1 mm
J-417	3.24		0.1705	88
J-413	3.17	5	0.1712	82
J-414	3.11	20	0.1732	68

18

Results of Ejecta



ISO 11227
Witness plate
（copper plate：C1100P-1/4H）
Thickness 2 mm （Hole 25 mm）



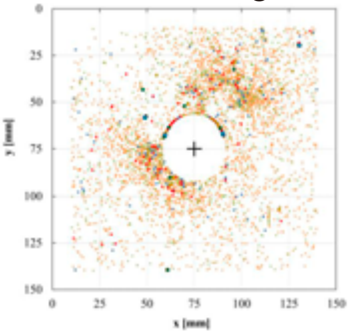
Epoxy CFRP (Toray, P13080F-3: Matrix 3800-2, Fiber M60JB) 2.41 km/s

Nishida et al., Proceedings of 7th European Conference on Space Debris, (2017)

19

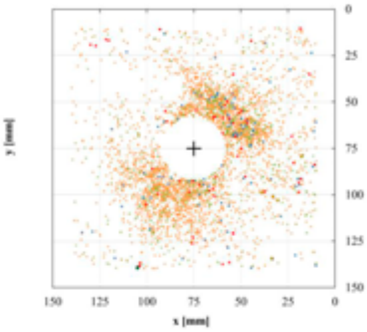
Results by Witness Plates (ISO 11227)

Without coating 3.24 km/s



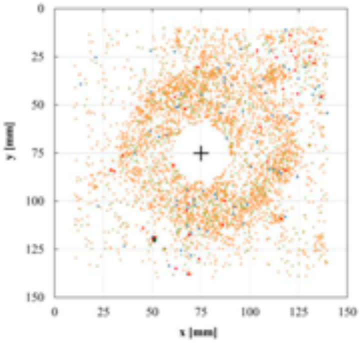
mm	
0.025～0.05	4381
0.05～0.075	1159
0.075～0.1	167
0.1～0.15	112
0.15～0.2	30
0.2～0.3	10
0.3～0.4	5

5 µm coating 3.17 km/s



mm	
0.025～0.05	4940
0.05～0.075	983
0.075～0.1	115
0.1～0.15	60
0.15～0.2	5
0.2～0.3	2
0.3～0.4	0

20 µm coating 3.11 km/s



mm	
0.025～0.05	5039
0.05～0.075	968
0.075～0.1	78
0.1～0.15	36
0.15～0.2	3
0.2～0.3	1
0.3～0.4	0

Conclusions

1. Shielding performance： Similar
2. Forward ejecta： Decrease
3. Effects of coating thickness： Unclear
4. Future plans：
   1） Reproducibility
   2） Effects of space environment
   3) Mechanism

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．

C06

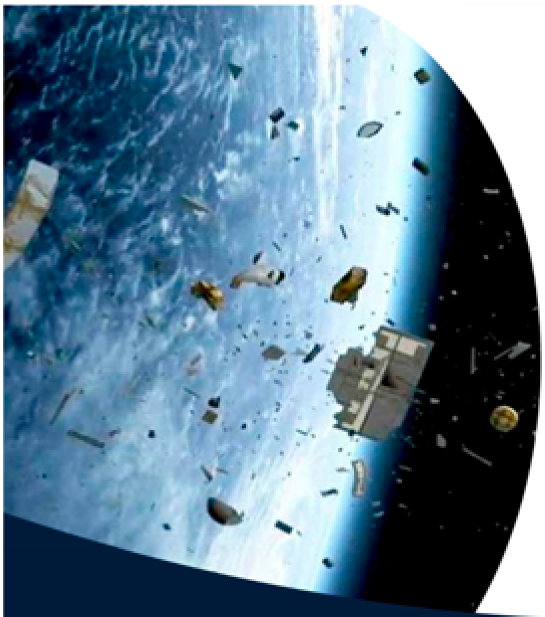
ELSA-d, ADRAS-J プロジェクト及び将来サービスのための地上システムと運用について

Ground System and Operation for ELSA-d, ADRAS-J, and Future Services

○小堀 加奈絵（アストロスケール）
○KOBORI Kanae (Astroscale Japan)

ELSA-d (End of life service by Astroscale - demonstration) とADRAS-J (Active Debris Removal by Astroscale-Japan)、2つのデブリ除去技術実証プロジェクトの開発対象は実証衛星本体だけではありません。衛星の運用とそれを実現する為の地上システムが不可欠です。アストロスケールは日本及び英国の 2 拠点に衛星管制センターを構築し、異常時対応やグローバルなチームでの運用体制を実現します。ELSA-d では日本の管制センターからの衛星コマンド送信は行いませんが、管制システムには衛星監視・制御機能に加え技術実証のコアとなる衛星搭載センサ画像解析機能が備わります。また外部 SSA サービスとインターフェースし、高精度軌道決定値及び衝突アラート提供を受けます。将来のミッションでは、これらシステム開発実績と運用知見を活用し、低コストでの地上セグメント構築を目指します。

The success of the ELSA-d (End of life service by Astroscale --demonstration) and ADRAS-J (Active Debris Removal by Astroscale-Japan) missions is dependent on a number of engineering factors, including the development of a ground system to monitor and control the satellites while in-orbit. Astroscale has established control centers in Japan and the United Kingdom to respond to non-nominal situations and to enable communication amongst the global team. For the upcoming ELSA-d mission, while no telecommands are sent from Astroscale Japan, each satellite is equipped with satellite monitoring and control functions, as well as on-board sensor image data, which are core to the demonstration. The system has an interface with an external Space Situational Awareness (SSA) service to receive highly accurate orbit determination and collision alerts. For future missions, we will establish ground segments at a lower cost by utilizing these system development results and operational knowledge.

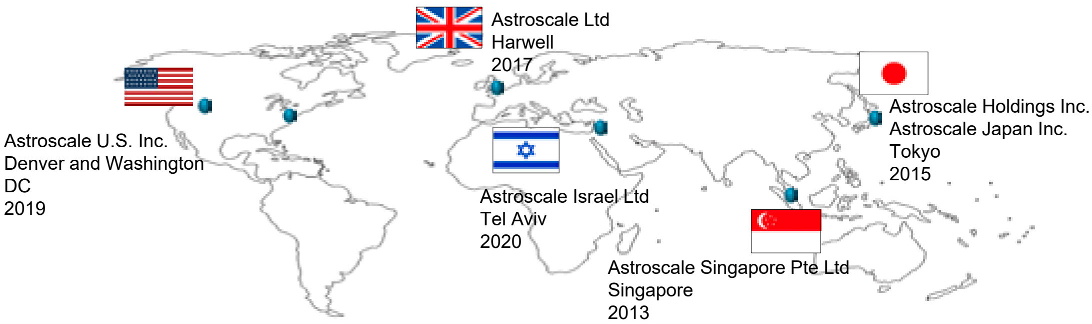


ELSA-d, ADRAS-Jプロジェクト及び将来サービスのための地上システムと運用について

- Ground System and Operation for ELSA-d, ADRAS-J, and future services -

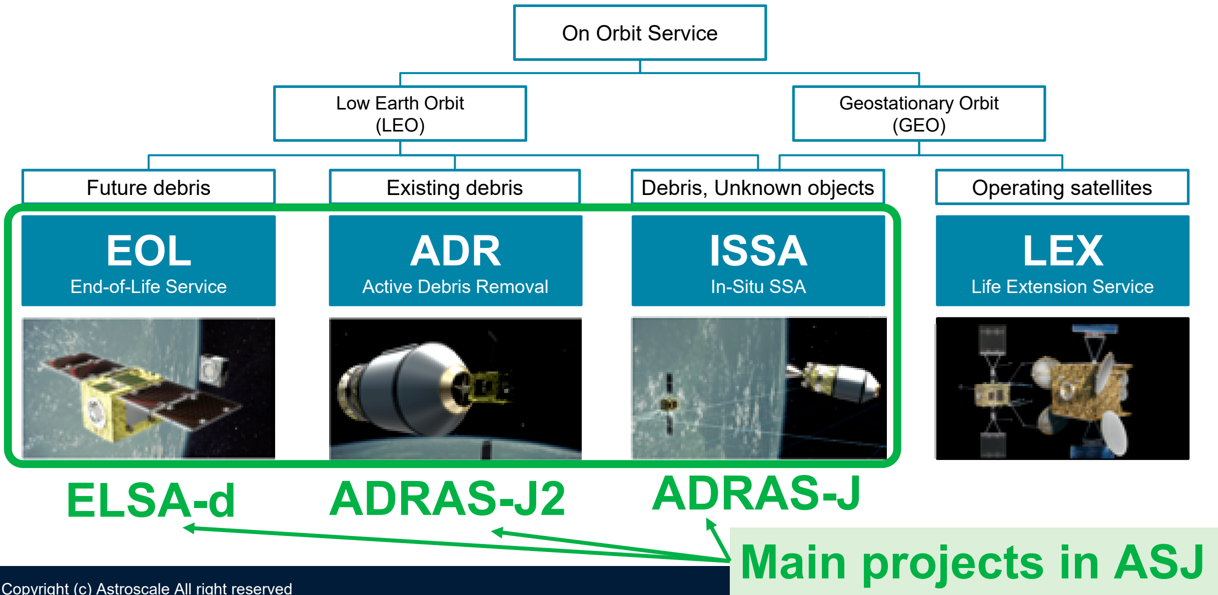
Astroscale Japan
Ground Segment and Spacecraft Simulator Manager
Kanae Kobori 小堀　加奈絵
2021 February 26

About Astroscale



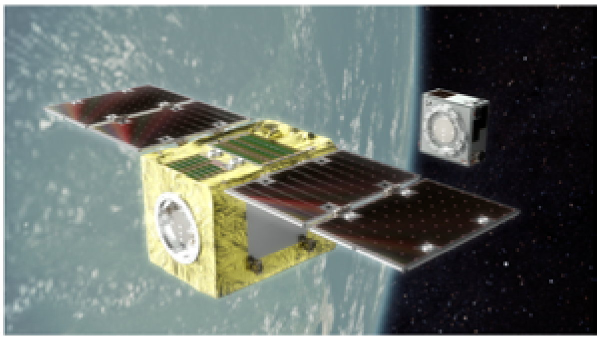
Established:	2013 May 4th
Founder:	Nobu Okada 岡田光信
Officers and employees:	170
Nationality:	11 countries
Head office:	Tokyo
Funding:	$198M (210億円)

Four services will be launched in sequence in the first half of the 2020s

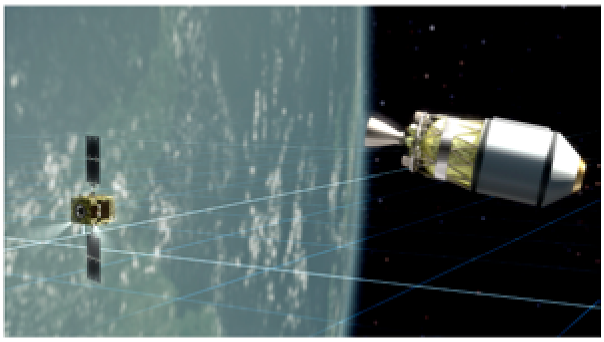


ELSA-d and ADRAS-J

ELSA-d
End of Life Services by Astroscale-demonstration



ADRAS-J
Active Debris Removal by Astroscale-Japan



What is necessary to operate these Satellites?

 5

Features needed for commercial LEO RPO mission control

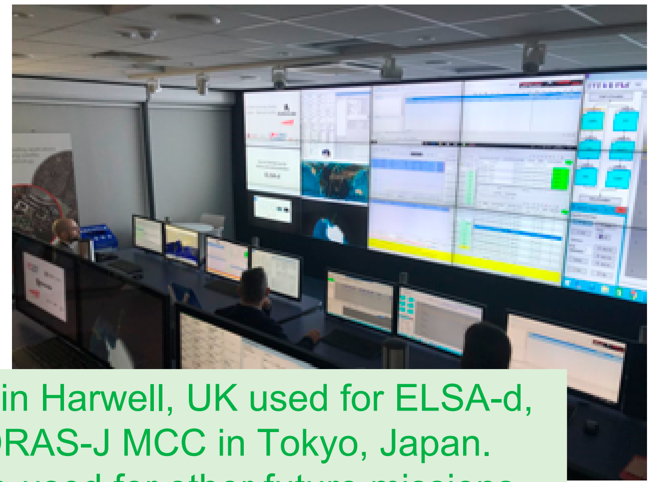
RPO: Rendezvous and Proximity Operation

- Continuous spacecraft visibility during critical mission phases
- Close linkage with SSA
  - Precise and frequent orbit determination
  - Conjunction alert
- Mission specific functions
  - Visualization image processing
  - Rendezvous and proximity operation support
- High fidelity satellite simulator for elaborate preparations
- Easy fit to various kinds of service mission

Developing control center and operation for LEO RPO are **challenging things** as same as the satellite development!

Mission Control Center (MCC)

Monitoring and controlling the Satellite from ground.

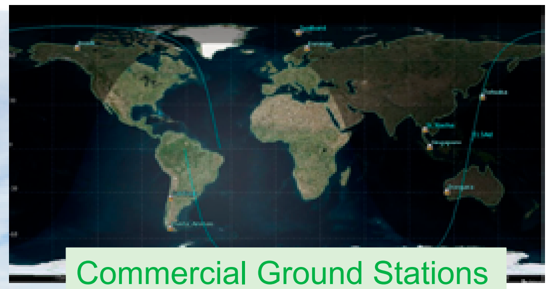


Astroscale has MCC in Harwell, UK used for ELSA-d, and is developing ADRAS-J MCC in Tokyo, Japan. Those systems are re-used for other future missions.

Ground Station (Antenna)

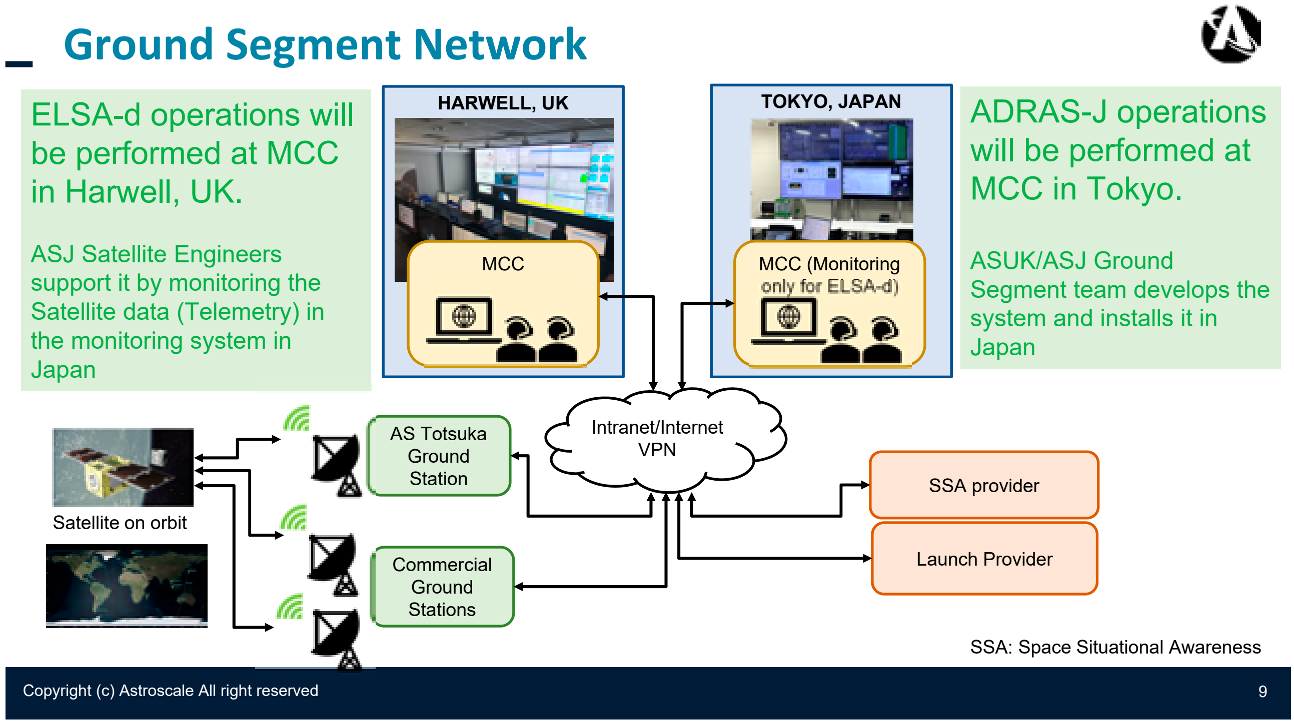
Receive the data from the satellite and send the operation command from MCC.

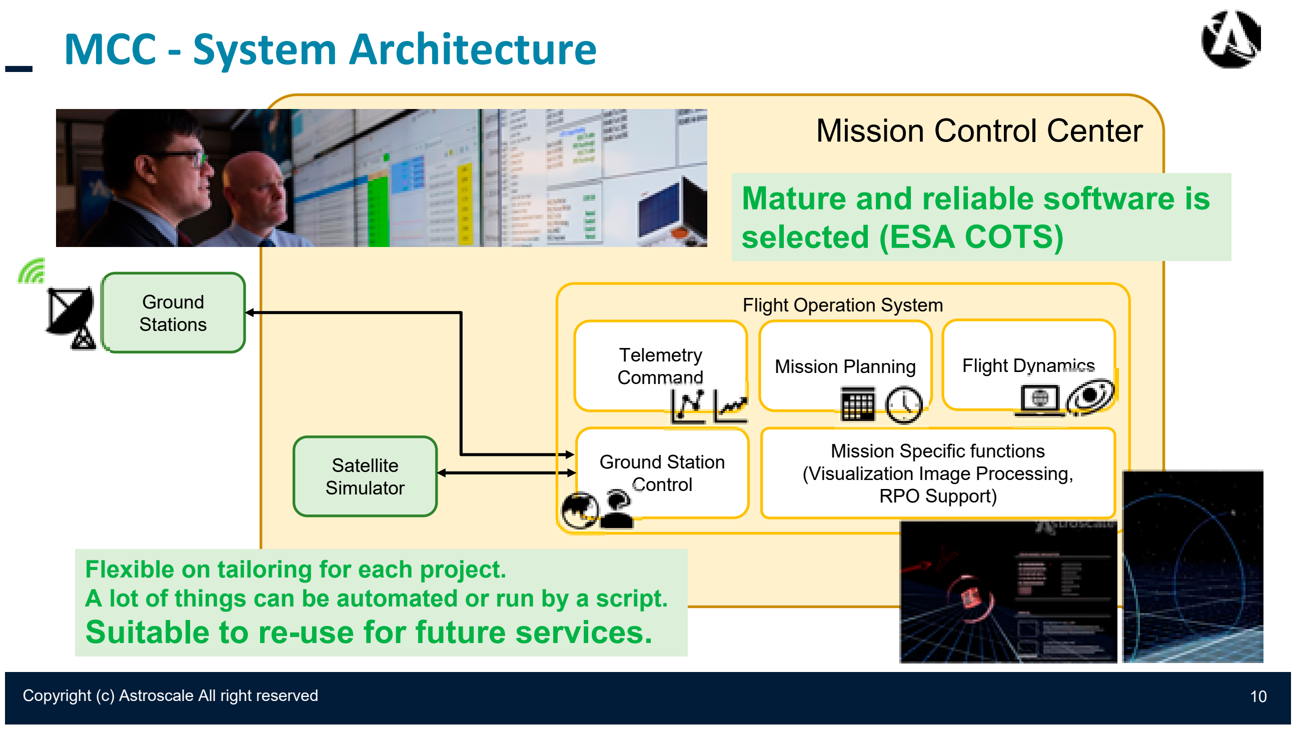
Astroscale Totsuka Station in Japan



Commercial Ground Stations

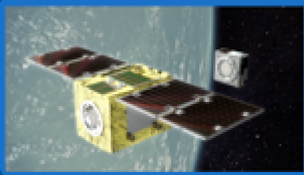
10 or more ground stations spreading all over the world provide the satellite visibility for ELSA-d, ADRAS-J, and other future missions.


Ground Segment Network
ELSA-d operations will be performed at MCC in Harwell, UK.
ASJ Satellite Engineers support it by monitoring the Satellite data (Telemetry) in the monitoring system in Japan
HARWELL, UK
MCC
TOKYO, JAPAN
MCC (Monitoring only for ELSA-d)
ADRAS-J operations will be performed at MCC in Tokyo.
ASUK/ASJ Ground Segment team develops the system and installs it in Japan
Satellite on orbit
AS Totsuka Ground Station
Commercial Ground Stations
Intranet/Internet VPN
SSA provider
Launch Provider
SSA: Space Situational Awareness
Copyright (c) Astroscale All right reserved
9


MCC - System Architecture
Mission Control Center
Mature and reliable software is selected (ESA COTS)
Ground Stations
Flight Operation System
Telemetry Command
Mission Planning
Flight Dynamics
Satellite Simulator
Ground Station Control
Mission Specific functions (Visualization Image Processing, RPO Support)
Flexible on tailoring for each project.
A lot of things can be automated or run by a script.
Suitable to re-use for future services.
Copyright (c) Astroscale All right reserved
10

Technical Development Elements for Astroscale On-Orbit Services

Satellite

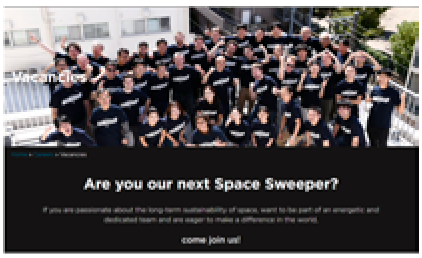


Ground Systems

In-orbit Operation

Thank you!
ご清聴ありがとうございました。

Astroscale is looking for new members!
If you are interested, please feel free to contact us.
アストロスケールでは、新しいメンバーを募集中です！
興味がある方は是非弊社までご連絡ください。



Astroscale website
https://astroscale.com/careers/vacancies

- Ground Segment Engineer
- Mission Design / Flight Dynamics / Astrodynamics Engineer
- Software Design Architect / Engineer
- Electrical Engineer
- Chemical Propulsion Engineer
- Senior Operation Engineer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C07

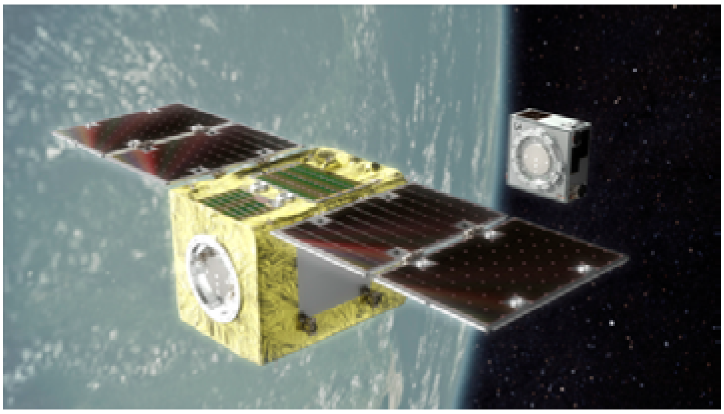
ELSA-d プロジェクト　ステータス-打ち上げに向けて-

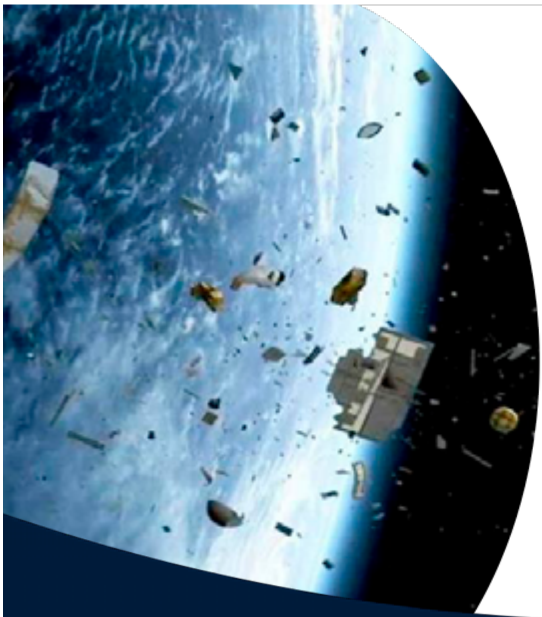
ELSA-d End-of-Life Debris Removal Mission: Preparing for Launch

飯塚 清太, ○岡本 章(アストロスケール), ELSA-d プロジェクトチーム
IIZUKA Seita, ○OKAMOTO Akira (Astroscale Japan), ELSA-d Project Team

ELSA-d (End of life service by Astroscale - demonstration) は軌道上で故障した衛星を取り除くための非協力接近捕獲の主要技術を実証するミッションです。全ての環境試験と機能試験が完了し、射場への輸送準備が整いました。また、迅速かつ円滑にミッションを完遂できるよう、異常対応も含めた運用訓練も実施しております。当プロジェクトの最新ステータスとこの前人未到のミッションをこの先数ヶ月でどのように実施するかを示します。

The ELSA-d (End of Life Services by Astroscale-demonstration) mission will demonstrate the key technologies for non-cooperative rendezvous and docking for defunct and satellites which have come to their end-of-life. All environmental and functional tests are complete and the spacecraft is ready for shipment to the launch site. In addition, intensive operation training has been conducted in order to achieve the mission and to be prepared for any off-nominal incidents. In this presentation, we would like to show the latest status of ELSA-d and how this novel mission will be conducted as we prepare for launch.





Astroscale

ELSA-d End-of-Life Debris Removal Mission: Preparing for Launch

February 26th, 2021

Astroscale Japan Inc.
ELSA-d Project Manager
Seita Iizuka

Key Business Markets

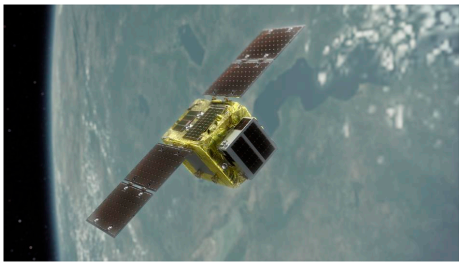
Services	End of Life (EOL) "Don't add any more debris"	Active Debris Removal (ADR) "Remove debris that is already there"
Potential Customers	Constellations, Private Satellite Operators	Governments, International framework
Client Objects	- Satellites that have failed in orbit or reached end of operational lifetime - 50~500kg	- Environmentally critical objects - 500kg+ (up to tonnes) - Existing debris
Rationale	- Protect operational service - Manage regulatory and reputational perspectives	- Demonstrate commitment to orbital sustainability - Assure spaceflight safety for all operators
	Global Responsibility	
Model	Unprepared approach and capture	Unprepared approach and capture
Astroscale provides	Servicer, Mission licensing, Customized insurance, Ground segment & operations, Universal DP, Retro-reflector	Servicer, Mission licensing, Customized insurance, Ground segment & operations

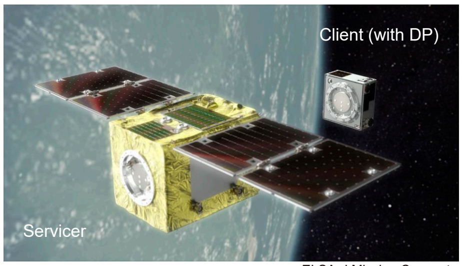
ELSA-d – An Overview

First unprepared rendezvous & docking mission in the world!

Key Mission Details

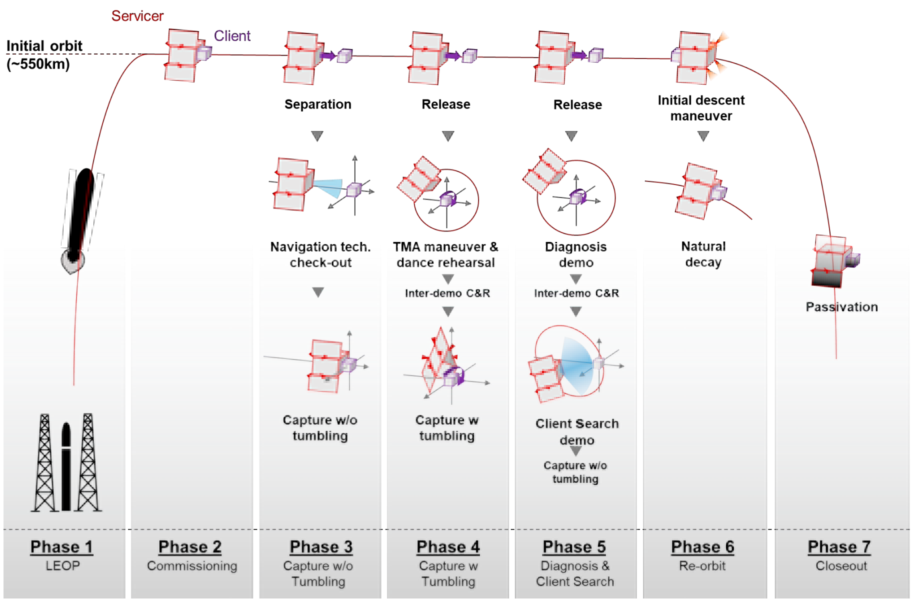
- Servicer: 175 kg
- Client: 17 kg with docking plate (DP)
- DP allows prepared servicing of client using proprietary magnetic capture system.
- Launch in March 2021
    - Signed with Glavkosmos / GK Launch Services, Soyuz 2
    - SSO (500-600 km), LTAN 10.30-11.00.
- Full phases of operations that would be necessary for a full EOL service, including client search, inspection, capture, re-orbit and de-orbit.





ELSA-d Mission Concept

ELSA-d – CONOPS



ConOps Video

https://youtu.be/HCWxdK7l0hI

ELSA-d – Key Capabilities – I

End-to-end Rendezvous Solution including far and short-range approach

- GNC processors (GNC command, sensor handling)
- Usual complement of attitude sensing e.g. star trackers, attitude control e.g. RWs and position sensing e.g. GPS
- Specialist rendezvous: ranging system, night navigation cameras (wide and short angle), day cameras, range finders, illumination device

Safety Evacuations and Passively Safe Trajectories fully executed in mission

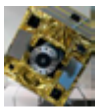
- Collision avoidance (passive and active abort)
- Movement to evacuation point
- Protected safety ellipse
- Manual experiment abort
- Protected critical functions (including de-orbit)
- Safety critical computing: FDIR and safety tasks
- Architectural redundancy
- High-fidelity ground-based simulation

Docking Plate (DP) to enable unprepared removal

- Designed with constellation customers in mind.

Magnetic Capture of non-tumbling & tumbling clients

- Capture system is designed to extend and retract and allow multiple captures and releases.



ELSA-d – Key Capabilities – II

Autonomous Flight Software targeting roughly ECSS Level-3 autonomy

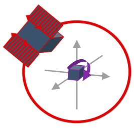
- Event-based autonomous operations
- Execution of on-board operations control procedures
- Only intermittent communication with ground stations (No satellite relay communication)

Re-orbit, De-orbit and passivation capabilities

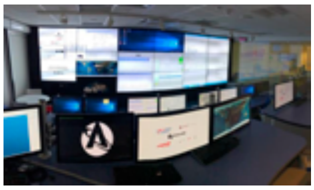
- Green propulsion system with high ISP and compatibility to small launch vehicles

Advanced Operational Capabilities

- Demonstration of client search capability.
- Fly-around inspections of client with operator assessment.



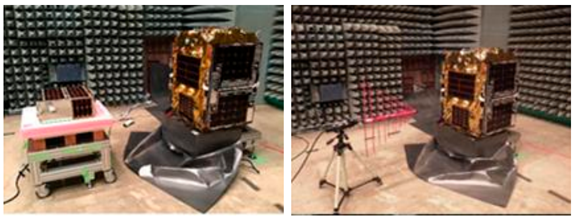
In-orbit Servicing Ground Segment designed specifically for EOL / ADR.



ELSA-d – AIT / V&V – I

- Environmental tests (Thermal vacuum, EMC, Acoustic, Vibration) have been completed at Tsukuba Space Centre in late 2019 / early 2020
- No significant issue has been observed and all tests have proceeded as planned
- All tests have been conducted efficiently with limited personnel (less than ten engineers have handled the tests including 24-hour shift during the thermal vacuum test)

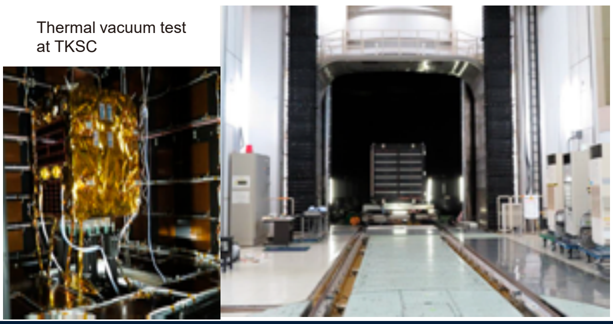
EMC test at TKSC



Acoustic test at TKSC

Vibration test at TKSC

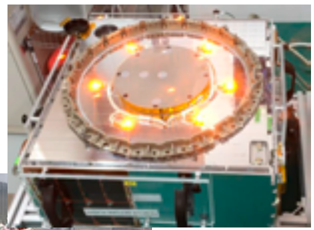
Thermal vacuum test at TKSC



ELSA-d – AIT / V&V – II

- Various function tests have been completed for the last eight months both in Servicer and Client
- The number personnel staying at the office has to be restricted due to COVID-19. IT technologies such as remote access and teleconference have utilised as much as possible
- ELSA-d would be operated by Astroscale UK office. Connectivity tests between the UK control centre and the actual satellites have been conducted repeatedly.
- Validation of operation procedures and operation training are ongoing, connecting both the UK and the JP office

Solar panels deployment test



Client's function test

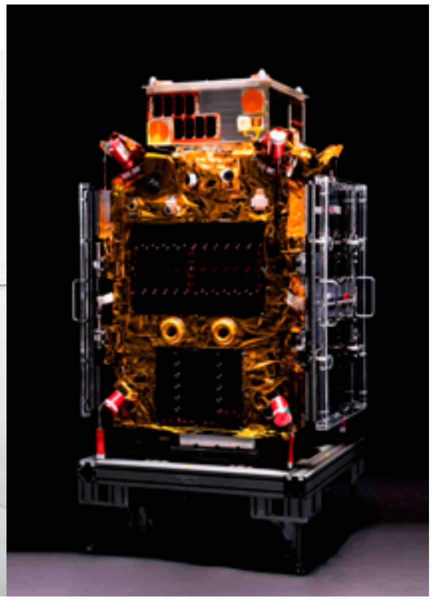
UK – JP interface tests & Operation training

RCS (thruster) function test

Ground support equipment used for Servicer's test

ELSA-d – AIT / V&V – III

ELSA-d is now ready for the shipment and the launch!



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C08

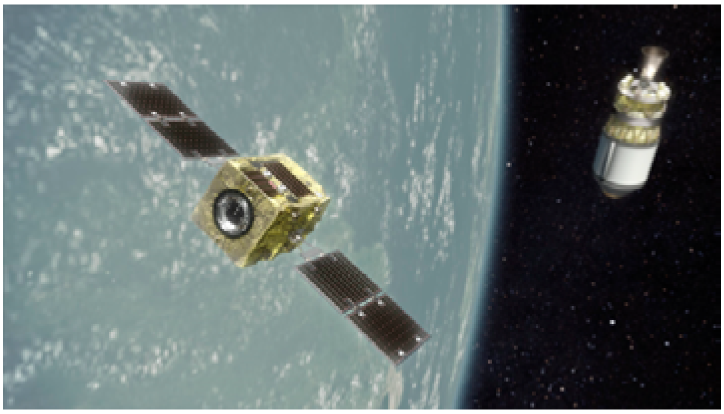
ADRAS-J プロジェクト概要-世界初大型デブリ除去実証技術とは-

ADRAS-J Project Overview -World first ADR Technology Demonstration-

○藤田 勝, 浅葉 薫, 足木 研介(アストロスケール), ADRAS-J プロジェクトチーム
○FUJITA Sho, ASABA Kaoru, ASHIKI Kensuke (Astroscale Japan), ADRAS-J project team

ADRAS-J(Active Debris Removal by Astroscale-Japan)は、軌道上にある使用済み宇宙機の除去技術を実証するミッションです。
また、同プロジェクトは、JAXA が世界に先駆け行う商業デブリ除去の技術実証（CRD2:商業デブリ除去実証）のフェーズ I の民間実施パートナーとして選定されており、2022 年度中の打上げを予定しています。フェーズ I では、非協力ターゲットデブリへの接近・近傍制御を行い、軌道上に長期間放置されたデブリの運動や損傷・劣化の様子を把握するため、画像・映像の取得を目指しています。得られる知見やデータは、2025 年以降に打ち上げを予定する除去・リエントリを含むフェーズⅡへ活用されます。ADRAS-J ではこれらの JAXA ミッションに加えアストロスケールが独自に実施する技術実証を行います。
アストロスケールは、ELSA-d プロジェクトの設計・開発・運用までに培った知見を ADRAS-J プロジェクトへ活用することで、より品質と信頼性の高いサービスを提供できるよう取り組んでいます。

JAXA selected Astroscale and its Active Debris Removal by Astroscale-Japan (ADRAS-J) satellite as commercial partner for Phase I of its Commercial Removal of Debris Demonstration project (CRD2), which will focus on the observation, characterization, and eventual removal of a Japanese rocket body. Phase I will be demonstrated by the end of the Japan Fiscal Year 2022 and includes data acquisition on an upper stage Japanese rocket body. Astroscale will be responsible for the manufacturing, launch and operations of the satellite that will characterize the rocket body, acquiring and delivering movement observational data to better understand the debris environment.



Astroscale

ADRAS-Jプロジェクト概要
- 世界初大型デブリ
除去実証技術とは –
ADRAS-J Project Overview
-World first ADR Technology
Demonstration-

2020, December, 9th

株式会社アストロスケール

CRD2 Phase1 (ADRAS-J)
Project Manager

Sho Fujita 藤田　勝

Astroscale Overview

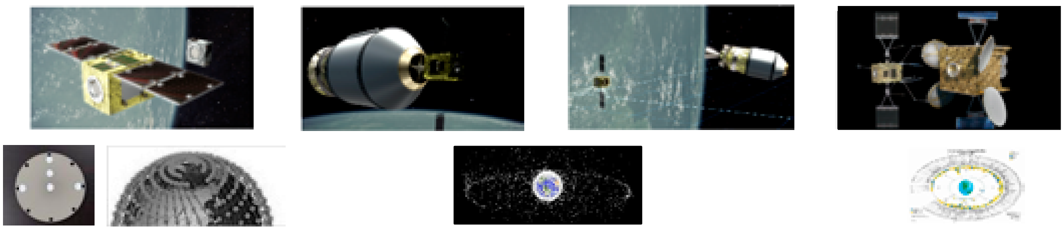
Establishment： 2013年
Head quarter： Tokyo, Japan
Funding： $191M
Mission： Develop innovative technologies, advance business cases, and inform international policies that reduce orbital debris and support long-term, sustainable use of space
Vision： Secure safe and sustainable development of space for the benefit of future generations
Services： EOL, ADR, ISSA, LEX

Astroscale Overview

The only company solely dedicated to on-orbit servicing across all orbits.

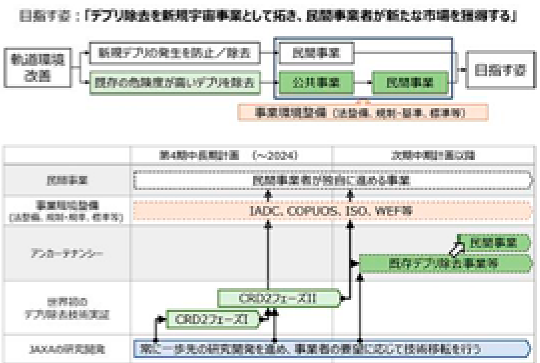
On-Orbit Service

- LEO
  - Future debris — **EOL** End-of-Life Service
  - Existing debris — **ADR** Active Debris Removal
- GEO
  - Debris, Unknown objects — **ISSA** In-Situ SSA
  - Operating satellites — **LEX** Life Extension Service



CRD2 Phase 1 Project

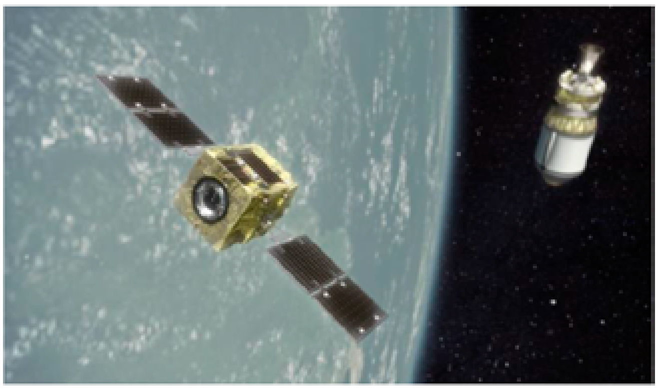
Astroscale is selected as a partner for JAXA's CRD2 Phase 1 Project from 2020 March for key technology demonstration for commercial ADR service.



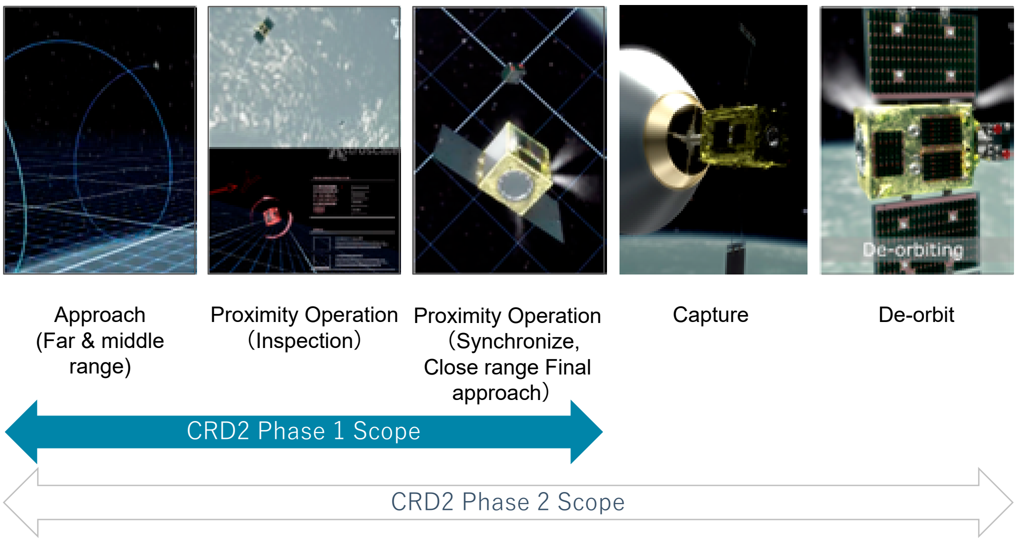
http://www.kenkai.jaxa.jp/research/debris/crd2/crd2.html

CRD2 Phase 1 Project

- First Challenges to demonstrate ADR Technology in the orbit
- First Challenges for mission procurement type contract. Thus, private company will proactively develop, own and operate spacecraft and demonstrate technologies based on its business strategy, and deliver mission products to JAXA. JAXA will provide technical supports.



Key Technologies for ADR



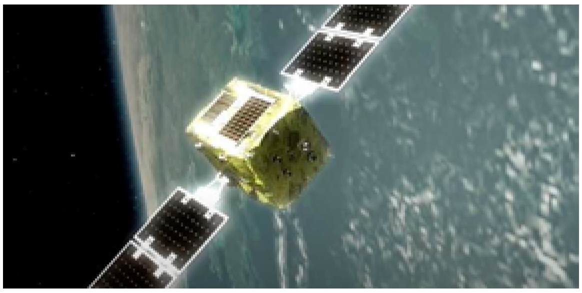
ADRAS-J Overview

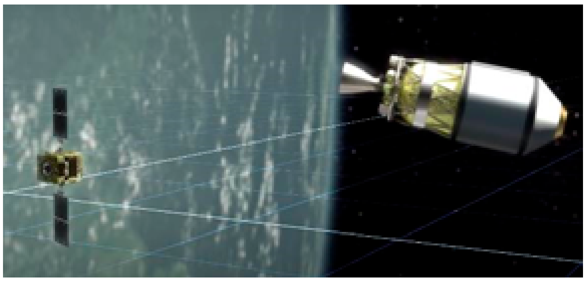
ADRAS-J: Active **D**ebris **R**emoval Service by **As**troscale
- Developed in CRD2 Phase1

Key Mission Details
- Chaser: ~180 kg
- Target: Japanese Rocket Upper Stage
- Launch targeting: within Japan fiscal year 2022

- Full range technology of RPO (Rendezvous and Proximate Operation) with Non-cooperative target will be demonstrated

- Astroscale will be responsible for the manufacturing, launch and operations of the satellite that will characterize the rocket body, acquiring and delivering movement observational data to better understand the debris environment.

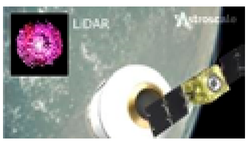




CRD2 Phase 1 - ADRAS-J - Features

Rendezvous Technology for Non-Cooperative Target

- Challenges for rendezvous to Non-Cooperative Target are
  - No Optical Markers on Target
  - No Communication link with Target
  - No Attitude control on Target
  - Uncertainty Target characteristics(attitude motion, surface damage and appearance condition)
- Approach and navigation technology with multiple types of sensor will be demonstrated



COTS Rendezvous Sensors

- COTS sensors will be used for Rendezvous

- State of the art sensing technology in ground-use consumer products will be applied for space-use

World First Real large Debris data Observed In Space

- Nobody knows attitude motion, surface damage and appearance condition of large debris in space yet

- World first in-situ observation data will contribute further understanding on debris behavior and environment.

CRD2 Phase 1 - ADRAS-J - Features

Safe Mission and System Design

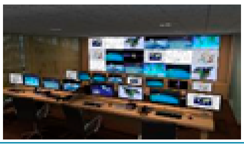
- 1 fail safe design
- Collision avoidance (passive and active abort)
- Safety ellipse trajectory
- FDIR
- Architectural Redundancy

Full Range Rendezvous System

- Not only close-range relative navigation technology but also full range rendezvous technology will be demonstrated
- Launch condition definition, Far range rendezvous trajectory design, absolute navigation
- Middle and close range trajectory design, relative navigation, close range trajectory design

Consolidated System Technology Including Ground Segment and Operation

- Astroscale is responsible for not only spacecraft but also ground segment development, launch vehicle procurement and in-orbit operation.

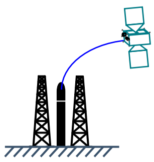


Leverage ELSA-d's outcome

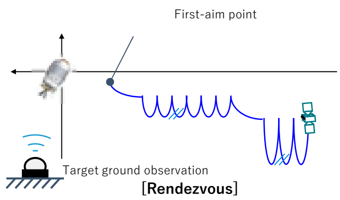
- ELSA-d is Astroscale's world first system to demonstrate End of life service technology which is ready for March 2021 launch.
- ADRAS-J leverage ELSA-d's outcome.

 9

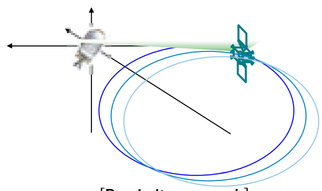
ADRAS-J Mission Scenario



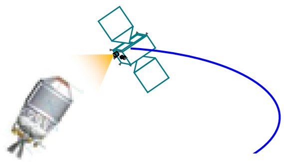
[Launch and Early Operation (LEOP) & commissioning]
The Chaser is inserted into its initial orbit and initial checks of functions are performed. The initial orbit is determined based on the phase angle of the Target at the time of launch.



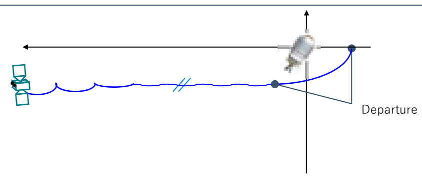
[Rendezvous]
By executing orbital maneuvers, the phase angle, orbital altitude and orbital plane of the Chaser is matched to that of the Target, and the Chaser arrives at the first-aim point behind the Target.



[Proximity approach]
Through relative navigation using the Chaser's optical sensors, the Chaser approaches to behind the Target. In this process, IRCam and LiDAR navigation will be demonstrated in orbit.



[Proximity operation]
Fixed-point observation and go-around observation of the Target, and testing of final approach to the PAF section of the rocket upper stage is conducted. In addition, if there are surplus resources, extra mission will be carried out.



[Departure]
Through orbital maneuvers, the Chaser will break away from Target proximity, move to an orbit below the Target, and end the mission.

 10

ADRAS-J Mission Scenario

ADRAS-J video https://youtu.be/5u_X33krhHY

Path Forward

- We will acquire capability and experiences to make our commercial ADR business viable through this CRD2-1 project.
- We will further leverage this by pursuing opportunity to demonstrate full ADR service technology, such as CRD2-2 opportunity, which is yet open for bid though.
- To make ADR constant and sustainable action, discussion over anchor tenancy to bring down Japan-derived debris after CRD2 program is necessary.
- We have actively advocated sustainable debris mitigation rules to many governments and organizations world wide

C09

デブリ環境改善に対するMHIの取り組み

MHI's Activities to Improve Space Debris Environment

○小早川 豊範, 渥美 正博, 志村 康治, 木村 友久（三菱重工業）
○KOBAYAKAWA Toyonori, ATSUMI Masahiro, SHIMURA Koji, KIMURA Tomohisa (MHI)

増加し続けるスペースデブリは宇宙活動の妨げとなり、国際問題となっている。デブリ同士の衝突による更なるデブリの増殖等も危惧されており、このまま増加を放置すれば飛翔中のロケットへのデブリ衝突等によるミッション喪失などのリスクも高まっていくことが想定される。ロケット打上げ事業者であり、宇宙活動の一プレーヤーでもあるMHIとしても、デブリ対策の取組みが重要であると認識している。MHIでは従来H-IIBロケット上段の制御再突入等のデブリ対策の取組みを実施してきたが、デブリ環境改善に対する更なる取り組みとして、MHIで検討中の超微小デブリ除去やデブリ同士の衝突回避構想について紹介する。

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 the conceptual studies about micro debris removal and collision avoidance between debris as further efforts.

MITSUBISHI HEAVY INDUSTRIES

デブリ環境改善に対するMHIの取組み (MHI's activities to improve Space Debris Environment)

第9回スペースデブリワークショップ

Toyonori Kobayakawa, Masahiro Atsumi, Koji Shimura, Tomohisa Kimura (MHI)

2/26 2021

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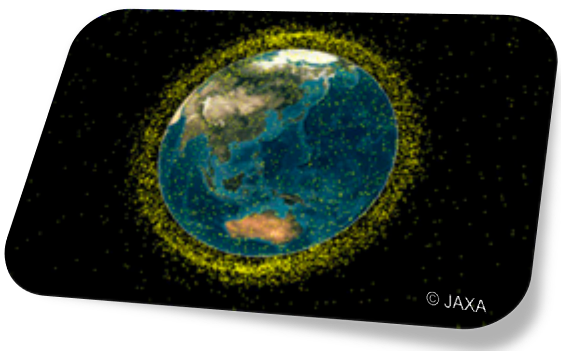
MITSUBISHI HEAVY INDUSTRIES

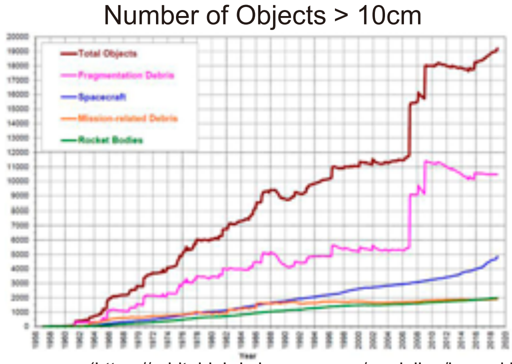


1/

1. Debris and Launch Service

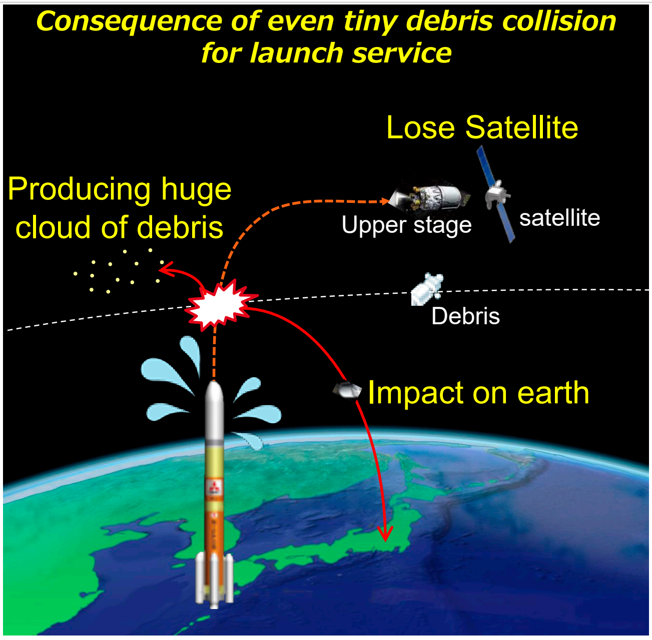
MITSUBISHI HEAVY INDUSTRIES

Number of Objects > 10cm



(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!



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2. Activities to provide sustainable and reliable launch service

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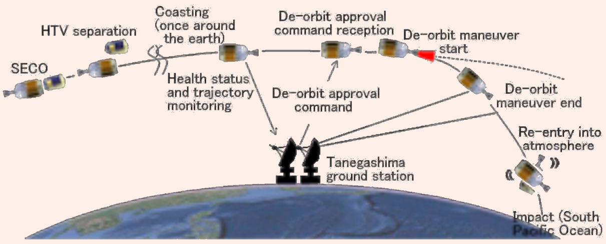
MHI's Activities so far

Passivation

✓ Venting Residual Propellant

Controlled Reentry (H-IIB)

(*All mission successfully completed !!*)



What we have to do next ?

Mitigation

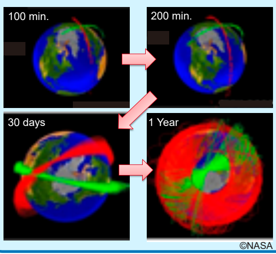
✓ ADR for trackable debris

✓ Micro debris removal

Collision prevention

✓ Nudge debris to change orbit and reduce collision probability

First collision accident (2009)
Iridium33 – Kosmos 2251



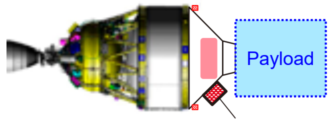
Collision produces huge cloud of non-trackable debris

3/

3. MHI's Future Plans for Sustainable Space Activities

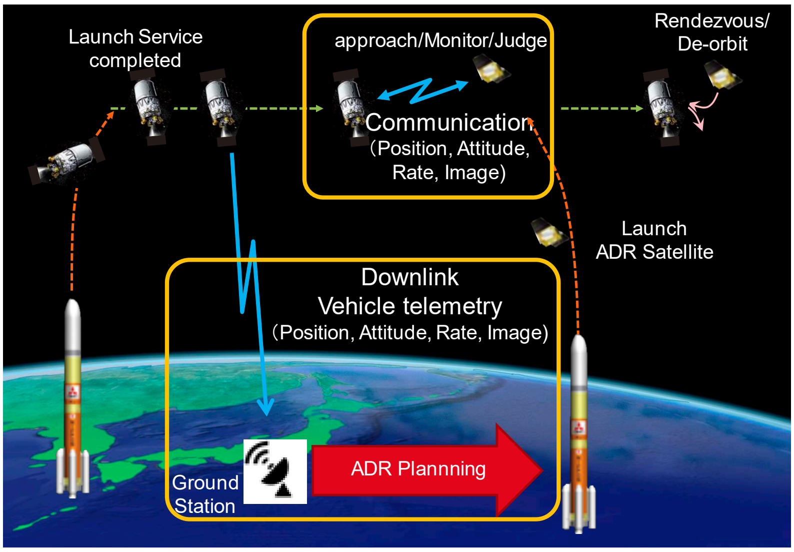
MITSUBISHI HEAVY INDUSTRIES

M-Pack and ADR support



- Monitoring Package for passivated spacecraft
- Independent from mission system
- Downlink following data
  - ✓ Position
  - ✓ Attitude Rate
  - ✓ Image

…etc



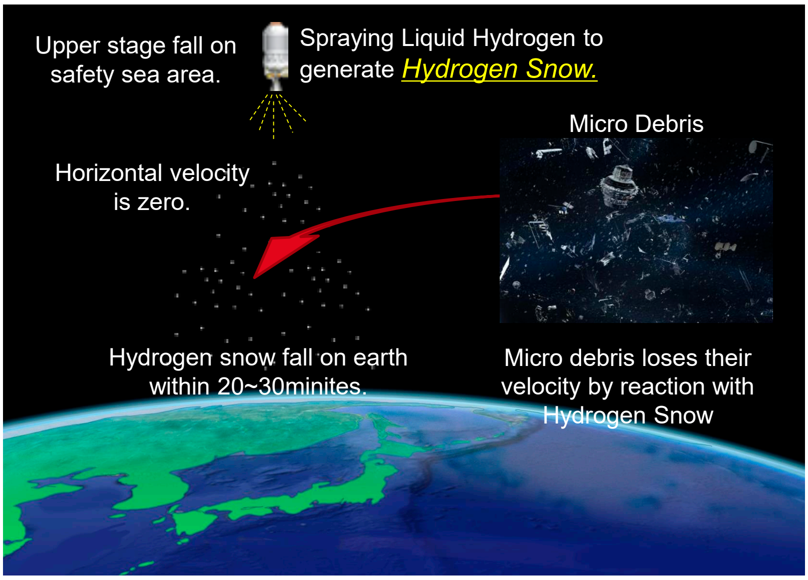
4/

3. MHI's Future Plans for Sustainable Space Activities

MITSUBISHI HEAVY INDUSTRIES

Micro Debris Removal - *Hydrogen Snow concept*

- Hydrogen is eco-friendly
- Hydrogen does not harm on debris because of low density
- Since hydrogen snow has only vertical velocity, it can remove debris from any direction



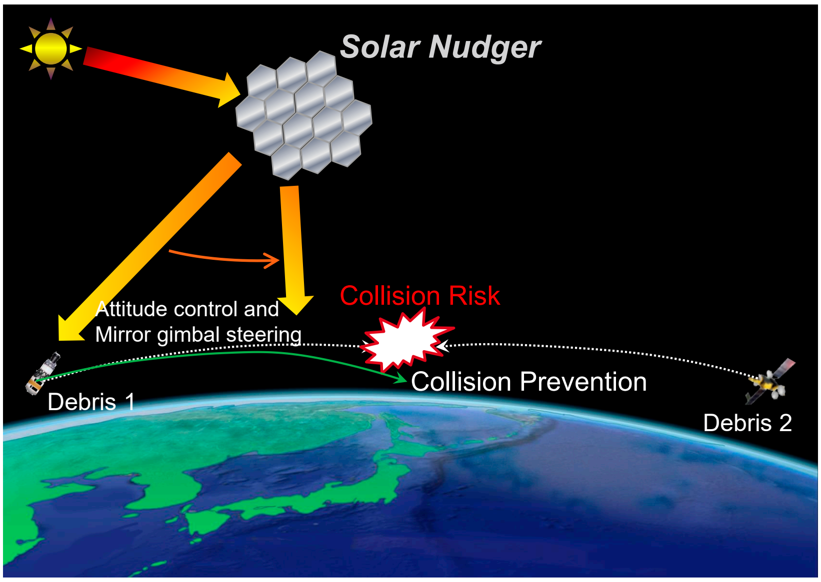
5/

3. MHI's Future Plans for Sustainable Space Activities

MITSUBISHI HEAVY INDUSTRIES

Collision Avoidance – *Solar Nudger Concept*

- Nudge debris by natural solar pressure
- Solar Nudger does not require
  - ➢ Power source to change debris orbit
  - ➢ Dangerous rendezvous
- Various application
  - ➢ Optical observation during night time
  - ➢ Shooting star



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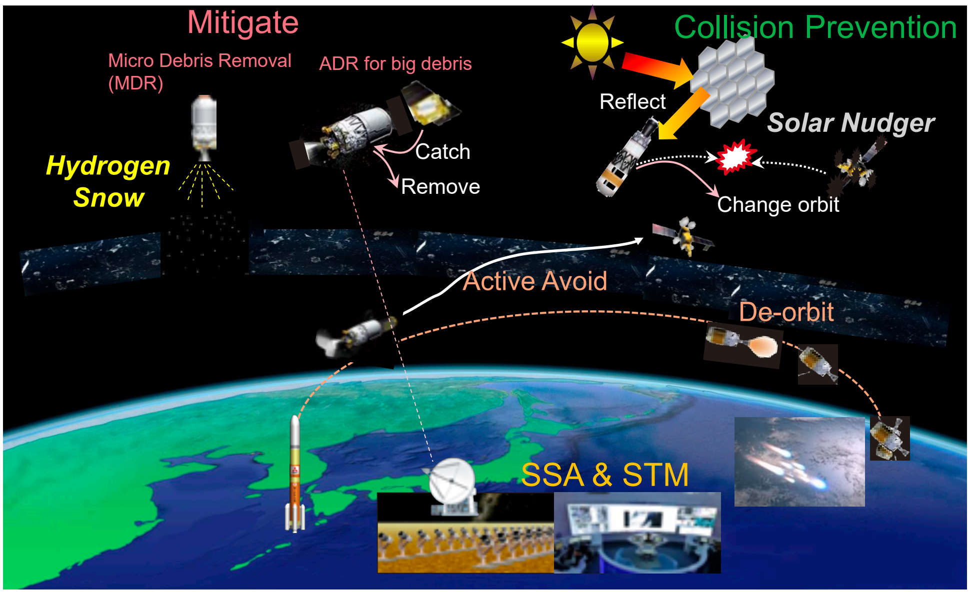
3. MHI's Future Plans for Sustainable Space Activities

MITSUBISHI HEAVY INDUSTRIES

MHI will do all-out effort for sustainable space activities!



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C10

衛星搭載パルスレーザーによる軌道離脱サービス

End-of-Life Deorbit Service with a Pulsed Laser Onboard a Small Satellite

○福島 忠徳, 平田 大輔, 足立 数馬, 板谷 優輝, 山田 淳（スカパーJSAT）、
津野 克彦, 小川 貴代, 和田 智之, 戎崎 俊一（理化学研究所）
○FUKUSHIMA Tadanori, HIRATA Daisuke, ADACHI Kazuma, ITAYA Yuki, YAMADA Jun (SKY Perfect JSAT), TSUNO Katsuhiko, OGAWA Takayo, WADA Satoshi, EBISUZAKI Toshikazu (RIKEN)

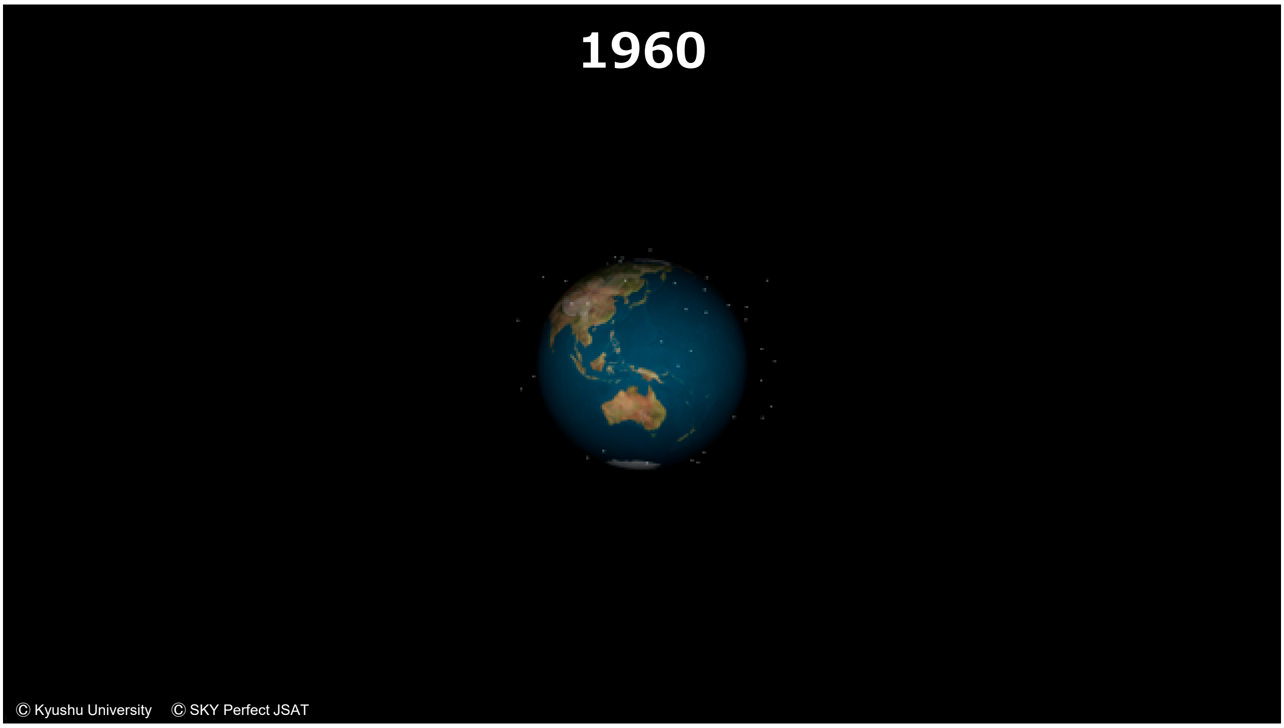
スカパーJSAT は、衛星からのレーザ照射により不用衛星を移動させて軌道離脱するサービスのための衛星の設計に着手した。レーザ照射により、材料物質が気化・プラズマ化する現象（アブレーション）を利用して、ターゲットとなる衛星に推力を生成する。JSAT と理研の共同研究では、アブレーション推力測定と概念検討を行い、その結果、約 200 W のペイロード電力の 150 kg クラスの小型衛星で、150 kg のターゲットを数 100 ㎞程度の高度変更が可能であるとの見解を得た。またレーザ方式は、4つの利点がある。(1)ターゲットに非接触で推力を生成可能なため、衝突リスクを低減可能。(2)任意のレーザ照射によりターゲットの回転調整が可能。 (3)ターゲット外壁物質のアブレーションにより、推力が発生するため、サービス衛星がターゲット移動用の燃料保持が不要。 (4)顧客の衛星に対して追加の仕様変更（キャプチャするためのハンドルなど）が不要。本発表では、EOL デオービットサービスのコンセプトと暫定スケジュールを紹介する。

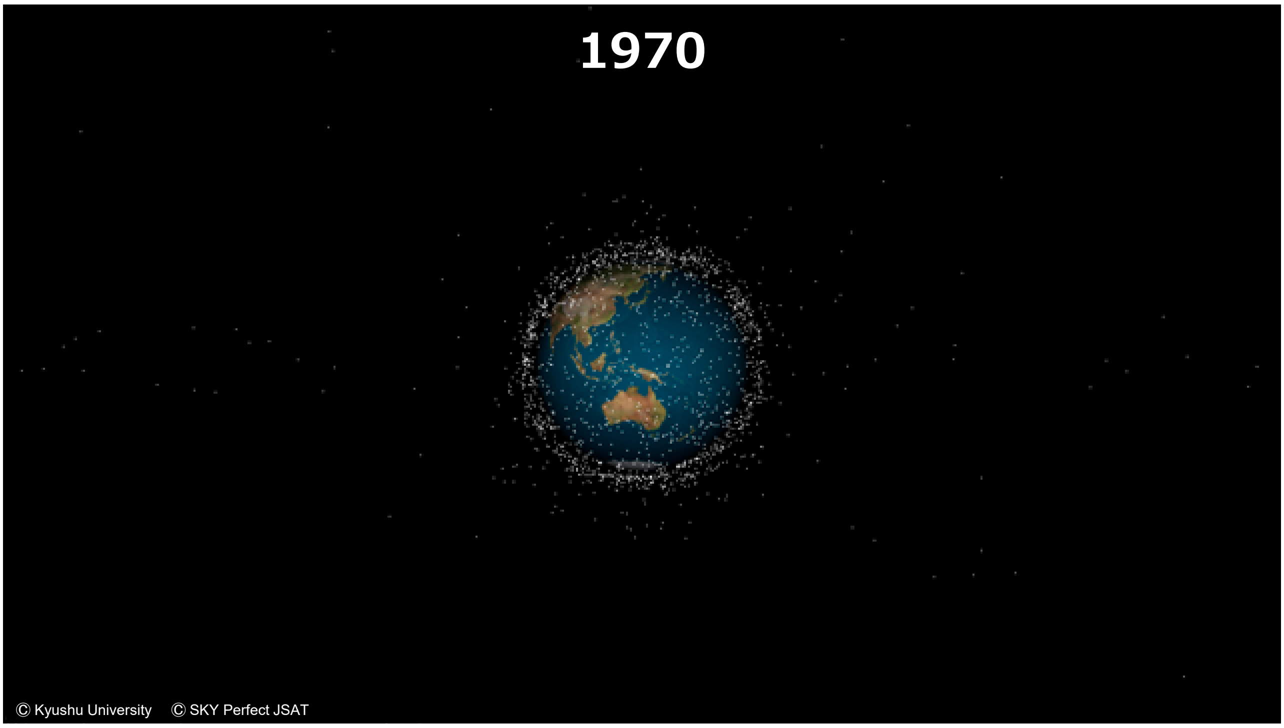
SKY Perfect JSAT Corporation has begun designing a brand-new end-of-life (EOL) deorbit service satellite to remove nonfunctional satellite targets from orbit. A service satellite with a laser system emits a focused laser beam to the target to generate laser ablation. The orbit and attitude (including rotational status) of the target can be changed sufficiently by the reaction force of the plasma/gas ejected from the target surface. Ground experiments, including high-precision measurements of the ablation reaction and a feasibility study of the service satellite, were performed in collaboration with JSAT and RIKEN. Our conceptual study shows that our service can deorbit a 150 kg target at an altitude of several hundred kilometers by means of a small laser satellite (150 kg) and a 200 W class Payload Power. We found four advantages of the laser ablation method over conventional active methods for the removal of nonfunctional satellites: (1) minimal risk of collision, since the laser satellite does not require any physical contact with the target; a high-intensity pulsed laser can ablate surface material of the target from a distance; (2) detumbling is also possible during the operation; (3) the service satellite is not required to carry additional fuel for the target because the required thrust is generated from vaporization and ionization of the target material; (4) additional specifications (e.g. a handle to capture) for customer satellites are not necessary. In this presentation, we present the concept and provisional schedule of our EOL deorbit service.

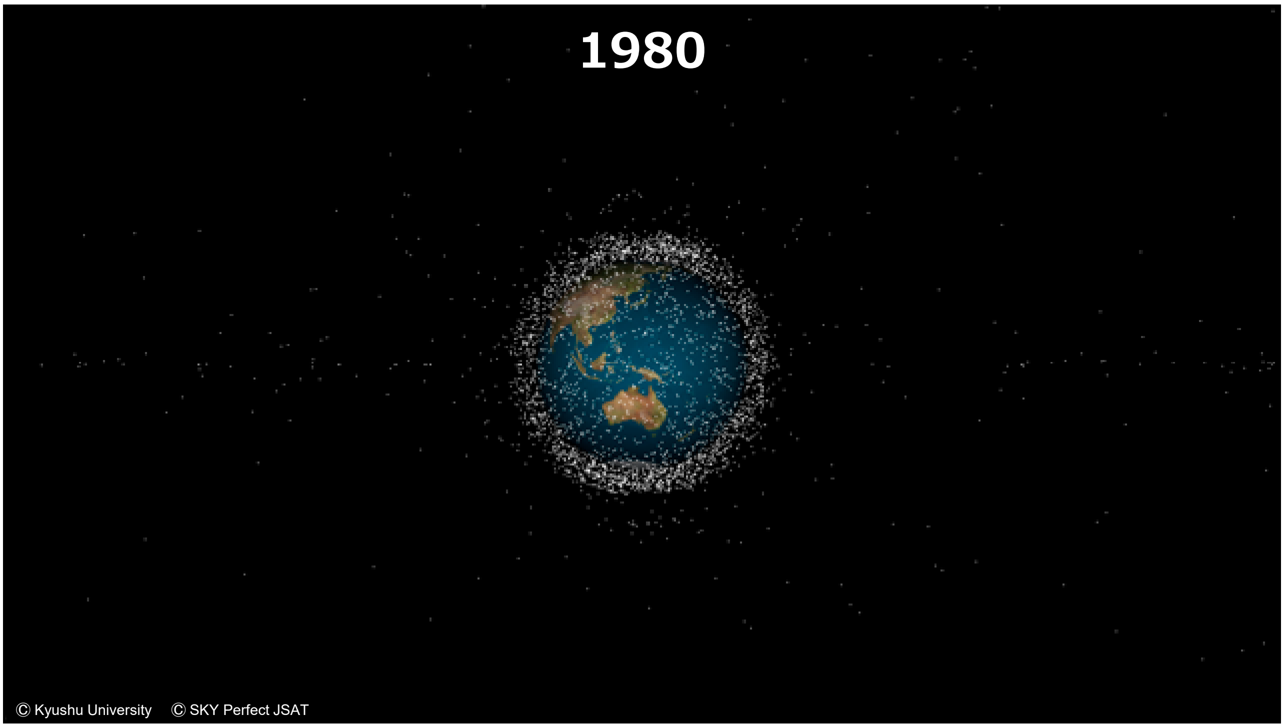
End-of-Life Deorbit Service with a Pulsed Laser Onboard a Small Satellite

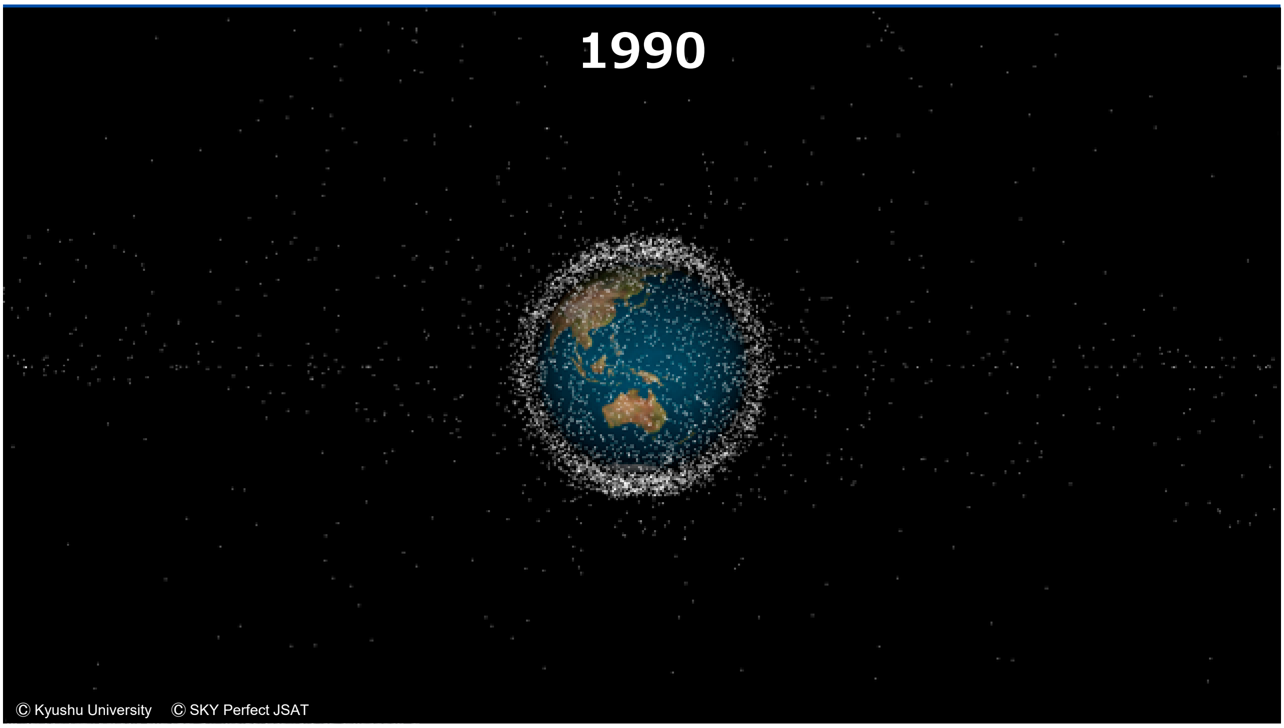
○ Tadanori Fukushima(†), Daisuke Hirata (†), Kazuma Adachi (†), Yuki Itaya (†), Jun Yamada (†)
Katsuhiko Tsuno(‡), Takayo Ogawa (‡), Satoshi Wada (‡), Toshikazu Ebisuzaki (‡)
(†): SKY Perfect JSAT, (‡): RIKEN

9th Space Debris Workshop 26 Feb, 2021




1970
Ⓒ Kyushu University　Ⓒ SKY Perfect JSAT


1980
Ⓒ Kyushu University　Ⓒ SKY Perfect JSAT


1990
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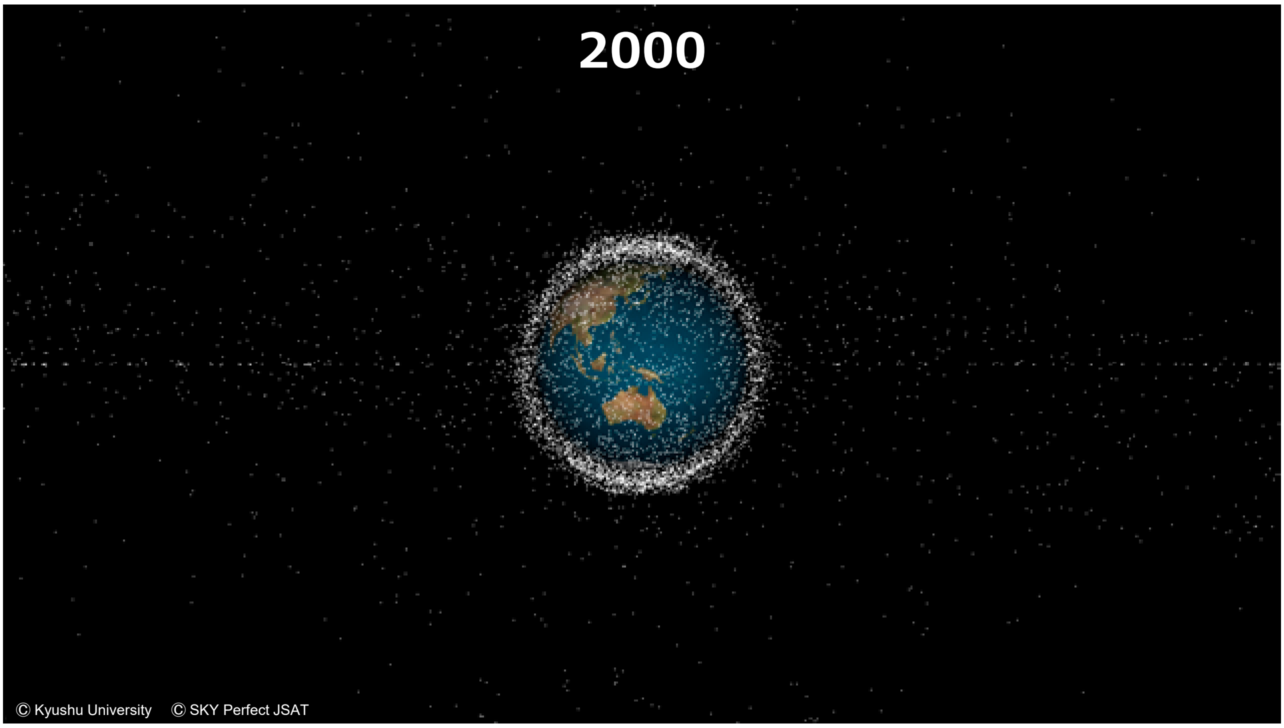
2000
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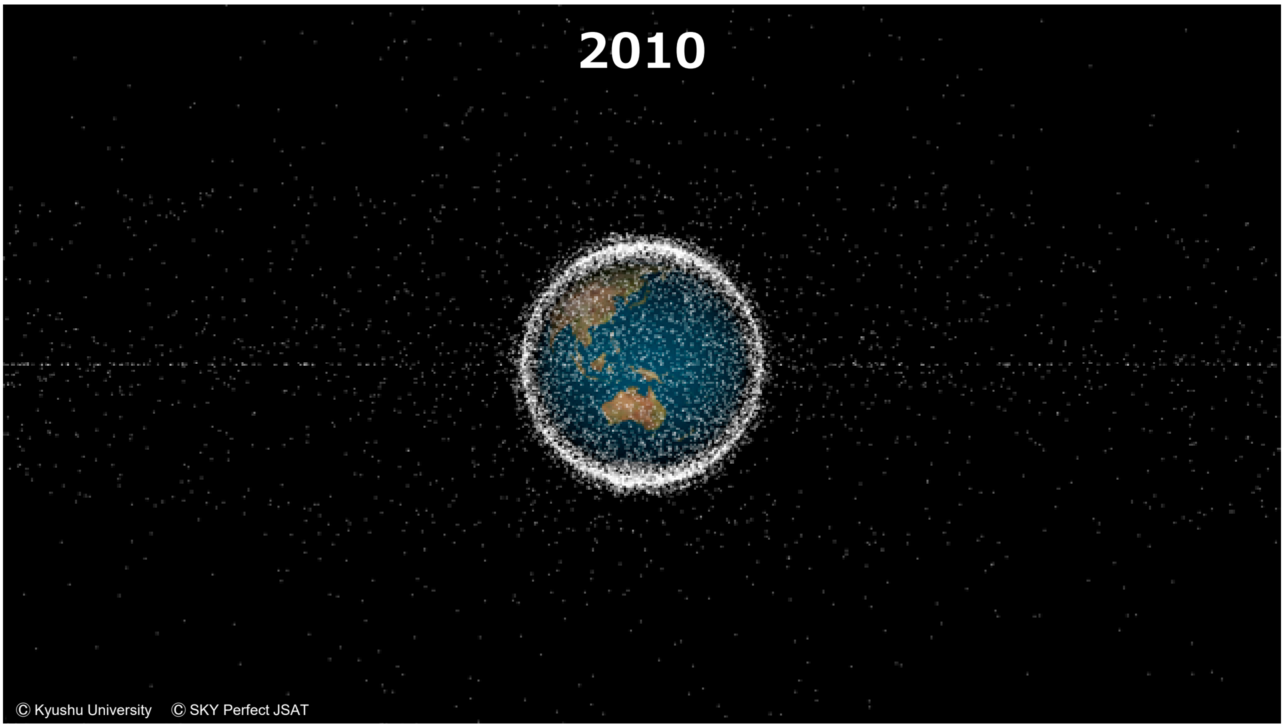
2010
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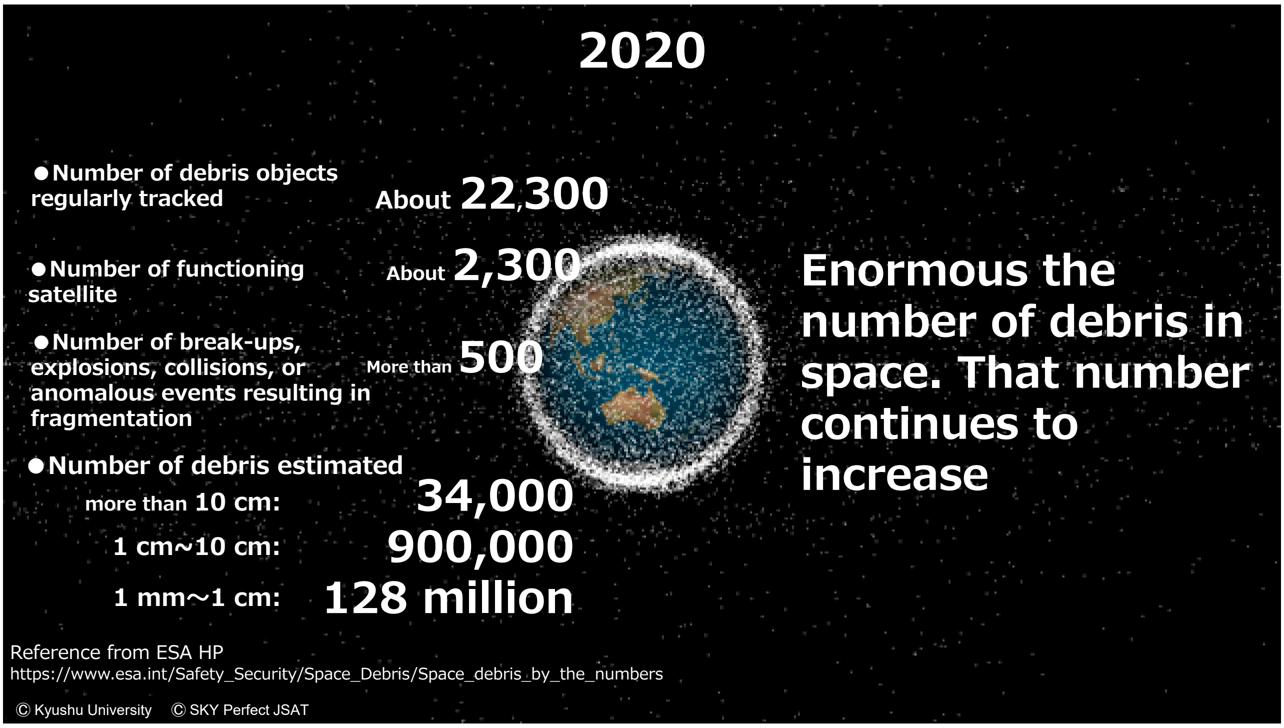

2020
●Number of debris objects regularly tracked
About 22,300
●Number of functioning satellite
About 2,300
●Number of break-ups, explosions, collisions, or anomalous events resulting in fragmentation
More than 500
●Number of debris estimated
more than 10 cm:
34,000
1 cm~10 cm:
900,000
1 mm~1 cm:
128 million
Enormous the number of debris in space. That number continues to increase
Reference from ESA HP
https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers
© Kyushu University　© SKY Perfect JSAT

LEO Environment Projection of the number of space debris (>10cm)

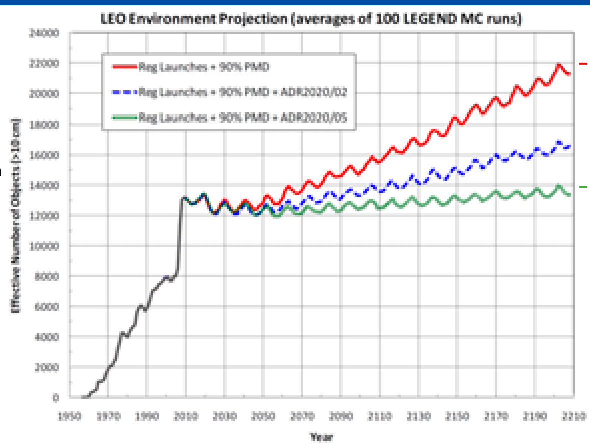
Removing five objects per year can stabilize the LEO*1 environment*2

*1 LEO: Low Earth Orbit
LEO is an Earth-centred orbit with an altitude of 2,000 km or less

*2 Active Debris Removal and the Challenges for Environment Remediation
By J.-C. LIOU1

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120013266.pdf

Fig.6. Projected increases of the future LEO populations (objects ≥10 cm) based on three different scenarios. Each projection is the average of 100 LEGEND MC simulations.



90% Post Mission Disposal

90% Post Mission Disposal
+
5 active debris removals per year

Activation of space use in next 10 years

The number of Objects Launched into Outer Space
(1957～Apr-2020)

9,386 satellites

United Nations Office for Outer Space Affairs
http://www.unoosa.org/oosa/osoindex/search-ng.jspx

The number of satellite for Mega-constellation
(in house investigation from news resources)

More than 50,000 satellites

OneWeb: more than 6,000
SpaceX: more than 42,000
Telesat：more than 300
Amazon：more than 3,000
other start up・・・・・・・・・

The satellites that will be launched in the next 10 years Significantly surpasses the number of satellites launched by humankind in the last 60 years

Congestion of satellites rapidly progresses in low earth orbit

The number of debris considered constellations

[*]: , 6700 satellites in 1000- to 1325-km altitudes with different inclinations and orbital planes, assumed to continue for 50 years.

+590% debris **582 catastrophic collisions in 200 year**

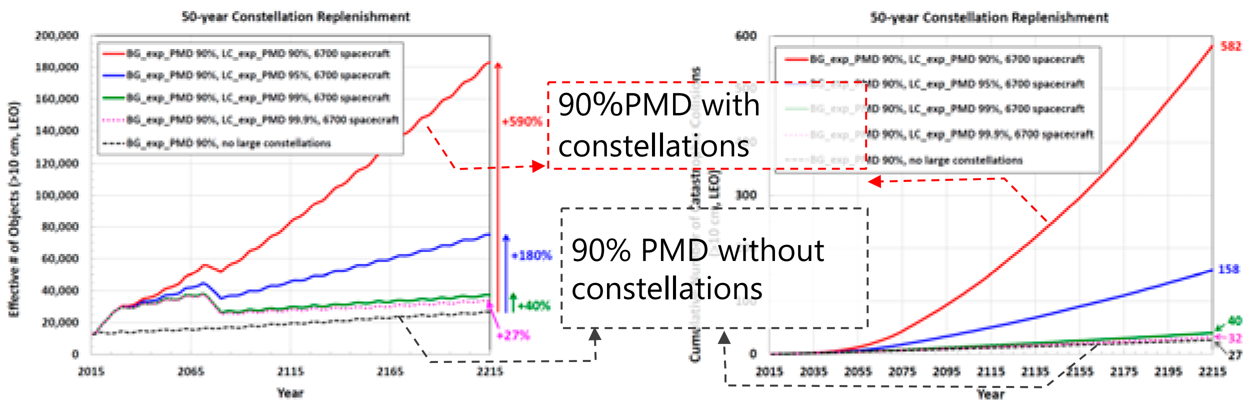


Figure 6. Results from LC scenarios where the LCs maintain full operations with spacecraft replenishment for 50 years. The total number of spacecraft in 3 LCs is 6700. The differences between the top four curves and the black-dashed curve in 2215 are +590% (red), +180% (blue), +40%(green), and +27% (purple-dotted), respectively.

Figure 7. Results from LC scenarios where the LCs maintain full operations with spacecraft replenishment for 50 years. The total number of spacecraft in 3 LCs is 6700. The total numbers of catastrophic collisions in 200 years for the 4 curves are (top to bottom) 582, 158, 40, 32, and 27, respectively.

Reference: National Aeronautics and Space Administration(NASA) Orbital Debris Quarterly News Vol 22, Issue 3 Sep 2018

Summary of space debris problem

Background
- Increasing the number of space debris
- Worse due to constellation

Problem
- Increasing mission ending risk due to collision of space debris

In case no improvement

Problem actualized
- Affect of space use, civilian life

Solution
- Achieve high PMD
  - End Of Life deorbit(*1)
- Active debris removals(*2)

Many countries and companies are in progress of active debris removal technology

*1: End Of Life deorbit: Service for post mission disposal at mission ending for a satellite

*2: Active debris removals: remove space debris

The Solution of SKY Perfect JSAT

9th Space Debris Workshop 26 Feb, 2021

SKY Perfect JSAT Corp. Proprietary

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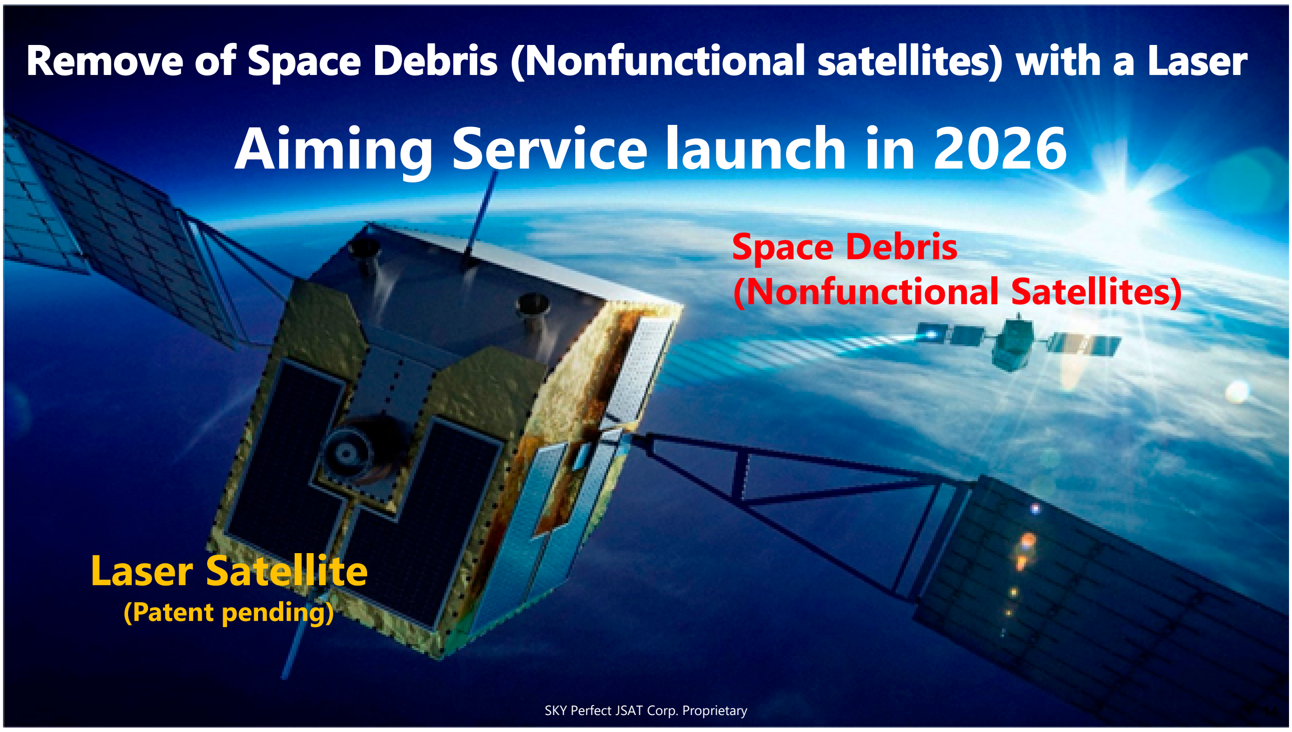
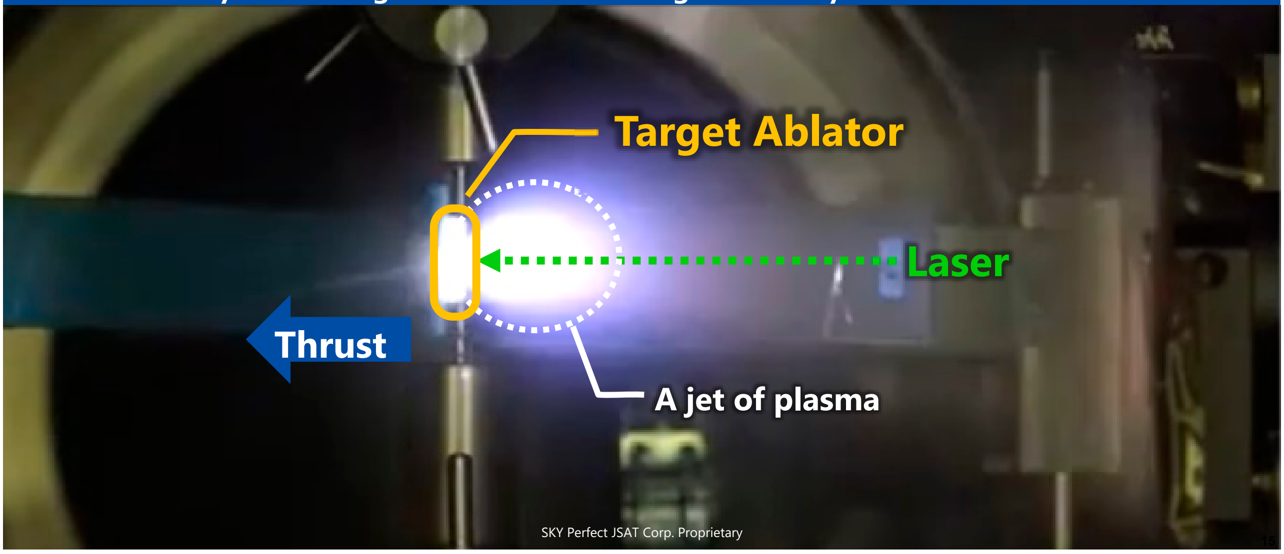


Key Technology: Laser Ablation

Laser ablation is the process of removing material as vaporized or ionized state from a solid surface by irradiating a material with a high-intensity laser beam.



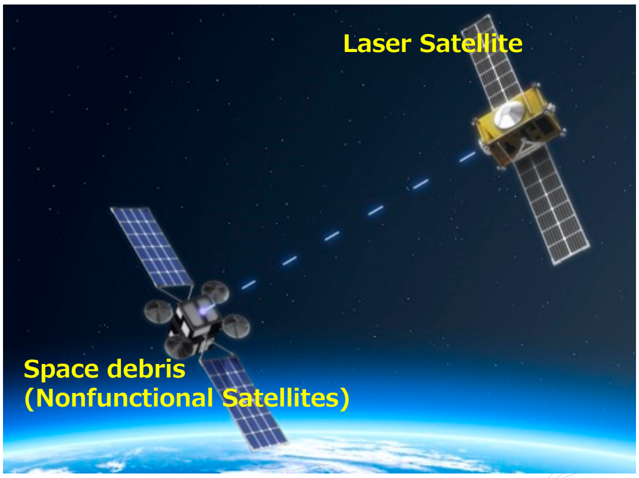
Advantages of Laser Method

❶Safety

- Move nonfunctional satellites from a distance with no physical contact
- Detumbling is also possible

❷Economy

- Laser satellite is not required to carry additional fuel for nonfunctional satellites
- No Additional Specifications (e.g. a handle to capture) for customer satellites



Thrust Performance for Aluminum

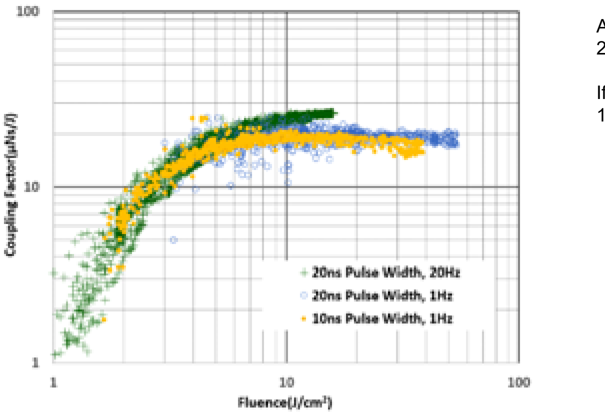


Fig. 4. Momentum-coupling factor for a 7075 aluminum target under three different conditions. Each data point corresponds to an individual laser pulse. See Data File 1 for underlying values for individual conditions.

Aluminum ablation Impulse (Coupling Factor) ≒ 20 μNs/J in the range more than 5 J/cm^2

If 1 pulse with 1 J at 50Hz, 50W Laser output and 1mN Thrust.

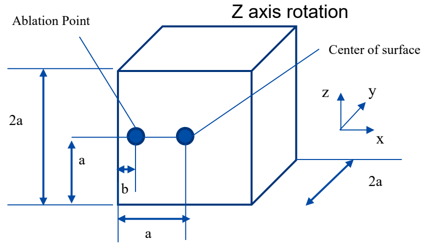
Reference: Vol. 28, No. 18 / 31 August 2020 Optics Express
Impulse measurement of laser induced ablation in a vacuum (Tsuno et al.)

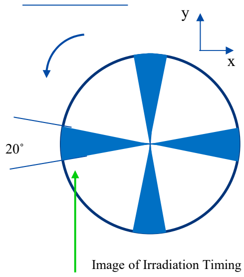
Detumbling Feasibility (Ideal cube type Target)

The torque generated by the laser ablation thrust have a capability of stopping the rotation at a sufficiently realistic speed.

	Item	Value
Pre-Condition	Satellite Mass, M	150 kg
	Initial Angular Velocity	1 rpm
	Length of a side of cube, 2a	1 m
	Ablation Point, b	0.1 m
	(*)Ablation Thrust, F (1J*36Hz)	0.72mN
	Irradiation timing efficiency for rotating objects	20°/90°
Result	Irradiation time	9000sec
	Operating time until rotation stops	0.5 day

(*) The ablation thrust value was tentatively used for this feasibility study. 36 W output laser power requires 180 W payload power if 20 % efficient from payload power to laser output. This Payload power would be sufficient small to mount to small satellite



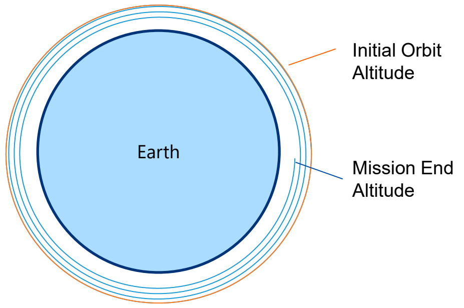


Deorbit Feasibility

- Small Altitude change such as delta 10 km can be possible quickly.
  - Risk Mitigation of Collision to their operational constellation satellites
  - Reduce collision avoidance operation for other operational satellites.
- Approx. 2 years of Laser ablation would be required to deorbit target satellite in IADC guideline orbit (25 years stay to reentry to atmosphere). It leads to the significant reduction of orbital time

Example of deorbit period of a certain satellite

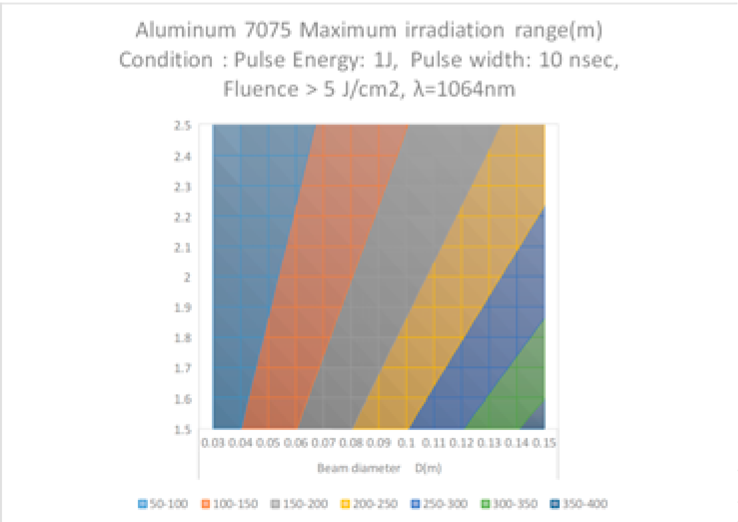
Item	Delta -10km	Delta - 600km
Satellite Mass, M	150kg	150 kg
Initial Orbit Altitude	1200 km	1200 km
(*1)Mission end Altitude	1190 km	600 km
(*2)Required Delta V	5 m/s	305 m/s
(*3)Ablation Thrust, F (1J*36Hz)	0.72mN	0.72mN
Operating days for deorbit	11 days	725 days



(*1) The mission end orbit altitude was a value tentatively determined for an orbit to re-enter the atmosphere in 25 years described IADC guideline. It should be determined by customer request.
(*2) Required Delta V was calculated by using Hohmann orbit equation with 1 km step, which is like spiral orbit
(*3) The ablation thrust value was tentatively determined for this feasibility study.

Irradiation Range (50m ~ several hundred meter)

- **Irradiation Range is determined by following condition**
  - Beam diameter at telescope
  - Beam Quality
  - Pulse Energy
  - Safe rendezvous distance between Laser satellite and Target object
  - Others..
- **It is possible to irradiate a laser with an intensity generating ablation from a distance of several hundred meters with a realistic beam diameter, pulse energy, and beam quality.**
- **The actual operating distance will be determined prior to design Fixed**



Summary and Conclusion

- **Feasibility study showed End Of Life Deorbit with Pulse laser is sufficiently feasible**
  - Detumbling can be performed at a sufficiently realistic speed.
  - Deorbit
    - Small Altitude change such as delta 10 km can be possible quickly such several weeks.
    - Approx. 2 years of Laser ablation would be required to meet IADC guideline orbit (25 years stay to reentry to atmosphere). It leads to the significant reduction of orbital time
  - Irradiation Range
    - Laser Irradiation from several hundred meters can be feasible with a realistic beam diameter, pulse energy, and beam quality.
- **By developing a laser irradiation method that can improve laser ablation thrust and improving the payload power that can be used with a laser, it is possible to handle even heavier objects**

C11

スペースデブリ発生防止用導電性テザーシステムとその実証

Electrodynamic Tether System for Space Debris Prevention and its Demonstration

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河本 聡美，大川 恭志（JAXA），佐藤 強，渡邊 武夫
（神奈川工科大学），佐藤 悠司，桒原 聡文（東北大学）
○EGAWA Yusuke, KAMACHI Koh, SUZUKI Daisuke, OKAJIMA Lena (ALE), KAWAMOTO Satomi,
OHKAWA Yasushi (JAXA), SATO Tsuyoshi, WATANABE Takeo (KAIT),
SATO Yuji, KUWAHARA Toshinori (Tohoku Univ.)

宇宙利用が急速に加速する昨今、衛星打ち上げ機会と小型衛星需要の増加、メガコンステレーションの台頭により、スペースデブリ対策としてミッション終了後の衛星の速やかな軌道離脱（PMD: Post Mission disposal）は宇宙の持続的な開発に重要な技術として位置づけられている。
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、2021 年の打ち上げを計画している。EDT は地球磁場とテザーに流れる電流の相互作用によるローレンツ力と空気抵抗を推進力として軌道離脱を行うため、地球磁場の影響する広範囲の軌道に存在する衛星に有効である。
開発した PMD デバイスは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。本講演では現在開発を行っている PMD デバイスと数値解析による軌道降下への影響及びミッション概要について紹介する。

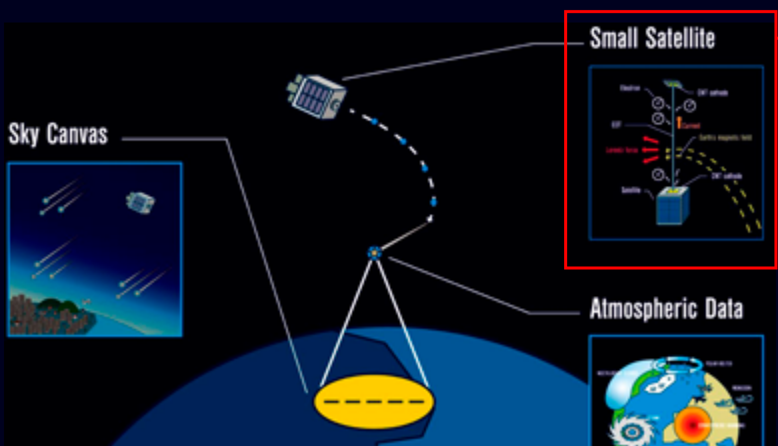
The rapid growth of space utilization, increase in demand for small satellites and their launch opportunities, and the rise of mega-constellations means an increased threat from space debris. Considering the current situation, Post-Mission Disposal (PMD) is considered to be important technique for the prevention of space debris and sustainable space development.
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 de-orbit of satellites. In this project, we are planning to launch a satellite equipped with a PMD device in 2021. The EDT is effective for satellites in a wide range of orbits within the Earth's magnetic field. It uses Lorentz force, an interaction between the Earth's magnetic field and electrical current flowing through the tether and atmospheric drag, to decrease the time needed to de-orbit.
Our developed PMD device is 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 details of the developed PMD device, the numerical analysis of de-orbit, and the mission overview.

Electrodynamic Tether System for Space Debris Prevention and Its Demonstration

Yusuke Egawa, Koh Kamachi, Daisuke Suzuki, Lena Okajima (ALE)
Satomi Kawamoto, Yasushi Ohkawa (JAXA)
Tsuyoshi Sato, Takeo Watanabe (Kanagawa Institute of Technology)
Yuji Sato, Toshinori Kuwahara (Tohoku University)

Feb. 26th, 2021 9th Space Debris Workshop

Our business activities



Throughout our three business activities and a new approach to create value in both entertainment and science, we aim to "make space closer for all of us together" and contribute to the **sustainable development of humankind**.

ALE, together with JAXA (Japan Aerospace Exploration Agency) has developed a space debris disposal device using Electrodynamic tether (EDT), enabling prompt deorbit of satellites after the completion of their mission.

- Forces satellites, rockets or other parts of spacecrafts to lower their altitude into Earth's atmosphere.
- Prevents space debris accumulation, even if the satellites, rockets and other parts of the spacecrafts loses their power supply.

Feb. 26th, 2021 9th Space Debris Workshop 2

Approach to Space Debris

For future launches, we will take measures to debris disposal before they are launched.
For satellites that are already in orbit, we will launch another satellite.

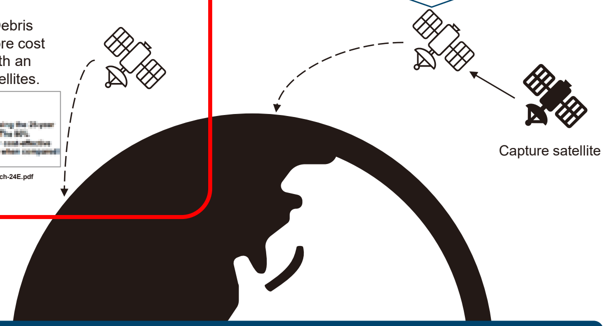
1 **Post-Mission Disposal (PMD)**
Satellites and upper stages of rockets have their own anti-debris devices and can de-orbit

J.C. Liou, Director of NASA's Debris Office, said that using "1" is more cost effective than "2" for dealing with an increasing number of small satellites.

Ref.：http://www.unoosa.org/documents/pdf/copuos/stsc/2020/tech-24E.pdf

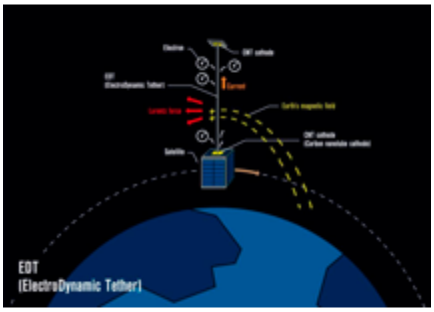
Our target

2 **Active Debris Removal (ADR)**
De-orbit satellite or upper stage of a rocket by another satellite (capture satellite)



It is necessary to take a two-step approach, firstly to ensure that "1" is thoroughly implemented, and then to compensate for the lack of debris countermeasures in "2".

EDT De-orbit Mechanism



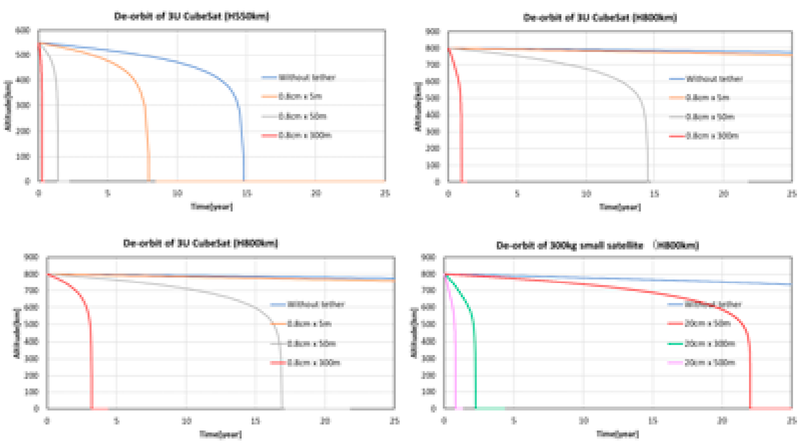
- **Lower attitude in LEO (~800 km)**
  Atmospheric drag is effective for de-orbiting.
  Large cross section generates large thrust.
- **Higher attitude in LEO (800~ km)**
  Low air density does not much contribute to de-orbiting. Emitting electrons enhances electromagnetic force and de-orbiting.

Large objects (satellite, part of rocket) also can de-orbit by electron emission.

Atmospheric drag effect

Electromagnetic force applied

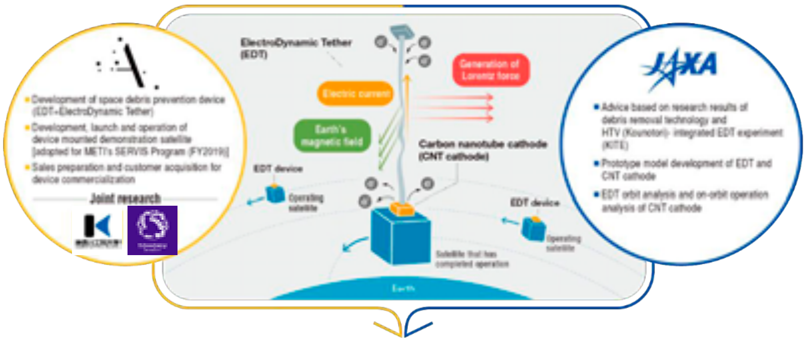
(Atmospheric drag + Electromagnetic force)



Collaboration with JAXA

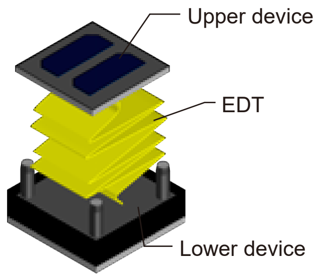
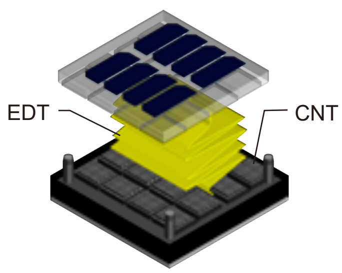
Minimizing the risk of first on-orbit demonstration through collaboration with JAXA, which has knowledge and technique of EDT.

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



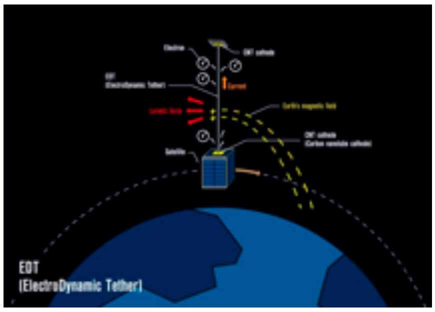
Extend conductive tether from EDT device mounted on microsatellite and de-orbit.
Mitigate the generation of space debris thereby contributing to sustainable space development.

Product Overview

	Standard Model	Carbon Nanotube Model
Appearance		
Function	● After deploy tether, Atmospheric drag and weak electromagnetic force are generated to de-orbit. ● Deploy tether by bus command and timer.	● After deploy tether, Atmospheric drag and weak electromagnetic force are generated to de-orbit. ● Deploy tether by bus command and timer. ● CNT electron emitter accelerates de-orbiting.

Proposal for Space Debris Disposal

Our Electrodynamic Tether (EDT) can solve the challenges and reinforce the efficiency of satellites operation.



EASY ATTACHMENT TO SATELLITES

Our EDT is **very small** device cheap.

FOCUS ON EACH MISSIONS

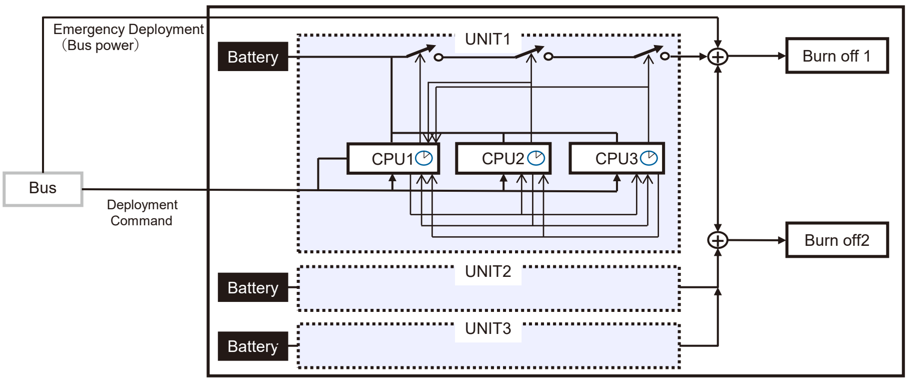
Our EDT is designed to be **particularly reliable for de-orbiting**.

AUTONOMOUS AND RAPID DE-ORBITING

Our EDT **works independently** and enables each satellites to be **de-orbited automatically and rapidly** even if the satellite system is faulted.

Secure Deployment

- Never deploy during the launch and Securely deploy after the mission.
  ・・・Triple Redundancy Decision System and Triple redundant operating system.
  ・・・Tether can be deployed by **Bus command**, **Timer**, and **Bus Power.**
  ・・・Autonomously deploy the tether by independent power supply even if the spacecraft has suffered an unrecoverable fault.
  ⇒Energy saving and long-time driving circuit.
  ・・・Highly reliable burning off system with double redundancy.
- Can be package in a small size, even for CubeSat



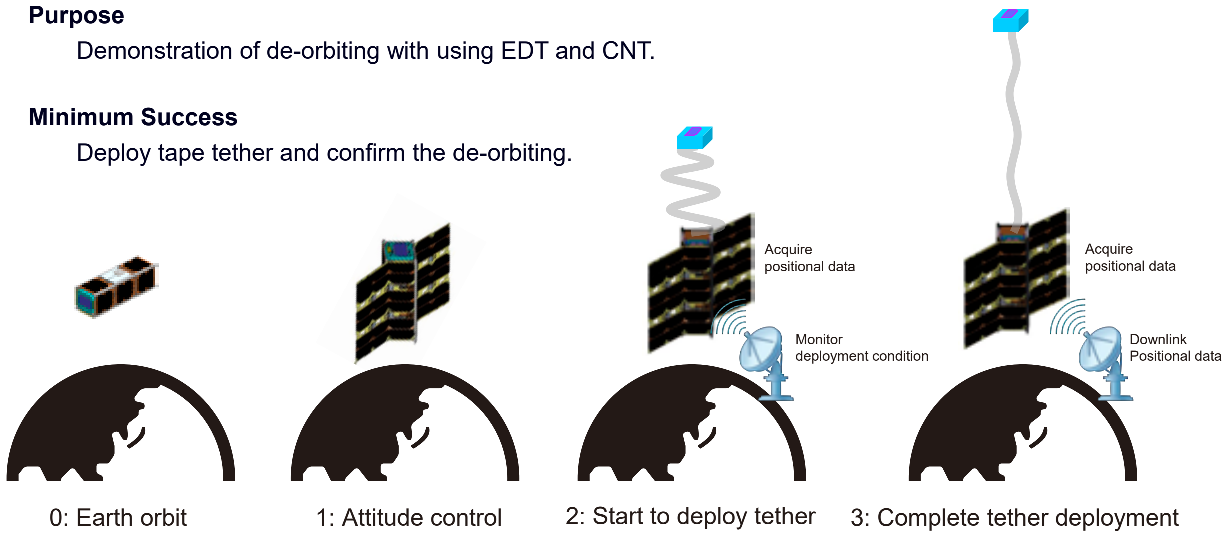
EDT-sat Project

Purpose

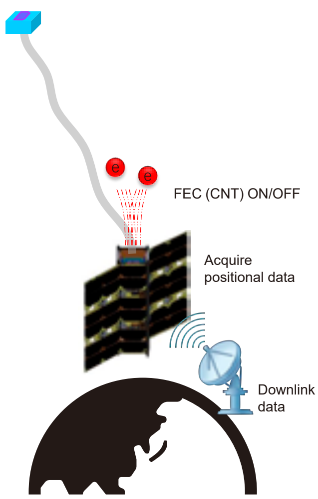
Demonstration of de-orbiting with using EDT and CNT.

Minimum Success

Deploy tape tether and confirm the de-orbiting.



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.

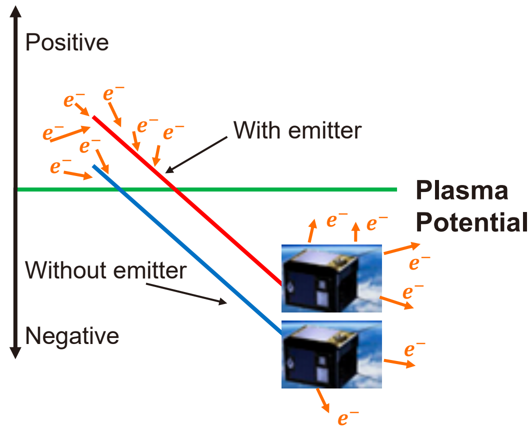
Performance Evaluation

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.



Performance Evaluation

Model

- ✓ • Tether model: Lumped mass model connected by springs and viscous dampers
- ✓ • Electron collection model: 2D-OML theory
- ✓ • Ion collection model: 2D-OML and Orbital velocity
- ✓ • Plasma model：IRI2016
- ✓ • Geomagnetic field：IGRF-12（10×10）
- ✓ • Atmosphere model：NRLMSISE-00
  ※ Average projected area is 2 / π of the tether width.

Conditions

Tether type: Tape type tether

Tether dimension: Parametric

Tether material: Metal plated polyimide film

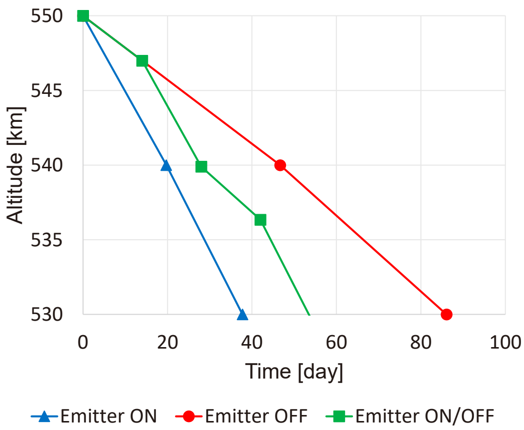
Electron emitter: With or Without

Maximum emission current: 10[mA]

Weight of satellite:5[kg]

Size of satellite:10[cm]×10[cm]×30[cm]

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.

Conclusions

- We developed PMD (Post-Mission disposal) device using EDT, which can be securely deployed in orbit.
- Our developed PMD device obtains the thrust from atmospheric drag and electromagnetic force.
- Atmospheric drag is dominant in lower attitude and electromagnetic force is effective in higher attitude.
- Secure tether deployment system utilize for redundant system functioning for a long time at low power consumption.
- Numerical analysis showed that our developed EDT can reduce the time of required to reenter the atmosphere even if it's in lower attitude.
- The demonstration of EDT-sat is planned to launch in FY2021.

Acknowledgment

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

ALE Co., Ltd.

C12

デブリ除去に向けた 1kW 級ホールスラスタシステムの研究開発

R&D status of JAXA 1-kW Hall Thruster System for Active Debris Removal

○張 科寅，渡邊 裕樹，松永 芳樹，月崎 竜童，
大川 恭志，近藤 大将，艸分 宏昌，山元 透（JAXA）
○CHO Shinatora, WATANABE Hiroki, MATSUNAGA Yoshiki, TSUKIZAKI Ryudo,
OHKAWA Yasushi, KONDO Hiromasa, KUSAWAKE Hiroaki, YAMAMOTO Toru (JAXA)

JAXA では商業デブリ除去実証やその先のデブリ除去事業等を目指し、1kW 級ホールスラスタの研究開発を進めている。500 キログラム級の衛星により、数トン級のデブリの除去を実施するためには、MNs 級のトータルインパルスと、高い比推力が要求されるため電気推進の利用が望ましく、中でも推力電力比が高くミッション期間の制約を満たしやすいことから、1kW 級ホールスラスタが最有力候補と考えられる。ただし、同電力帯の既存ホールスラスタは一般に寿命が短く不足するため、JAXA では技術試験衛星 9 号機で実証される長寿命ホールスラスタ技術をベースとして、低コスト長寿命な小型ホールスラスタシステムの実現を目指している。ホールスラスタヘッドや中和器だけでなく、電源や流量制御器を含めた推進システムとしての研究開発状況を報告する。

JAXA is conducting R&D on a 1kW-class Hall thruster system for active debris removal. The Commercial Removal of Debris Demonstration (CRD2) phase II mission target is several tons of weight, which requires MNs-class of total impulse and high-specific impulse to accomplish. In addition, mission duration is also important from a commercial perspective. Therefore, electric propulsion, especially Hall thruster is the first candidate because of its relatively high thrust-to-power ratio. Since life-limit is challenging for conventional small Hall thrusters, JAXA is targeting low-cost long-life 1kW-class Hall thruster system, utilizing technologies to be demonstrated on JAXA ETS-9 satellite. Research and development status of the system is reported.

R&D status of JAXA 1-kW Hall Thruster System for Active Debris Removal
デブリ除去に向けた1kW級ホールスラスタシステムの研究開発

○Shinatora Cho, Hiroki Watanabe
Yoshiki Matsunaga, Ryudo Tsukizaki
Yasushi Ohkawa, Hiromasa Kondo
Hiroaki Kusawake, Toru Yamamoto
(JAXA)

Background

CRD2 (Commercial Removal of Debris Demonstration)

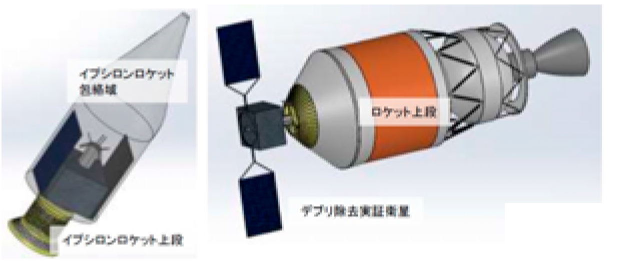
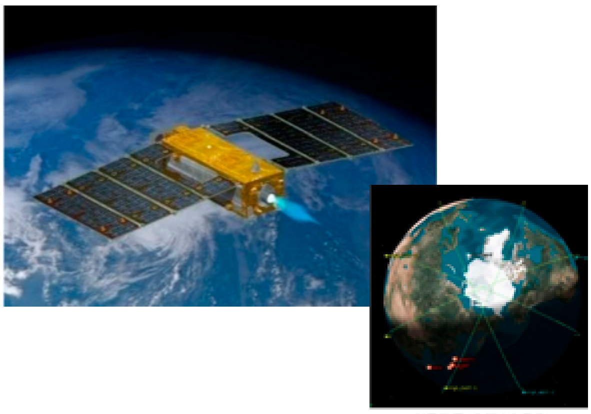


図4 検討結果を反映した衛星外観

イプシロンロケットへの搭載を可能とし、PAF1194のデブリに対応した衛星サイズ（航法センサの取り付け条件）を実現。
打上重量500kg以内での実現性の目途を得た。

Successor mission of TSUBAME (SLATS)

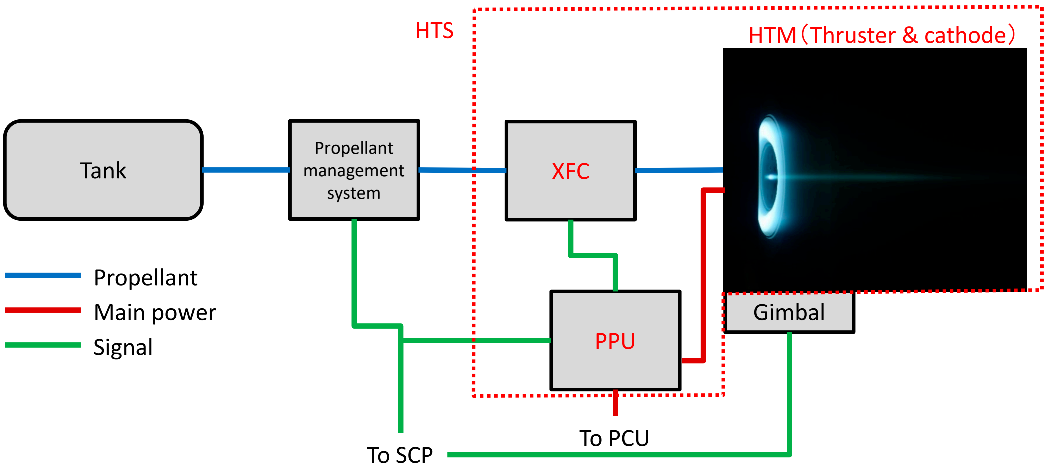


衛星配置（北極から見る）

- **Long-life, powerful, low-cost and robust EP system** demands for JAXA LEO missions
- FY2019, JAXA started research and development of 1-kW class Hall thruster system (in-house)

➡FY2021, initiating EM-phase
➡FY2024, FM ready
➡FY2025, CRD2 phase2 mission: satellite launch

HTS(Hall thruster system) components



HTM（Thruster & cathode）

- **Life-test necessary.**

PPU（Power processing unit）

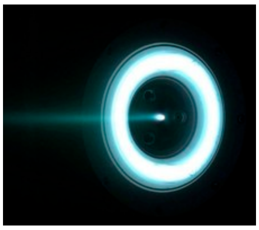
- **Mass & cost driver.**

XFC（Flow controller）

- **Important in terms of HTM/PPU interface.**

HTM key concepts

HTM-LM firing

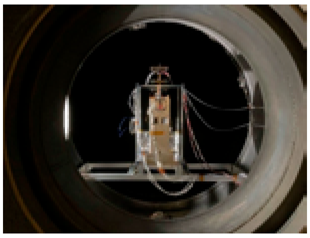


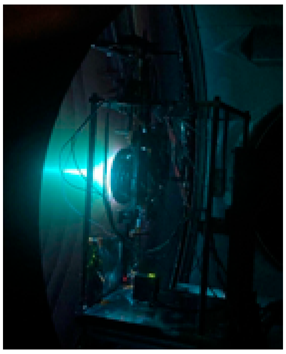
HTM-BBM image

Advanced materials

- **Target**: Long life small Hall thruster **(10,000 hrs, 10,000 cycles)**
- Key technologies :
  -Internal mounted cathode
  -Low-erosion magnetic field topology
  -Radiative cathode heater
  will be demonstrated in JAXA Engineering Test Satellite-9's 6-kW Hall thruster
- **Unified design of Hall thruster with internal cathode**
- **Advanced materials and structures** (patents to be published)
- Fully utilization of **JAXA ion thruster neutralizer heritage**
- **Physics-based modeling** and design tools

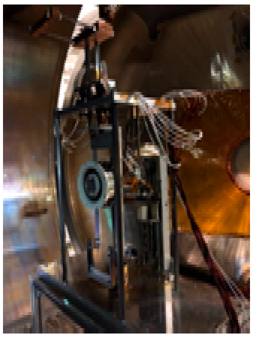
HTM Operations and setups in JAXA facilities

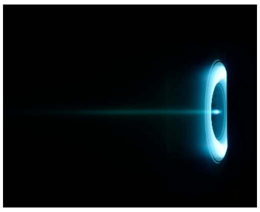




3m ion thruster chamber (Chofu)

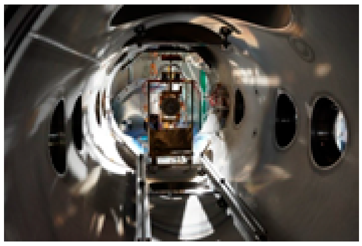
3E-6 torr @1kW

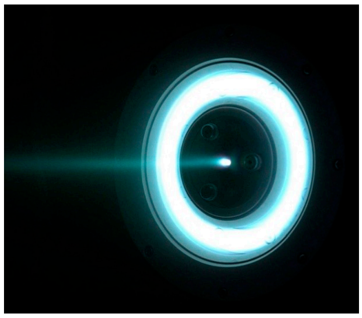




Space science chamber (ISAS)

4.5E-5 torr @1kW

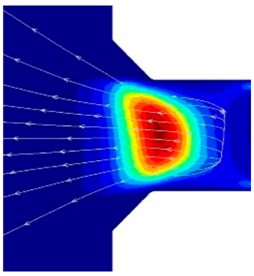




Small EP chamber (ISAS)

3E-5 torr @1kW

Measurement & modeling: thrust performance



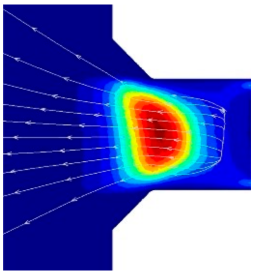
Mass, momentum, and energy conservation

- Plasma production
- Beam trajectories
- Thrust, discharge current, etc.
- Erosion due to sputtering
- Energy loss and deposition

Experiment VS simulation

	Experiment (ISAS)	PIC simulation
Background pressure	4.5E-5 torr	(input) 0 torr
Discharge voltage	300.8 V	(input) 300 V
Xe anode mass flow rate	3.5 mg/s	(input) 3.5 mg/s
Discharge current	2.9 A	2.7 A
Thrust	58.2 mN	57.9 mN
Anode Isp	1694 s	1689 s
Anode thrust/power ratio	66.2 mN/kW	71.3 mN/kW
Anode efficiency	55%	59%

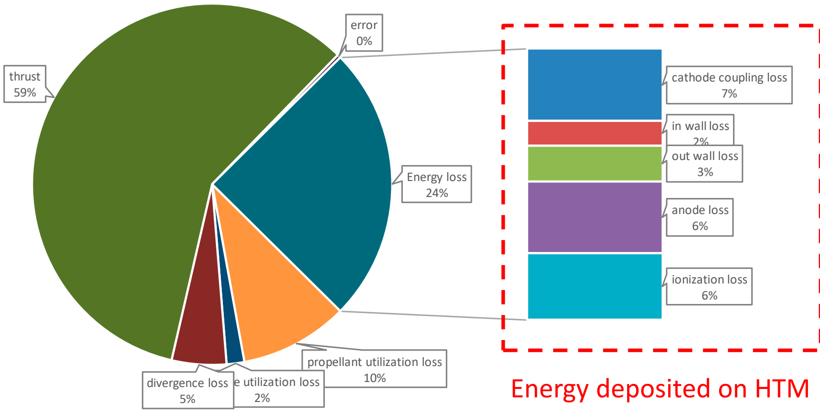
Measurement & modeling: energy balance and thermal analysis



Mass, momentum, and energy conservation

- Plasma production
- Beam trajectories
- Thrust, discharge current, etc.
- Erosion due to sputtering
- Energy loss and power deposition

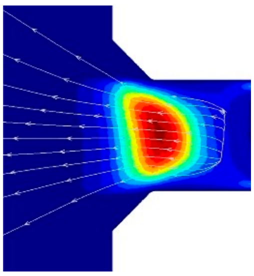
Energy balance



Energy deposited on HTM

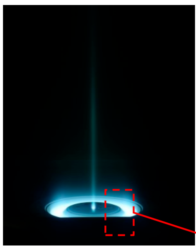
Thermal analysis

Measurement & modeling: erosion and life estimation

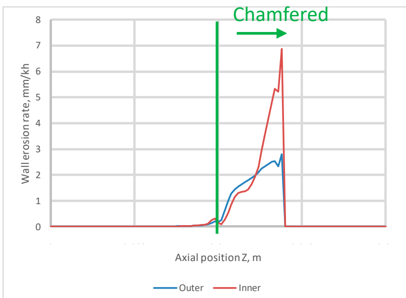


Mass, momentum, and energy conservation

- Plasma production
- Beam trajectories
- Thrust, discharge current, etc.
- Erosion due to sputtering
- Energy loss and power deposition



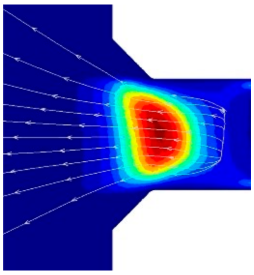
Channel observation after HTM operation



Simulated channel erosion rate

Life estimation

Measurement & modeling: beam divergence and interference

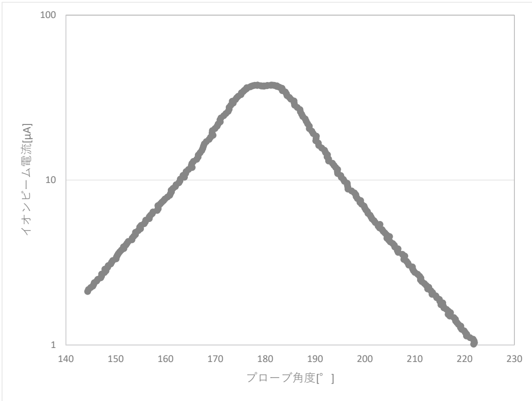


Mass, momentum, and energy conservation

- Plasma production
- Beam trajectories
- Thrust, discharge current, etc.
- Erosion due to sputtering
- Energy loss and power deposition

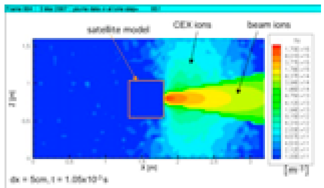
Engine model

Ion beam measurement



- Measured by Faraday cup at 1.26 m downstream of HTM-BBM
- Beam divergence:
  27 deg (90% current)
  30 deg (95% current)
- Estimated error: ±3 deg

Satellite plume interference
Muranaka, IEPC-2007-197



Technology development status

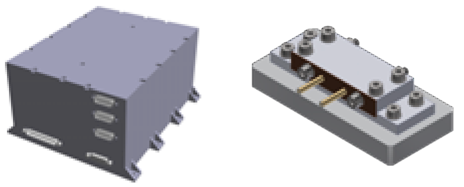


Image of PPU-EM (left) and XFC-BBM (right)

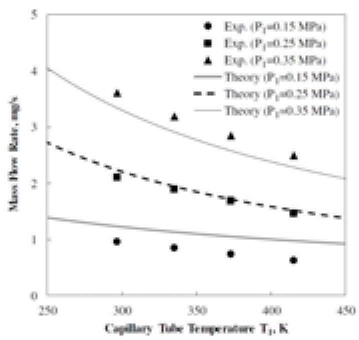


Fig. 14 Comparison of mass flow rates between experiment and theoretical estimation [turbulent case, Eq. (10)].

Flow control characteristics by capillary flow controller (Kinefuchi, JPP vol.36, No. 4, 2020)

HTM
- 240 hrs, 100 cycles completed by LM
- 20 hrs, 10 cycles completed by BBM
- Further BBM life-test planned
- Shock and random vibration analyzed. BBM mechanical tests planned

PPU
- Light-weighted, low-cost PPU
- Anode coupling test successfully completed with HTM-LM
- PPU-BBM coupling test with HTM-BBM planned

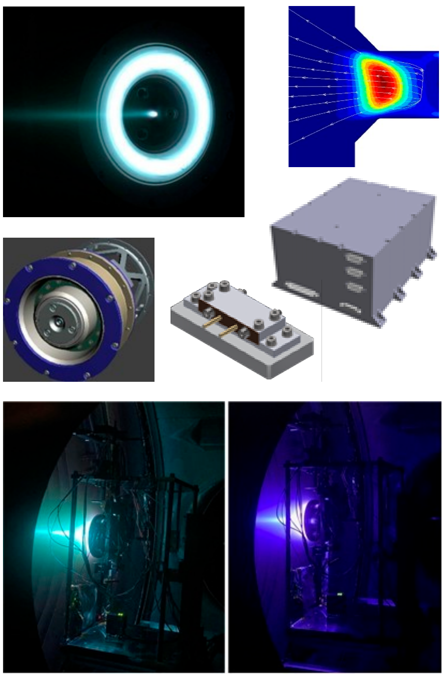
XFC
- Light-weighted, robust, low-cost capillary flow controller
  (based on journal publication)
- BBM Coupling test planned

➡Initiating EM phase in FY2021

HTS key specifications

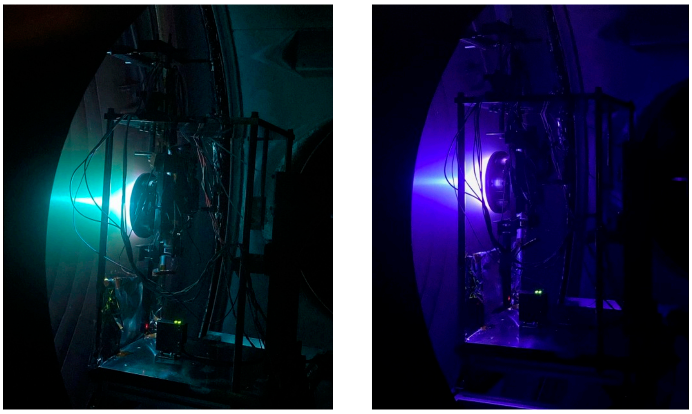
Items	Target (TBD)	BBM results (@HTM 887W, 3E-6 torr)
Total power [W]	≦1100	-
HTM power [W]	(1000)	887
Life [hrs]	≧10000	240 (LM) and 20 (BBM) completed
ON cycles	≧10000	100 (LM) and 10 (BBM) completed
Total Isp [s]	≧1600	1543
Total Thrust/power ratio [mN/kW]	≧61	65.6
Plume divergence [degree]	≦45	27 (90% current)
Total mass [kg]	≦15	~10

Summary: Novel 1-kW class Hall thruster system



- **Unified design of Hall thruster with internal cathode**
- **Advanced materials and structures** (patents to be published)
- **High performance**: Isp 1600sec, 65 mN/kW
- **Long life**: 10,000 hrs, 10,000 cycles(expected)
- **System friendly**: low-plasma oscillation, high-environmental resistance, beam divergence~30deg
- **Cost-effective, low-mass power supply and flow controller**
- **200 hrs operation completed** at JAXA ultrahigh-vacuum facility
- **Physics-based modeling** and design tools
- FY2019 project started. **FY2021 initiating EM phase**

THANK YOU FOR LISTENING



Xe (left) and Kr (right) operation

C13

ADR 作業の為の非協力的ターゲット捕獲・把持機構の検討

A Study of Target Capture Device for Active Debris Removal

○中西 洋喜, 川口 直毅, 林 輝明, 鷲 優希, 橋本 拓哉,
増田 雄斗, 多賀 啓介（東京工業大学）
○NAKANISHI Hiroki, KAWAGUCHI Naoki, HAYASHI Teruaki, WASHI Yuki, HASHIMOTO Takuya,
MASUDA Yuto, TAGA Keisuke (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 order to realize the active debris removal (ADR), capturing debris and attaching a debris removal device (ex. micro thruster, EDT, and deorbit membrane) to debris is a key technology. Any space robot hands in existence cannot capture debris because they require their dedicated fixtures on the capture target. It is essential to establish a simple grasping system for the uncooperative target without such fixtures. The authors study such a grasping system that can grasp the original structure on debris or grasp its whole body. The system can also become a fixing mechanism for debris deorbit devices after separating from the service satellite (robot). In this presentation, the overview of our gripping systems and the latest issues are introduced.

ADR作業の為の非協力的ターゲット捕獲・把持機構の検討
A Study of Target Capture Device for Active Debris Removal

Hiroki Nakanishi, Naoki Kawaguchi, Teruaki Hayashi,
Yuki Washi, Takuya Hashimoto, Yuto Masuda

Tokyo Institute of Techonology

Space Debris WS (2020.Feb.26)

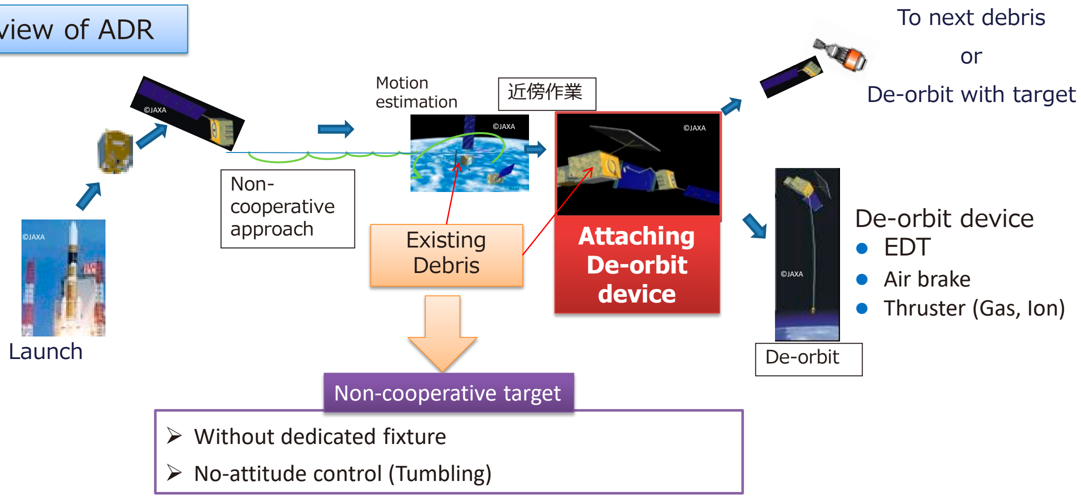
目次

- 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

ADR（Active debris removal）

Overview of ADR

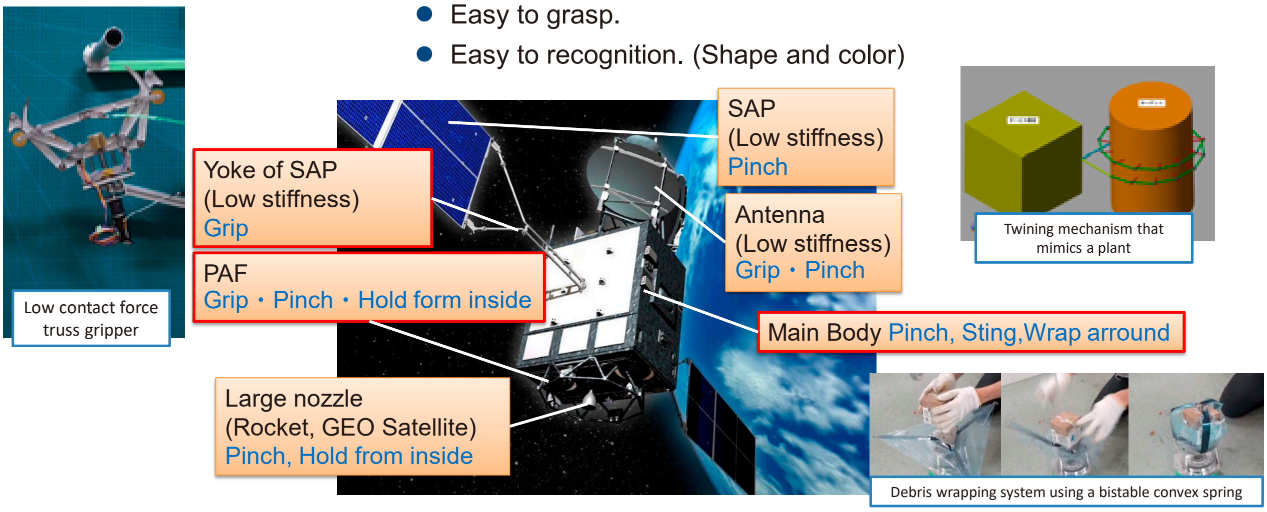


Purpose：
Establishment of a mechanism that enables secure grasping and fixing without causing destruction or ejection by contact force.

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

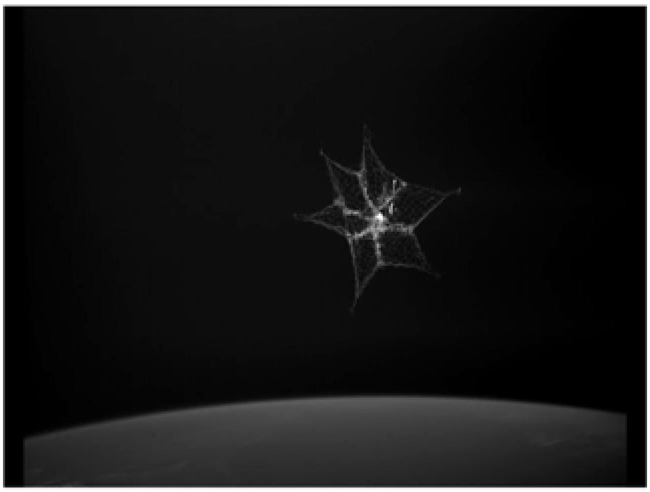
Debris wrapping system using bi-stable convex spring

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



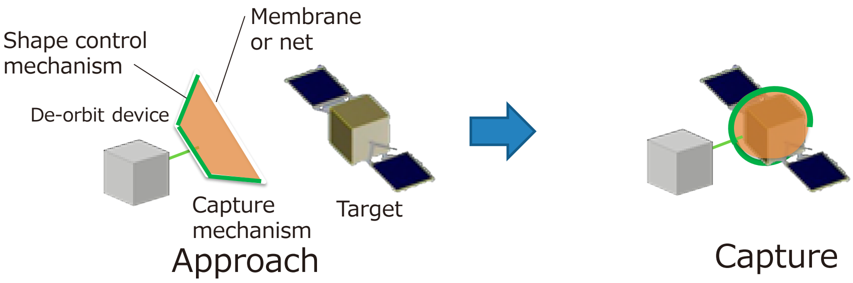
Net casting at RemoveDEBRIS mission ©SSTL

Debris wrapping system using bi-stable convex spring

Wrapping whole body of a target

Concept of the gripper

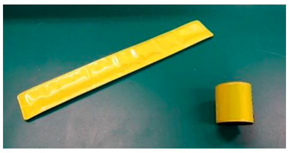
A mechanism that
- holds the shape until contact with the target maintains the grasping state.
- until the deorbit after the completion of grasping.

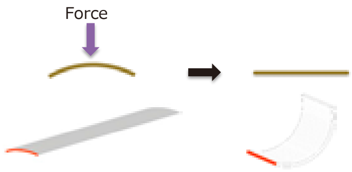


- A structural material that can maintain both the unfolded and grasped shapes is used as a support material for the net and membrane to control the operation of the capture mechanism.

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.

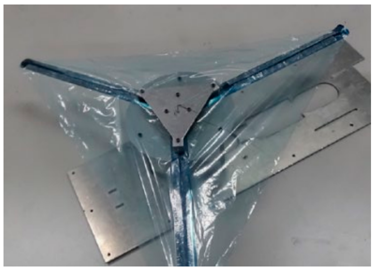




Cross-sectional change of convex spring before and after deformation

Advantages of Convex Spring

- Maintaining its shape
- Automatic contact detection
- Maintaining wrapping force

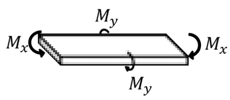


A prototype capture mechanism combined with a membrane.
The gripper is activated when the target contacts the center of the gripper.

Dynamics modeling

From bending theory of thin plate,

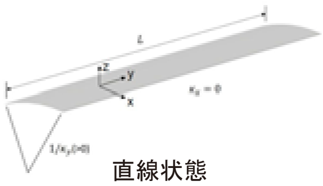
$$\begin{bmatrix}\mathbf{N}\\ \mathbf{M}\end{bmatrix} = \begin{bmatrix}\mathbf{A} & \mathbf{0}\\ \mathbf{0} & \mathbf{D}\end{bmatrix}\begin{bmatrix}\boldsymbol{\varepsilon}\\ \Delta\boldsymbol{\kappa}\end{bmatrix}$$



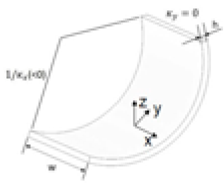
$$\mathbf{M} = \begin{bmatrix}M_x\\ M_y\end{bmatrix} = \mathbf{D}\Delta\boldsymbol{\kappa} = \frac{Eh^3}{12(1-\nu^2)}\begin{bmatrix}1 & \nu\\ \nu & 1\end{bmatrix}\begin{bmatrix}\Delta\kappa_x\\ \Delta\kappa_y\end{bmatrix}$$

$\mathbf{A}$	Axial rigidity matrix
$\mathbf{D}$	Bending stiffness matrix
$\mathbf{N}$	Stress
$\mathbf{M}$	Bending moment
ν	Poisson's ratio
κ_{x_0}	Curvature in coiled state (no load)

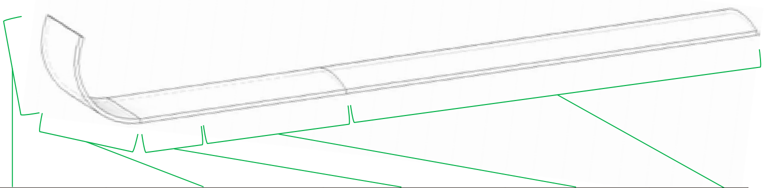
$\boldsymbol{\varepsilon}$	Strain
$\Delta\boldsymbol{\kappa}$	Increment of curvature
E	Young's modulus
h	Board thickness
w	Width of spring
κ_{y_0}	Cross-sectional curvature in straight state



直線状態



巻き付き状態

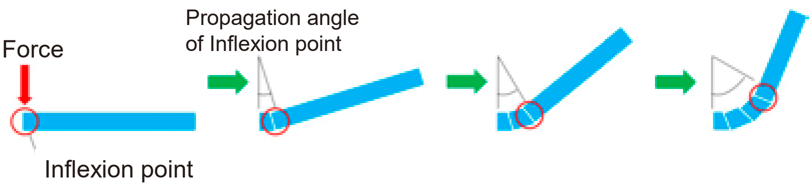


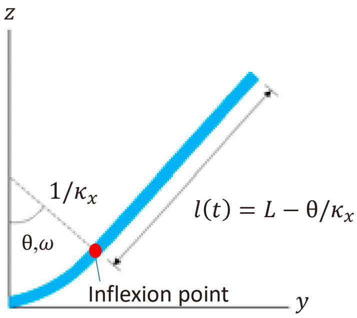
State / Bending moment	Coil stable	Coil transition	Flat	Convex transition	Convex stable
M_x	$D\nu\kappa_{y_0}$	$D\left(\Delta\kappa_x + \nu\kappa_{y_0}\right)$	$D\left(\kappa_{x_0} + \nu\kappa_{y_0}\right)$	0	0

The Coiling torque τ is given as $\tau = wM_x$

Dynamics modeling

Propagation of coiling torque ⇒ Coiling motion of spring





Equation of rotational motion around an inflection point

$$I\frac{d^2\theta}{dt^2} = \tau_0 \quad \begin{cases} \tau_0 = \dfrac{Ewh^3}{12(1-\nu^2)}(\kappa_{x_0} + \nu\kappa_{y_0}) \\ I \cong \dfrac{1}{3}\rho wh\left(L - \dfrac{\theta}{\kappa_{x_0}}\right)^3 \end{cases}$$

The propagation distance along the spring $l(t)$ is:

$$l(t) = \frac{\theta}{\kappa_{x_0}}$$

$$= L - \sqrt{L^2 - \frac{\beta L}{\kappa_{x_0}}t^2} \quad (\mathbf{0} \leq \boldsymbol{l}_{(t)} \leq \boldsymbol{L})$$

$$\beta = \frac{Eh^2(\kappa_{x_0} + \nu\kappa_{y_0})}{4(1-\nu^2)\rho L^3}$$

E	Young's modulus
ρ	Density
w	Width
h	Thickness
L	Length

κ	Curvature
ν	Poisson's ratio
I	Inertia moment around inflexion point
τ_0	Coiling torque

Modeling of convex spring

In case that the spring contacts with a target,
the model become complicated.

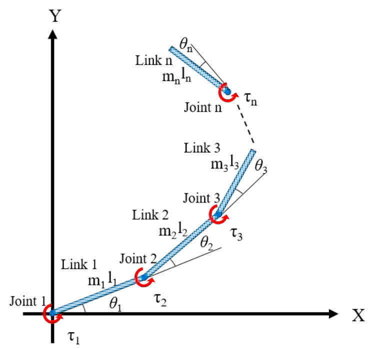
⇒ Approximation with multi link model

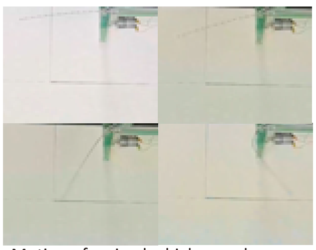
Equation of motion $[\mathbf{I}_{(\theta)}][\ddot{\theta}] + [\mathbf{I}_{\mathbf{V}(\theta)}][\dot{\theta}^2] + [c][\dot{\theta}] = [\tau]$

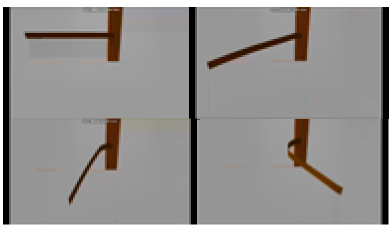
from Specification of spring

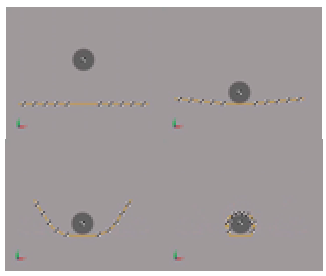
from Coiling torque model

from Torque Propagation model




Motion of spring by high speed camera

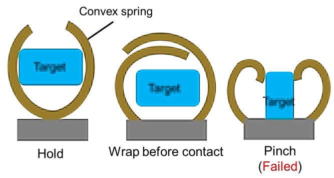

Simulation result

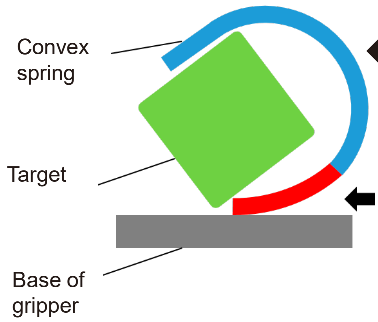

Numerical simulation of target capture

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





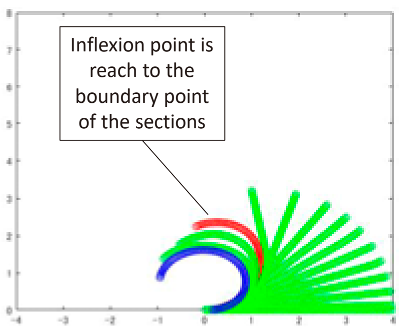
End tip side
Fast propagation of inflexion point
⇒Fast tightening up

Root side
Slow propagation of inflexion point
⇒ Inhibiting end tip coiling before enclosing

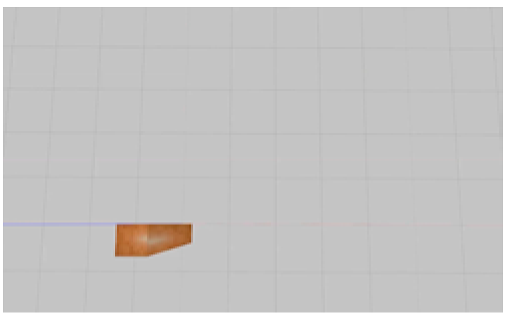
This is achieved by changing the curvature of the cross-sectional shape.

Design of convex spring for gripper

Simulation results with different cross-sectional curvature in the middle of the spring



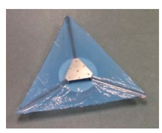
History of spring motion

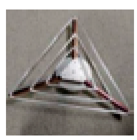


Simulation result (1/5 speed)

An ideal motion of convex spring is obtained by selecting and combining the spring parameters.

Next issue — Construction of a mechanical model of a mechanism that combines a membrane or net with a convex spring.





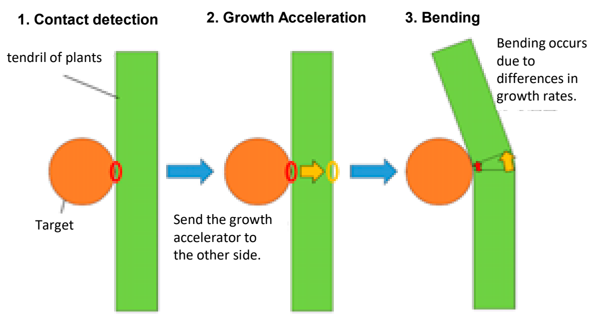
Twining mechanism that mimics a plant

Twining characteristics of plants

Thigmotropism of tendril of plants

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.

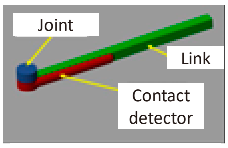
- Applying this property to a multi-link arm enables adaptive wrapping around a target.
- Each link is controlled independently by its own contact detection, so each link has the characteristics of a swarm robot.
  - **Easy to modularize.**
  - **Various configurations can be taken according to the target.**

Purpose

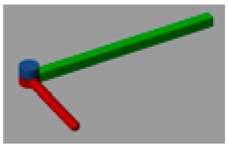
Design and algorithm of an adaptive winding mechanism based on a thigmotropism of tendril is discussed.

Concept design of twining mechanism

Module unit

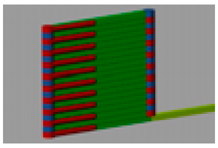


Stored state

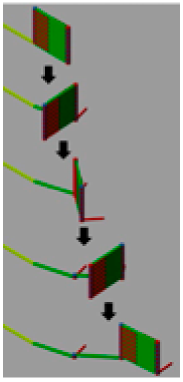


Deployed state

Integration design



Stored state of twining mechanism



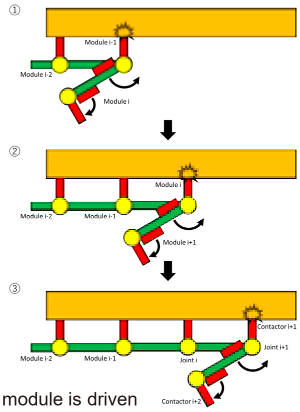
Growth and twining motion

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

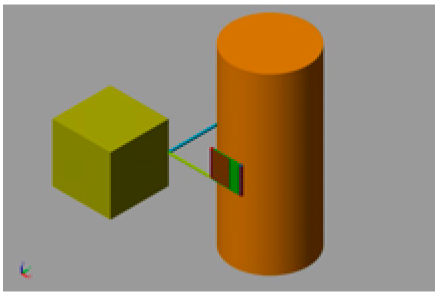


Caging operation is achieved when each module is driven based on its own and neighboring modules' contact history.

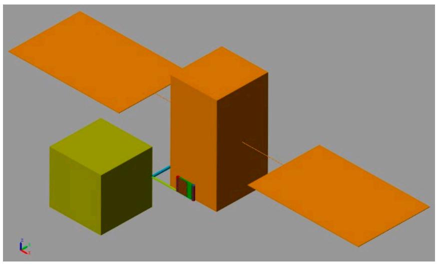
Algorithm for target tightening

- ✓ 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.

Simulation

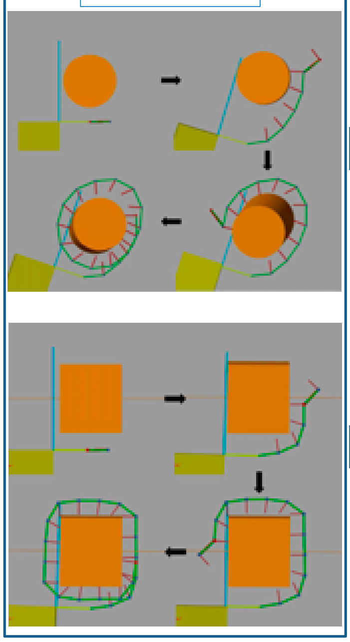


Capture of cylindrical targets (rockets)

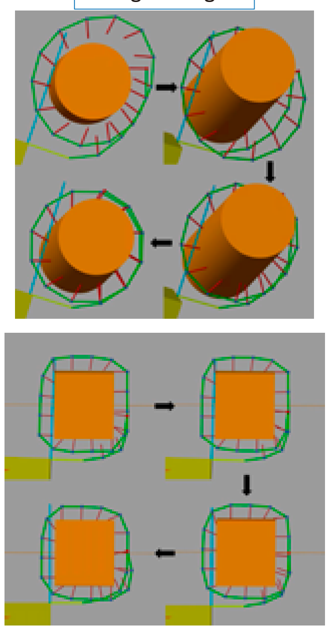


Capture of box-shaped target (satellite)

Caging



Tightening

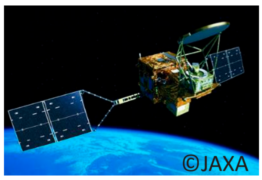


Low contact force truss gripper

Acknowledgement
2017-2019 Joint research of JAXA-Tokyo Tech
「Research on Deorbit Device Attaching System for Large Scale Debris」

Low contact force truss gripper

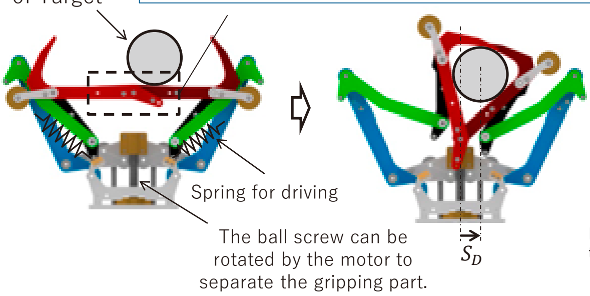
Assumed target :
Rockets and satellites with rod-like structures such as truss-type PAF (e.g. Cosmos 3M)

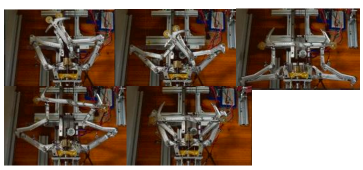


Concept :
Hand and mounting mechanism for attaching a device by simply pressing down.

Model 2018

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.



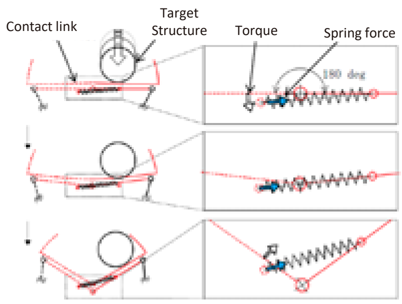


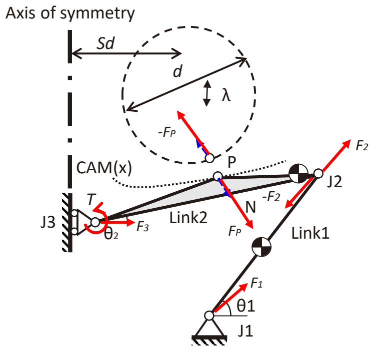
Reversing the disconnection motor restores the initial state.

Capture and separation motion

Dynamics modeling of Low contact force truss gripper

The condition for the mechanism to work:
Work exceeding the elastic energy in the open state of the mechanism is given from the outside.

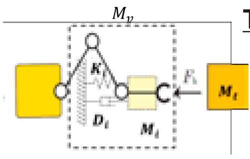




Requirement for energy K to be given to gripper

- Minimum energy required to actuate the EE K_{min}
- Maximum allowable energy K_{max} to avoid causing structural failure

$$K_{min} \le K \le K_{max}$$

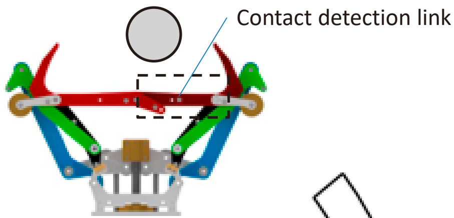


Transfer energy

When the virtual mass due to the mechanical impedance of the robot arm (Nakanishi, 2010) matches the virtual mass of the target contact point (Asada, 1983), impedance matching occurs and the transfer energy is maximized.

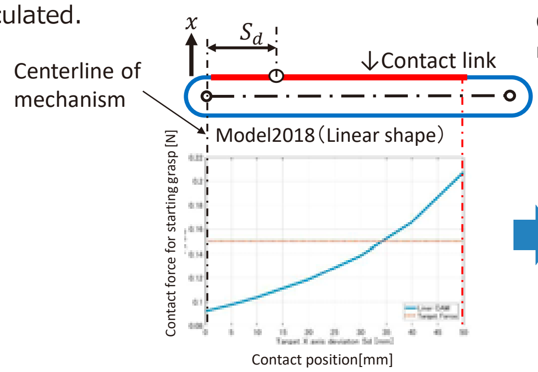
Low contact force truss gripper

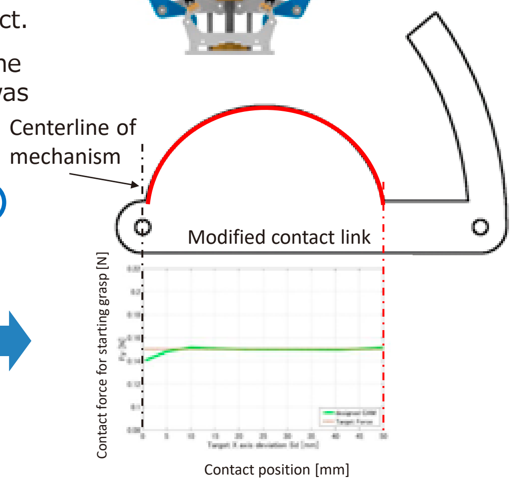
Improvement of the shape of the contact



When the contact detection link is a straight line, the amount of work due to the contact force changes depending on the position of the contact.

From the dynamics model, the shape in which the hand moves regardless of the contact position was calculated.





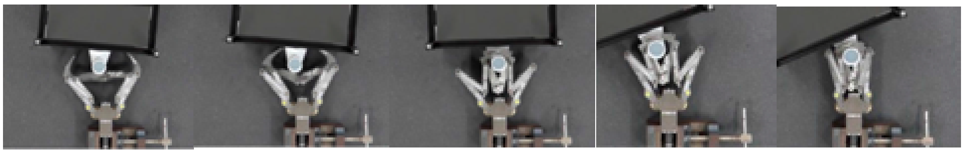
Relationship between the contact point and contact force for starting grasp

Low contact force truss gripper (Model 2020)

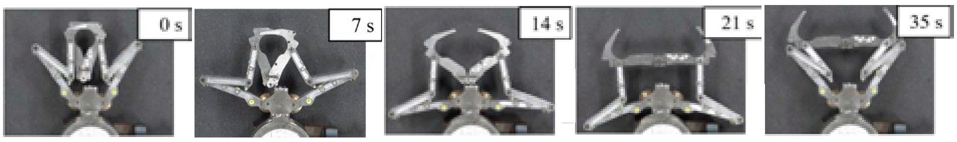
Modification of gripper

- 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

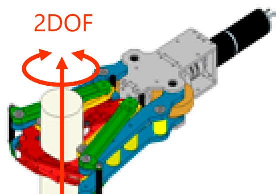


Recovery motion



Low contact force truss gripper

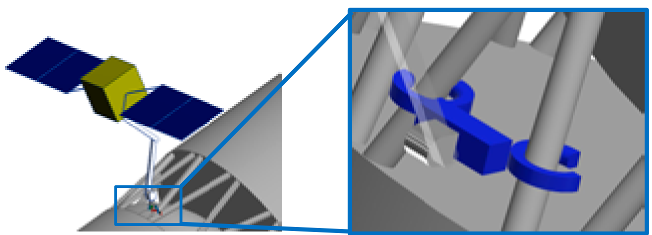
Extension to 6DOF constraints



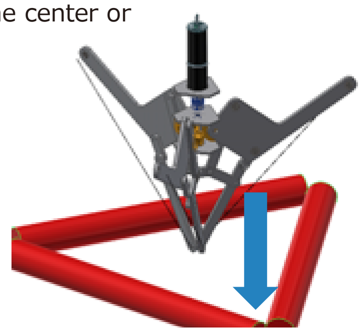
- When using a thruster as a deorbit device (when a controlled deorbit is required, such as for large debris), it is necessary to ensure that all six degrees of freedom are constrained.
- Fixation by friction is difficult to guarantee because it depends on surface conditions.

Realization of 6DOF constraint by grasping multiple trusses simultaneously

We are considering a mechanism for capturing by pressing against the center or the base of the V-shaped section of the truss.



トラス把持イメージ



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 bistable convex were clarified.
- A mechanism that mimics the twining motion of plants is being investigated.
- The mechanical analysis and design of a hand that can grasp a truss structure by simply pushing on it are clarified.

2017-2019 Joint research of JAXA-Tokyo Tech "Research on Deorbit Device Attaching System for Large Scale Debris."

C14

ロバスト性の向上を目指したデブリ捕獲機構のコンセプトと開発状況

Concept and Development Status of Robustness Improved Caging Based Debris Gripper (HKK)

○谷嶋 信貴, 岡本 博之, 壹岐 賢太郎, 渡邊 惠佑, 奥村 哲平（JAXA）
○TANISHIMA Nobutaka, OKAMOTO Hiroyuki, IKI Kentaroh, WATANABE Keisuke, OKUMURA Teppei (JAXA)

宇宙活動の安全を維持するための手段として、ADR が注目されている。大型のデブリを除去するためには、捕獲する技術が必要となる。そこで筆者らは、過去の研究で 3 式の伸展機構から構成される捕獲機構を検討し、提案した。この捕獲機構は PAF を有する大型デブリに対してケージングによる捕獲、フォームクロージャによる把持を実現することが可能であり、先行研究によってコンセプトの実現性を実験により示した。 しかし、制御が不可能であり、かつ捕獲把持されるような設計となっていない対象の捕獲把持を目的としている以上、ミッションの確実な成功のために故障許容設計は非常に重要である。そこで、筆者らは先行研究のコンセプトを維持しながら1故障許容を可能とすることで捕獲機構のロバスト性の向上を実現する新しい捕獲機構のコンセプトを考案した。 本発表では、ロバスト性の向上を目指したデブリ捕獲機構のコンセプト提案と、その試験モデルの開発状況を紹介する。

ADR is attracting public attention as one of the method to ensure the safety of space missions. In order to remove the large sized debris, the capturing gripper is required. Therefore, the authors have studied and proposed the debris gripper consisting of three extension mechanisms. This gripper can realize caging-based capture of the PAF, and grasp it by a form closure. This concept and mechanism's feasibility are experimentally verified. However, since the target of such gripper is un-controllable object and does not designed to be grasped, fault tolerant design is very important to ensure the success of the mission. Therefore, we developed a new concept of debris gripper that improves the robustness of the previous gripper by adding fault tolerant design. In this presentation, we propose a new robustness improved debris gripper's concept and development status of the test model.

Concept and Development Status of Robustness Improved Caging Based Debris Gripper (HKK)

Tanishima Nobutaka, Okamoto Hiroyuki, Iki Kentaro,
Watanabe Keisuke and Okumura Teppei (JAXA)

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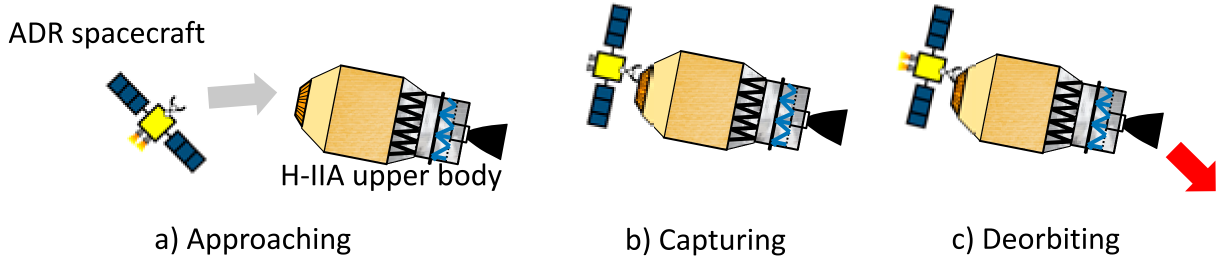
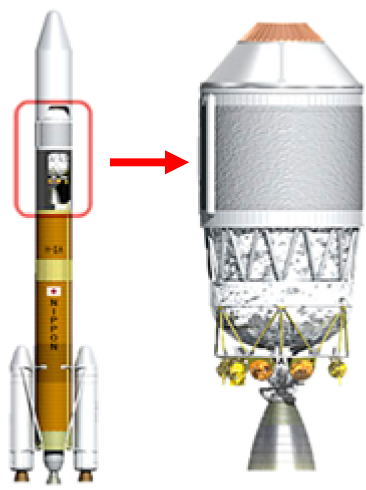
Introduction : Role of the Gripper



Capturing and ***Grasping*** functions are required to the gripper realizing Active Debris Removal.

Introduction : Target and Grasping Point



Information of the H2A upper body	
Length (m)	9.2
Diameter (m)	4.0
Mass (t) without propellant	3.1

H-IIA is one of the candidates of ADR target, ***PAF*** is selected as capturing and grasping point.

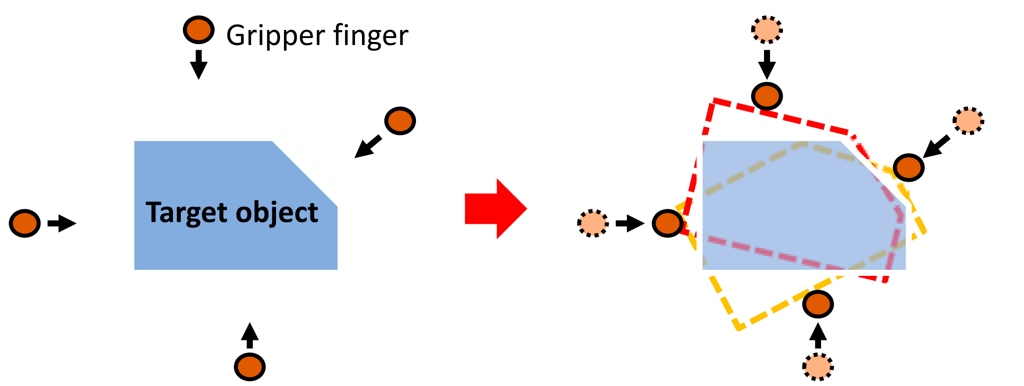
Images and Information from : *https://global.jaxa.jp/projects/rockets/h2a*

Introduction : Requirements

- Capable of capturing PAF, even position, attitude, relative velocity and angular velocity existing.
- Avoid push the target away during the capture.
- Grasps the PAF during ADR spacecraft deorbiting.
- Retry capability for capturing failure, and future ADR missions.
- Simpler design considering to use on orbit.

These would be the minimum requirements to the gripper.
Developed 1st BBM of the Caging Based Debris Gripper.

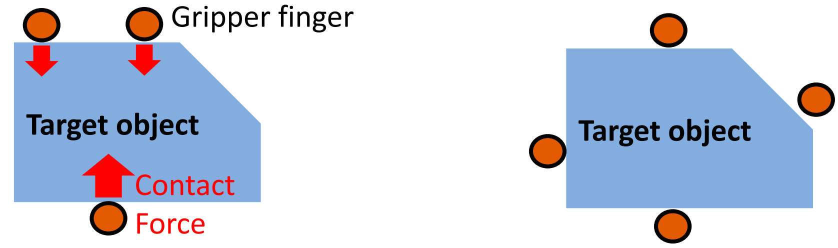
Caging Based Debris Gripper BBM1 : Capturing Method



a) Before Caging configuration satisfied b) After Caging configuration satisfied

Caging technique accepts larger position and attitude errors, and avoid pushing target away.

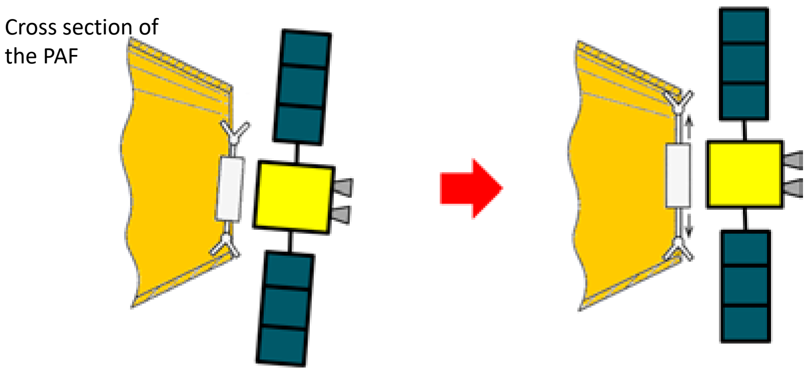
Caging Based Debris Gripper BBM1 : Grasping Method



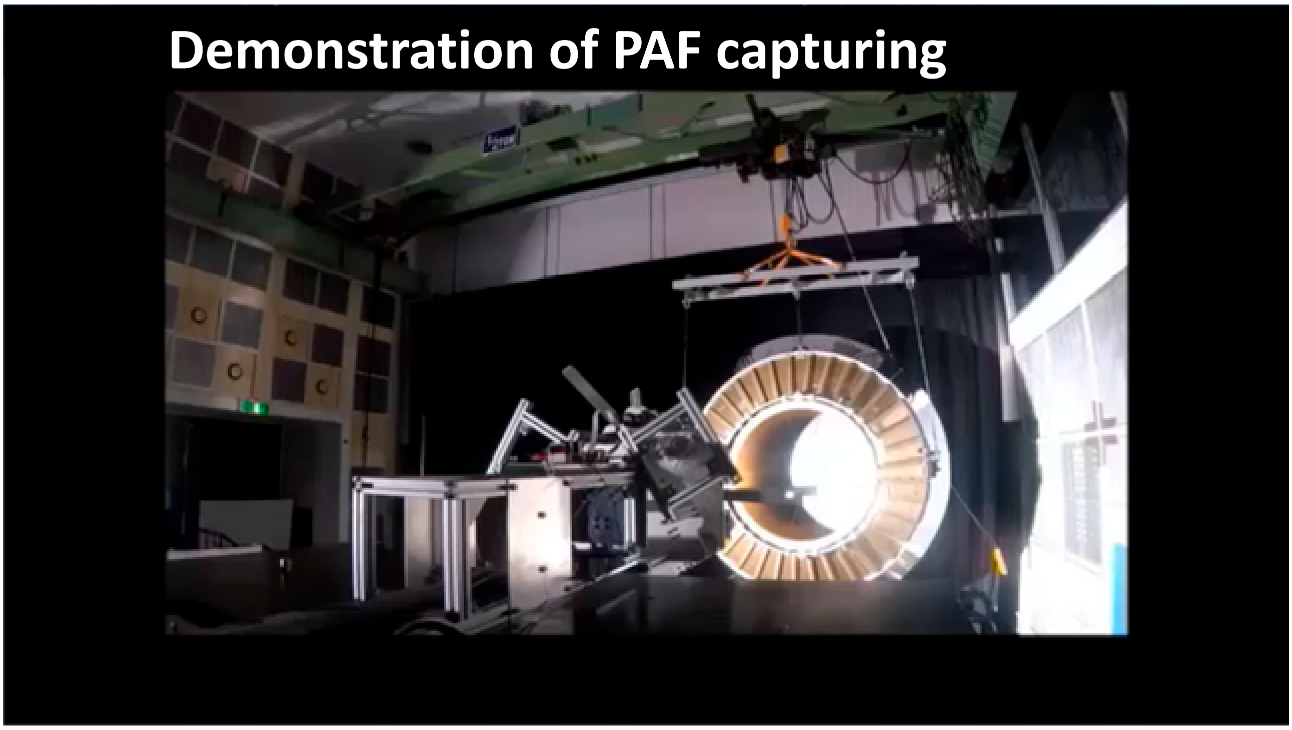
a) Force closure b) Form closure

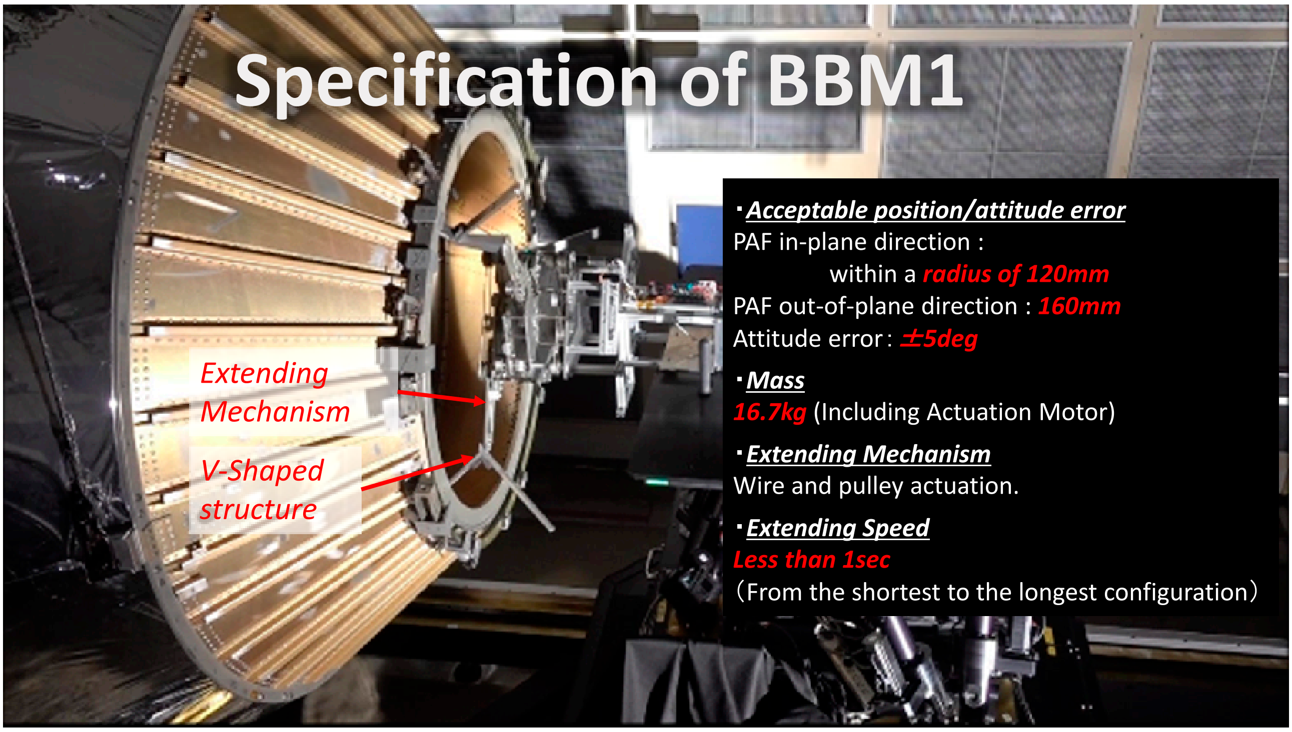
Form closure geometrically enclose the target, meaning it does not affected by the unknown contact dynamics.

Caging Based Debris Gripper BBM1 : Concept



The gripper consisted of extending mechanism, and V shaped structure at the end of the extending mechanism .


Demonstration of PAF capturing


Specification of BBM1
Extending Mechanism
V-Shaped structure
・Acceptable position/attitude error
PAF in-plane direction :
within a radius of 120mm
PAF out-of-plane direction : 160mm
Attitude error : ±5deg
・Mass
16.7kg (Including Actuation Motor)
・Extending Mechanism
Wire and pulley actuation.
・Extending Speed
Less than 1sec
（From the shortest to the longest configuration）

Summary of BBM1

Experimental verification and demonstration showed BBM1 satisfied the requirement, and the gripper can capture and grasp the PAF.

BUT,

- Not redundant to failure.
- Requires the discussion and design improvement to use in space.

BBM2 development

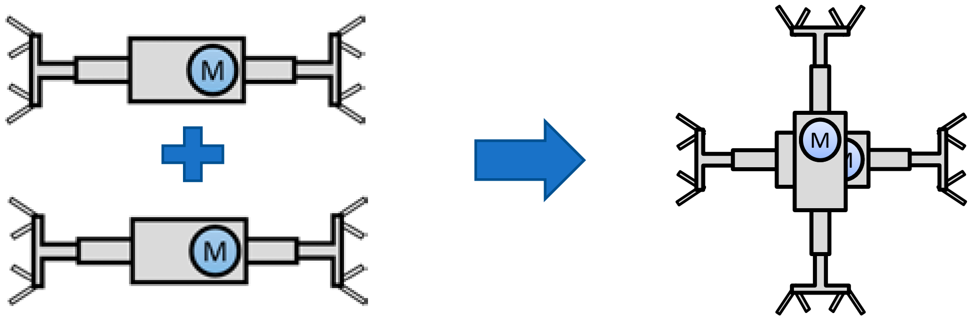
Concept of BBM2

- Capture and grasp the target with the same technique.
  →Caging capture and Form closure.
- Redesign the model to have redundancy.
  →1 Failure Operational design.

Activity to increase TRLs.

- Experiment and analysis to use in space.
  →Discussing the requirement and introducing the status.

Conceptual design



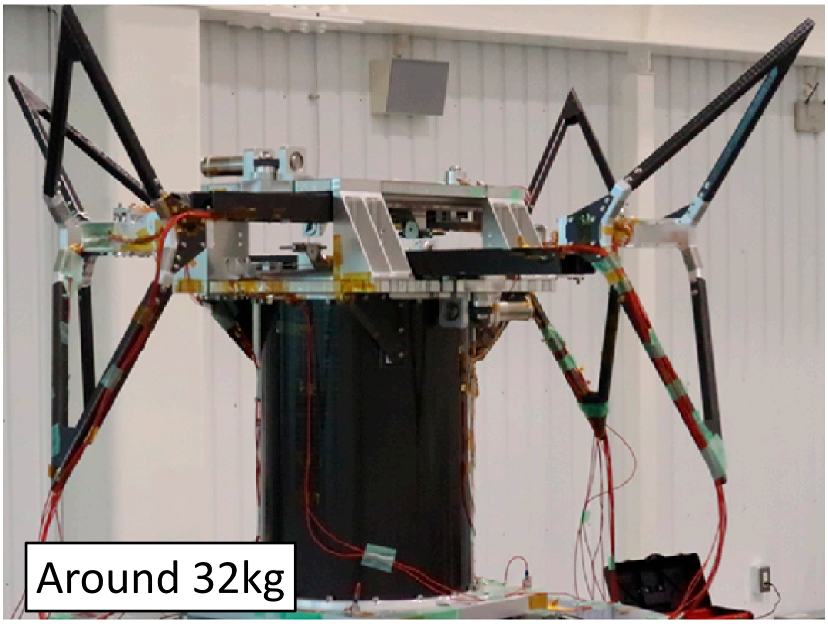
Composed of 2 systems. Each individual system can capture the debris without the other system, meaning this gripper is fully redundancy to the 1 failure.

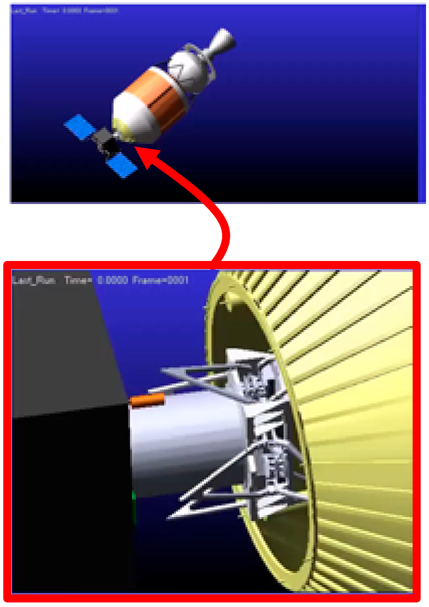
→ Named「JAXA HKK」(捕獲機構 **H**o**K**aku **K**iko)

To be used as satellite's component of capturing and grasping the debris, these are the part of the items that should be evaluated experimentally, analytically, or both.

- Misalignment tolerant
- Actuation mechanism
- Safety against launch vibration
- Thermal test
- Safety against collision and contact force
- Safety against generated stress during capturing

Developed JAXA HKK BBM2

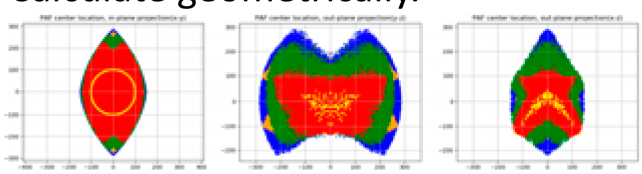




JAXA HKK BBM2 : Misalignment tolerant

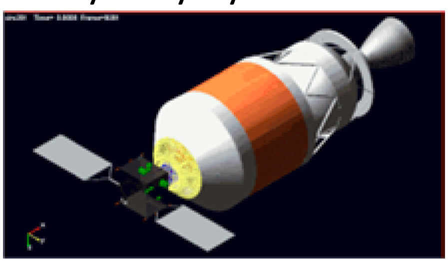
Acceptable misalignment of position and attitude are affected by the design of the V shape.

→Calculate geometrically.



・Caging based acceptable misalignment
PAF in-plane direction :
within a ***radius of 50mm***
PAF out-of-plane direction : ***100mm***
Attitude error : ***±10deg***

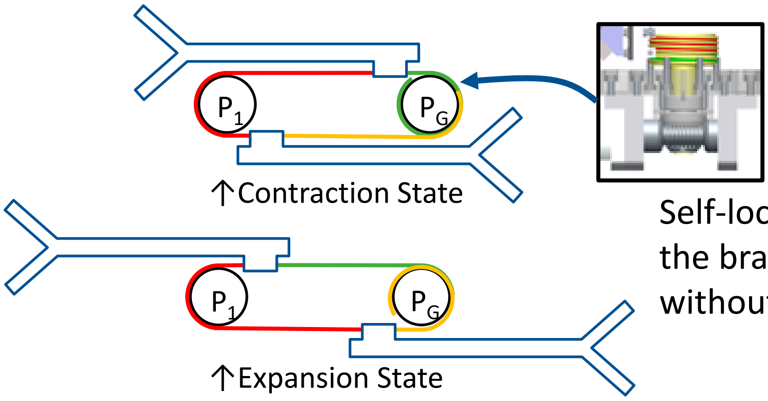
→Analyze by dynamics simulator.



Developing the multibody dynamics simulator using ***ADAMS***.

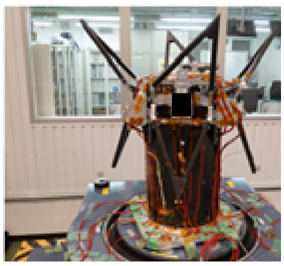
JAXA HKK BBM2 : Actuation Mechanism

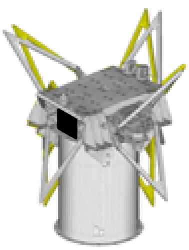
- ✓ During the deorbit phase, the gripper should keep grasping the target even there is no power supply.
- ✓ Actuation mechanism should composed of the parts can be used in vacuum, thermal environment.



Self-locking worm gear and wheel for the brake of the actuation mechanism, without power supply.

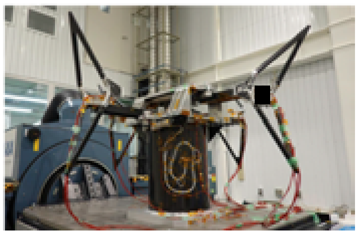
JAXA HKK BBM2 : Safety against launch vibration





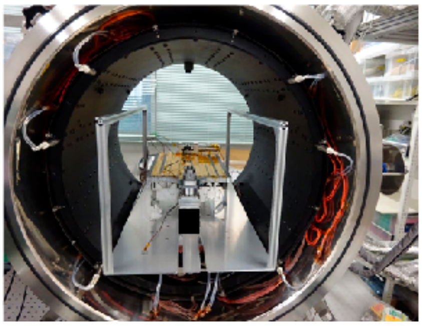
Create a structural mathematical model for both contraction and expansion state.

By the vibration test, model correlation is conducted.

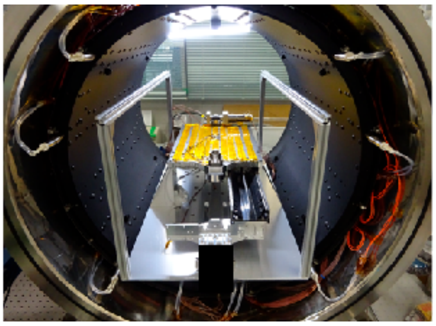


Planning minor modification of the design to withstand the several types of launching rockets' vibration.

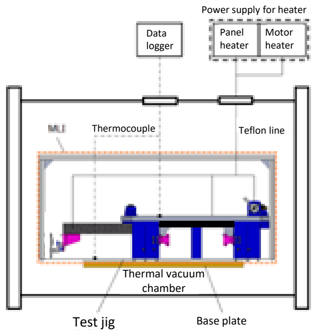
JAXA HKK BBM2 : Thermal test

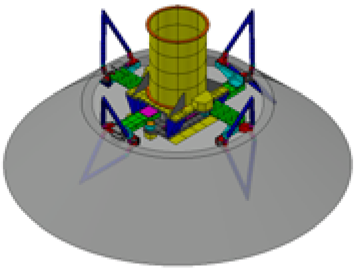


Contraction State



Expansion State



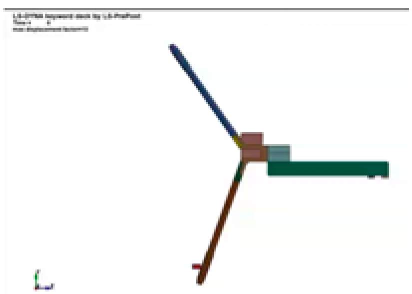


Create a thermal mathematical model for both contraction and expansion state.

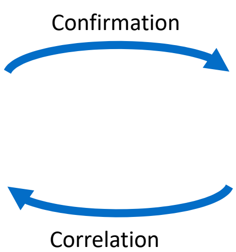
By the partial thermal test, model correlation is conducted.

JAXA HKK BBM2 : Safety against collision and contact force

✓ Even in the worst possible condition of the collision, large-scale plastic deformation should not occur.



Simulating the collision using LS-dyna

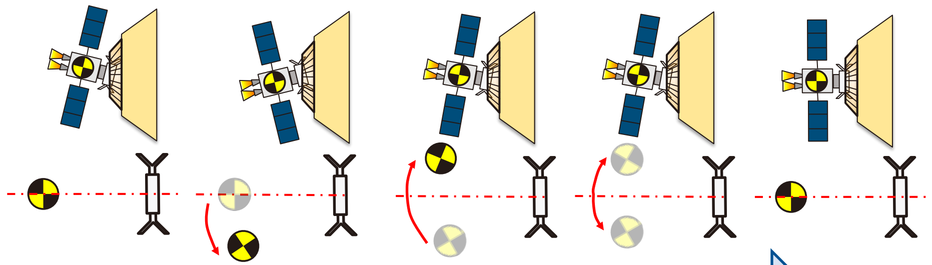


Experiment with BBM2

JAXA HKK BBM2 : Safety against generated stress during capturing

Rough sketch of ADR satellite, gripper and PAF during capturing phase.

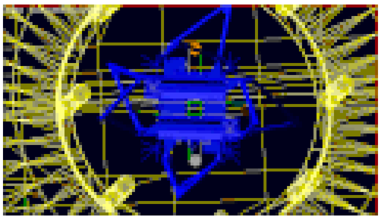
Sketch of ADR satellite CoG and gripper during capturing phase.



Capture start → Stress generated caused by errors absorption → Capture finish

LS dyna ⇄ Experiment (Confirmation / Correlation)

LS dyna → Reflect the contact parameter to ADAMS flex



Developing the multibody dynamics simulator with FEM.

Summary

- Concept and design of Caging Based Debris Gripper BBM1 is introduced.
- JAXA HKK, aiming robustness improved model and increasing TRLs of BBM1, is introduced.
- Items that should be discussed are proposed, and status of each items are introduced.

Future Plan

- Continue development activities.
- Prepare technical documentations and provide the technologies to the business operators who want to use JAXA HKK technologies for ADR.

Thank you for your attention!!

Any questions?

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C15

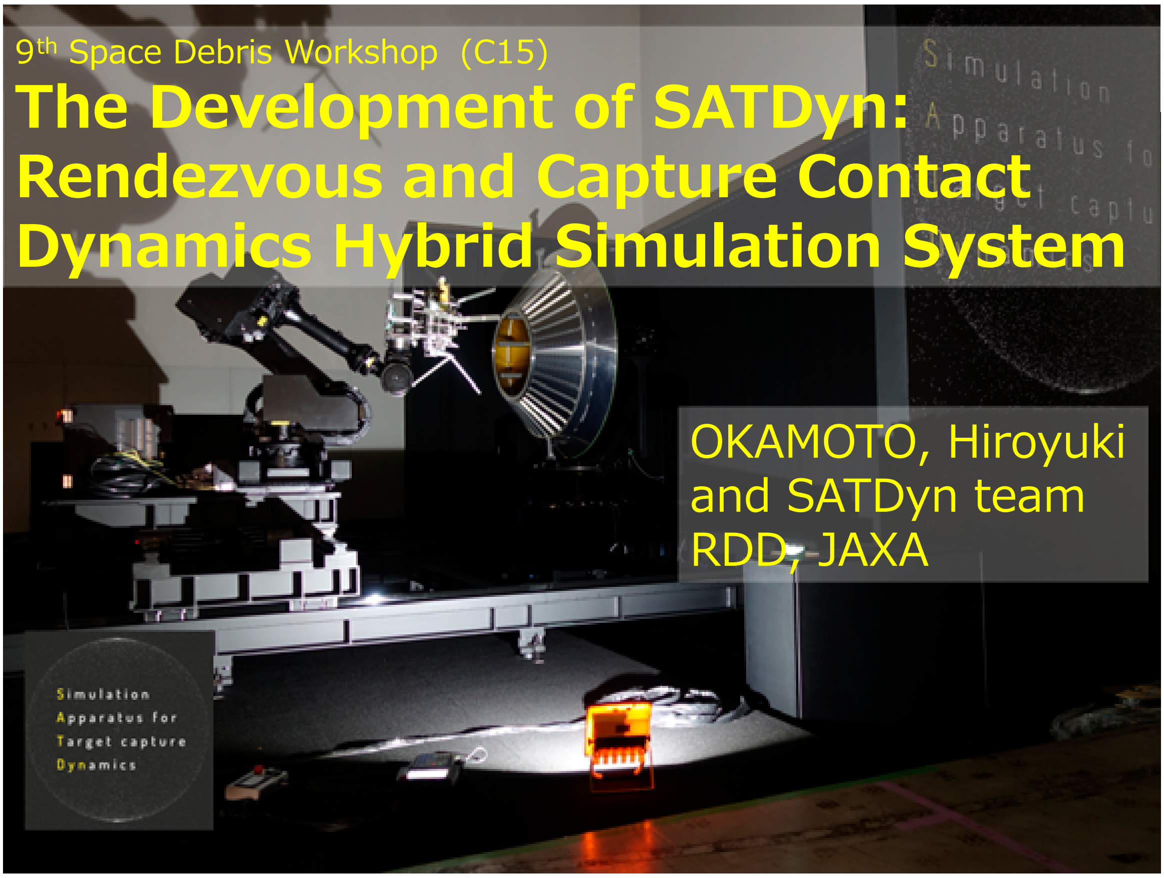
動ターゲット捕獲検証プラットフォーム(SATDyn)の開発

The Development of SATDyn:Rendezvous and Capture Contact Dynamics Hybrid Simulation System

○岡本 博之, SATDyn チーム(JAXA)
○OKAMOTO Hiroyuki, SATDyn Team (JAXA)

JAXA では実物大のランデブならびに捕獲ダイナミクスの検証を行うハイブリッドシミュレータである動ターゲット捕獲検証プラットフォーム(通称:SATDyn)を開発している。SATDyn はチェイサ部とターゲット部で構成されている。チェイサ部は 10m x 7m のガントリステージとその上に搭載されている 6 自由度ロボットアームで構成されており、チェイサ衛星の重心の運動が模擬される。ロボットアームと捕獲機構の間に力トルクセンサが搭載され、計測された力トルクを用いてチェイサの力学計算を行いチェイサ CG 位置ならびに姿勢を再現する。高速の衝突現象シミュレーション用に高速プラットフォームをロボットアームと捕獲機構の間に具備する予定である。ターゲット駆動装置は 3 自由度の姿勢運動装置でターゲットの姿勢運動を再現する。実物大の 1194PAF 模型がターゲットとして準備されている。チェイサならびにターゲットの位置姿勢計測用のモーションキャプチャシステムが具備されている。また、SATDyn エリアはできる限り暗幕で覆われ、迷光をできる限り除去している。模擬太陽光も準備されており、可視光センサによる航法のシミュレーションにも供される。SATDyn は JAXA 研開共用設備として共用予定である。

JAXA is developing the real-scale hardware dynamics simulator for the tumbling target rendezvous and capturing, called SATDyn (ab. Simulation Apparatus for Tumbling target capturing DYNamics). SATDyn consists of the chaser dynamics part and the target dynamics part. The chaser dynamics part equips 10m x 7m stroke gantry stage with 6-DOF robotic arm, by those the chaser CG dynamics will be simulated. The force torque sensor is equipped between the SATDyn robotic arm and the real target capturing device. The output of FT sensor is used as the input for the dynamics calculation, and the calculated CG position and attitude is expressed by the robotic arm. The fast actuating 6-DOF platform is planed to be equipped between the robotic arm and FT sensor for simulating the high speed contact dynamics. The target dynamics part equips the 3-DOF attitude simulation device by which the target dynamics will be simulated. The real-scale 1194PAF is prepared as the target. SATDyn has the motion capture system for measuring the position and attitude of the chaser and the target. The black curtain is surrounded SATDyn area to reduce the unexpected light condition. Solar simulator is also prepared for the visual based navigation simulation.

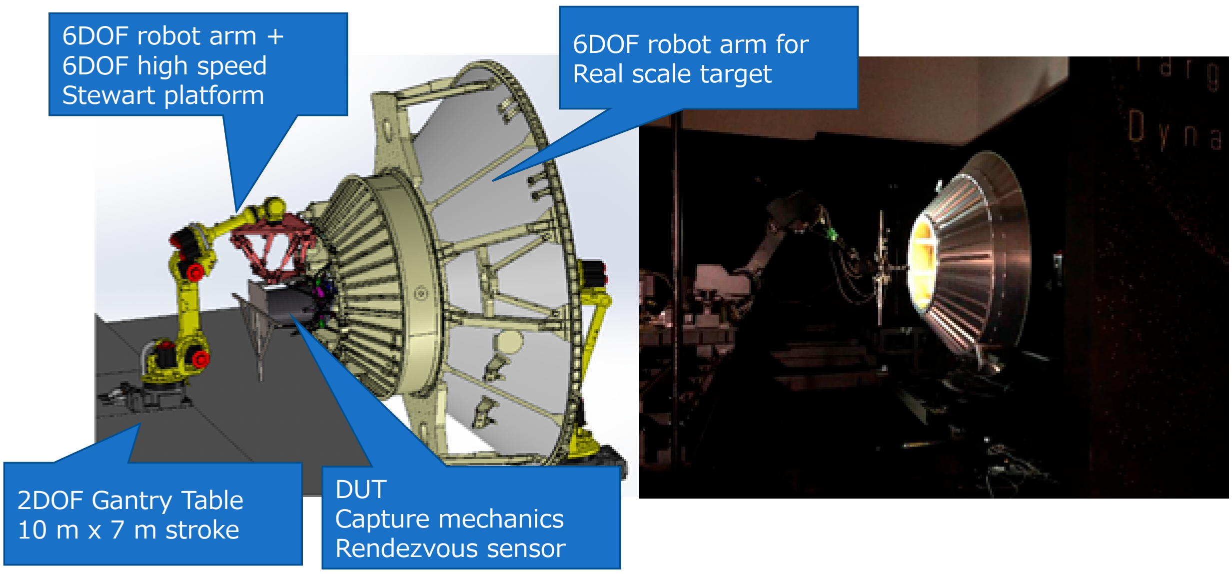


JAXA

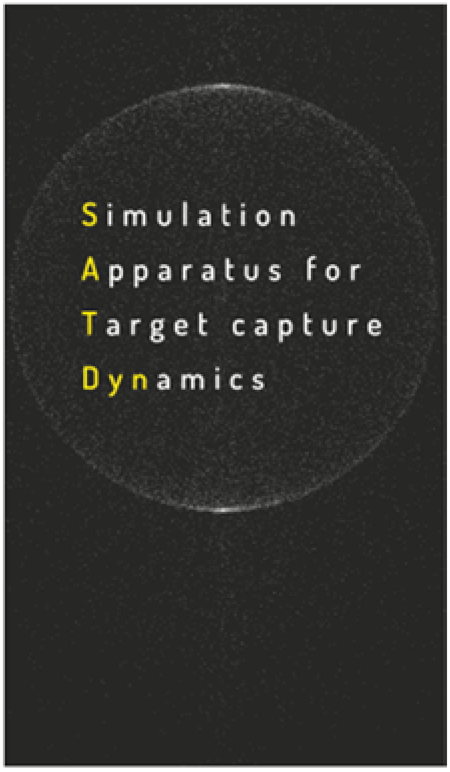
SATDyn

Simulation Apparatus for Target capture Dynamics (SATDyn)

- **Numerical and Physical hybrid simulation system including contact dynamics**
- **ADR proximity operation simulation with real hardware (navigation sensor systems, capturing mechanics)**
- **10m x 7m stroke 2DOF Gantry table with 3x6DOF Robotic arms for the chaser's relative motion simulation with external force torque measurements**
- **Solar simulator (Xe lump) and Full area motion capture system**



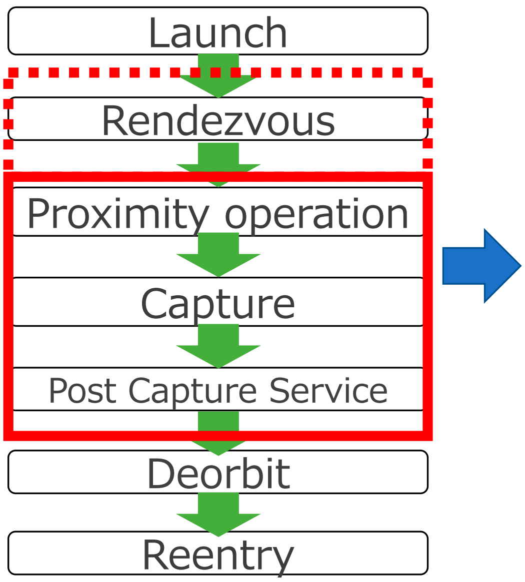
Agenda



- Background and Objective
- Design
- Current Status
- Summary

Background

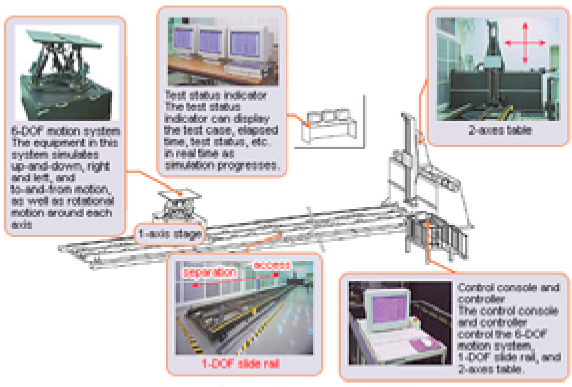
ADR Sequence Sample



Ground Test Facility Required for verification of those technologies

Background

- JAXA has the Rendezvous and Docking Operation Test System (RDOTS) .
  - The RDOTS was established as a system to demonstrate the rendezvous technology of the H-II Transfer Vehicle (HTV), a spacecraft used to transport supplies to the International Space Station (ISS).
- Capturing dynamics is not in the scope of RDOTS



5

Objective

- Integrated on-ground ADR verification system is needed
  - Rendezvous and capturing the tumbling large target is a candidate of ADR method
- Due to the 1G environment on ground, numerical and physical hybrid simulation techniques are being studied.
  - Motion dynamics is numerically calculated
  - Forces and torques are physically measured using real hardware
  - Dynamic open loop test with preplanned orbit
  - Dynamic closed loop test with force/torque feedback simulation

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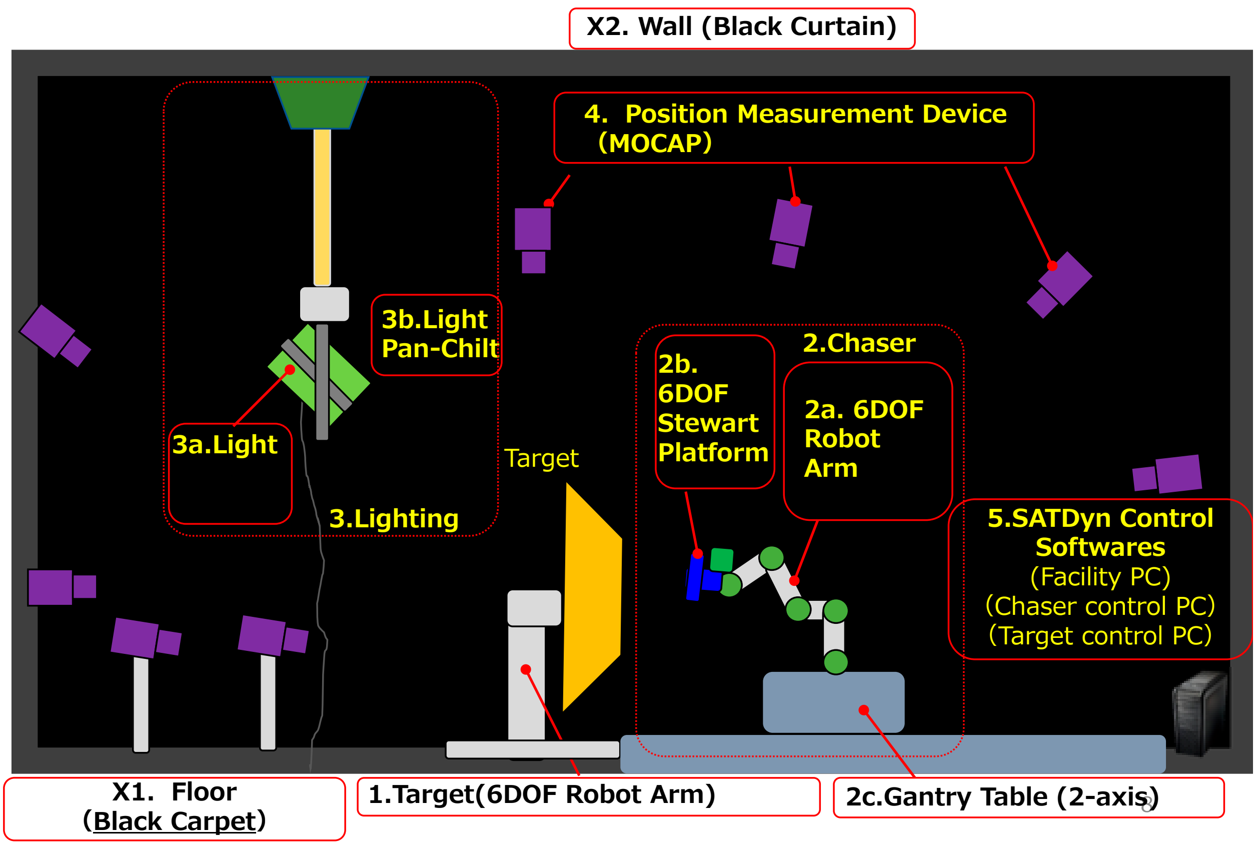
Objective

Hybrid Simulator
- Issue: Instability due to the system delay
- Countermeasures: Low delay robot
  - Assumed Chaser-Target system natural frequency is less than 5 Hz at capturing
    - Nominal 4Hz
  - 2 Robots are equipped for the chaser dynamics simulation
  - 1 for large maneuver with less response
  - 1 for small maneuver with high response

Optical Environment Simulator
- Required for the visual based navigation
- Issue: Solar simulation (illumination area, direction), Darkroom (darkness, stray light)
- Countermeasures : Dark curtain
  - The model fidelity is more important

7

SATDyn Schematics



Development Plan

- Assumed Use Cases
- CRD2Phase-I tests
  - Navigation sensor (sub-scale model test)
- CRD2Phase-II tests
  - Capture device dynamics test（Full scale model test)
  - Force torque feed-back simulation test
- Others
  - Satellite debris capture, Docking, etc.

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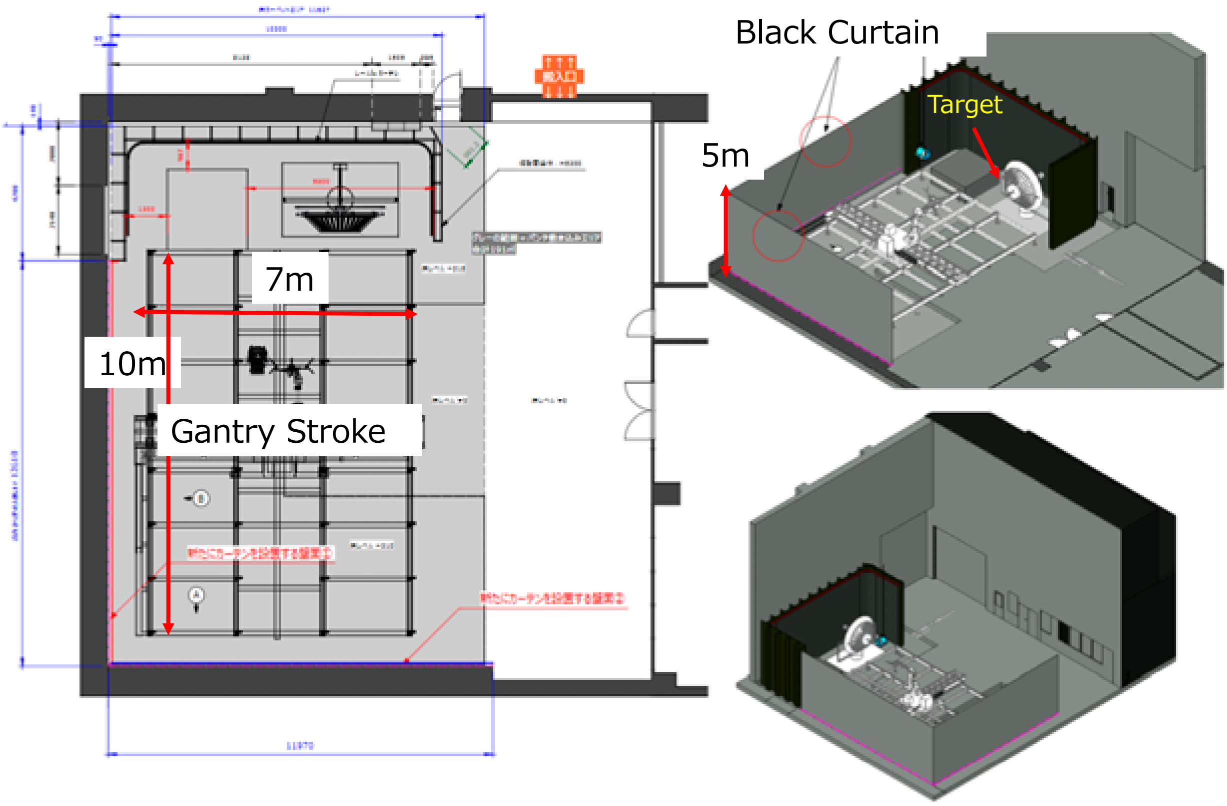
SATDyn design

Specifications:

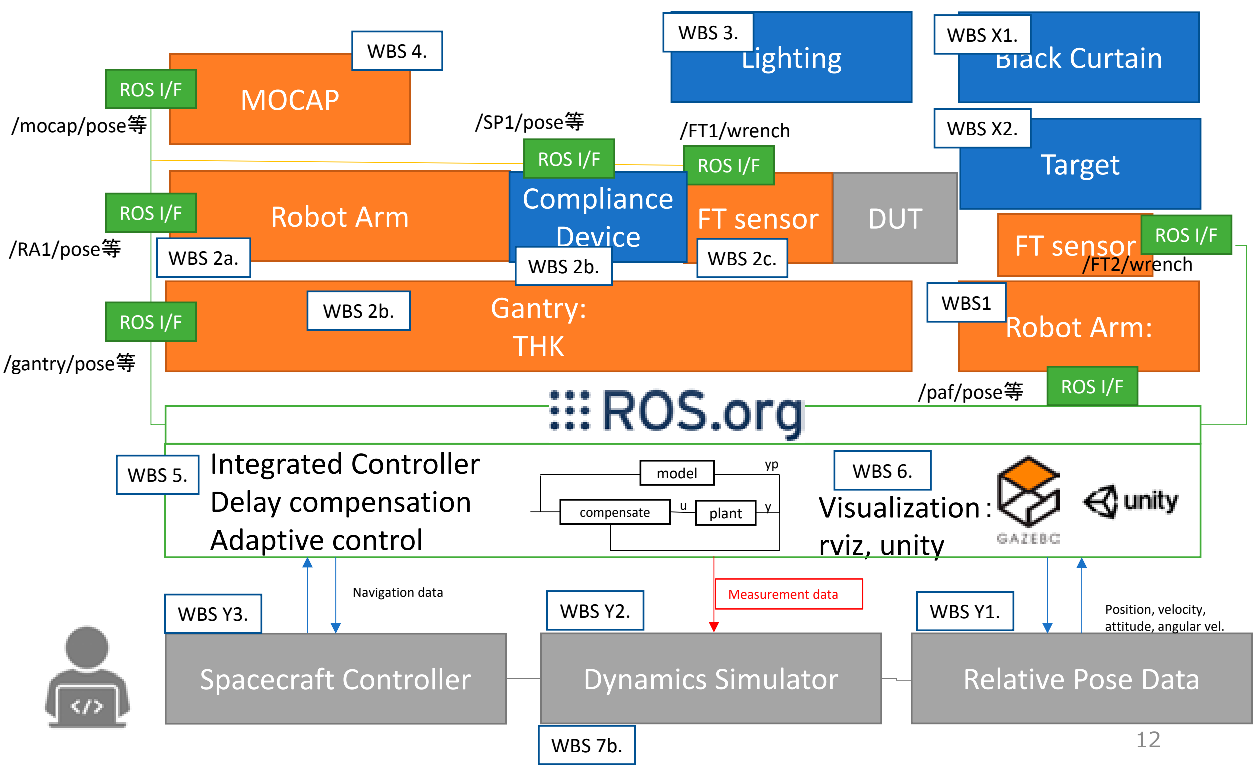
- 2D gantry rails for fly around operation simulation
  - 3 m/s over velocity capability
- 6DOF chaser dynamics simulation
  - 40 kg DUT capability
  - 130 kg DUT without contact dynamics simulation
  - AC 100V supply for DUT
  - Wired LAN interface
- 6DOF target dynamics simulation
  - 200 kg Target/DUT capability
- Around 0.5 solar irradiation (50,000 lux) with black curtains
- Full area motion capture

10

SATDyn Construction



SATDyn Software Architecture



Current Status

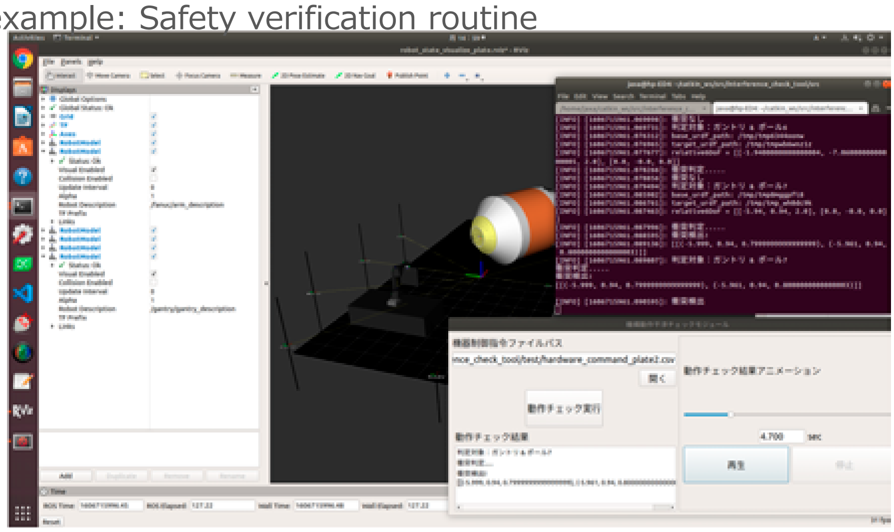
- 2D Gantry, 6DOF chaser arm and 3DOF target gimbal are ready.
  - Fast acting 6DOF platform will be installed this March.
  - 6DOF robotic arm for the Target will be installed this March.
- Mocap, FT sensors, Xe lump and Black curtains are ready.
- SATDyn is still in development but can be used.
  - JAXA sensor test has been conducted.
  - CRD2 phase I sensor test has been conducted.

13

User Interface

- System utilizes Robotic Operation System (ROS)
- Preparing CSV file interfaces for DOLT
- Another dedicated interface is TCP/IP which is similar to the Optical simulator in Chofu
- UDP interfaces may be installed for DOCT

GUI example: Safety verification routine



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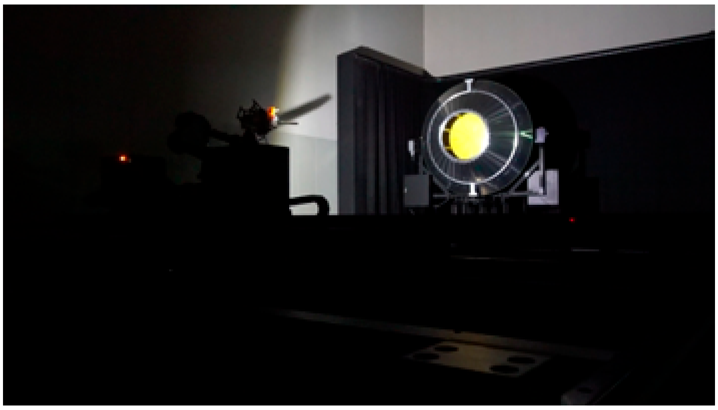
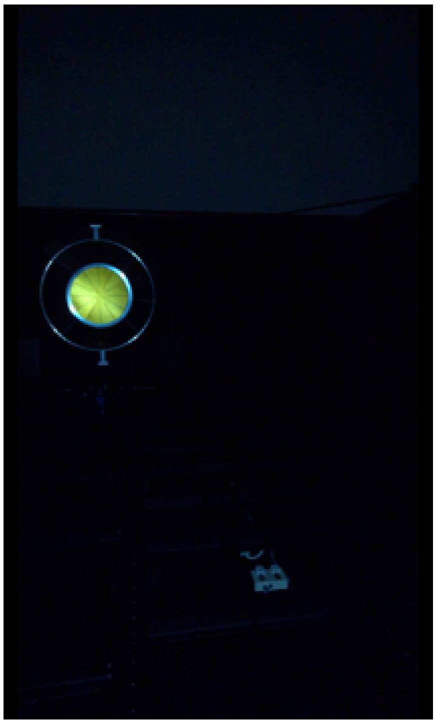
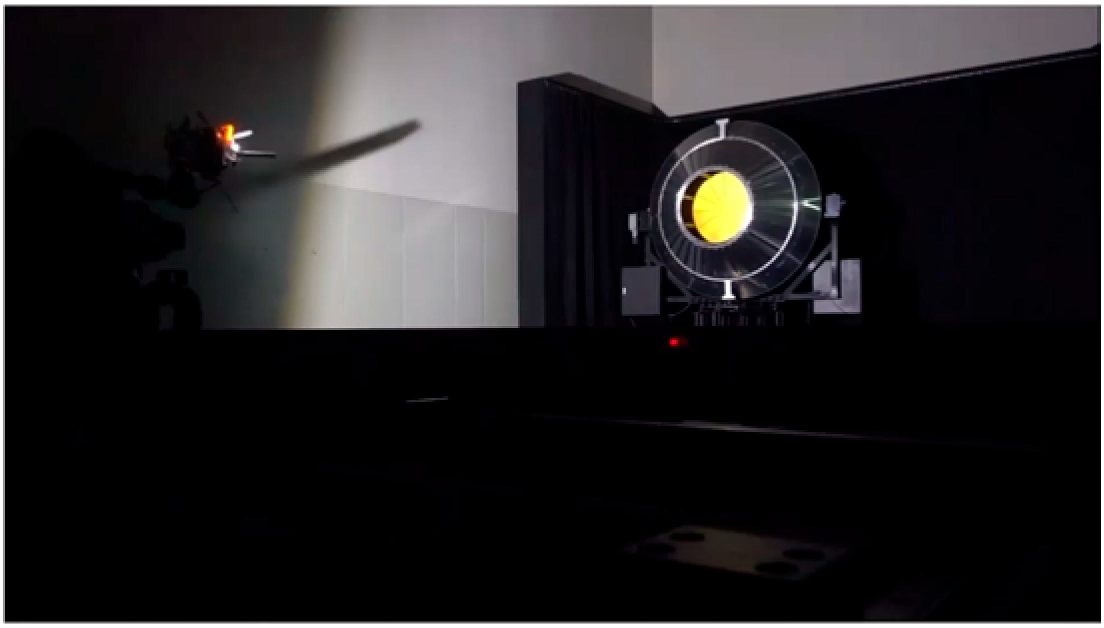
Demo

- Demonstration movies
- From ground
- From chaser





Demo



Demo

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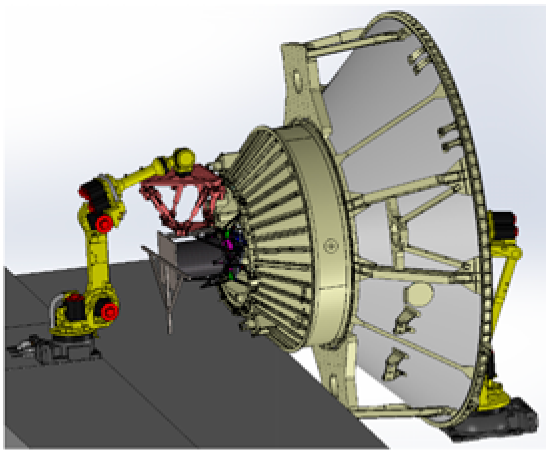
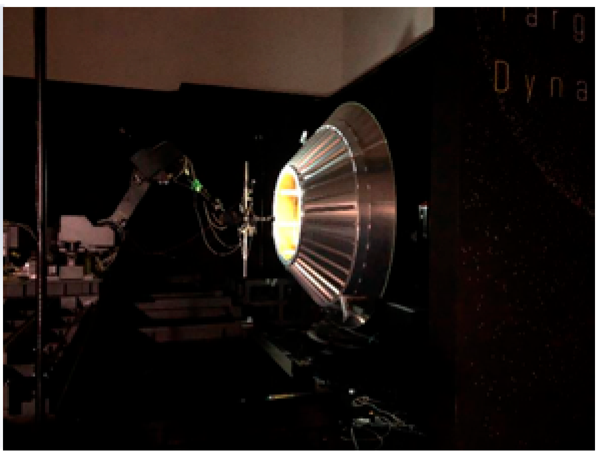
Summary

- Hybrid simulator "SATDyn" is in development now
- HKK, capturing mechanics, will be subjected into the verification with SATDyn in this year
- The facility is open as a shared facility of JAXA
  - **User feedback is important for the SATDyn development**





C16

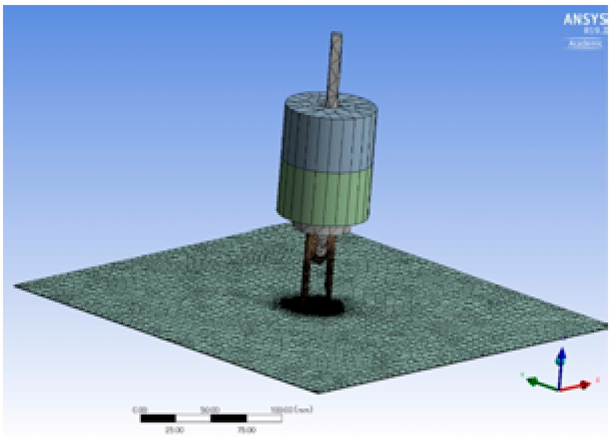
ADR 用銛機構の性能向上に向けた日本刀技術導入の検討

A Study on Improving Performance of Harpoon Mechanisms in ADR Using Japanese Sword Technologies

○渡部 武夫(神奈川工科大学), 坂本 武司(有明高専), 佐藤 強(神奈川工科大学)
○WATANABE Takeo (Kanagawa Institute of Technology), SAKAMOTO Takeshi (National Institute of Technology, Ariake College), SATO Tsuyoshi (Kanagawa Institute of Technology)

著者らの研究グループは、これまで、始原天体の表層サンプリング装置の貫入性能を高めるために日本刀技術を応用することを試み、実験的検討を中心に様々な研究を実施してきた。それらの知見を活かし、近年は日本刀技術を能動的デブリ処理(ADR)における銛機構の性能向上に役立てるための検討を始めている。この研究は、特に、シンプルな構造を保ちつつ、ターゲットとなる衛星表面の薄板構造をより小さな力学的条件で貫通させることができる銛機構の開発を目指すものである。
日本刀技術は、日本古来より対象物を効率よく切断または貫通するために高められてきた伝統技術で、1000 年以上の歴史を持つ非常に枯れた技術とみなすことができる。日本刀技術は主に「作刀技術」と「操刀技術」からなり、それぞれ多くの技術要素から構成される。本発表では、日本刀技術の特長やこれまでの取り組み状況などを紹介する。

Traditional Japanese sword smithing has become a mature technology in Japan, one that has been refined since antiquity to cut or pierce an object as efficiently as possible.
Japanese sword smithing has a history of more than 1000 years, including a rich, progressive improvement of refining techniques, and their effectiveness has been furthered by centuries of enhancing the finesse of the operating of a sword.
Against that background, the authors have been conducting research on applicability of traditional Japanese sword technologies to enhance penetration power of sampling device for the surface layer of minor planets. Also, based on these researches, improving performance of the harpoon mechanisms in active debris removal (ADR) was investigated of experiments and finite element method (FEM). The objective of this research is to develop a harpoon that can penetrate the thin-gauge structure of a target satellite's surface. Another objective is maintaining reliability of the harpoon mechanism while seeking a simple and effective design.
In this presentation, some features of Japanese sword technologies and the status of their research activities are shown.



ADR用銛機構の性能向上に向けた日本刀技術導入の検討

A Study on Improving Performance of Harpoon Mechanisms in ADR
Using Japanese Sword Technologies

神奈川工科大　渡部武夫
Takeo Watanabe (Kanagawa Institute of Technology
有明高専　坂本武司
Takeshi Sakamoto (National Institute of Technology, Ariake College)
神奈川工科大　佐藤強
Tsuyoshi Sato (Kanagawa Institute of Technology)

1

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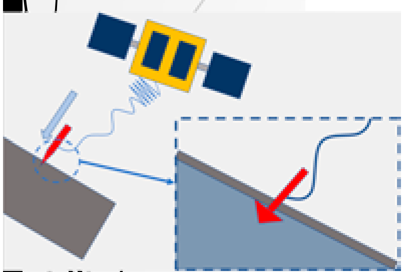
KANAGAWA INSTITUTE OF TECHNOLOGY

Application of Japanese Sword Technology
日本刀技術の応用

2



Debris Capture Technology by Harpoon Mechanism
(Penetration and Coupling into Aluminum Plate)
銛機構によるデブリ捕獲技術(アルミ板に対する貫入と結合)

⇩

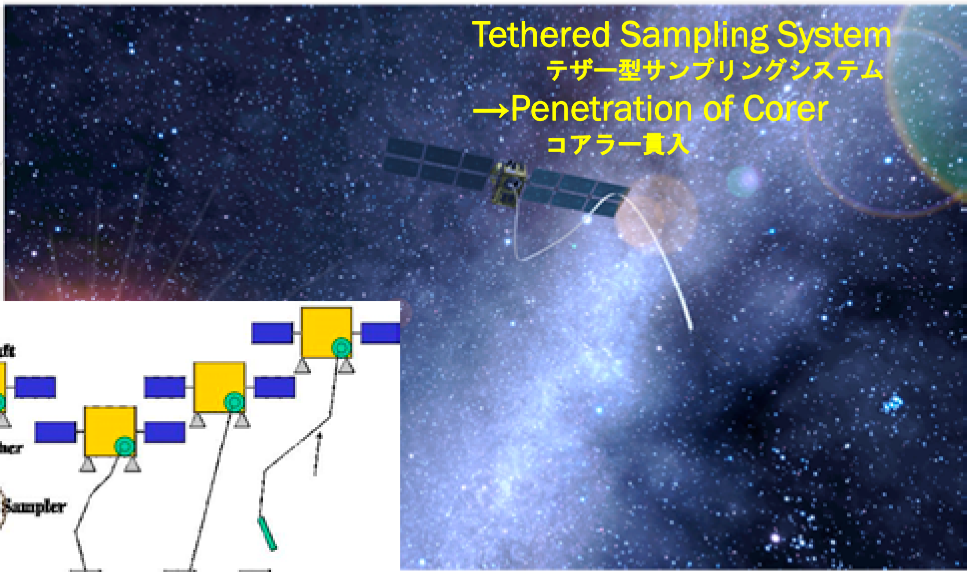
Simple structure and mechanism
シンプルな構造、機構
Controllability of secondary debris
二次デブリの抑制
Reduction of mechanical conditions required for penetration
貫入に要する力学的条件の低減

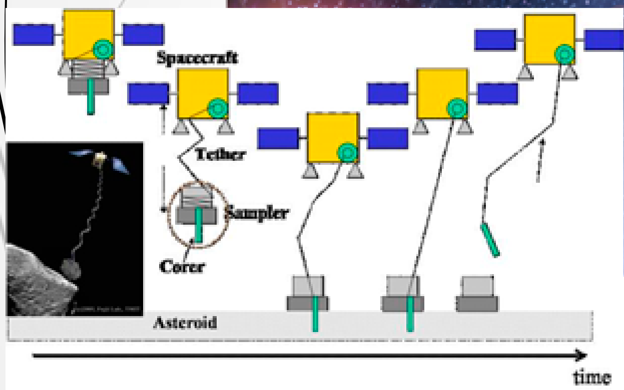
⇩

Application of Japanese Sword Technology
日本刀技術の応用

Background

3

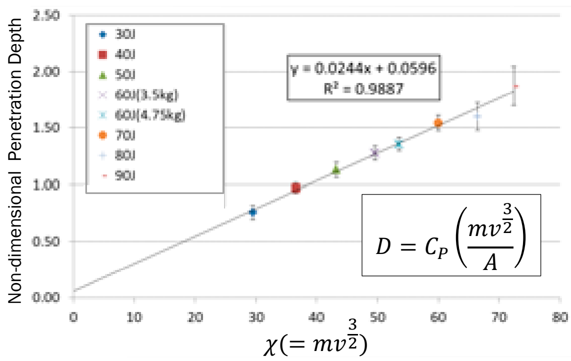




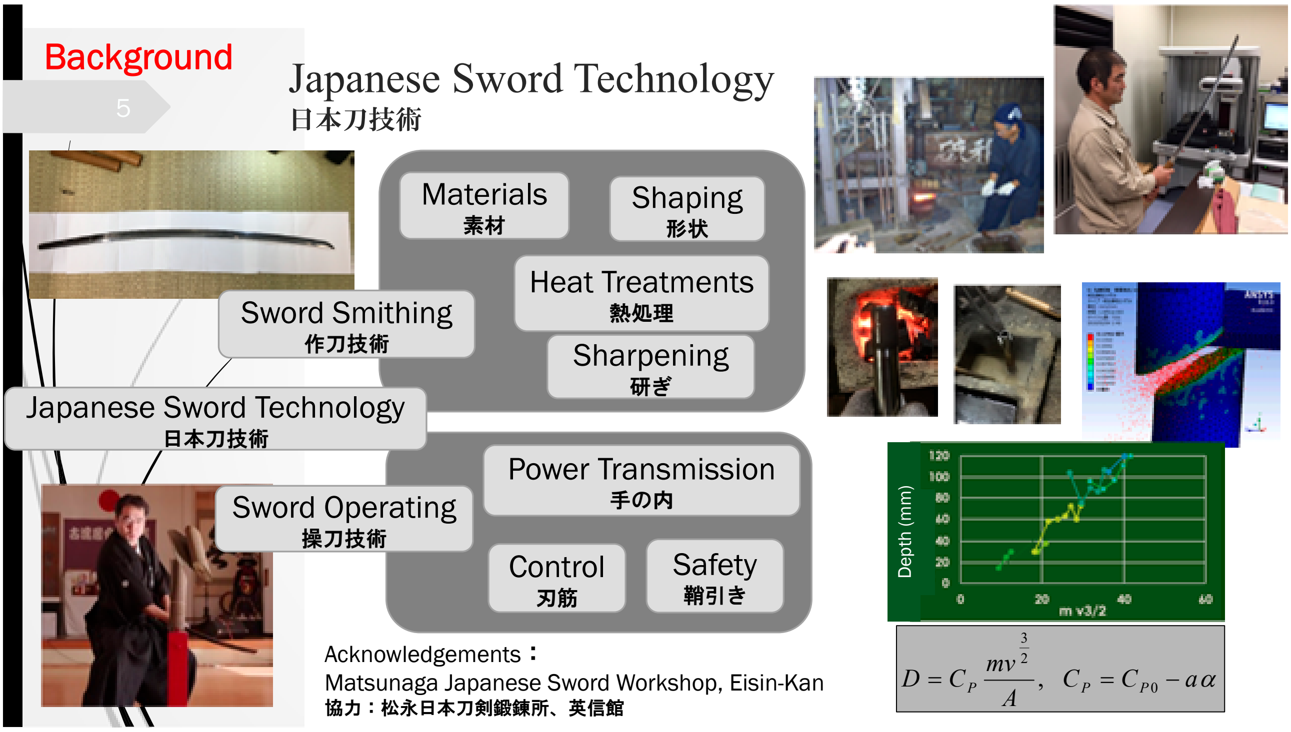
Background

4

Penetration of Corer
コアラー貫入性能



- Penetration Test for Light weight concrete
  軽量コンクリートに対する貫入実験
- Sharpening the tip to enhance penetration performance >> Japanese Sword Technology
  貫入性能向上のために、先端を鋭く加工→日本刀技術の応用


Background
5
Japanese Sword Technology
日本刀技術
Materials
素材
Shaping
形状
Heat Treatments
熱処理
Sword Smithing
作刀技術
Sharpening
研ぎ
Japanese Sword Technology
日本刀技術
Power Transmission
手の内
Sword Operating
操刀技術
Control
刃筋
Safety
鞘引き
Acknowledgements：
Matsunaga Japanese Sword Workshop, Eisin-Kan
協力：松永日本刀剣鍛錬所、英信館
Depth (mm)
m v3/2
$D = C_P \frac{mv^{\frac{3}{2}}}{A}, \quad C_P = C_{P0} - a\alpha$


Background
6
Sword Smithing 作刀技術
The four elements: material, shape, heat treatment, sharpening
素材、形状、熱処理、研ぎ
Material: “TAMA-HAGANE”,
素材：玉鋼
Shape: taking measurements from a Japanese sword and design
形状：真剣からの採寸・設計
Heat treatment
熱処理：焼き入れ
Sharpening
研ぎ

Background

7

Measurement and analysis equipment, Examples of measurement

測定・分析装置、測定例

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AUTOMATED MULTIPURPOSE X-RAY DIFFRACTOMETER
全自動多目的X線回折装置
SmartLab

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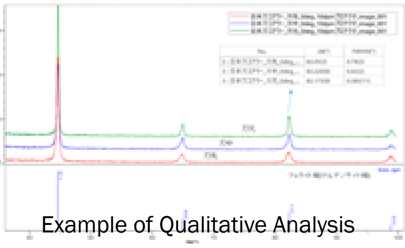
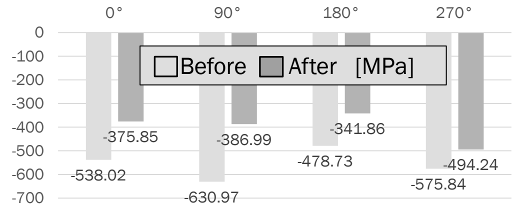
MICRO-AREA X-RAY RESIDUAL STRESS MEASUREMENT SYSTEM
微小部X線応力測定装置
AutoMATE II

Device Quality Control Considerations through Scientific Analysis
Supported by Rigaku Corporation
各種科学的分析によるデバイスの品質管理を検討
協力：株式会社リガク



Example of Qualitative Analysis



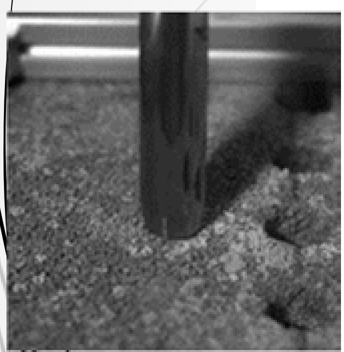
Example of Residual Stress Measurements

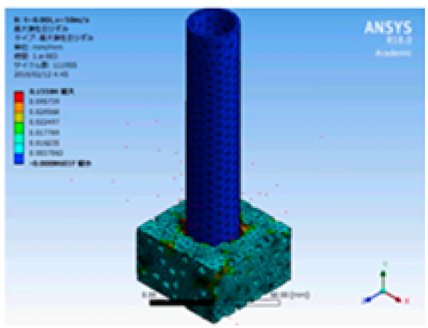
Background

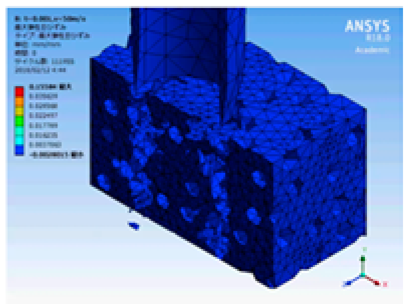
8

Penetration of Corer (Experiment / FEM)

コアラー貫入解析（実験／有限要素法解析）





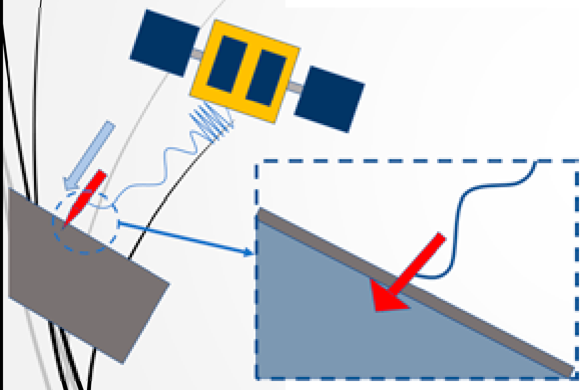


Examples of Drop Weight Experiment and FEM Analysis
落錘実験とFEM解析

神奈川工科大学
KANAGAWA INSTITUTE OF TECHNOLOGY

9

Application to Harpoon Mechanisms
銛への応用



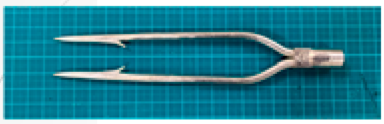
Key elements of harpoon technology:
Penetration performance and combining
銛技術の主要要素：貫入性能＋結合性能

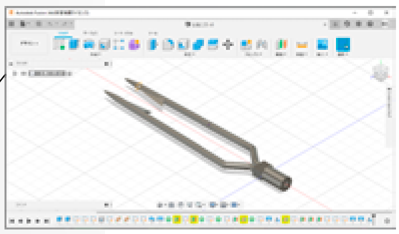
>>Control of Penetration and Fracture
in Thin Plate Structures
>>薄板構造への貫入と破壊のコントロール

>>Combining by barb mechanism
>>カエシによる結合

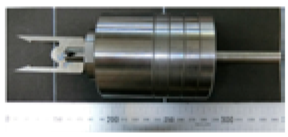
10

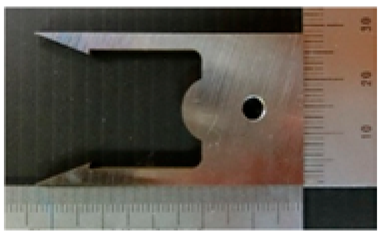
TOSA-Futamata
土佐二又銛





Traditional Japanese harpoon tips
(TOSA-Futamata: biforked harpoon)
伝統的な二又銛（土佐二又銛）

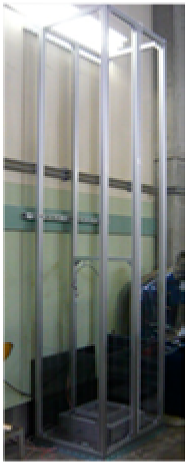


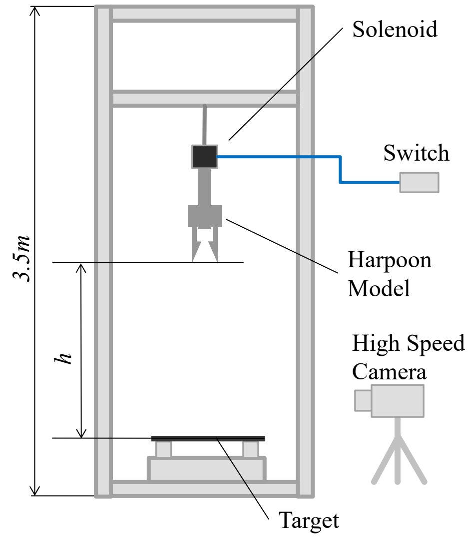


An experimental model adapted to a metal plate
金属板からの切り出し加工

11

Drop Test System
3.5m級落錘式試験機





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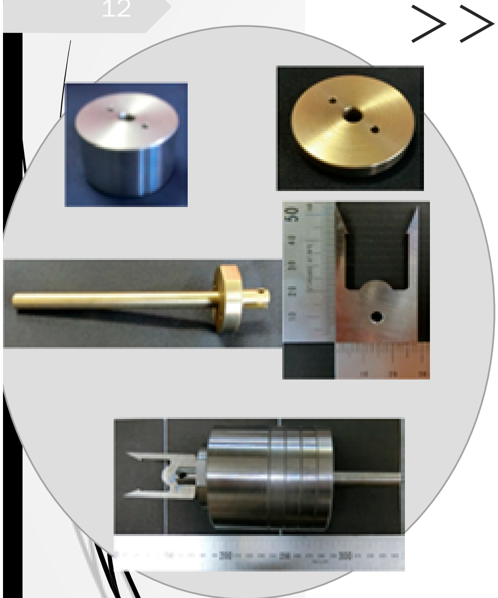
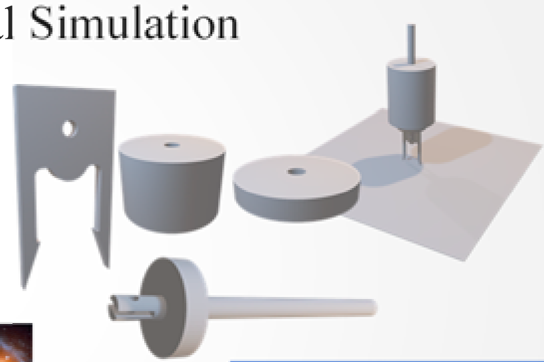
12

Experimental Equipment / 3D Models
>>Numerical Simulation





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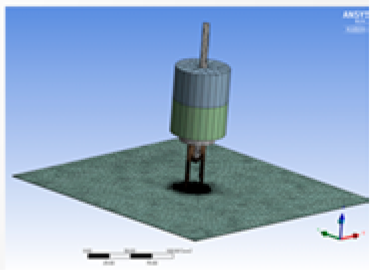

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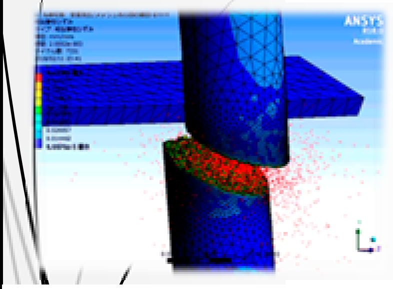
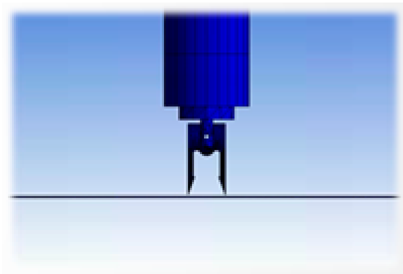
Simulation of Harpoon Penetration



Simulation of Cutting with the Japanese Sword
日本刀で藁を切断時の数値解析

Biforked Harpoon models
二叉銛モデル



Simulation of Harpoon Penetration
銛貫入のシミュレーション

神奈川工科大学
KANAGAWA INSTITUTE OF TECHNOLOGY

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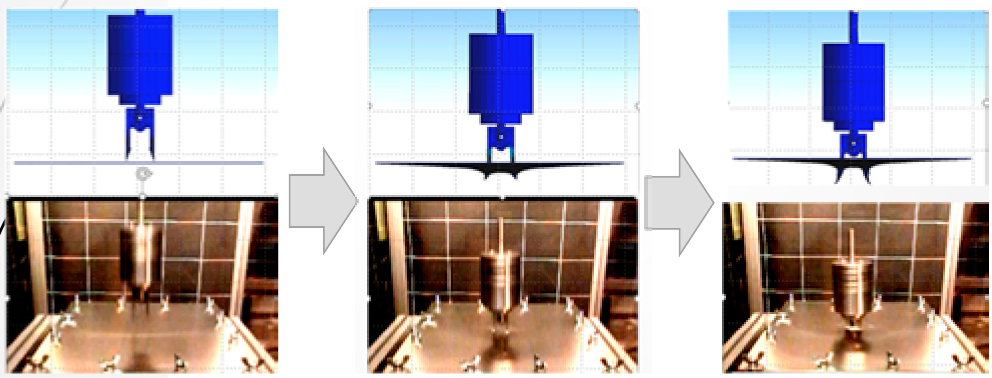
Biforked Harpoon Test Results and Simulations

m：2.2[kg]　h：1.56[m]（34.3[J]）



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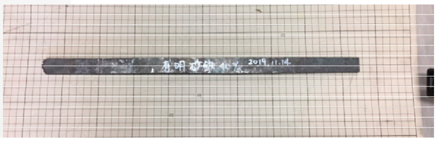
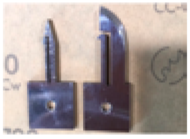
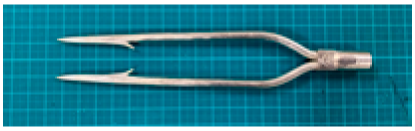
Conclusions and Future Works

- Activities to apply Japanese sword technology to improve the penetration performance of debris catching harpoons are presented
  デブリ捕獲用銛の貫入性能を高めるために、日本刀技術の導入を検討
- Introduction to sword smithing and sword operating techniques
  作刀技術と操刀技術について紹介
- Exemplify the results of experiments and numerical simulations with basic models
  基礎的なモデルを用いた実験と数値シミュレーションの結果を例示
- Prototyping of the experimental model using Sword smithing technology
- 作刀技術による実験モデルの試作と実験の準備

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and Keita Itagaki（板垣慶太）

ポスターセッション

Poster Session

P01

東京大学木曽観測所モザイク CMOS カメラ「トモエゴゼン」による高速移動天体サーベイ

Survey of Fast Moving Objects with a CMOS Mosaic Camera, Tomo-e Gozen, at Kiso Observatory

〇大澤 亮，酒向 重行，紅山 仁，諸隈 智貴（東京大学），
浦川 聖太郎，奥村 真一郎（日本スペースガード協会），渡部 潤一（国立天文台），
柳沢 俊史，黒崎 裕久，吉川 真（JAXA），Tomo-e Gozen プロジェクト
○OHSAWA Ryou, SAKO Shigeyuki, BENIYAMA Jin, MOROKUMA Tomoki (University of Tokyo),
URAKAWA Seitaro, OKUMURA Shin-ichiro (JSGA),WATANABE Jun-ichi (NAOJ), YANAGISAWA Toshifumi, KUROSAKI Hirohisa, YOSHIKAWA Makoto (JAXA), Tomo-e Gozen Project

東京大学木曽観測所では 1.05 m シュミット望遠鏡用の旗艦観測装置として高感度 CMOS センサを使用したモザイクカメラ, トモエゴゼン (Tomo-e Gozen) の開発を進めてきた. トモエゴゼンは広視野・高感度・連続読み出しを達成した初の天文用カメラであり，合計 20 平方度の領域を最大 2 Hz でモニタリングできる. 木曽観測所ではトモエゴゼンの動画撮影能力を活かして，高速移動天体サーベイを実施している. 一視野あたり 2 Hz で 9 秒間の動画観測を繰り返すことで, 3 時間程度で約 7,000 平方度の領域を監視できる. 月距離の数倍以内に近づいてきた地球接近小惑星や，静止軌道付近にある人工衛星やスペースデブリの検出にも高い能力を発揮する.これまでに 13 天体の地球接近天体の発見に成功した. 発表ではサーベイの概要と移動天体を抽出する手続きについて解説する.

Tomo-e Gozen is a newly-developed mosaic CMOS camera mounted on the 1.05-m Schmidt Telescope at Kiso Observatory, the University of Tokyo. Equipped with highly sensitive CMOS sensors, Tomo-e Gozen becomes a unique camera for astronomy with a high sensitivity, a wide field-of-view, and a capability of video observation. Tomo-e Gozen is able to monitor a 20 square-degree sky continuously at up to 2 Hz. The video observation with Tomo-e Gozen provides an opportunity for a survey of fast moving objects. About 7,000 square-degree area can be observed in about 3 hours, while a single field is monitored at 2 Hz for 9 seconds. One of main scientific targets is a near-earth asteroids which approach to the Earth within a few lunar distances, while this survey achieves a high performance in detecting artificial satellites and space debris as well. We have discovered 13 new near-earth asteroids as of September 11th, 2020. In the presentation, we'll describe details of the survey and explain the procedure to extract fast moving objects from the video data.

Survey of fast moving objects with a CMOS mosaic camera, Tomo-e Gozen, at Kiso Observatory

Ryou Ohsawa[1], Shigeyuki Sako[1], Jin Beniyama[1], Tomoki Morokuma[1],
Seitaro Urakawa[2], Shin-ichiro Okumura[2], Jun-ichi Watanabe[3],
Toshifumi Yanagisawa[4], Hirohisa Kurosaki[4], Makoto Yoshikawa[5], Tomo-e Gozen Project

[1]Univ. Tokyo; [2]JGSA; [3]NAOJ; [4]RDD/JAXA; [5]ISAS/JAXA

Summary

- A wide-field CMOS mosaic camera Tomo-e Gozen is developed in Kiso Observatory, which has a capability to monitor a sky of about 20 sq-deg. at up to 2 fps.
- We develop a pipeline to efficiently extract fast moving objects from video data obtained in the Tomo-e Gozen's High-Cadence Transient Survey.
- In the first 1.5 years of operation, Tomo-e Gozen has detected 20 new near-earth asteroids, as well as a number of cataloged and uncataloged space debris.

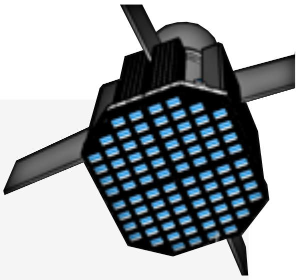

Fig 1. The Tomo-e Gozen camera.

Background

There are a number of space debris orbiting the Earth. It is important to track their motions and to comprehend statistics of the space debris for sustainable space utilization. Currently only a fraction of the space debris, however, is monitored. There has been increasing demand in finding untracked space debris. Untracked space debris is usually observed as moving objects. A typical apparent motion of the debris is larger than 10 arcsec/sec. A practical method to find such fast moving objects in a blind survey is required.

Tomo-e Gozen

Tomo-e Gozen is a newly-developed mosaic CMOS camera (Fig. 1) mounted on the 1.05-m Schmidt Telescope at Kiso Observatory, the University of Tokyo. Equipped with highly sensitive CMOS sensors, Tomo-e Gozen becomes a unique camera for astronomy with a high sensitivity, a wide field-of-view, and a capability of video observation. Tomo-e Gozen is able to monitor a 20 square-degree sky continuously at up to 2 fps.

Tomo-e Gozen daily carries out a transient survey. About 7,000 square-degree area is observed in about 3 hours. In each field, Tomo-e Gozen obtains videos at 2 fps for 9 seconds (Fig. 2). More than 15,0000 video clips are recorded in a clear night. This makes Tomo-e Gozen one of the most powerful facilities to detect fast moving objects in a blind survey.

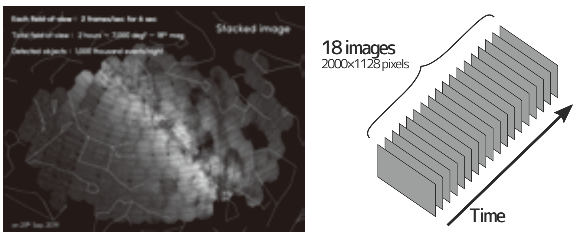

Fig 2. An overview of the Tomo-e Gozen transient survey.

One of main scientific targets is a near-earth asteroids which approach to the Earth within a few lunar distances. On the other hand, this survey achieves a high performance in detecting artificial satellites and space debris as well. To make the best use of this survey, we have developed an automated pipeline to extract fast moving objects from video data.

System Overview

The fast moving object processing system is schematically described in Fig 3. Sources are extracted from the entire video. A mask for fixed sources are created from the first and last frames. Fixed sources are masked out. Moving object candidates are identified by clustering the remaining sources.

We adopted two tricks to facilitate the clustering process. First, a k-nearest neighbor graph is constructed (orange arrows), where each edge is regarded as a proposed motion vector. Then, a line segment clustering algorithm is applied to the edges. The clustered sources are indicated by the green arrows. The pipeline can process the data immediately owing to the tricks.

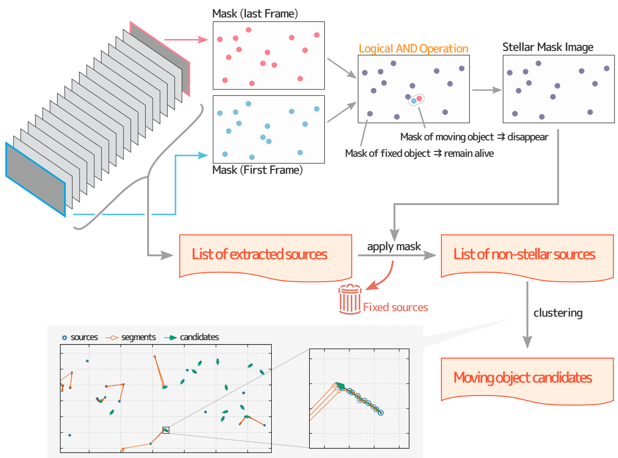

Fig 3. A schematic view of the moving object clustering procedure.

The formal operation has started since October 2019. As of February 2021, 20 near-earth asteroids have been newly discovered (Fig. 4). Tomo-e Gozen has been recognized as one of the leading facilities in the NEA detection. A lot of uncataloged space debris is detected as well. The right panel of Fig. 4 shows the sky distribution of detected objects on October 5, 2020. Objects without counterparts are indicated by the arrows with the orange circles.

Refer to the poster presented by K. Mitsuda et al. for detailed statistics.

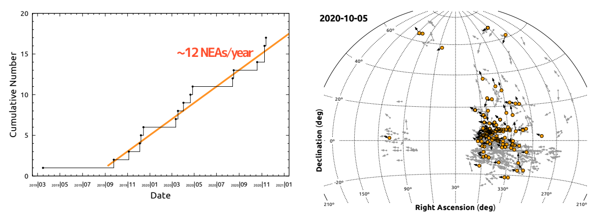

Fig 4. Statistics of the fast moving object processing pipeline outputs.

This research has been partly supported by Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (KAKENHI) Grant Numbers 26287106, 16H02158, 16H06341, 18H01272, 18H01261, 18H04575, and 18K13599. This research is also supported in part by the Japan Science and Technology (JST) Agency's Precursory Research for Embryonic Science and Technology (PRESTO), the Research Center for the Early Universe (RESCEU), of the School of Science at the University of Tokyo, and the Optical and Near-infrared Astronomy Inter-University Cooperation Program.

P02

東京大学木曽観測所モザイク CMOS カメラ「トモエゴゼン」による人工天体の検出効率と性質について

Detection Efficiency and Properties of Artificial Bodies Observed with a CMOS Mosaic Camera, Tomo-e Gozen, at Kiso Observatory

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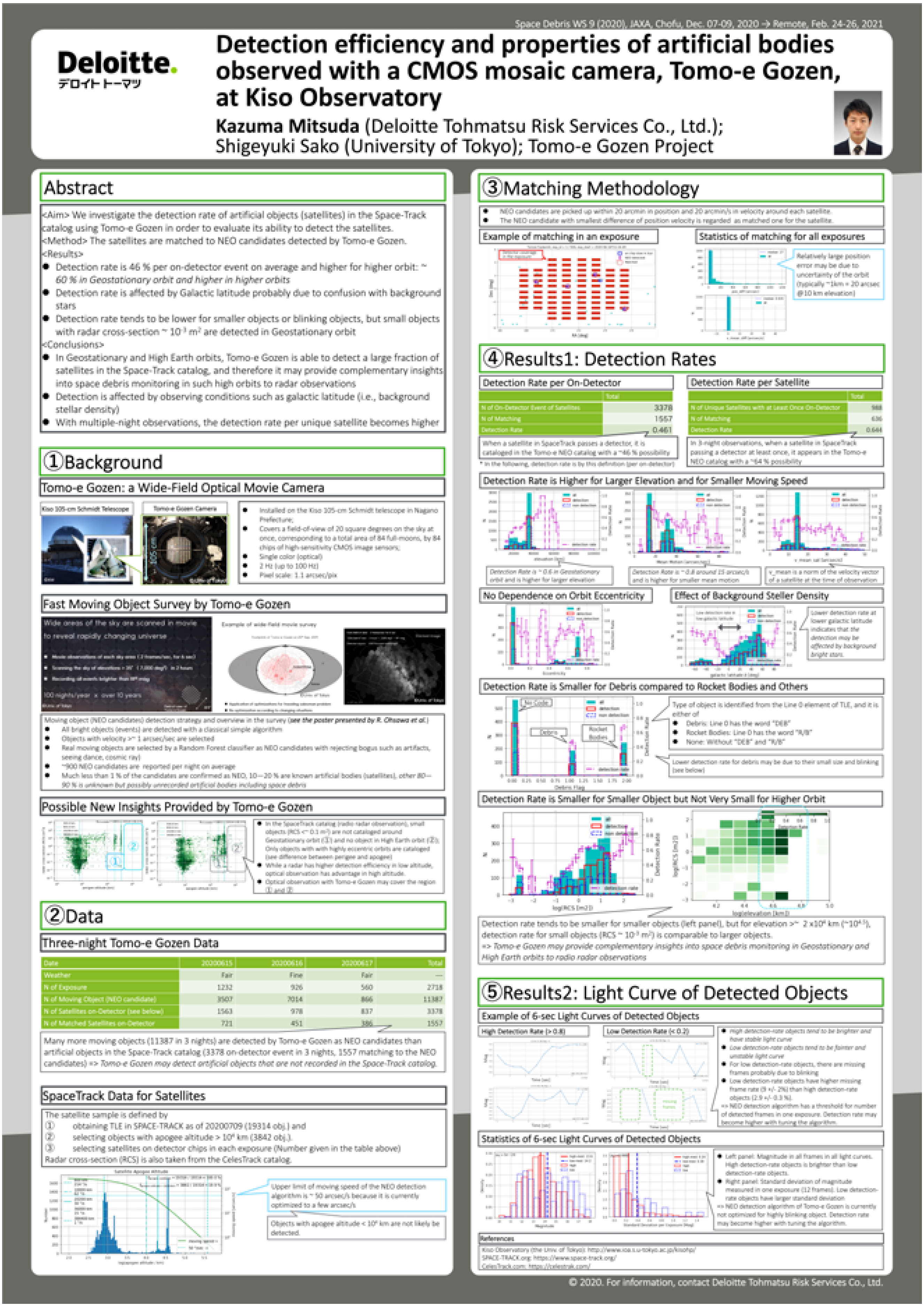
酒向 重行(東京大学), Tomo-e Gozen プロジェクト
○MITSUDA Kazuma (Deloitte Tohmatsu Risk Services Co., Ltd.),
SAKO Shigeyuki (University of Tokyo), Tomo-e Gozen Project

本講演ではトモエゴゼン(Tomo-e Gozen)の高速移動天体サーベイで観測された人工天体の性質について報告する。トモエゴゼンは東京大学木曽観測所の 1.05m シュミット望遠鏡に搭載されたカメラであり、合計 20 平方度の領域を最大 2Hz でモニタリングすることができる。高速移動天体サーベイでは約 7000 平方度の領域が一晩に複数回で観測される。このサーベイでは地球接近小惑星などの移動天体の発見を目的としているが、スペースデブリなどの人工天体も候補も含めて一晩に平均 900 件程度がコンタミとして検出される。我々は、トモエゴゼンで観測された人工天体候補と Space-Track カタログに登録されている人工天体のマッチングを行った。その結果得られた、トモエゴゼンによる人工天体の観測効率や観測された人工天体の性質に加え、スペースデブリの個数、分布、光度曲線などについて報告する。

We present Tomo-e Gozen observations of artificial bodies observed through the survey of fast moving objects. Tomo-e Gozen is a mosaic CMOS camera mounted on the 1.05-m Kiso Schmidt Telescope at Kiso Observatory and is able to monitor a 20 square-degree sky continuously at up to 2 Hz. In the survey, ~7000 square-degree areas are observed a few times per night. In addition to scientific astronomical targets such as near-earth objects, artificial bodies such as space debris are detected, as contaminations, ~900 times per night on average including candidates. We matched the detected artificial body candidates with the Space-Track catalog. We present the result of the matching such as the detection efficiency and properties of artificial bodies observed with Tomo-e Gozen as well as the number counts, distribution, and light-curve of space debris.


Space Debris WS 9 (2020), JAXA, Chofu, Dec. 07-09, 2020 -> Remote, Feb. 24-26, 2021
Deloitte.
デロイト トーマツ
Detection efficiency and properties of artificial bodies observed with a CMOS mosaic camera, Tomo-e Gozen, at Kiso Observatory
Kazuma Mitsuda (Deloitte Tohmatsu Risk Services Co., Ltd.); Shigeyuki Sako (University of Tokyo); Tomo-e Gozen Project
Abstract
<Aim> We investigate the detection rate of artificial objects (satellites) in the Space-Track catalog using Tomo-e Gozen in order to evaluate its ability to detect the satellites.
<Method> The satellites are matched to NEO candidates detected by Tomo-e Gozen.
<Results>
Detection rate is 46 % per on-detector event on average and higher for higher orbit: ~ 60 % in Geostationary orbit and higher in higher orbits
Detection rate is affected by Galactic latitude probably due to confusion with background stars
Detection rate tends to be lower for smaller objects or blinking objects, but small objects with radar cross-section ~ 10^-3 m^2 are detected in Geostationary orbit
<Conclusions>
In Geostationary and High Earth orbits, Tomo-e Gozen is able to detect a large fraction of satellites in the Space-Track catalog, and therefore it may provide complementary insights into space debris monitoring in such high orbits to radar observations
Detection is affected by observing conditions such as galactic latitude (i.e., background stellar density)
With multiple-night observations, the detection rate per unique satellite becomes higher
①Background
Tomo-e Gozen: a Wide-Field Optical Movie Camera
Kiso 105-cm Schmidt Telescope
Tomo-e Gozen Camera
Installed on the Kiso 105-cm Schmidt telescope in Nagano Prefecture;
Covers a field-of-view of 20 square degrees on the sky at once, corresponding to a total area of 84 full-moons, by 84 chips of high-sensitivity CMOS image sensors;
Single color (optical)
2 Hz (up to 100 Hz)
Pixel scale: 1.1 arcsec/pix
Fast Moving Object Survey by Tomo-e Gozen
Wide areas of the sky are scanned in movie to reveal rapidly changing universe
100 nights/year × over 10 years
Example of wide-field movie survey
Moving object (NEO candidates) detection strategy and overview in the survey (see the poster presented by R. Ohsawa et al.)
All bright objects (events) are detected with a classical simple algorithm
Objects with velocity >~ 1 arcsec/sec are selected
Real moving objects are selected by a Random Forest classifier as NEO candidates with rejecting bogus such as artifacts, seeing dance, cosmic ray)
~900 NEO candidates are reported per night on average
Much less than 1 % of the candidates are confirmed as NEO, 10−20 % are known artificial bodies (satellites), other 80−90 % is unknown but possibly unrecorded artificial bodies including space debris
Possible New Insights Provided by Tomo-e Gozen
In the SpaceTrack catalog (radio-radar observation), small objects (RCS <~ 0.1 m^2) are not cataloged around Geostationary orbit (①) and no object in High Earth orbit (②); Only objects with with highly eccentric orbits are cataloged (see difference between perigee and apogee)
While a radar has higher detection efficiency in low altitude, optical observation has advantage in high altitude.
Optical observation with Tomo-e Gozen may cover the region ① and ②
②Data
Three-night Tomo-e Gozen Data
Date | 20200615 | 20200616 | 20200617 | Total
Weather | Fair | Fine | Fair | —
N of Exposure | 1232 | 926 | 560 | 2718
N of Moving Object (NEO candidate) | 3507 | 7014 | 866 | 11387
N of Satellites on-Detector (see below) | 1563 | 978 | 837 | 3378
N of Matched Satellites on-Detector | 721 | 451 | 386 | 1557
Many more moving objects (11387 in 3 nights) are detected by Tomo-e Gozen as NEO candidates than artificial objects in the Space-Track catalog (3378 on-detector event in 3 nights, 1557 matching to the NEO candidates) => Tomo-e Gozen may detect artificial objects that are not recorded in the Space-Track catalog.
SpaceTrack Data for Satellites
The satellite sample is defined by
① obtaining TLE in SPACE-TRACK as of 20200709 (19314 obj.) and
② selecting objects with apogee altitude > 10^4 km (3842 obj.).
③ selecting satellites on detector chips in each exposure (Number given in the table above)
Radar cross-section (RCS) is also taken from the CelesTrack catalog.
Upper limit of moving speed of the NEO detection algorithm is ~ 50 arcsec/s because it is currently optimized to a few arcsec/s
Objects with apogee altitude < 10^4 km are not likely be detected.
③Matching Methodology
NEO candidates are picked up within 20 arcmin in position and 20 arcmin/s in velocity around each satellite.
The NEO candidate with smallest difference of position velocity is regarded as matched one for the satellite.
Example of matching in an exposure
Statistics of matching for all exposures
Relatively large position error may be due to uncertainty of the orbit (typically ~1km = 20 arcsec @10 km elevation)
④Results1: Detection Rates
Detection Rate per On-Detector
| Total
N of On-Detector Event of Satellites | 3378
N of Matching | 1557
Detection Rate | 0.461
When a satellite in SpaceTrack passes a detector, it is cataloged in the Tomo-e NEO catalog with a ~46 % possibility
* In the following, detection rate is by this definition (per on-detector)
Detection Rate per Satellite
| Total
N of Unique Satellites with at Least Once On-Detector | 988
N of Matching | 636
Detection Rate | 0.644
In 3-night observations, when a satellite in SpaceTrack passing a detector at least once, it appears in the Tomo-e NEO catalog with a ~64 % possibility
Detection Rate is Higher for Larger Elevation and for Smaller Moving Speed
Detection Rate is ~ 0.6 in Geostationary orbit and is higher for larger elevation
Detection Rate is ~0.8 around 15 arcsec/s and is higher for smaller mean motion
v_mean is a norm of the velocity vector of a satellite at the time of observation
No Dependence on Orbit Eccentricity
Effect of Background Steller Density
Lower detection rate at lower galactic latitude indicates that the detection may be affected by background bright stars.
Detection Rate is Smaller for Debris compared to Rocket Bodies and Others
No Code
Debris
Rocket Bodies
Type of object is identified from the Line 0 element of TLE, and it is either of
Debris: Line 0 has the word "DEB"
Rocket Bodies: Line 0 has the word "R/B"
None: Without "DEB" and "R/B"
Lower detection rate for debris may be due to their small size and blinking (see below)
Detection Rate is Smaller for Smaller Object but Not Very Small for Higher Orbit
Detection rate tends to be smaller for smaller objects (left panel), but for elevation >~ 2 x10^4 km (~10^4.3), detection rate for small objects (RCS ~ 10^-3 m^2) is comparable to larger objects.
=> Tomo-e Gozen may provide complementary insights into space debris monitoring in Geostationary and High Earth orbits to radio radar observations
⑤Results2: Light Curve of Detected Objects
Example of 6-sec Light Curves of Detected Objects
High Detection Rate (> 0.8)
Low Detection Rate (< 0.2)
High detection-rate objects tend to be brighter and have stable light curve
Low detection-rate objects tend to be fainter and unstable light curve
For low detection-rate objects, there are missing frames probably due to blinking
Low detection-rate objects have higher missing frame rate (9 +/- 2%) than high detection-rate objects (2.9 +/- 0.3 %).
=> NEO detection algorithm has a threshold for number of detected frames in one exposure. Detection rate may become higher with tuning the algorithm.
Statistics of 6-sec Light Curves of Detected Objects
Left panel: Magnitude in all frames in all light curves. High detection-rate objects is brighter than low detection-rate objects.
Right panel: Standard deviation of magnitude measured in one exposure (12 frames). Low detection-rate objects have larger standard deviation
=> NEO detection algorithm of Tomo-e Gozen is currently not optimized for highly blinking object. Detection rate may become higher with tuning the algorithm.
References
Kiso Observatory (the Univ. of Tokyo): http://www.ioa.s.u-tokyo.ac.jp/kisohp/
SPACE-TRACK.org: https://www.space-track.org/
CelesTrack.com: https://celestrak.com/
© 2020. For information, contact Deloitte Tohmatsu Risk Services Co., Ltd.

P03

低軌道 NEO 観測小型衛星

Small Satellite for NEO Observation from LEO

○平子 敬一, 柳沢 俊史, 黒崎 裕久, 神谷 浩紀（JAXA）
○HIRAKO Keiichi, YANAGISAWA Toshifumi, KUROSAKI Hirohisa, KAMIYA Kouki (JAXA)

地球接近天体（NEO）やデブリの地上からの観測は、太陽や月による照射環境や天候や大気の揺らぎの影響を受ける。特に太陽と地球の間にある物体の発見は困難である。この制約を除去するために、低コスト、短期間な宇宙からの観測を検討した。衛星の検討にあたり、光学観測望遠鏡、軌道条件、打上ロケット、観測シーケンスなどのミッションプロファイルを仮定した。これらの仮定のもとで衛星の概念検討を実施してマイクロ衛星の一つの解を得た。 衛星の規模は 60×60×80cm、質量は 65kg となった。概念検討により 3 つの技術課題を抽出し、各々の課題に対する対策の実現性の見通しを得た。検討にあてって仮定したミッションプロファイルの曖昧さを考慮しても、NEO 観測衛星は 100kg 級で実現できると考える。この衛星は運用中や運用終了した衛星に危険を及ぼすデブリの観測にも有効である。ポスターは NEO 観測の概念検討結果の概要を紹介する。

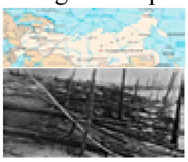
Near Earth Object “NEO” and debris observation from ground site is restricted by the light condition from the sun and the moon, atmospheric condition and fluctuation. Especially it is difficult to detect objects between the sun and the earth. In order to release from these restrictions, observation from space is considered with low cost and short development period. Mission profile of NEO observation satellite such as dimension and mass of an optical telescope, orbital condition, rocket interface and observation sequences had been assumed. Under those assumption, feasibility study of satellite had been carried out and one of result of small satellite was obtained. Dimensions of the satellite is 60×60×80cm and its mass is about 65kg. In this feasibility study three technical issues are recognized and possibility of solutions are introduced. Considering an ambiguity of the assumption, NEO observation satellite will be realized by small satellite with 100kg class. This technology is useful for observing debris which is hazardous for operating or post mission satellites. This poster shows outline of a small satellite for NEO observation.

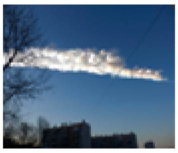
Small satellite for NEO observation from Low Earth Orbit

HIRAKO Kei-ichi, YANAGISAWA Toshifumi, KUROSAKI Hirohisa, KAMIYA Kouki (JAXA)

Near Earth Object (NEO) had caused significant damages to local areas.

Tunguska explosion

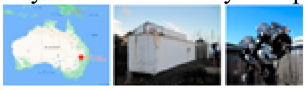




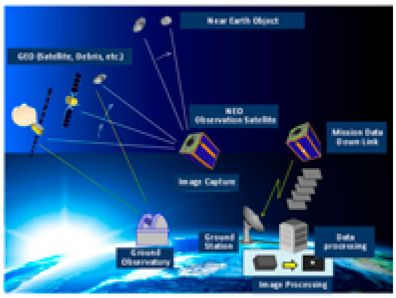
Chelyabinsk meteorite

For ground-based observation with 20cm-class small telescopes located in Japan and Australia, **we have discovered 11 NEOs since March of 2017**

Mt. Nyukasa observatory in Japan



Siding Spring Observatory in Australia



Observation from ground and space **contributes to SSA.**

Our research team is considering the observation network for these NEOs. We call our activity "**JANESS**", **JA**xa **NE**o **S**urvey **S**ystem.

We have carried on feasibility study of 100kg class of micro-satellite to observe NEO from low earth orbit.

Mission Concept

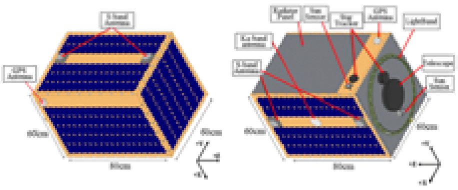
- Telescope(Refferred from ground telescope)
  Size;200×220×620mm, Mass;16kg,
  Power Consumption:16W, FOV;3.5×3.5deg,
  Size of 2D Image sensor; 2048×2048pixcel
  Resolution: 16bit/pixcel
- Stability during exposure; Better than 0.002deg/24sec
  (In order to obtain high S/N)
- 2 observation modes.
  NEO Mode; Orient one direction in inertial axis.
  24seconds exposure, 32 images.
  GEO Mode; Orient one point on GEO.
  4seconds exposure, 32 images.

(Ex.)Sequence of NEO Mode

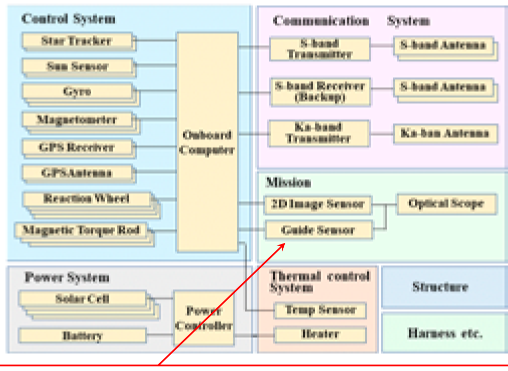
(a) Orient to required directed direction.
(b) Obtain 32 images with 24 exposure time.
(c) Orient to next direction.
(d) Obtain 32 images with 24 exposure time..
(e) Repeat sequence (c) and (d).
(f) Attitude maneuver to orient antenna to ground station.
(g) Down link stored data.
(h) Return to sequence (a).

Ride share or piggy back launch.
Altitude;650km, Sun Synchronous Orbit, Local Sun Time;12:00, Rocket I/F;LightBand.

Result of conceptual design of the satellite system

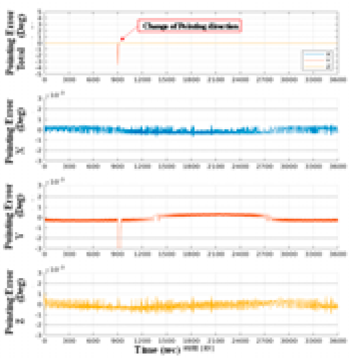


Power;60W(EOL)
Battery; 6Ah
Bus Voltage;24〜33V
HK;S-Band
Data;Ka-Band



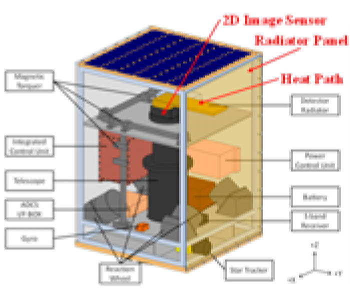
- Mass;65kg, Size;60×60×80cm
- Telescope is fixed on satellite body.
- Pointing control is achieved by attitude control of the body.
- Solar cells are mounted on satellite body. In order to eliminate source of micro vibration, deployable solar panel is not applied.
- Components with flight heritage of small satellite are selected.

A Guide Sensor detects micro change of direction of line of sight



Using the signals from a guide sensor, stability better than 0.002deg/24sec will be achieved. (By simplified 3 axis simulation)

- To reduce thermal noise, 2D image sensor shall be cooled below -70°C.
- +Y panel is used as a radiator panel.
  ➡ Incident light from the sun to +Y panel shall be avoided. (Restriction on the operation)
- Under high temperature condition, temperature of 2D image sensor exceeds -70°C.



Researched with IHI Corporation and Meisei Electric. Co., Ltd.

P04

超高分子量ポリエチレン繊維複合材/アルミニウム合金デブリバンパーからのイジェクタの低減

Reduction in Ejecta from Ultra-high Molecular Weight Polyethylene Fiber Composites/ Aluminum Alloy Debris Bumper

○正木 聖広，西田 政弘（名古屋工業大学），
野村 幸弘（東洋紡），東出 真澄（JAXA）
○MASAKI Masahiro, NISHIDA Masahiro (Nagoya Institute of Technology),
NOMURA Yukihiro (Toyobo), HIGASHIDE Masumi (JAXA)

超高分子量ポリエチレン繊維の複合材は，防御材料として有望である．この材料とアルミニウム合金を接着したデブリバンパーを用いて，イジェクタを低減しつつ，バンパーとしての性能は同等もしくは向上するようなデブリバンパーを目指して，研究している．その結果を報告する．

A composite using ultra-high molecular weight polyethylene fiber is a promising material for defense materials. Our group proposed an aluminum alloy plate glued with the composite to reduce ejecta so as not to decrease bumper performance. We would like to report some results using ultra-high molecular weight polyethylene fiber composites.

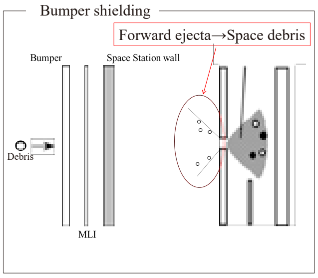
Reduction in Ejecta from Ultra-high Molecular Weight Polyethylene Fiber Composite / Aluminum Alloy Debris Bumper

Masahiro Masaki[1)], Masahiro Nishida[1)], Yukihiro Nomura[2)], Masumi Higashide[3)]

1)名古屋工業大学 / Nagoya Institute of Technology
2)東洋紡 / TOYOBO
3)宇宙航空研究開発機構 / JAXA

1. Reduction of Fragmentation Debris

Need to development of debris bumper that is less likely to generate fragmentation debris

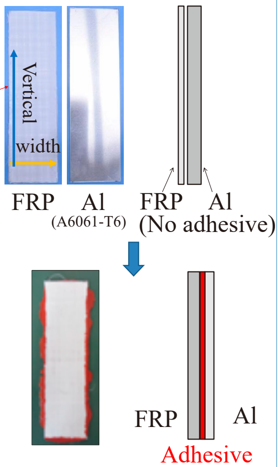


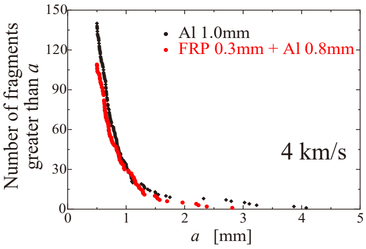
2. FRP (Fiber Reinforced Plastics)

FRP: Dyneema® Unidirectional Sheet Material:
Dyneema® HB26 (DSM) (UHMwPE fiber composites)

- Low density
- Impact resistance

The vertical direction of the fibers is the collision surface



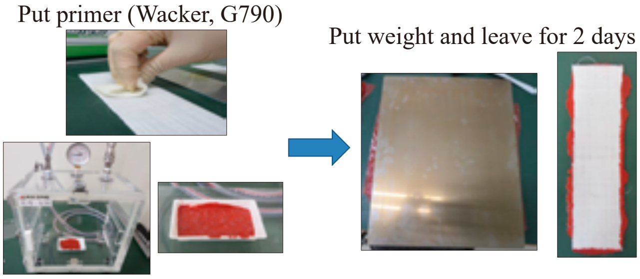


Fuchita, Master thesis, Nagoya Institute of Technology (2018)

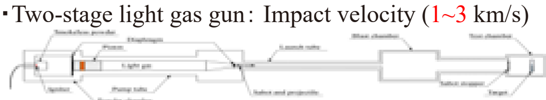
This study verifies the effect of the adhesive on the amount of forward ejecta

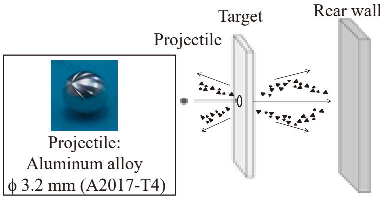
3. Experiment Methods

- Adhesive (Wacker, RTV-S 691) method
  Put primer (Wacker, G790)

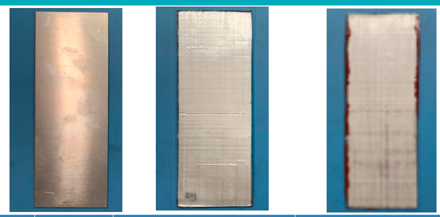


- Two-stage light gas gun: Impact velocity (1~3 km/s)





4. Targets

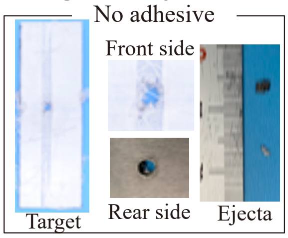


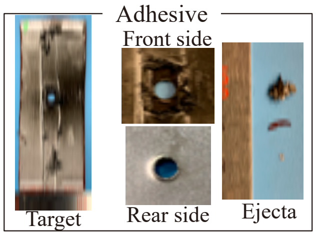
	Al 1.0 mm	FRP 0.3 mm+Al 0.8 mm (No adhesive)	FRP 0.3 mm+Al 0.8 mm (Adhesive)
Area density (g/cm^2)	0.270	0.242	0.272

Fuchita, Master thesis, Nagoya Institute of Technology (2018)

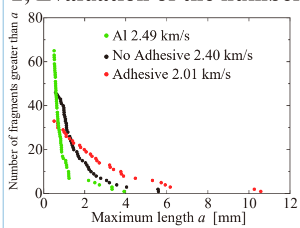
5. Experiment Results

1, Targets and ejecta after impact experiments





2, Evaluation of the number of forward ejecta



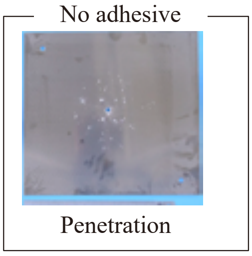
Relationship between ejecta and adhesive

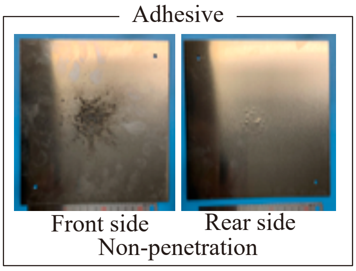
Percent of each ejecta

		No adhesive	Adhesive
Total number of forward ejecta (Length $a \geq 0.5$mm)		49	33
Percentage (%)	FRP	6.12	39.4
	Adhesive		57.1
	Al	93.9	12.1

Total number of forward ejecta: Adhesive < No adhesive < Al
(Length $a \geq 0.5$mm)

3, Evaluation of rear wall





6. Summary

Ejecta

- Adhesive's ejecta was lowest
- When classified by ejecta type, aluminum, which has a high density was very low at about 12%

Rear wall

- Defensive performance was improved

This adhesive improved bumper performance

P05

電気推進噴出流の照射による宇宙デブリの脱軌道技術の研究とその実証超小型衛星 OSU4 の開発

Study on Non-Contact Space Debris Deorbit Technology by Using Irradiation of Electric Thruster Exhaust Flows and Development of the 4th Osaka Sangyo University Nano-Satellite for Its Practical Experiment in Space

○田原 弘一，山本 拓海，島田 貴久，水出 蒼真，三村 篤史（大阪産業大学），
池田 知行（東海大学）
○TAHARA Hirokazu, YAMAMOTO Takumi, SHIMADA Takahisa, MIZUIDE Soma, MIMURA Atsushi (Osaka Sangyo University), and IKEDA Tomoyuki (Tokai University)

近年、地球周辺軌道上での宇宙デブリの数は爆発的に増加しており国際的な問題となっている。大阪産業大学では、宇宙用スラスタ、特に電気推進機の研究開発の技術・経験を活かし、電気推進機そのものを用いた、新たな非接触式デブリ処理方法の研究開発を行ってきた。その方法は電気推進機の噴出流をデブリに照射し、反力（力積）を与え、デブリを減速させ、デブリを降下させることにより、大気圏再突入までの期間を短縮するというものである。この方法ではデブリの回転制御も可能である。今発表では、パルスプラズマスラスタ、ホールスラスタを用いて、除去の対象となるデブリを想定したターゲットにプラズマ流を照射し、力積・反力を測定した結果を報告する。さらに、図 1 に示すような、大阪産業大学（OSU）・超小型衛星 4 号機を用いた、本研究技術の宇宙実証実験の概要と電気推進機を用いたベアテザー電子捕集に関する地上模擬実験についても紹介する。

The 4th Osaka Sangyo University (OSU) satellite, as shown in Fig.1, is planned as a nano-satellite in order to achieve a main mission in which space debris makes deorbit by electric propulsion. The principle of deorbiting space debris is exposure of thruster plume to space debris by an electric thruster; that is, reaction impulse is given to debris, and after that debris decreases velocity and deorbits. Accordingly, the OSU4 satellite can deorbit space debris with safety without contacting with space debris and the satellite. Our university is developing four kinds of electric propulsion. These electric thrusters are investigated, and for the OSU4 satellite for deorbiting space debris a suitable electric thruster will be selected. Reaction impulse bit of a pulsed plasma thruster (PPT) is measured on a downstream plate by pendulum method. As a result, a reaction impulse bit is average 1.718mNs. Because a previously directly measured thruster impulse bit of the PPT was about 2.2mNs, a reaction impulse bit is about 30% decrease. The OSU4 satellite is developing for launching in 2022. Ground-based experiment on current collection by a bare-tether using a Hall thruster is also presented.

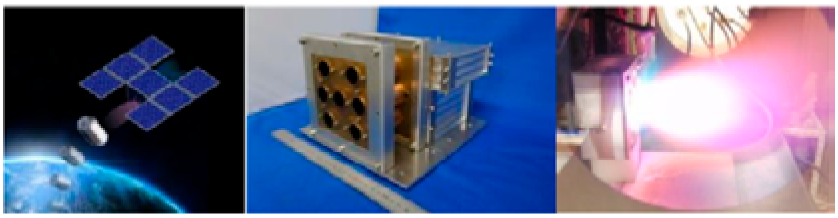


Fig.1 4th Osaka Sangyo University OSU Nano-Satellite with pulsed plasma thruster system for Non-Contact Space Debris Deorbit.

電気推進噴出流の照射による宇宙デブリの脱軌道技術の研究とその実証超小型衛星OSU4の開発

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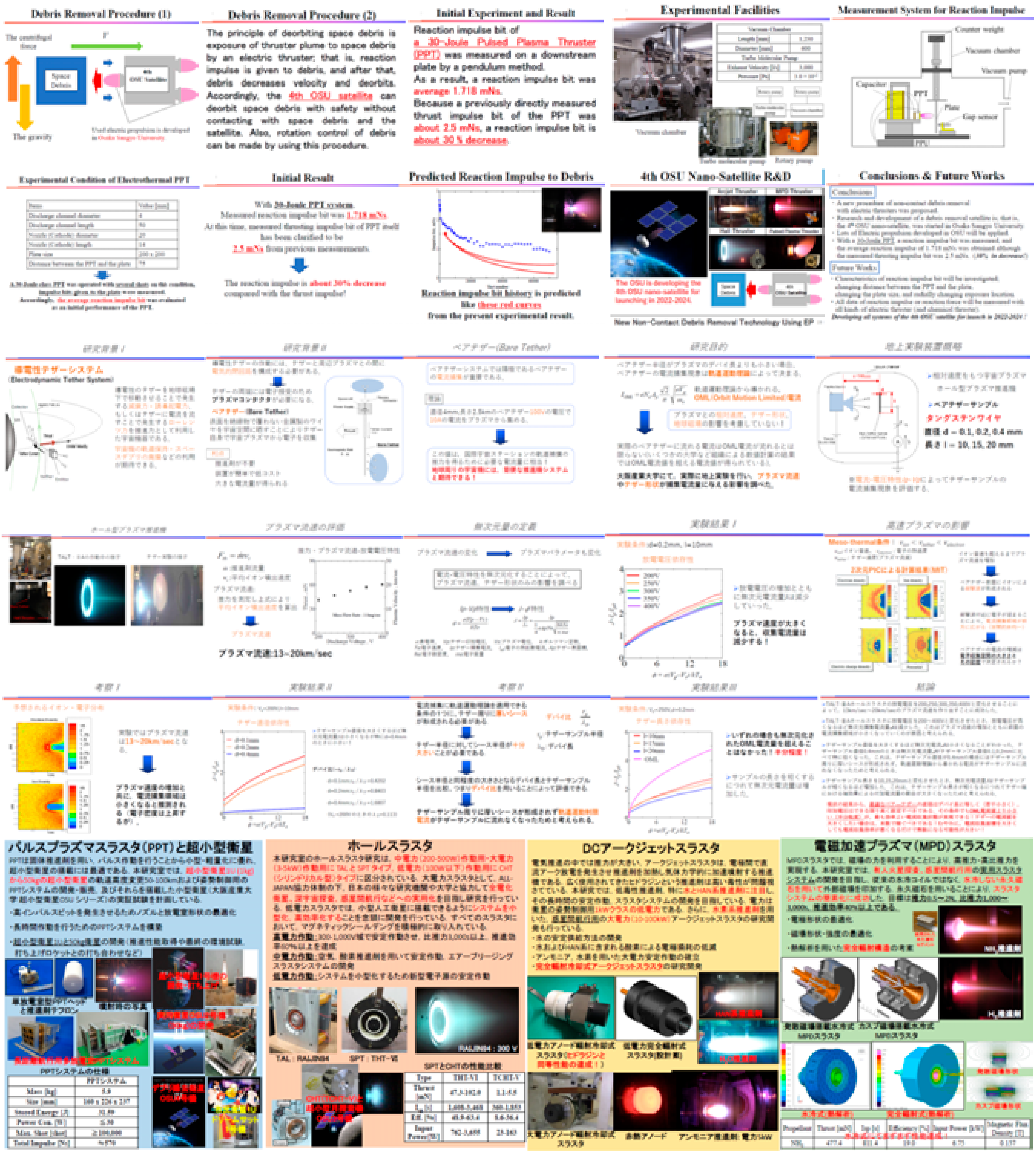
田原弘一, 山本拓海, 島田貴久, 水出蒼真, 三村篤史(大阪産業大学), 池田知行(東海大学) E-mail: hirokazu.tahara@ge.osaka-sandai.ac.jp
Hirokazu Tahara, Takumi Yamamoto, Takahisa Shimada, Soma Mizuide, Atsushi Mimura (Osaka Sangyo University), and Tomoyuki Ikeda (Tokai University)

概要：近年、地球周辺軌道上での宇宙デブリの数は爆発的に増加しており国際的な問題となっている。大阪産業大学では、宇宙用スラスタ、特に電気推進機の研究開発の技術・経験を活かし、電気推進機そのものを用いた、新たな非接触式デブリ処理方法の研究開発を行ってきた。その方法は電気推進機の噴出流をデブリに照射し、反力（力積）を与え、デブリを減速させ、デブリを降下させることにより、大気圏再突入までの期間を短縮するというものである。この方法ではデブリの回転制御も可能である。今発表では、パルスプラズマスラスタ、ホールスラスタを用いて、除去の対象となるデブリを想定したターゲットにプラズマ流を照射し、力積・反力を測定した結果を報告する。さらに、大阪産業大学（OSU）・超小型衛星4号機を用いた、本研究技術の宇宙実証実験の概要と電気推進機を用いたベアテザー電子捕集に関する地上模擬実験についても紹介する。

Abstract: The 4th Osaka Sangyo University (OSU) satellite is planned as a nano-satellite in order to achieve a main mission in which space debris makes deorbit by electric propulsion. The principle of deorbiting space debris is exposure of thruster plume to space debris by an electric thruster; that is, reaction impulse is given to debris, and after that debris decreases velocity and deorbits. Accordingly, the OSU-4 nano-satellite can deorbit space debris with safety without contacting with space debris and the satellite. Our university is developing four kinds of electric propulsion. These electric thrusters are investigated, and for the OSU-4 satellite for deorbiting space debris a suitable electric thruster will be selected. Reaction impulse bit of a pulsed plasma thruster (PPT) is measured on a downstream plate by pendulum method. As a result, a reaction impulse bit is average 1.718mNs. Because a previously directly measured thruster impulse bit of the PPT was about 2.2mNs, a reaction impulse bit is about 30% decrease. The OSU-4 nono-satellite is developing for launching in 2022. Ground-based experiment on current collection by a bare-tether using a Hall thruster is also presented.



P06

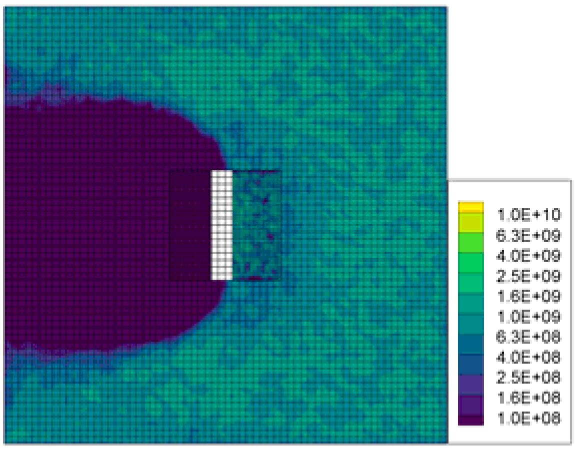
スペースデブリ除去装置への応用を目指した帯電薄膜による抗力増大装置の開発研究

Study on Drag Force Intensifier Applying Charged Membrane for Space Debris Removal

○村中 崇信（中京大学），奥村 哲平（JAXA），上野 一磨，
大塚 俊輔（中京大学），大川 恭志（JAXA）
○MURANAKA Takanobu (Chukyo Univ.), OKUMURA Teppei (JAXA), UENO Kazuma, OTSUKA Shunsuke (Chukyo Univ.), OHKAWA Yasushi (JAXA)

近年の宇宙活動の拡大に伴い，地球周回衛星の運用において，軌道上に存在するスペースデブリ（以後デブリ）が大きなリスクとなりつつある．そこで，これらデブリの数を低減する目的で，運用を終えた人工衛星が自ら軌道離脱し，地球大気圏に突入するPMD(Post Mission Disposal)のアイデアが検討されている．そのひとつに，宇宙機のミッション期間終了後に，軌道上で薄膜を展開し，薄膜に作用する高層大気の抗力を利用するデブリ除去装置が提案されている．本研究グループは，この薄膜を帯電薄膜とすることで高層大気中のイオンの抗力を増大させる新たなデブリ除去デバイスを考案し，実用化に向けた基礎研究を進めている．本発表では，この帯電薄膜デバイスの抗力増倍効果について述べ，抗力増倍に適した膜面への電圧印加手法について提言する．図はその一例として，数値計算によって得られた右から左に流れるイオンの数密度を示す．効果的膜面帯電により下流側へのイオンの回り込みが回避される様子を示す．

Increase of space debris has been becoming serious risk for spacecraft operation in near Earth orbit as space activities expand. To reduce the number of these space debris, methods for de-orbiting spacecraft by itself to the Earth after its lifetime are proposed. These methods are so called post mission disposal, PMD. A PMD device has successfully demonstrated in low Earth orbit (LEO) to produce atmospheric drag by using a deployable membrane. To enhance the drag for effective debris removal, we propose a new device composed of a charged membrane to utilize ions existing in the orbit. In this study, we present the magnification of the ion drag onto the charged membrane compared to that onto non-biased membrane, and also present appropriate method to bias the membrane to utilize the ion sheath to produce the ion drag. The figure shows a cross sectional view of the density of ions flowing right to left around charged membrane obtained by a numerical simulation. In the figure, an effective biassing method prevents turning of ions onto the downstream surface.



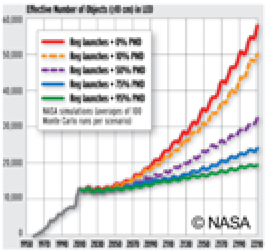
Study on Drag Force Intensifier Applying Charged Membrane for Space Debris Removal

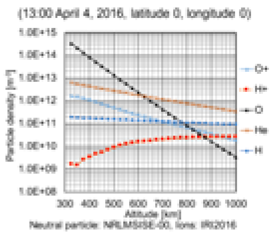
○Takanobu Muranaka[1], Teppei Okumura[2], Kazuma Ueno[1], Shunsuke Otsuka[1], Yasuhi Ohkawa[2]

[1]Chukyo University, Japan, [2]JAXA

Abstract: Increase of space debris has been becoming serious risk for spacecraft operation in near Earth orbit as space activities expand. To reduce the number of these space debris, methods for de-orbiting spacecraft by itself to the Earth after its lifetime are proposed. These methods are so called post mission disposal, PMD. A PMD device has successfully demonstrated in low Earth orbit (LEO) to produce atmospheric drag by using a deployable membrane. This device has the advantages of low-cost and simplicity of its component but disadvantage of uncontrollable drag. To improve the device, we propose a new device composed of a deployable charged membrane to utilize ions existing in the low earth orbit. In this study, we introduce the system concept and components, and present numerical analysis to determine appropriate biasing method on the surface of the membrane to utilize the ion sheath to increase the ion drag.

1. Background & Purpose of This Study

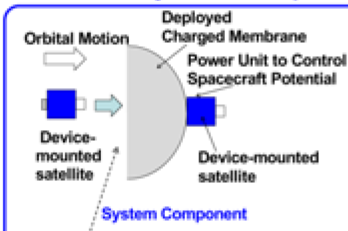


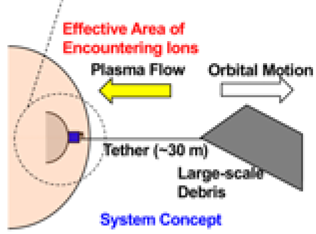


- Expansion of space utilization activities increases the number of space debris
- These debris collide with others producing a lot of smaller debris that would cause further collisions to spacecraft and their destruction in orbit (Kessler syndrome[1]).
- Removal of expecting debris (used satellite, parts of launch vehicles, etc.) is of importance to suppress increasing of debris (called Post Mission Disposal, PMD).
- One of a conventional PMD system uses a deployable membrane capturing the neutral particles to produce drag force, which had already been demonstrated on-orbit at the altitude of 400 km.
- This PMD system is very simple, but a large-scale structure is necessary to produce sufficient drag force for a large-scale debris.
- Using a charged membrane instead of the conventional one can utilize an ion sheath to attract orbital ions to generate more drag keeping the scale of the membrane.

[1] Kessler, D. J., Collisional Cascading: The Limit of Population Growth in Low Earth Orbit, Advances in Space Research, 11, pp. 63-66, 1991

2. System Concept and Component





Charged Membrane:

- Major component of the system (1m x 1m to 3m x 3m)
- Negatively charged to attract ions by a mounted power unit
- Biasing method to utilize ion sheath should be considered
- Expanded sheath around negatively charged membrane can collect more ions

Features:

- Comparatively simple and low-cost
- Applicable as both PMD and ADR devices
- In use of ADR device, using tether (~30m) can avoid ion wake downstream debris
- Attracted ions onto the membrane enhance drag force
- Attracted ions as well as neutral particles contribute to generate drag force

3. Utilizing Ion Sheath by a Biassing Method on the Charged Membrane

Intensified Drag force

Drag force can be estimated as sum of the drag forces by neutral particle and ions

$$F_D = \frac{1}{2}C_D\rho_n v_D^2 A_m + \frac{1}{2}C_D\rho_i v_i^2 A_m^*$$

C_D: drag coefficient, ρ:density, v:velocity, A_m: area of membrane

Neutral drag: determined by orbital parameters

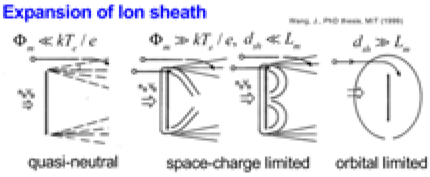
Ion drag:

ρ_i, v_i: determined at the surface of membrane

A_m*: effective area of the membrane utilizing ion sheath

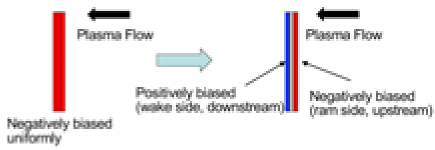
- Ion drag is intensified on the negatively charged membrane compared to that on non-biased membrane.
- Magnification of the ion drag can briefly be estimated by the magnification of the ion current onto the membrane

Expansion of Ion sheath



- Ion sheath expands as absolute value of the negative potential on the membrane increases.
- Current collection of the ions onto the surface of the membrane can be controlled by the potential.

Effective Biasing Method on the membrane to Utilize Ion Sheath in LEO



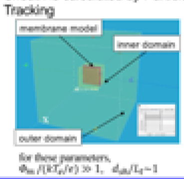
Biasing the ram (upstream) and wake (downstream) sides of the membrane separately can be effective to utilize ion sheath

- ram : negatively biased to attract ions
- wake : positively biased to repel ions

Numerical Analysis of Sheath and Current Collection in LEO

We performed numerical simulations To evaluate potential structure around the membrane, using MUSCAT2

- MUSCAT2: 3D multi-grid ES particle code
- Developed by JAXA
- Sheath is calculated by Particle-In-Cell, current collection by Particle Tracking

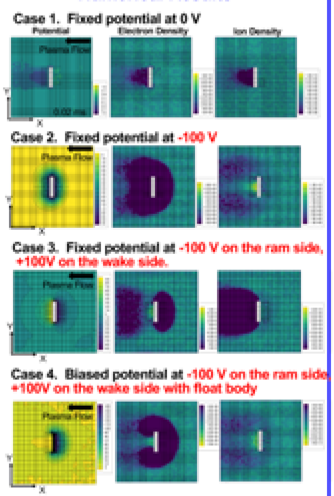


for these parameters, $\Phi_m/(kT_e/e) \gg 1,\ d_{sh}/L_s \sim 1$

dx/λD (inner)	0.77
dx/λD (outer)	1.5
dt (PIC)	0.25ω_pe
[illegible]	4.3 × 10²
[illegible]	333
ion	O⁺
Mach No. (ion)	3.0

domain (inner)	3.2m × 3.2m × 3.2m
domain (outer)	6.4m × 6.4m × 6.4m
membrane	3.0m × 3.0m × 0.3m

Numerical Results



- In case 3, ions are almost repelled in the wake region of the membrane, that can be considered directivity of the drag is maintained
- In case 4, potentials of ram and wake side have changed to be -200V and 0V, respectively due to excess of electron current (Float potential is converged to be −100V), and characteristic potential structure around the membrane is shown

Conclusion:

- We propose a drag force intensifier using charged membrane for de-orbiting a large-scale debris
- The system is designed to apply ion drag as well as drag of neutral particles
- To enhance the ion drag, directivity of the ion current onto the membrane is controlled by a biassing method on the membrane: negative potential on the upstream surface, positive potential on the downstream surface.
- Effect of the biassing method to utilize the ion sheath for ion drag is analyzed by numerical simulations; the results show the biassing method is effective, the electrically floating potential will determine the magnitude of the potentials onto the surface of the membrane.
- Estimation of the magnification of the drag by ion drag is on-going by post processing of the numerical results.

P07

EDTを用いたPMDデバイスにおけるテザー伸展についての初期検討

Initial Study on Tether Deployment in PMD Device
Using EDT

○坂元 洋輝, 渡部 武夫, 佐藤 強, 大﨑 一樹, 佐藤 洸輔(神奈川工科大学),
蒲池 康, 岡島 礼奈(ALE)
○SAKAMOTO Hiroki, WATANABE Takeo, SATO Tsuyoshi, OSAKI Kazuki, SATO Kohsuke (KAIT),
KAMACHI Koh, OKAJIMA Lena (ALE)

著者らはEDT(Electrodynamic Tether)を用いた超小型衛星用PMD(Post Mission Disposal)デバイスについて研究開発を行っている。このデバイスは衛星の運用終了後、折り畳んで収納したテープテザーを展開し、テザーに流れる電流と地球磁場との相互作用によって発生するローレンツ力と大気抵抗を推進力として利用することで、使用済み衛星の軌道離脱を支援することを目指している。しかし EDT は地球磁場を利用するため、運用条件に応じてテザーの伸展方向に制約が生じる場合がある。そのためテザー展開時の初期条件がテザーの伸展挙動に与える影響について検討することは、テザー伸展の失敗リスクを低減するための設計や運用指針の策定に役立つと考えられる。本研究では軌道平面内における二重振り子型の簡易モデルでシステムを記述し、モンテカルロ法による解析を行った。テザーで繋がれた子衛星の放出時の初期条件に対し、伸展の成否を判定する任意の指標を用いてテザー伸展の成否を検討した。本稿ではその結果に関して報告する。

The authors are conducting research on post mission disposal (PMD) device for microsatellites using electrodynamic tether (EDT). In this PMD device, the atmospheric drag and the electromagnetic force are utilized for the propulsion of deorbit. In case of PMD device using EDT, the direction of tether deployment is constrained by the trajectory of satellites because of the electromagnetic force is generated by the interaction between the current flowing in the tether and Earth's magnetic field. Therefore, the effect of initial conditions such as deployment velocity, deployment angle, and so on were evaluated by numerical simulations using Monte Carlo method. In this paper, the trend of tether deployment based on numerical simulations were shown.

Initial Study on Tether Deployment in PMD Device Using EDT

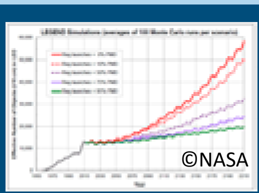
Hiroki Sakamoto, Takeo Watanabe, Tsuyoshi Sato, Kazuki Osaki, Kohsuke Sato (KAIT)
Koh Kamachi, Lena Okajima(ALE Co., Ltd.)

1. Background

The growth of micro-satellite business and concept of micro-satellite mega constellations plan.

Concern about mass production of space debris from the post mission satellites.

The needs for mitigation of space debris on LEO.



Space debris increases on LEO.
→Environmental issues in space.

PMD device concept overview

- PMD technology is the method to de-orbit a satellite quickly after a mission.
- The authors are conducting research on post mission disposal (PMD) device for micro-satellites.
- This PMD device supports re-entry of a micro-satellite by **atmospheric drag** and **electrodynamic tether propulsion (electromagnetic force).**
- The electromagnetic force is generated by the interaction between **the current** flowing in the tether and **earth's magnetic field.**
  →The direction of tether deployment is constrained by the trajectory of satellites.

2. Purpose and what was done

To evaluate the effect of initial conditions such as deployment velocity, deployment angle, and angular velocity of the satellite.

To provide the method to evaluate the trend of tether deployment for random initial conditions by numerical simulations using monte carlo method.

3. Evaluation method

Analysis procedure

Input
- Input **random values** within the specified range for each initial condition.
  →monte carlo method

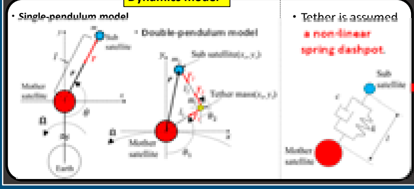
Initial condition
- **Initial velocity v_0**
- **Initial angle θ_0**
- **Angular velocity of the satellite $\dot{\theta}_0$**

Random number range

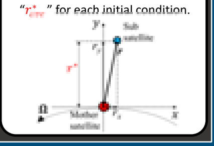
Initial velocity v_0[m/s]	0.05~1.0
Initial angle θ_0[rad]	0~2π
Angular velocity of the satellite $\dot{\theta}_0$[rad/s]	0~2π

Evaluate the trend
- Determine the success or failure of tether deployment for each initial condition.
- Plot on the 3D graph.

Dynamics model
- Single-pendulum model
- Double-pendulum model
- Tether is assumed a non-linear spring dashpot.



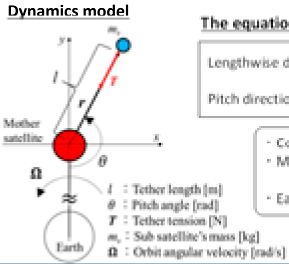
Output
- The index "r^*" output.
- Calculate the mean value "r^*_{ave}" for each initial condition.



4. Dynamics model

Single-pendulum model

Dynamics model



The equation of motion

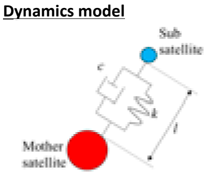
Lengthwise direction : $\ddot{l} - l\dot{\theta}^2 - 2\Omega l\dot{\theta} - 3\Omega^2 l\cos^2\theta = -\frac{T}{m_s}$

Pitch direction : $l\ddot{\theta} + 2\dot{l}\dot{\theta} + 2\Omega l\dot{\theta} + 3\Omega^2 l\sin\theta\cos\theta = 0$

- Consider only the motion in the orbital plane.
- Mother satellite : On a circular orbit. Much heavier than the sub satellite.
- Earth : A perfect circle.

Tether model

Dynamics model



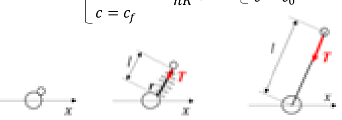
- Tether is assumed **a non-linear spring dashpot.**
- Deploy tether from its folded state.

Deployment model

Phase0 $[l = 0]$

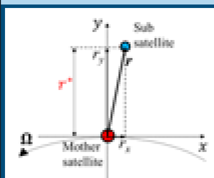
Phase1 $[|\boldsymbol{r}| < l_0]$: $k = k_f = a\frac{Ebt^3}{nR^m}$, $c = c_f$

Phase2 $[|\boldsymbol{r}| \geq l_0]$: $k = k_0 = E\frac{A}{l_0}$, $c = c_0$



$T = 0$ $\quad$ $T = k_f(0 - l) - c_f\dot{l}$ $\quad$ $T = k_0(l_0 - l) - c_0\dot{l}$

5. The index "r^*"



- The index "r^*" is the y-component of the sub satellite position vector $\boldsymbol{r}$.
- Determine the success or failure of tether deployment for each initial condition using the mean value "r^*_{ave}".

$r^*_{ave}/l_0 > 0.6$: Success in the zenith direction.
$-0.6 < r^*_{ave}/l_0 < 0.6$: Failure to deploy.
$r^*_{ave}/l_0 < -0.6$: Success in the earth center direction.

6. Example of analysis result

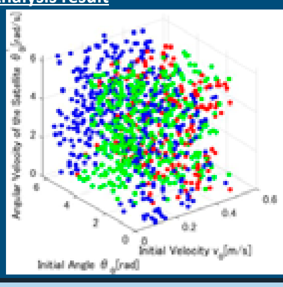
Analysis conditions

Initial tether length l_i[m]	0.01
Tether length l_0[m]	10.0
Weight of the sub satellite m_s[kg]	0.10
Orbital altitude [km]	500
Orbit angular velocity Ω[rad/s]	1.103 × 10⁻³

Tether specification

Tether material	ALPET
Thickness t[m]	45.0 × 10⁻⁶
Width b[m]	0.01
The interval of folded R[m]	0.10
Young's modulus E[GPa]	5.0
Phase1 spring constant k_f[N/m]	0
Phase1 attenuation coefficient c_f	0
Phase2 spring constant k_0[N/m]	0.001
Phase2 attenuation coefficient c_0	0.045

Analysis result



Green	Success in the zenith direction
Red	Failure to deploy
Blue	Success in the earth center direction

- Confirmed that the initial velocity and the initial angle had significant effects on the success or failure of tether deployment.

7. Conclusions

- The method to evaluate the trend of tether deployment was shown.
- This method will be useful in designs that reduce the risk of deployment failure.

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P08

スペースデブリ捕獲に向けたデブリ模擬構造への金属銛撃込みに関する数値解析

Numerical Simulations on Harpooning Metal Anchors for Capturing Space Debris

田中 宏明, ○玉置 悠人（防衛大学校）
TANAKA Hiroaki, ○TAMAKI Yuto
(National Defense Academy of Japan)

金属銛を用いたスペースデブリ捕獲に関して，数値解析モデルを構築した．構築した数値解析モデルを用いて，円錐形状，半球形状および二山形状の先端部を有する金属製銛の撃ち込みについて評価を実施した．解析の結果，全体的には先端二山の形状を用いることで，より少ない速度での貫入が可能となることを明らかにした．先端丸形状の銛では先端円錐に比べても，貫入のために大きな速度が必要である．ただし，先端二山形状では，銛により貫入孔部が円板として切り出されてしまうため，新しいデブリが生じる問題がある．

Numerical models for investigating the penetration behavior of a metal anchor were studied and their applicability was demonstrated. Effects of anchor head shapes on loading anchors on debris structures were investigated through numerical simulations. Johnson-cook model was used in the numerical simulations and the penetration behaviors during harpooning the anchors to flat or tilted targets were analyzed. Three types of anchor head shapes, cone, double bladed and sphere, were employed and their penetration behaviors were compared. It was observed from the results that the minimum penetration velocity of double-bladed head was lower than those of the other head shapes and it indicates that the required kinematic energy for capturing can decrease. However, a small piece was generated during the penetration using the double-bladed head anchor and it can be a new space debris.

Numerical Simulations on Harpooning Metal Anchors for Capturing Space Debris

スペースデブリ捕獲に向けたデブリ模擬構造への金属銛撃込みに関する数値解析

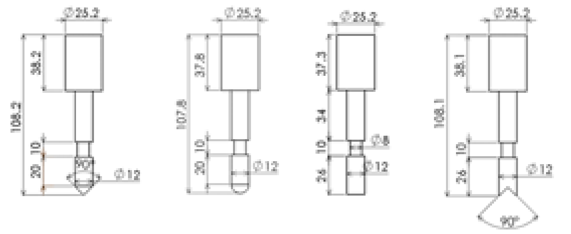
Hiroaki Tanaka and Yuto Tamaki (National defense academy of Japan)

Effects of anchor head shapes on loading anchors on debris structures were investigated through numerical simulations to obtain an appropriate anchor shape for capturing space debris.

Anchors

Four types of anchor head shapes were employed.

SS400 steel was used as the material of the anchors.
Mass of the anchors were 203.5g.



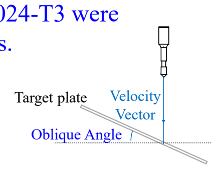
(A) Cone (B)Sphere (C) Flat (D) Double bladed

Target simulating space debris

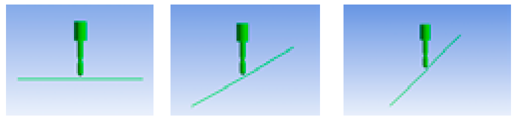
Plates made of aluminum alloy Al2024-T3 were used as the targets of the simulations.

Parameters of the target plate

Material	Aluminum Alloy (A2024-T3)
Size(mm)	250 × 250 × 1
Oblique angle [deg]	0, 30, 45



Definition of the oblique angle.



0 [deg] 30 [deg] 45 [deg]

An anchor and a target at each oblique angle.

Numerical model

Johnson–Cook models with triangular mesh was employed for target plate.

Strain (viscoelasticity model)

$$\sigma = [A + B\varepsilon_p^n][1 + C\ln\dot{\varepsilon}_p][1 - \frac{T - T_0}{T_m - T_0}]^m$$

Damage initiation criterion

$$\varepsilon_f = [D_1 + D_2(\exp D_3\frac{p}{\sigma})][1 + D_4\ln\dot{\varepsilon}_p][1 + D_5\frac{T - T_0}{T_m - T_0}]$$

Overall damage variable

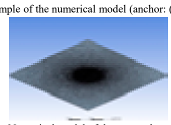
$$D = \sum\frac{\Delta\varepsilon}{\varepsilon_f} \quad \text{(intact while } D < 1.0\text{)}$$

Parameters of the JC model used in this study

A (MPa)	B (MPa)	n	C	m
265	426	0.34	0.015	1
D_1	D_2	D_3	D_4	D_5
0.13	0.13	−1.5	0.011	0

※ Lesuer (2000) , Experimental investigation of material models for Ti-6Al-4V and 2024-T3

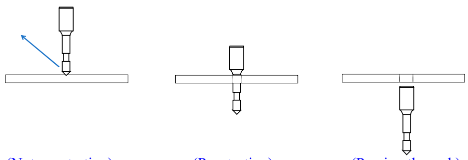
Example of the numerical model (anchor: (a) cone).



Numerical model of the target plate.
Four edges of the plate were fixed.

Numerical simulation results

Three types of docking states were observed.
Penetrating state is suitable for capturing.



(Not penetrating) (Penetrating) (Passing through)

Major penetration states during harpooning

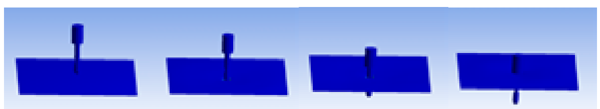
Minimum penetration velocities achieving penetrating states are obtained.

Minimum penetration velocities of four anchors

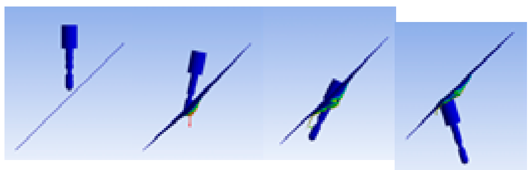
Oblique angle	Cone	Sphere	Flat	Double bladed
0 deg	13.0	13.0	21.5	15.5
30 deg	16.0	23.5	22.0	15.5
45 deg	35.0	38.5*	31.5*	18.5

*Anchor passed through at the minimum penetration velocity

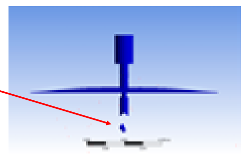
Example of the penetration behavior. (cone shape head)



Sphere and flat shape anchors can not make suitable docking states at the oblique angle of 45 deg.



A small piece was generated during the penetration using the double-bladed head anchor.



- **The minimum penetration velocity of double-bladed head was lower than those of the other head shapes.**
- **Sphere and flat shape anchors can not make suitable docking states at the oblique angle of 45 deg.**
- **A small piece was generated during the penetration using the double-bladed head anchor and it can be a new space debris.**

P09

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

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

We have developed a streaks detection algorithm for images coming from the Tomo-e camera of the 1M telescope at Kiso Observatory. It follows a computer vision approach, with the next stages: preprocessing, thresholding, Hough transform, and clustering of streaks. A set of artificial streaks were superimposed over real Tomo-e images, and with a background noise of the real frames estimated in 550 ADU, and a peak brightness of the artificial streaks ranging from 630 to 1150 ADU, all streaks were detected correctly. The algorithm took 0.52 seconds to detect 8 artificial streaks in one of the 84 image sensors, when running in a 1.1GHz dual core CPU processor with RAM 8 GB. Real images will be tested at a later stage. The Tomo-e camera survey has a minimum time between frames of 6 seconds, which corresponds to 12 consecutive images of 0.5 seconds exposure each, for one particular region of the sky. Currently the algorithm is being exported to a GPU NVIDIA Quadro RTX 8000 dual system with 144 multiprocessors, that will allow the algorithm to process in parallel over the 84 image sensors of the camera, with the aim to detect all streaks under 6 seconds.

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

Manuel Cegarra Polo, Toshifumi Yanagisawa, Hirohisa Kurosaki (JAXA)
Ryou Ohsawa, Shigeyuki Sako (University of Tokyo, Tomo-e Gozen Team)

We have developed a streaks detection algorithm for images coming from the Tomo-e camera of the 1M telescope at Kiso Observatory. It consists in three stages: preprocessing (removal of stars), detection (based in Hough transform) and analysis (photometry, astrometry and TLE database matching). The detection stage is run in a 4 x GPU NVIDIA Quadro RTX8000 system, allowing the algorithm to preprocess and detect streaks in each FITS file (~40 Mpixels) in ~100 ms.

Tomo-e Gozen Camera

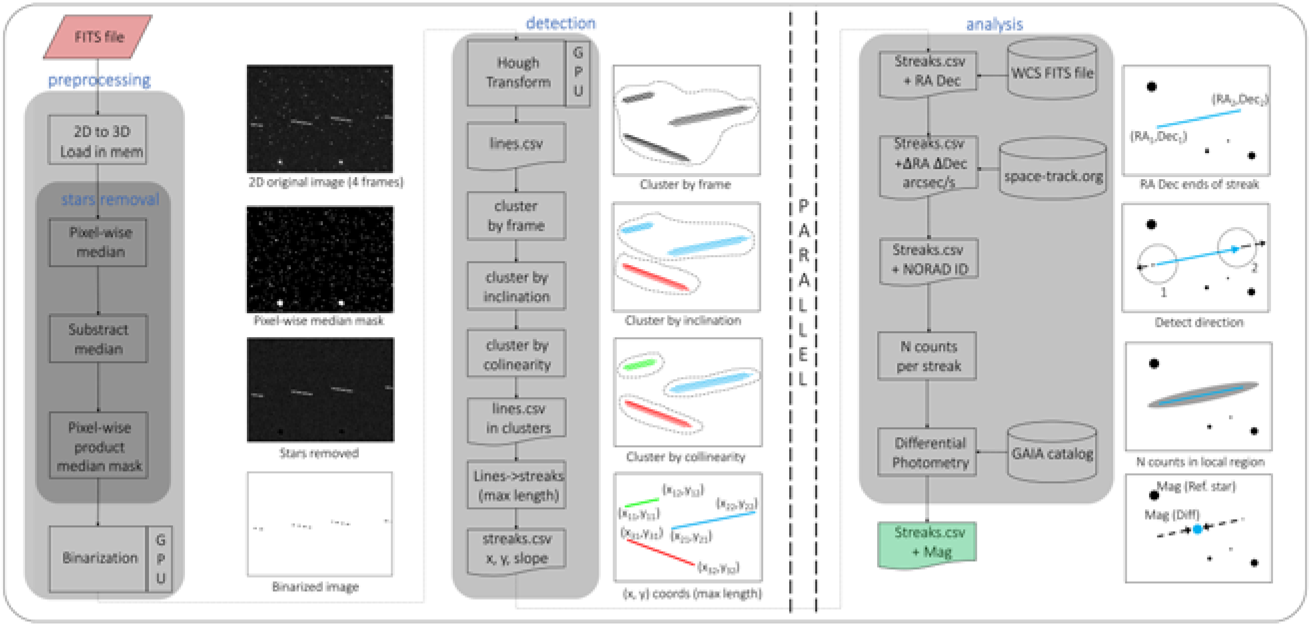
Array of 84 CMOS sensor covering FOV 9º diameter
credit: www.ioa.s.u-tokyo.ac.jp/tomoe

FITS : 2000 x 1128 x 18 = 40.6 Mpixels (162 MB)
Frame: 40.6 x 84 sensors ~= 3.4 Gpixels (13.6 GB)
Data rate: ~ 1.5 – 1.7 TB / hour (~20 s nudging time)

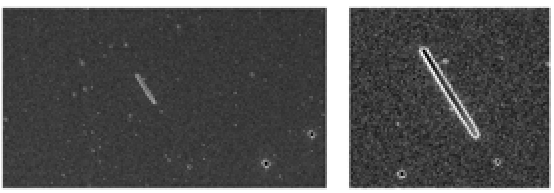
Features

- GPU system: 4 x NVIDIA Quadro RTX8000
- Preproc. and detection speed = ~100 ms per FITS file.
- Analysis speed = ~8-15 seconds per FITS file.
- Preprocessing and detection in PARALLEL analysis
- Orbital altitude (observation range 30º - 90º):
  - 550 km → 4200 km (one end within boundaries)
  - 1100 km → 4200 km (both ends within boundaries)
- Astrometry: - RA Dec coordinates of streaks ends.
  - Direction: RA Dec arcsec/s

Process



Results



SL-8 R/B (NORAD 16766) ZOOM SL-8 R/B (NORAD 16766)

- 21.084 FITS files analyzed ~ 3.4 Tbtyes
- 2 hours observation time processed in ~ 1 hour
- 85 FITS files with streaks detected
- 30 out of 35 objects identified (83%)

Conclusions and next steps

- **Fast system**: ~100 ms detection and 8-15s analysis -> **Real-time**
- Detect RA Decs of streak ends -> **accurate astrometry**
- Sensitivity: Detect objects down to **+11 Mag**
- **Identification**: matching with space-track.org **elsets database**

- **Increase sensitivity**: stacking method (Yanagisawa, Trans. Japan Soc. Aero. Space Sci.Vol. 44, No. 146, pp. 190–199, 2002)
- **Increase orbital altitudes**: detect streak ends in different sensors

Acknowledgements

- Research funded by JSPS and JAXA
- FITS files provided by Tomo-e Gozen Team University of Tokyo
- GPU system (GDEP Learning Box II) provided by JAXA

パネルディスカッション

Panel Discussion

Panel Discussion 1

日本の民間デブリ関連ソリューション事業化に向けた挑戦
The Challenges for Commercializing Space Debris Solutions in Japan

モデレータ：上野浩史（JAXA）
パネリスト：蔵本順（ALE）、田治米伸康（アストロスケール）、中村友哉（アクセルスペース）泉山卓（IHI）、久保田伸幸（KHI）、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）、金澤誠（Space BD）
Moderator: UENO Hiroshi (JAXA)
Panelist: KURAMOTO Jun (ALE), TAJIME Nobuyasu (Astroscale), NAKAMURA Yuya (Axelspace), IZUMIYAMA Taku (IHI), KUBOTA Nobuyuki (KHI), HATTA Shinji (MUSCAT Space Engineering), FUKUSHIMA Tadanori (SKY Perfect JSAT), KANAZAWA Mac (Space BD)

大型コンステレーションの登場に代表される宇宙利用が急速に進む中で、宇宙デブリが将来に向けた継続的な軌道利用に対する脅威と叫ばれる様になって久しい。世界各国が、デブリ問題の現状把握・対応検討し、国内法で今後打上げられる人工衛星・ロケット等に対して、デブリ化しない為の適切な施策を執ることを運用主体に求めている。国内でも、宇宙基本計画に宇宙デブリ対策が明記され、日本国を代表する領域として確立されることが期待されている。この流れの中で、宇宙デブリ問題は官のみならず民間でも注目度が高まりつつあり、宇宙デブリ問題を事業として取り扱う企業が国内でも増えつつある。本パネルでは、これらの企業が一堂に会し、宇宙デブリ化防止・除去に関する技術開発、地上からの観測、モデリング等多岐に亘る事業概要を紹介すると共に、当該企業の抱える技術・事業展開に関する課題を明らかにし、協調の可能性、政府への期待・提案を模索する。

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. Countries all over the world have been demanding that future satellite operators and rockets take appropriate measures to prevent contributing to the space debris problem. In Japan, the Basic Plan on Space Policy specifies space debris countermeasures and is expected to be established as a standard representing Japan. Following this trend, the space debris issue has been attracting more and more attention not only from the government but also from the private sector, and the number of companies offering solutions to the space debris issue is increasing. In this panel, we will introduce the business strategy outline of these companies in various fields such as technology development for space debris prevention/removal, ground-based observation, and modeling, etc. We will also identify the challenges facing these companies' technology and business development, and explore the possibility of collaboration and what they expect and propose to the government.

モデレータ：**上野浩史**（JAXA新事業促進部）
Moderator：UENO Hiroshi (JAXA)
JAXA 新事業促進部　J-SPARC プロデューサ
軌道上サービス・宇宙ロボットに係る新規宇宙関連事業の創出活動に従事
これまでに、ETS-VIIトラス遠隔操作実験装置の開発運用、宇宙ロボット研究、「きぼう」ロボットアーム・結合機構の開発運用、有人探査に関わる研究、機構の新規ミッション企画を経て、現在に至る。

パネリスト：**蔵本順**
Panelist：KURAMOTO Jun (ALE)
株式会社ALE External Relations Manager
2017年よりALEに参画し、産官との連携を担当
同社EDTプロジェクトの事業開発を担当

パネリスト：田治米伸康
Panelist：TAJIME Nobuyasu (Astroscale)

株式会社アストロスケールBusiness Development & Regulatory Affairs

2019年よりアストロスケールに参画し、衛星運用終了時の除去（EOL）、既存デブリの除去（ADR）、軌道上での宇宙状況把握、衛星寿命延長といった軌道上サービスの事業開発を担当。

アストロスケール入社前は製薬企業において新薬開発に携わり、アジア・米国の駐在を経て、経営戦略策定、M&A、JV運営など事業開発に従事。

早稲田大学ビジネススクール修了、北里大学薬学部卒業。

パネリスト：中村友哉
Panelist：NAKAMURA Yuya (Axelspace)

株式会社アクセルスペース　代表取締役CEO

1979年三重県生まれ。2007年東京大学大学院工学系研究科航空宇宙工学専攻博士課程修了。在学中、世界初の大学生手作り超小型衛星CubeSat（キューブサット）を含む3機の超小型衛星の開発に携わる。卒業後、同専攻での特任研究員を経て2008年にアクセルスペースを設立、代表取締役に就任。創業以来、世界初の民間商用超小型衛星WNISAT-1やスタートアップが初めて手がけるJAXA衛星RAPIS-1を含む5機の開発・運用に成功。また、自社事業として多数の超小型衛星で全世界を毎日観測する地球観測網AxelGlobeの構築を進めており、2018年本プロジェクト向け初号機GRUS-1Aを打上げ、2019年画像提供サービスを開始。現在、観測頻度向上のための追加4機の打ち上げを間近に控えている。2015年より内閣府宇宙政策委員会宇宙産業・科学技術基盤部会委員。

パネリスト：泉山卓
Panelist：IZUMIYAMA Taku (IHI)

IHI宇宙開発事業推進部主幹

ISS/ロケット/衛星等のシステム開発に従事

光学SSA情報サービスを提供中

パネリスト：久保田伸幸
Panelist： KUBOTA Nobuyuki (KHI)

川崎重工業株式会社　航空宇宙システムカンパニー 宇宙システム設計部 統括基幹職

1987年のKHI入社以来、ETS-Ⅶや ISS等の宇宙機器開発に従事、現在はデブリ除去を初めとした、新しい宇宙事業に取組中。

パネリスト：八田真児
Panelist：HATTA Shinji (MUSCAT Space Engineering)

MUSCATスペース・エンジニアリング株式会社

2004 九州大学大学院航空宇宙工学専攻修了

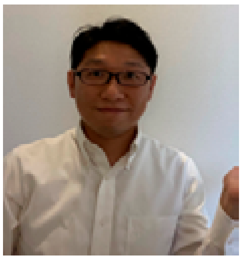
2004~2007 九州工業大学宇宙環境技術研究センター勤務

2006/9 MUSCATスペース・エンジニアリング（株）設立

現在に至る

付記：2019/5 八田・山本宇宙推進機製作所（株）設立登記

パネリスト：福島忠徳
Panelist：FUKUSHIMA Tadanori (SKY Perfect JSAT)



スカパーJSAT株式会社　デブリ除去プロジェクト プロジェクトリーダ

理化学研究所　衛星姿勢軌道制御レーザ開発研究チーム　チームリーダを兼務。

静止通信衛星の運用準備から衛星の軌道上引き渡し、および定常運用まで14年間に渡るの一連の衛星運用を経験。また静止衛星の宇宙物体（デブリ）との接近回避運用を経験し、デブリ問題を解決するため、2019年社内スタートアップ公募に有志と共にスペースデブリ除去事業を提案。1年間のFSを経て、スカパーJSATのデブリ除去の事業化を率いている。2020年春から理化学研究所内に、スペースデブリ除去用のレーザーの設計開発を行うチームを設立。

パネリスト：金澤誠
Panelist：KANAZAWA Mac (Space BD)

Space BD株式会社　COO 兼 事業開発部長

2011年三井物産株式会社入社。金属資源本部にて、アジア太平洋地域における資源リサイクル事業・再生可能エネルギー事業の新規事業開発及び投資管理業務に従事。PwCアドバイザリー合同会社等を経て、2017年よりSpace BD株式会社に参画。

早稲田大学政治経済学部卒業、シドニー工科大学MBA。


第9回スペースデブリワークショップ 2021年2月24日（水）13：00〜14：30
『日本の民間デブリ関連ソリューション事業化に向けた挑戦』
福島忠徳
スカパーJSAT株式会社　デブリ除去プロジェクトリーダ。理化学研究所　衛星姿勢軌道制御レーザ開発研究チームリーダを兼務。14年間の衛星運用の実務経験を活かし、スカパーJSATデブリ除去の事業化を推進。
田治米 伸康
株式会社アストロスケール
Business Development &
Regulatory Affairs
早稲田大学ビジネススクール修了、北里大学薬学部卒業
金澤誠
Space BD株式会社
COO 兼 事業開発部長
三井物産㈱金属資源本部で、アジア太平洋地域におけるリサイクル事業等の新規事業及び投資管理業務に従事。PwCアドバイザリー合同会社等を経て2017年より参画。
泉山 卓
IHI宇宙開発事業推進部主幹
ISS/ロケット/衛星等のシステム開発に従事
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モデレータ
上野浩史
JAXA 新事業促進部　J-SPARC
プロデューサ
軌道上サービス・宇宙ロボットに係る関連事業に従事
久保田伸幸
川崎重工業株式会社　宇宙システム設計部統括基幹職
1987年のKHI入社以来、ETS-ⅧやISS等の宇宙機器開発に従事、現在はデブリ除去を初めとした、新しい宇宙事業に取組中。
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宇宙環境技術研究センター勤務
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External Relations
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アンカーテナンシー
Anchor tenancy
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株式会社アストロスケール
Business Development &
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早稲田大学ビジネススクール修了、北里大学薬学部卒業
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プラットフォーム
Private sector platform
泉山 卓
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国際競争力・国際ルール
International institution
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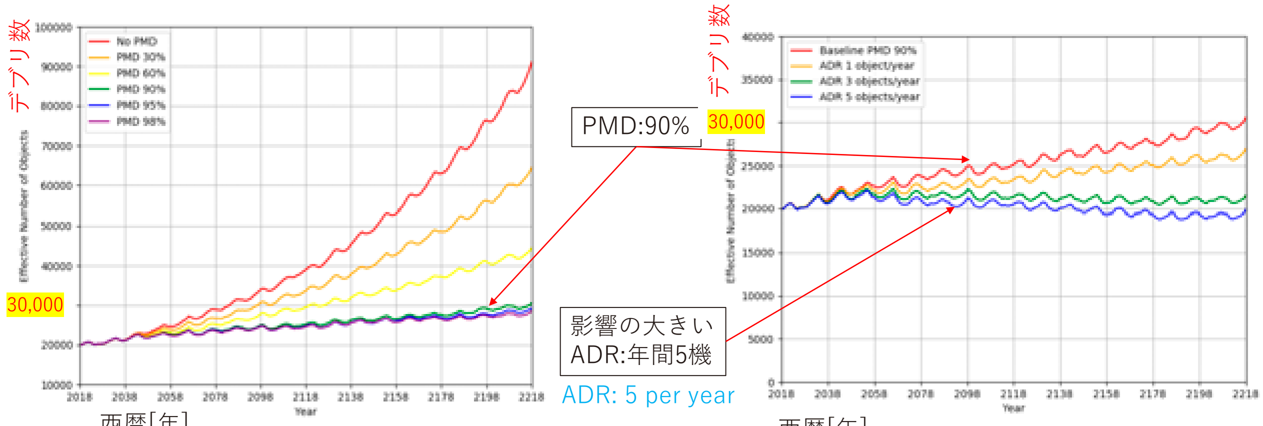
議論の前提（1/2）：PMDとADRによる効果 Effect of PMD/ADR

PMD:運用終了後の軌道離脱　ADR:アクティブなデブリ除去
PMD:Post Mission Disposal　ADR:Active Debris Removal

軌道上の全衛星に関してミッション終了後、90%を25年以内に軌道から除去(PMD)し、機能を喪失した衛星を1年に5機以上積極的に除去(ADR)することにより、低軌道スペースデブリの増加は抑制し得る。



PMDの効果Effect of PMD　ADRの効果Effect of PMD

議論の前提（2/2）：PMDとADRの位置づけPositioning of PMD/ADR

- 措置/実施行為であってハードウェアを指すものではない
- PMD/ADR are measure or practical action, are not hardware itself

PMD（運用終了後の軌道離脱）
Post Mission Disposal

ADR（既存デブリを含むパッシブでない除去）
Active Debris Removal

各パネリストによる発表について Panelist Presentation Format

発表時間：５分（各パネリスト毎） Time Period: 5 minutes each panelist

発表構成：前半：事業紹介、後半：テーマへの意見・提言 First half: company presentation, Second half: comments on the theme

テーマ：

アンカーテナンシー、国際競争力・国際ルール、プラットフォーム

Theme: Anchor Tenancy, International Institution, Private Sector Platform

意見・提言のフォーマット

① What：何をしてもらいたいのか、何をするのか？ What will you do?

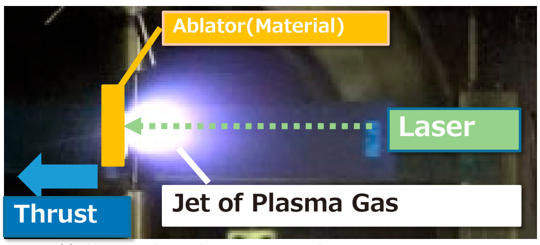
② Why：なぜ、①が必要なのか、関係者が納得できるか。①の実現で、何がどう変化するか？ Why it is needed?

③ How１：どうやって①を実現するのか？実現性はあるのか？課題は何か？ How to realize?

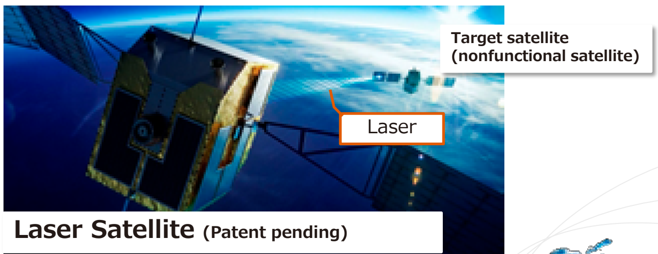
④ How２：①の実現にあたり、あるいは①が実現したら、民間企業として、どう貢献するのか、できるのか、したいのか？ How your company contribute to it?

SKY Perfect JSAT EOL Deorbit service

Item	Contents
Service	• A laser satellite irradiates space debris (nonfunctional satellites) with a laser to generate ablation (vaporization/Ionization) of surface material), which generates thrust against the debris to lower its altitude and finally dispose of it by entering the atmosphere. • Aiming for on-orbit demonstration in 2024 and service start in 2026
Potential Customers	• Company building up mega constellation as a measure of Backup deorbit function • Space organization/country/NGO (potential customer will gradually change)
Advantages	**Safety: Low collision risk:** Laser satellite generate thrust on target satellite from a distance (i.e 50m~200m (TBD))
	Availability: Tumbling object: Laser satellite can slowdown rotating satellite by irradiating in proper cycle.
	High Economy: **(1)** No fuel is required on the target object(surface material can be turned into propellant) →Contribute to reducing satellite weight. **(2)** No requirement for customer satellite design change
Laser Team	RIKEN Team has experts for laser design and capability to design from scratch



Laser ablation experiment in a vacuum environment



Vision for problem solving of space debris

- We (space industries people) have to procced to solve space debris problem from the back ground of Increasing the amount of space debris with orbital collisions and rapid increase in space use if we are to continue to use space environment

	Improving PMD rate	Remove high risk objects
Future launched Objects	Implement technologies(ADR, Others) and/or regulations	regulations
Post launched Objects	ADR	ADR

1st stage: Seed

1.Awareness
- Common understanding that space debris problem is space SDGs.
- Proactively sharing Japan's activities on space debris and promotion international discussions.

2.Regulation
- Discussion to approve new technologies (i.e. ADR)
- Discussion to enhance debris mitigation guideline

3.Technologies and market
- Technologies development in-house
- Discussion to constant anchor tenancy

4. Discussion of Insurance frame work for ADR

2nd stage: Implementing in each country

- Establishment of awareness of the necessarily to improve the debris environment in the world
- Budgeting to solve space debris problem in each country

Regulation/Technology Implementation for keeping High PMD rate in each country

On orbit demonstration on several technologies in each country

Limited Insurance frame work is executed for ADR or others

3rd stage: Goal

Common regulation / Technology implementation for keeping High PMD rate

Establishment of (1)NGO funded by several countries or (2)Space insurance funds operated by insurance fee of satellite owner

(1)International bidding for ADR of high risk space objects ->Selection of Effective ADR service

(2) Deorbit (ADR service) against Failed Satellite

Achievement:
- Space Sustainability
- Improving living standards

7 9th Space Debris Workshops in Japan (24 Feb,2021) SKY Perfect JSAT Corp. Proprietary

Kawasaki Powering your potential

Kawasaki Heavy Industries' efforts to remove debris

■ Microsatellite under development in-house demonstrates the technology essential for debris removal, Based on the technology acquired here, we will develop various space products and businesses.

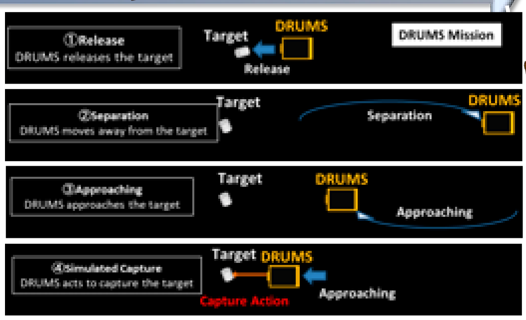
60cm cube
60kg

DRUMS : ADR Demo Satellite (Launch: FY2021)

Approach
Observation
Capture
Mission control

Technology Acquisition

On-Orbit service (Including debris removal)



 Kawasaki Powering your potential 8

Anchor tenant & Certification of excellent environmental improvement company

①What :

- The basic space plan / process chart clearly states the policy of removing rockets / satellites launched by the government on a regular basis (about once a year), and the government becomes an anchor tenant for budgeting.
- Companies working on debris removal (including PMD) have established certification systems such as "Eruboshi" and "Kurumin" as excellent companies for environmental improvement so that they can be announced at home and abroad, giving preferential treatment when participating in national competition.

②Why :

<Why is it needed?>

- In the situation where the space object launched by the country is debris, it is the responsibility of the launch to remove it, which is essential from the viewpoint of sustainable use of outer space.
- Give companies an incentive to work on debris removal through a certification system, dissemination, etc.

<What will change?>

- While carrying out debris removal at anchor tenants, standardize the technology to the de facto standard and expand from domestic to international private debris removal activities, leading to the promotion of the space industry and the acquisition of foreign currency.
- As a Japan-led environmental improvement and SDGs initiative, the country can send information to other countries.

Anchor tenant & Certification of excellent environmental improvement company

③How 1 :

<How to achieve>

- Anchor tenants limit spending only to debris, which is the responsibility of the government and has a large environmental impact.
- Corporate certification is implemented in conjunction with the introduction of an international rating scheme.

<Is it feasible?>

- The government will make the budget known as the act of destroying the environment and increase the feasibility.
- We think that corporate certification is feasible depending on the preferential treatment when participating in the competition.

<What are the challenges？>

- Debris for which private business is responsible needs to create a scheme for private funding.
- Until the scheme is established, the cost of the private sector taking the initiative in debris removal is an issue. In addition to corporate certification, I would like to request that the government provide subsidies such as subsidies.

④How 2 :

- Recognized as a business with a certain degree of predictability even in the early days by anchor tenants.
- We actively work to remove debris and contribute to the maintenance of the space environment.

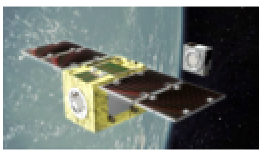
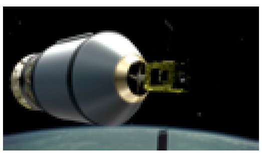
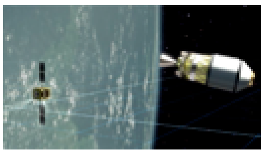
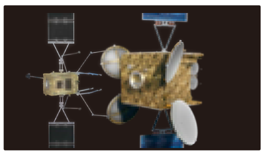
A Global Company Solving a Global Problem

Founded:	May 2013
Founder & CEO:	Nobu Okada
Nationalities Represented:	11
Headquarters:	Tokyo
Funds raised:	$191M

Astroscale

On-orbit Servicing Across LEO and GEO

- On-orbit Servicing
  - LEO
    - Future debris: **EOL** End-of-Life Service
    - Existing debris: **ADR** Active Debris Removal
    - Defunct objects: **ISSA** In-Situ SSA
  - GEO
    - GEO satellites: **LEX** Life Extension Service

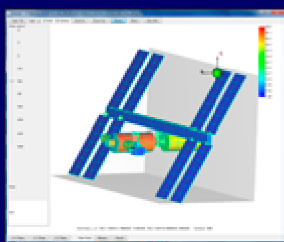
Solutions

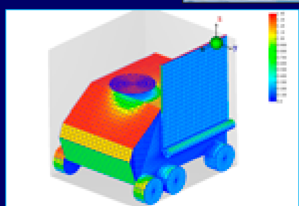
WHAT 何をするのか	WHY なぜ必要か	HOW 1 どのように実現するのか	HOW 2 民間企業として どのように貢献するか
• Drive discussions on institutionalization and standardization regarding debris removal.	• Actively remove large debris originated from Japan and take responsible actions for the sustainable use of space.	• Implement the JAXA Commercial Removal of Debris Demonstration (CRD2), which is the first in the world to carry out active large-scale debris removal (ADR)	• Support from various aspects such as developing technology, business model and regulation. • Implement CRD2 Phase 1.
	• Demonstrate the debris removal technology through above activities and that will enable to lead discussions on institutionalization and standardization in the long run.	• Institutionalization and standardization efforts to mitigate debris after the end of mission of government satellites	• Provide services for improving the space environment (debris removal, life extension, etc.)

MUSCAT Space Engineering Co., Ltd.

MUSCAT

- Since Apr. 2007 software development about debris
- Development of debris collision & damage risk analysis tool (TURANDOT)
- Prediction of debris collision
  - Where on spacecraft surface ?
  - What is the size of the debris ?
  - How often is it ?
  - How serious the damage is ?
- Effective protection design,
  - Not only for satellites but also for lunar rovers

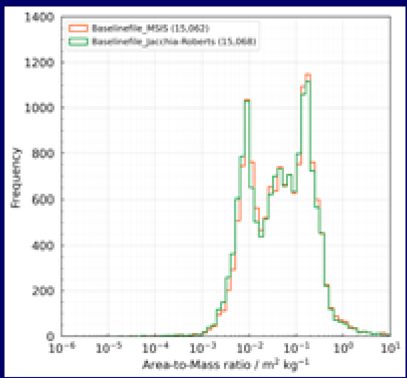




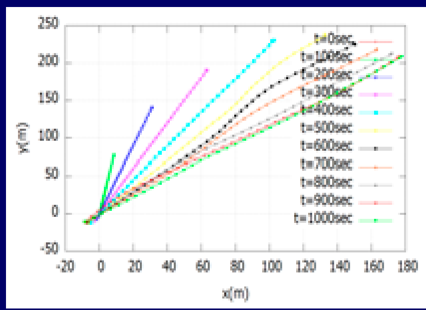
TURANDOT: Tactical Utility for Rapid ANalysis of Debris on Orbit Terrestrial

MUSCAT Space Engineering Co., Ltd.

- Modeling or Analysis is essential for evaluation of ADR/PMD.



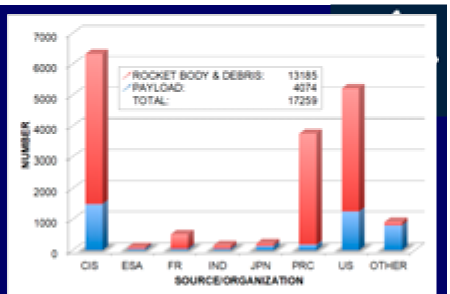
Debris model



Dynamics of Electro Dynamic Tether
Analysis of devices for PMD

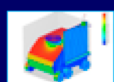
SDWS_20_12_07_muse 15

What necessary for Japan?



- Requirement:
  - Original debris model and economic model
  - Precise one including utility, cost, external cost etc.
- Quantitative evidence for discussion & action. If not,
  - Japanese/Japanese companies' claim was accepted, but it was a waste of effort.
  - Japanese/Japanese companies conducted ADR/PMD, but loss increased.
- Systematic actions!

Observation → Database → Original debris model → Economic model / Engineering model → Field research of impact on real industry → Decision making



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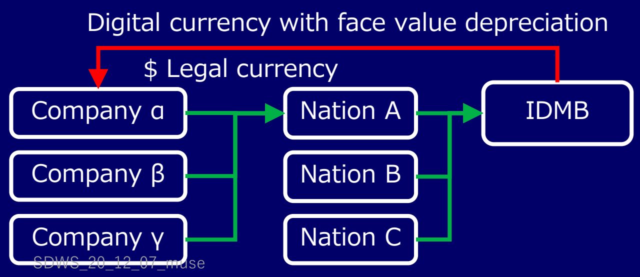
An idea of the incentive

- International Debris Mitigation Bank
  - Management of satellite deposit system
  - Making use of digital currency technology
  - Depreciation starts after launching. → Utilization fee for the orbital space
  - After PMD/ADR, the depreciation stops.
  - The depreciation value corresponds for the fund for ADR.



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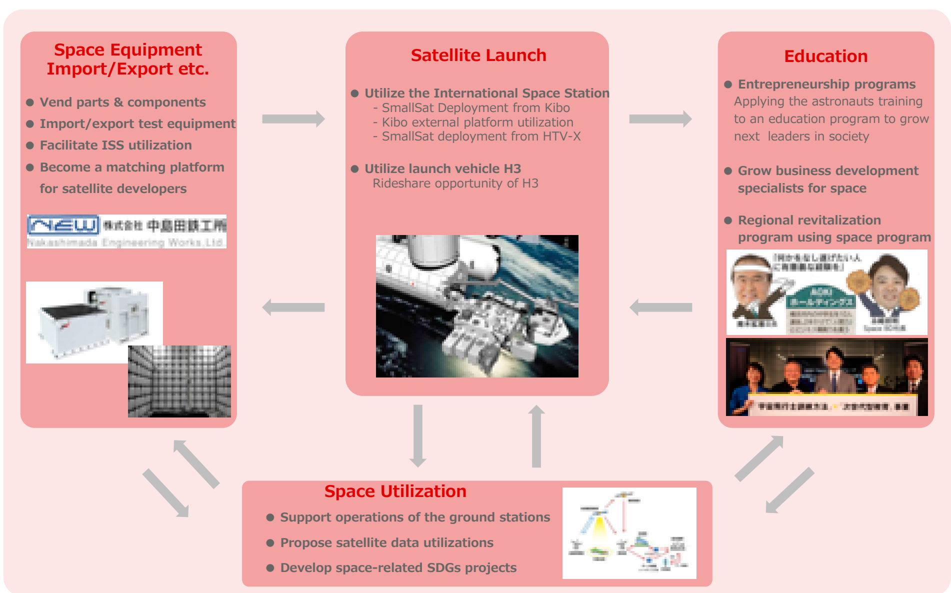
Space BD Business Overview

Space BD

Bring Dreams and Commerce into Space



A proposal for debris issues

Space BD

1. What: What do we need?

> Continuous supports (anchor tenancy) for technology development and IOD looking beyond the tightened international regulations of debris-prevention technology

2. Why: Why do we need?

> Japanese technology, products, and services must have the international competitiveness in the future where the debris-prevention technology becomes the standard

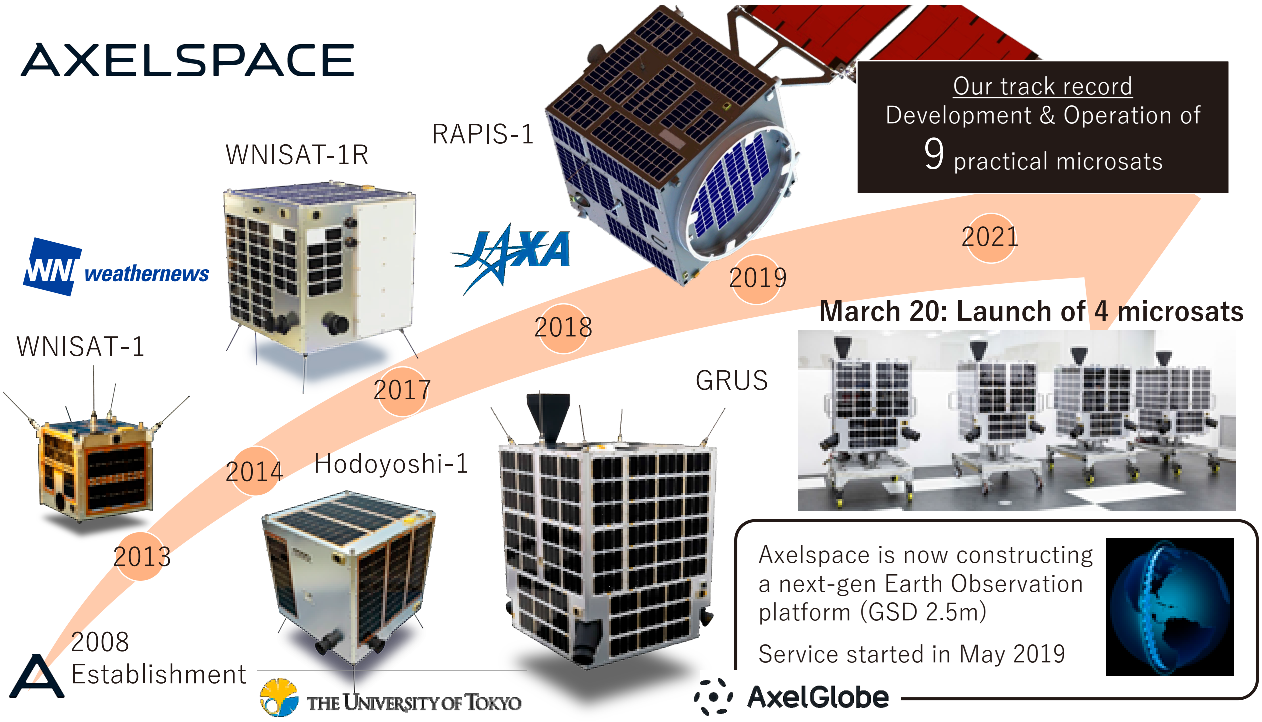
3. How-1: How will we achieve it?

> Provide technology demonstration faster than other countries
> Propose IOD with cubesat may be economical and practical as a solution for financial challenge

4. How-2: How will Space BD contribute when "How-1" achieved?

> Provide quick and easy access to space
> Contribute to overseas marketing with the global network

AXELSPACE



AXELSPACE

What we do

We are not a space debris-related business operator, but a constellation player launching a number of satellites into the orbit. As the discussion on debris regulations is becoming more and more active internationally, it is very important to create effective rules that are acceptable to all players. We would like to have a voice in the creation of these rules.

弊社は「デブリ関連事業者」ではなく、コンステレーションの構築を推進する立場。デブリの規制議論が国際的に活発になってきている中、全てのプレイヤーが受け入れ可能な、実効的なルールを作ることは非常に重要である。これらルールづくりに際し、発言権を確保したい。

AXELSPACE

Why necessary

Rules that do not reflect the opinions of various space business operators will never be effective and will create players that do not follow them. As a result, the rules will not be fair and will become a dead letter, and the problem will not be solved. In order to avoid a system where only law-abiding players suffer loss, it is necessary to involve major space business operators from the beginning.

宇宙利用事業者の意見の反映されないルールでは実効性に欠け、従わないプレイヤーを生むことになる。結果フェアなルールにならず形骸化し、問題解決に至らない。正直者がバカを見るような仕組みにならないためにも、主要な宇宙事業者を最初から巻き込む必要がある。

AXELSPACE

How we can contribute

It can be a good idea for stakeholders in Japan to get together to create some organization to appeal for a certain direction in the international arena, in areas where their interests coincide. By doing so, Japan will be able to have a certain amount of influence in terms of effective rule making and incentive design.

日本国内のプレイヤーが集まって何らかの組織をつくり、利害の一致する分野において、国際的な場であるべき方向性を訴えていくことを検討してもよいのではないか。そうすることで、実効的なルール策定やインセンティブ設計に関して日本が一定の影響力を持つことができるのではないか。

第9回 スペースデブリワークショップ（2021/2/24～2/26）

Doc. No. JGM1-20 0909

パネルディスカッション
「日本の民間デブリ関連ソリューション事業化に向けた挑戦」
Challenge for Space Debris Solution Business in Japanese Private Sector

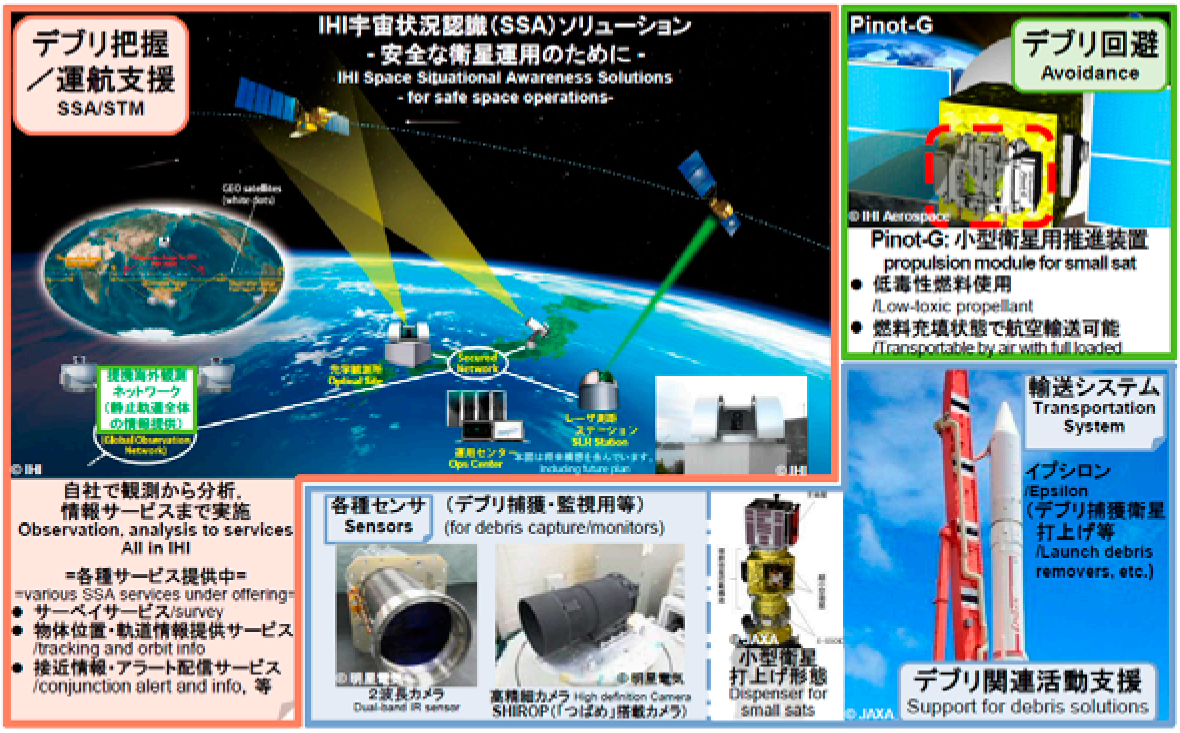
IHI

2021年 2月24日
24 February 2021

IHI Corporation
宇宙開発事業推進部
Space Development Department

IHIグループのデブリ関連ソリューション事業
Space Debris Solutions Business in IHI Group

IHI



民間デブリ関連ソリューション事業化に向けた提案

Actions to energize Commercial Space Debris Business in Japan

IHI

「日本モデル」の実現のために
安全・安心な宇宙活動の基盤として重要な観測情報を民間から提供
To demonstrate "Japan Model" as best practices for space debris issues
Provide commercial space observation services, important platform for safe and secure space operations

① **What**：何をしてもらいたいのか、何をするのか？
- **宇宙航行・活動の安全確保**
  Safe and secure space transportations and operations

②**Why**：なぜ、必要なのか？ 何がどう変化するか？
- **宇宙活動の活性化**
  Economic growth in Space

③**How**：どうやって実現するのか？ 実現性はあるのか？ 課題は何か？
- **国際ルール確立と遵守の仕組み構築** / establish international rules and compliance mechanisms
  - ➢ **世界が範とすべき「日本モデル」の確立と啓蒙 ⇒ 知識から共感へ**
    Establish "Japan Model" as the world best "model" for space debris issues and enlightenment through demonstration ⇒ knowledge to sympathy and respect
  - ➢ **国内連携による実践をもとに世界に向けてリーダーシップの発揮**
    Show Japanese leadership toward the world through demonstration of the "model" in public-private collaboration

□ **課題：インセンティブ，ルールを守らない人を守る人へ変える方策**
ISSUE: Incentives, Measures to change the entities who do not follow the rules to those who follow

④**How**：実現に向けて，民間企業として、どう貢献するのか？
- **国内連携に向けた宇宙状況認識サービスの提供と技術開発**
  For collaborated demonstration, IHI can offer SSA Information Services and develop necessary technologies.

Backup

IHI

小型衛星向け低毒推進系ユニット：Pinot-G

IHI

ピノ
Pinot-Gとは？

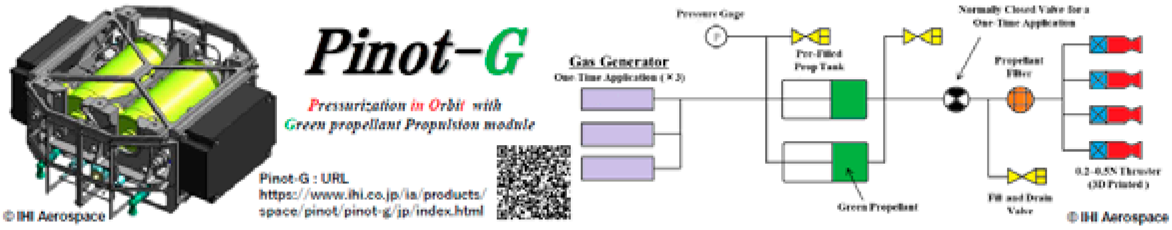
　スタートアップなど、小型衛星ユーザーにとって安全で扱いやすい推進系として開発中の低毒推進系ユニットであり、以下を特徴としています。

- 空輸も可能な非爆発性推進薬と軌道上加圧システムの採用で実現する地上運用の安全性
- 制御回路を含めた推進系に必要な機器すべて備えたAll-in-Oneパッケージ
- 積層造形の適用、スラスタ性能を抑え、高価な耐熱材を不要とすることで実現した低コスト。

Pinot-Gで広がる小型衛星の可能性

　本機シリーズにより、小型衛星で以下を実現可能とするものです。

- 最小構成型 ⇒ デブリとの衝突回避のための高い機動性（回避行動による機会損失の最小化）
  ★混雑の一途をたどる地球低軌道での安心・安全な衛星運用にとって、衝突回避能力は必要不可欠。
- 推薬量増量型 ⇒ 寿命末期の投棄軌道への遷移（ISO規定への対応）、コンステレーション／フォーメーションフライトにおける高度維持（軌道制御）によるミッションの延命



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Propulsion module for small satellite : Pinot-G

IHI

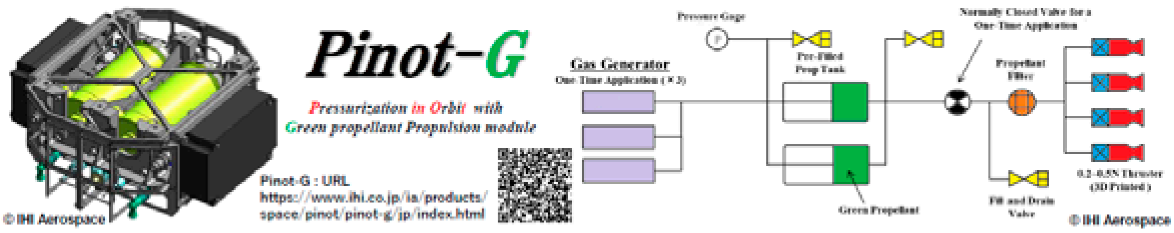
What is the Pinot-G?

This propulsion module is being developed as a safety-focused product for all small satellite. It has the following features;

- Safety : Air-cargo transportation is available, because the system is designed to use non explosive fuel and no high-pressure gas on the Launch-site.
- All-in-one : Since all the necessary equipment is packaged, it can be used be simply connecting the RS-232 cable.
- Reasonable price : Additive manufacturing, Optimization of thruster performance and design

Functions to be provided to small satellites

- Minimum configuration ⇒ Quick mobility to realize collision avoidance maneuvers
  ★This capability is essential for secure satellite operations in the increasingly crowded LEO.
- High-capacity fuel option ⇒ De-orbit (for SDGs in Space) and Orbit Maintenance (to increase satellite life time)



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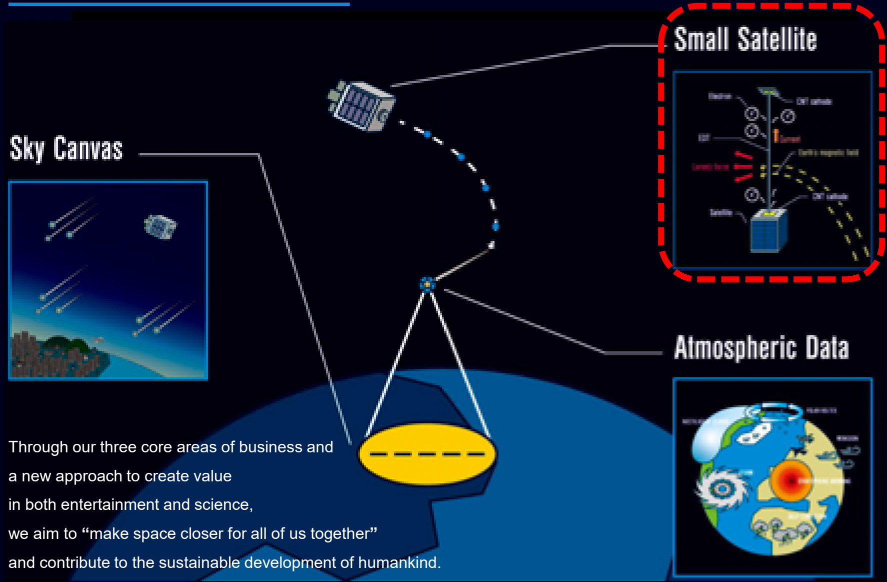
ご清聴ありがとうございました

IHI
Realize your dreams

Our Business

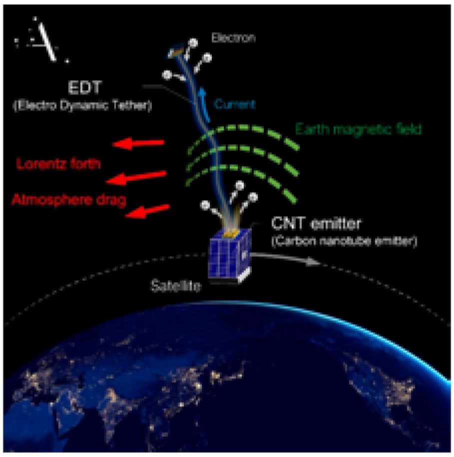


Through our three core areas of business and
a new approach to create value
in both entertainment and science,
we aim to “make space closer for all of us together”
and contribute to the sustainable development of humankind.

Small satellite

How the EDT works

The EDT is a PMD (Post-Mission Disposal) device that generates Lorentz force/atmospheric resistance from the earth's magnetic field and drag from Earth's atmosphere to deorbit satellites.



- An electric current flowing under the Earth's magnetic field generates a force that slows down the satellite. The force to decelerate is also obtained from atmospheric resistance from contact with the earth's atmosphere. Although this force is relatively small, it is constant and cumulative, resulting in a high degree of deceleration.
- The addition of carbon nanotube (CNT) emitters, developed by JAXA, ensures that the current flows even in a passive state. The tether can be used to decelerate the vehicle even without power from the bus.
- Because of its independent release mechanism, ALE's EDT can achieve operation and deorbit even if the satellite suffers an unrecoverable failure.
- The EDT is deployed autonomously by a timer. The timer and deployment mechanism are triple redundant to prevent accidental deployment at launch or during operations, and reliable deployment at the scheduled deployment time.

Proposal: Establishment of "Private Sector Platform for Space Debris"

What What do we do?	• **Establishment of a platform for discussion on debris by the private sector in cooperation with the government, ministries and agencies, and JAXA.** Activities sample - Sharing of information on international debris (including STM, if necessary) trends - Gathering of opinions of private companies and discussion on this
Why Why do we need to?	• **"Space Debris" is a common issue not only for operators who run debris business, but also for others such as launch or satellite operators.** - There is no chance to win in global market if technology development, rulemaking, and commercialization are conducted separately. - Need to avoid a situation where the framework created by the world is imposed on us later.
How 1 How do we achieve? Is it feasible? What are the challenges?	• **The core functions are already existing among JAXA and some private companies, and through the coordination of these functions, we will build a system that enables private companies to understand global situations and make proposals as Japanese private sector.** Issues - Necessary to confirm the extent to which resources within JAXA and private companies can be allocated to this project. - Structure and measures to make the organization effective
How 2 How will you, as a private company, contribute to?	• **Establish a position as a player in the debris industry by developing the EDT business** - Improve Japan's presence in PMD technology through early demonstration (scheduled for 2022) - Gathering information and gaining the right to speak by entering the market

パネルディスカッションのまとめ
～日本の民間デブリ関連ソリューション事業化に向けた挑戦～

■ SDGsに向けた宇宙環境の保全、デブリ事業の産業振興の観点から、アンカーテナンシ―など政府資金によるデブリ対応を継続的に実施していただくことを要望したい。
- ➢ 日本として、他国に先駆けて、環境改善に取り組む姿勢を示し、世界への共感を醸成する。
- ➢ 技術開発だけでなく、デブリ対策への仕組み作りへの資金投入により、市場開拓・産業振興・普及促進を諮るインセンティブとなり、民間事業者の国際競争力の確保につながる。
- ➢ 実績を示すことにより、国際ルール化に向けた影響力のある発信が期待できる。

■ 日本発で、国際舞台で影響力のある発信を担えるよう、民間プラットフォームを創設することを検討する。
- ➢ 全体の方向性を定め、定量的な根拠を示し、世界の模範となる「日本モデル」を確立する。
- ➢ 国際動向をタイムリーに把握し、日本の民間事業者群から世界に先駆けて発信する。
- ➢ 日本の民間事業者としての声を業界の意向として、関連政府機関にインプットする。

Summary of Panel Discussion
～The Challenges for Commercializing Space Debris Solution in Japan～

■ Desire to implement debris measures by continuous governmental support for environment preservation towards SDGs and industrial development of debris business
- ➢ To show the attitude of the environmental improvement effort ahead of the world for creation of the sympathy
- ➢ To provide the incentive aimed at industrial promotion and anticipate the assurance of international competitiveness by investment of the technology development as well as mechanism of the debris measure
- ➢ To expect the influence on international institutions by early accomplishment

■ Consider to found the platform among private sectors for an appeal of international presence from Japan
- ➢ To establish Japanese model referred from worldwide by defining the global direction and showing the quantitative rationale
- ➢ To aware the international trend timely and to announce the information from Japanese private sectors to the world
- ➢ To talk to Japanese government related as the intention of the debris communities

Panel Discussion 2

法政策的見地からのデブリ対策に対する産学官の役割
Law and Policy Perspectives of the Roles of Industry, Academia and the Government for Space Debris Issues

モデレータ：竹内悠（JAXA）
パネリスト：新谷美保子（TMI総合法律事務所）、大塚聡子（NEC）、渡邉亜希子（スカパーJSAT）、吉田良太（JAXA）
Moderator: TAKEUCHI Yu (JAXA/Keio University)
Panelist: SHINTANI Mihoko (TMI Associates), OTSUKA Akiko (NEC), WATANABE Akiko (SkyPerfect JSAT), YOSHIDA Ryota (JAXA)

我が国はいち早くNASDAデブリ発生防止標準を策定し、観測、発生防止、防護、そして除去と総合的な研究を続けてきた宇宙デブリ先進国と言える。しかし、技術開発においても産業振興の観点でも安全規制の観点でも世界のフロントランナーとなり切るには至っておらず、デブリ対策の分野で世界を先導するには越えなければならない大きな課題が横たわっているように見える。本パネルでは、法政策的な側面からこの課題にアプローチし、産業界、アカデミアそして国の果たすべき役割について論じたい。特に、今日の日本のデブリ分野の産業振興のために持つべき視点、法政策的観点でのこれまでの施策のレッスンズラーンド、そして今後検討の必要がある法政策的論点について、法務及び政策研究のバックグラウンドを有するパネリストと共に論じる。

Japan has been one of the frontrunners of tackling the space debris issue in the early 2000s. JAXA, formerly NASDA, issued its space debris mitigation standard in 1996 and continuously conducted comprehensive activities, including researches on observation, mitigation, protection and removal. However, Japan has not been achieved its position as the world leader neither in the area of technology development, industry promotion nor safety regulation. It seems a huge challenge lying down along this achievement. This panel will approach from a law and policy perspective to this challenge in order to focusing on the roles of industry, academia and the government. The panel, consisted by the law and policy experts, will provide particular interests in the necessary vision for promoting the existing Japanese space debris related industries, in the lessons-learned from the passed policies, and in the necessary discussions for the near-future law and policy for space debris issues.

モデレータ：竹内悠
Moderator: TAKEUCHI Yu (JAXA/ Institute of Space Law, Keio University)
JAXA/慶應義塾大学宇宙法研究センター
実務の傍らで国際宇宙法、特に宇宙交通管理（STM）の法的側面の研究を続けている。

パネリスト：新谷美保子
Panelist : SHINTANI Mihoko (Senior Partner Attorney, TMI Associates)
TMI総合法律事務所パートナー弁護士
Space Port Japan理事、内閣府「宇宙活動法における第三者損害賠償制度に関するアドバイザリー・グループ」メンバー、内閣府・経産省「宇宙ビジネスを支える環境整備に関する論点整理タスクフォース」委員

パネリスト：**大塚聡子**
Panelist ：OHTSUKA Akiko (Space System Division, NEC Corporation)
NEC宇宙システム事業部エキスパートエンジニア
博士（システムズ・エンジニアリング）
慶應義塾大学システムデザイン・マネジメント研究所研究員

パネリスト：**渡邉亜希子**
Panelist : WATANABE Akiko (Legal Affairs Division, SkyPerfect JSAT)
スカパーJSAT株式会社法務部アシスタントマネージャー
慶応義塾大学院大学　法学研究科（宇宙法専修コース）修了

パネリスト：**吉田良太**
Panelist : YOSHIDA Ryota (Research & Development Directorate, JAXA)
JAXA研究開発部門研究推進部主任
商業デブリ除去実証プロジェクト主任兼務

パネルディスカッション２
「法政策的見地からのデブリ対策に対する産学官の役割」

モデレータ：竹内悠（JAXA／慶応義塾大学）
パネリスト： 新谷美保子 (TMI 総合法律事務所)
大塚聡子 (NEC)
渡邉亜希子 (スカパーJSAT)
吉田良太（JAXA）

本パネルディスカッションでは、法政策的な経験の豊富な４人のパネリストを迎えて、デブリ対策に必要な産学官の役割について、議論を交わした。

●規制は産業振興につながるのか。

宇宙活動法のような規制法は、規制の側面だけでなく、コーポレートリスクを予見させるものとして産業促進的な効果がある。しかし、現代においては規制法や規制的手法のみでは片手落ちになっており、産業界の自主的な取り組みや経済的手法を組み合わせたポリシーミックスが必要な時代になっている。参考例として環境政策が上げられる。環境汚染に対しては､それを規制する規制法が存在するが、それに加えて、業界のガイドラインや ISO 基準等の自発的取り組み、排出権取引や課徴金、優遇税制、預託金制度等の経済的手法が組み合わさって行政目的を達成しようとしている。宇宙分野も同様の政策展開が必要になっている。デブリ政策の主眼を産業振興に置くよりも、環境改善や維持に据えると考えやすい。まずは宇宙環境の改善が必要であるという規制がかかったが、そこに環境政策的な視点が加わった結果としてビジネスチャンスが生まれてくるととらえれば、世間の理解も得やすいのではないか。

●JAXA の役割の変化

JAXA が展開している商業デブリ除去事業（CRD2）は従来の宇宙開発の形からはかなり踏み込んだ事業であり、長年 JAXA の方針に従って粛々とやってきた宇宙産業にとっても括目に値する。JAXA は歴史上日本の宇宙開発の技術実証機関としての役割を担ってきており、自らデブリを排出してきた事実がある。今後は、これまでの使命であった技術開発成果の創出に加え、新たに宇宙環境の維持・改善も使命とする必要のある時代となった。

●国際ルールの考え方、あり方

規制に対してはその規制を執行・統制する主体、すなわち罰則を強制できる主体が必要であるように思えるが、国際社会においてはそのような主体が明確でないことが、規制の弱体化につながっていないか。

たしかに国際社会には絶対的な警察権限を持った主体が存在していないが、罰則はトップダウンのものだけではない。業界で共通化されたルールは、たとえそれが法律や条約となっていなかったとしても、業界のプレイヤーであれば当然に知っておかなければならないルールであれば、それに則っていなかったために陥った失敗や損害に対して訴えられた際に、裁判所がその事業のプロとしての注意（善管注意義務）を怠ったと判断して、損害賠償責任を負わされることになる。そういう意味での罰則としての民事責任は一つの統制手段として活きていると言える。他の衛星に対する衝突確率を満たしていることを打上げ前に確認する国際機関が出現しなくとも、その基準が国際的な技術標準であれば、その基準を満たしていなかった場合の民事責任を嫌ってその基準を予め遵守するインセンティブが発生してくる。

その意味で、世界経済フォーラムが作成している Space Sustainable Rating（SSR）の仕組みは、レ―ティングが高い事業者がエコな運用をしている事業者として顧客からの利用・注文が集中することに寄与する仕組みになり得、これが世界的に信頼されてくるとより良い世界になってくるだろう。

●国際ルールの目指す方向性

基準を満たしていなければ、満たしていないほうが悪いと評価され民事責任を負いうる基準が有意義になってくるが、そのような責任の対象となる基準はどこに、どのように設定されるか。

あまり認識されていないが、実は、日本の宇宙活動法は世界に類を見ないほど宇宙環境への配慮を謳っている。活動法 22 条と関連規則には法律自体に衛星管理の許可条件としてデブリ低減を明確に要求している。これほど明確に規定している国内法は世界でも類を見ないということをより認識する必要がある。

国際ルールは収れんすることなくどんどん出てきた方がよく、日本がするべきことは、技術で世界の先頭を走ることだ。技術のベースがあれば、日本のルールをベースと下国際的なルール作りを日本が先導できる。すでに宇宙活動法が先駆的存在であり、これに加えて技術に裏打ちされた日本としての基準を打ち出し、ビジネス化していく時にそれらの基準をメッセージとして打ち出すことで、世界を巻き込むポテンシャルを持っている。したがって、有効な国際ルールを見つけて適用するのではなく、日本が技術力向上を背景に数ある国際ルールの中から自らの技術に合致するものを有力なものに変えていく、ということだ。そこに技術力を背景とした説得力が生まれる。

ただし留意すべきなのは、条約のような強制力を持った形で国際的な権利関係を整理しようとする場合には非常に長い時間を要するので、これを座して待つことは得策ではない。

●世界に打って出る日本の基準

国際法には、慣行に一定の要件が備わると法律になる、国際慣習法という法形態がある。基準はそれに類似性があり、国家が基準を順守していくことが慣行の現れとなり、やがては法律に準ずる力を持ってくる可能性を秘めている。日本として基準に準拠した実行を重ねることの重要性はそこにある。日本の宇宙業界における基準は長らく JAXA の技術基準が中心となってきた。これは国内宇宙業界へのヒ

アリング等も経ており、非現実的な要素を排除したよくできた基準である。日本の宇宙コミュニティーは基準の作り方においても実現性の高い方法が慣習として機能しているというコミュニティーといえ、日本の基準はすぐにでも国際的に打ち出せるものと言ってよい。他方で ISO 等の国際場裏では日本の考え方がなかなか反映されない背景には、基準そのものの優位性というよりも交渉力、法政策の問題が強いようだ。

●アンカーテナンシーによる産業醸成

デブリ除去を日本の民間事業として確立し、産業として持続可能なものに育っていくためには国によるアンカーテナンシーが必要という議論がある。しかし国による一方的なアンカーテナンシーだけでなく、それに呼応した民間側や市民側の役割も必要で、総合政策として形成していく必要がある。宇宙輸送や地球観測データのように将来的に長く継続していく見通しが立っている事業に対するアンカーテナンシーと異なり、軌道上サービスやデブリ除去事業は、これからデブリが発生しないような技術が発達してくる可能性を持った分野であり、変化の渦中にある形態と言えよう。この分野で現在必要とされているのは、アンカーテナンシーというよりは、公共事業としての社会的な初期投資であろう。その意味で CRD2 のような国のプロジェクトにより民間による除去実証が続けられれば、産業として育っていけるのではないか。ただし、CRD2 のような国による資金拠出は数回程度に留まることもあり、アンカーテナンシーというほど長期の財政出動の有効性には疑問が残る。

●日本がデブリ対策でグローバルリーダーになるためには。

日本の規制基準が国際化し、日本の宇宙機に対する技術的な信頼が寄せられるという現実が近いが、誰が、どのような役割を担って世界に打って出ていくか。

すべての要素がそろって初めて国際的に意味のあるアピールができる。産業界は、デブリ観測をする、あるいはデブリとならないような設計をし、そのような運用を行うといった技術面を実現していくところで貢献しつつ、国際調整においてはそれらの技術を裏付けとした強い主張を政府を中心に行っていく、というように、国としてのチームを構成していくことが重要だ。技術戦略の立案においても、最終的には国としての戦略になるだろうが、チャレンジングな技術開発面での効果的な支援のあり方も含め、産学官のチームでの検討が必要になる。

現在の国際宇宙ビジネスの主戦場である宇宙輸送事業と衛星コンステレーション事業に、残念ながら日本企業は主役で参戦していない。グローバルリーダーとなるためには、日本の宇宙産業が世界にとってなくてはならない存在になることが重要である。国際市場での強い事業者がおり、国としての技術力もあり、国際戦略もあり、国内的に効果的な法律や基準もそろっている、そういう国になれば、アメリカであっても無視できなくなる。

元来、日本は衛生環境について意識の高い国民性であり、それを活かした一定の価値観の提示を国がするべきである。デブリを低減、回収しなくてはならない、第三者の軌道上物体の権利を侵害してはならない、といった普遍的な価値観を示し、それを素地として民間事業者に自由な事業活動が展開できる環境を用意することで、名実ともにグローバルリーダーとなれるだろう。

●産学官の役割（結語）

それぞれのプレイヤーがそれぞれの守備範囲を糾合して初めて日本としての国際的な地位を築ける。デブリ対策において国に期待したいのは、例えば宇宙基本計画工程表などにおいてより具体的なマイルストーンを設定して、国全体の旗振り役となることだ。民間においては事業のリスクテイクとのバランスを取りながらも、宇宙を使う企業としての責任、自己の技術力、ビジネス力を試す機会でもある。

デブリ問題は関係者の間では切迫感が急速に増している実感があるにもかかわらず、世間ではあまり知られていない。地球温暖化問題のように、世の中一般でも話題に上るような情報発信を行い、対策の必要性に対する機運を高める必要がある。

その上で、産学官のチームとして、事業展開におけるリスクを法政策的な側面で担保できる事項を具体的に政府に意見していくというプロセスが必要となる。法政策的な側面では欧州は損害賠償リスクを国が一部負担するような産業振興策も打ち出しており、日本も検討する必要がある。

デブリ除去技術を日本として獲得し、これを活用していかなければならないということは明白になった。国は守るべき価値観を明確にし、その意識を広める役割、学は様々な意見をぶつけ合って議論を喚起する役割、その解決策となり得る技術を JAXA が開発して、産業界がそれを使ってビジネスにしていく、これらの総合力を日本の力としてアピールしていく、こうしたことを All Japan のチームとして実現していくことが必要な状況になっている。

※本パネルディスカッションの一部は JSPS 科研費 20H01438 の助成を受けたものである。

以上

（文責：竹内）

Panel Discussion 2
Law and Policy Perspectives of the Roles of Industry, Academia and the Government for Space Debris Issues

Moderator: TAKEUCHI Yu (JAXA)
Panelist: SHINTANI Mihoko (TMI Associates)
OTSUKA Akiko (NEC)
WATANABE Akiko (SKY Perfect JSAT)
YOSHIDA Ryota (JAXA)

In this panel discussion, four panelists with a wealth of legal and policy experience were invited to discuss the roles of industry, academia, and government necessary for space debris policy.

●Will regulation lead to industrial development?

Regulatory law, such as the Space Activities Act, together with its regulatory aspects, it retains industry-promoting effect as raising the predictability of corporate risks that activity implies. However, in today's world, regulatory laws and regulatory methods alone are not enough, and a policy mix that combines voluntary efforts by industry or economic methods is necessary. Environmental policy is a good example. In addition to the regulatory laws that regulate environmental pollution, voluntary efforts such as industry guidelines or ISO standards, and economic methods such as emissions trading, surcharges, preferential taxation, or deposit systems are being combined to achieve administrative objectives. A similar policy development is needed in the space sector. Rather than focusing on the promotion of industry, it would be easier to think of space debris policy in terms of environmental preservation. It would be easier to gain the public's understanding if business opportunities are created as a result of an environmental policy perspective.

●The Changing Role of JAXA

JAXA's commercial space debris removal project (CRD2) is a significant departure from traditional space development, and has large implication to the space industry, which has been following JAXA's policies for years. JAXA has historically played a role as a technology demonstration organization for Japan's space development and has discharged numbers of space debris by itself. From now on, in addition to its traditional mission of producing technological development results, JAXA will need to take on a new mission of maintaining the space environment.

●The concept of international rules and how they should be

It seems that regulations require an entity that can enforce and control the regulations by penalties, for example, but in the international community, the lack of clarity of such an entity may be leading to the weakening of regulations.

It is true that there is no entity with absolute police authority in the international community, but penalties are not only top-down. If there are rules that are common to the industry, even if they have not been made into laws or treaties but are rules that players in the industry must know. In this case, if a company is sued for failure or damage due to failure to follow that rules, the court will judge that the company failed to exercise professional care (duty of care) and hold the company liable for damages. In this sense, civil liability as a penalty is also an effective means of control. Even if there is no international organization that confirms that the probability of collision with other satellites is met before launch, if the standard is an international technical standard, there will be an incentive to comply with that standard in advance because of the risk of civil liability if the standard is not met.

In this sense, the Space Sustainable Rating (SSR) system developed by the World Economic Forum can be a system that contributes to the concentration of use and orders from customers as a business that has a high rating and is operating in an eco-friendly manner. The world will be a better place if this system is trusted worldwide.

●The Direction of International Rules

Consideration to civil liability as another effect of non-legally binding standard, it is necessary to distinguish where and how will the standards for such liability be set?

Although it is not widely recognized, Japan's Space Activities Act actually calls for consideration of the space environment to a degree unparalleled in the world. Article 22 of the Law and related regulations clearly require space debris mitigation as a condition for spacecraft control license in the law itself. We need to be more aware of the fact that there is no other domestic law in the world that provides such a clear stipulation.

International rules should come out more and more without convergence, and what Japan should do is to lead the world with technology. With a base of technology, Japan can take the lead in creating international rules based on Japanese rules. Japan is already a pioneer in the Space Activities Act, and in addition to this, Japan has the potential to involve the world by setting out its own standards backed up by technology, and by putting these standards out as a message when it comes to business. Therefore, it is not a matter of finding and applying effective international rules, but of transforming those that match Japan's own technology into influential ones from among the many international rules with the background of improved technological capabilities. This is where the power of persuasion based on technological strength comes into play.

It should be noted, however, that it is not advisable to sit back and wait for an enforceable treaty for controlling the rights among the international community, as it will take too much long time.

●Japan's Standard for Reaching Out to the World

There is a form of law in international law called customary international law, which becomes law when certain requirements are attached to a practice. The standards have similarities to this, and a state's compliance with the standards will become a manifestation of its practice, which may eventually have the power to become equivalent to law. This is where the importance of Japan's repeated implementation of compliance with standards lies. For a long time, the main standards in the Japanese space industry have been the JAXA technical standards. This is a well-developed standard that eliminates unrealistic elements, based on hearings with the domestic space industry. It can be said that the Japanese space community is a community where a highly feasible method of creating standards functions as a customary practice, and it is safe to say that Japanese standards can be launched internationally immediately. On the other hand, in the international arena such as ISO, Japanese ideas are not easily reflected because of bargaining power and legal policy issues rather than the technical advantages of the standards themselves.

●Industry promotion through anchor tenancy

There is an argument that anchor-tenancy by the government is necessary to establish debris removal as a private business in Japan and to develop it into a sustainable industry. However, it is necessary to consider the roles of the private sector and citizens to respond to the anchor-tenancy by the government, namely a comprehensive policy is required. Unlike the anchor-tenancy for projects that are expected to continue for a long time in the future, such as space transportation or earth observation data application, on-orbit services and debris removal projects are the fields in the midst of change that have the potential to develop technologies to prevent the generation of space debris in the future. What is currently needed in this field is not anchor tenancy *per-se* but rather initial social investment as a public project. In this sense, if the private sector continues to demonstrate the removal of space debris through national projects such as CRD2, it may be able to grow as an industry. However, the government's financial contribution to CRD2 may be limited to a few times, and the effectiveness of long-term public investment as anchor tenancy is questionable.

●How Japan can become a global leader in space debris issue.

The reality is that Japan's regulatory standards will soon be internationalized, and technological confidence in Japanese spacecraft will be in place, but who will take on the role and what role will they play in launching into the international community?

Only when all the elements come together can we make a meaningful appeal to the international community. It is important to form a national team in which industry contributes to the realization of the technical aspects, such as space debris observation, space debris mitigation by design and operation, while the government plays a central role in making strong arguments based on these technologies in international coordination. It is important to form a national team. In the planning of technology strategies, it will be necessary for the industry-academia-government team to consider how to provide effective support for challenging technology development, although the strategy will ultimately be a national one.

Unfortunately, Japanese companies are not playing a leading role in the space transportation and satellite constellation business, which is the main battlefield of the current international space business. In order to become a global leader, it is important for Japan's space industry to become an indispensable part of the world. If Japan becomes a country equipped with strong operators in the international market, original technology, international strategy, and effective laws and standards, even the United States will not be able to ignore it.

Japan has always been a nation with a high level of awareness about sanitation, and the government should take advantage of this to present a certain set of values. Japan can become a global leader in both name and reality by demonstrating universal values such as the need to reduce and recover space debris, and the need not to infringe on the rights of third parties of orbital objects, and by providing an environment in which private companies can freely develop their business activities based on these values.

●Roles of Industry, Academia and Government (Conclusion)

Japan's international status can only be established when each player denounces their respective areas of expertise. In the area of debris countermeasures, for example, it is fair to say that the government needs to set more specific milestones in the Basic Space Plan timetable, and act as a flag-bearer for the entire country. For the private sector, this is an opportunity to test its responsibility as a company using outer space, as well as its own technological and business capabilities, while maintaining a balance with risk-taking.

The space debris issue is not well known to the public, although there is a sense of urgency among those involved that it is rapidly increasing. As with the issue of global warming, it is necessary to disseminate information to the general public to raise awareness of the need for countermeasures.

Then, as a team of industry, academia and government, it will be necessary to provide specific opinions to the government on matters that can guarantee the risk of business development in terms of legal policy. In terms of legal policy, Europe has come up with a policy to promote industry in which the government bears part of the risk of compensation for damages, and this is something that Japan needs to consider.

It has become clear that Japan needs to acquire space debris removal technology and make use of it. The role of the national government is to clarify the values that need to be protected and to spread awareness of these values, the role of academia is to stimulate debate by exchanging various opinions, JAXA is to develop technologies that can provide solutions to these issues, and industry is to use these technologies to conduct business, and the overall strength of these activities is to be promoted as Japan's strength. It is now necessary for the All Japan team to achieve these goals.

* This panel was partially supported by JSPS KAKENHI (B) Grant Number JP20H01438.

付録　ワークショッププログラム

Appendix: Workshop Program

第９回スペースデブリワークショップ　プログラム

※開催時に配布
講演申込をもとに作成

2021 年 2 月 24 日(水), 25 日(木), 26 日(金)

オンライン

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

2 月 24 日（水）10:00 ～ 18:10

10:00 **開会挨拶** 張替正敏（JAXA）

司会: 堀川康（元 JAXA）

10:05 A01. JAXA のスペースデブリ関連活動紹介
○山中浩二（JAXA）

10:35 A02. JAXA 追跡ネットワーク技術センターにおける宇宙状況認識に関する活動の現状
○渡邊優人，植本有海，畠山拓也，中村信一，池田沙織，日南川英明（JAXA）

10:55～11:00 換気休憩

11:00 A03. JAXA 商業デブリ除去実証（CRD2：Commercial Removal of Debris Demonstration)の最新状況
○山元透（JAXA）

11:20 A04. JAXA スペースデブリ発生防止標準 JMR-003 の最新状況
○佐藤健一，仁田工美，吉原徹（JAXA）

11:40～13:00 昼休み

13:00 パネルディスカッション 1
「日本の民間デブリ関連ソリューション事業化に向けた挑戦」
モデレーター：上野浩史（JAXA）

パネリスト： 藏本順（ALE）
田治米伸康（アストロスケール）
中村友哉（アクセルスペース）
泉山卓（IHI）
久保田伸幸（KHI）
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）
金澤誠（Space BD）

14:55～15:00 休憩

司会: 柳沢俊史，日南川英明（JAXA）

15:00 A05. Space Debris Related Activities in Russia
○Vladimir Agapov (Astronomical Scientific Center)

15:45 A06. New Space and the Need for Space Debris Mitigation
○Stijn Lemmens (ESA)

16:30～16:40 休憩

司会: 竹内悠（JAXA）

16:40 A07. Space Traffic Management at IAA-IAF Level
○Christophe Bonnal (CNES)

17:10 A08. Latest Developments on Space Debris Modelling Activities at CNES
○Juan-Carlos Dolado-Perez (CNES)

17:40 A09. Modeling the Space Debris Environment - Latest Improvements and Updates
○Carsten Wiedemann, A. Horstmann (TU Braunschweig), S. Hesselbach (DLR), V. Braun, H. Krag (ESA), S. Flegel (unaffiliated), M. Oswald (Airbus Defence & Space), E. Stoll (TU Braunschweig)

2月25日（木）10:00 ～ 17:40

司会: 花田俊也（九州大学）

10:00 B01. 九州大学における宇宙デブリのモデリング
丸山貴大, 吉村康広, ○花田俊也（九州大学）, 河本聡美（JAXA）

10:20 B02. 推移モデルを用いた宇宙機の軌道投入許容量の検討
○長岡信明, 河本聡美, 北川康弘（JAXA）, 花田俊也（九州大学）

10:40 B03. JAXA独自のデブリ推移予測用ベースラインファイルの開発状況
○河本聡美, 長岡信明, 北川康弘, 柳沢俊史, 上野浩史（JAXA）, 中渡瀬竜二, 上田裕子, 八田真児（MUSCATスペース・エンジニアリング）, 花田俊也（九州大学）

11:00～11:05 換気休憩

司会: 長岡信明（JAXA）

11:05 B04. 低軌道ADRミッションにおけるターゲット物体の姿勢運動解析
○松下悠里（九州大学）, 板谷優輝（スカパーJSAT）, 吉村康広（九州大学）, 福島忠徳（スカパーJSAT）, 花田俊也（九州大学）

11:25 B05. 経済学からのデブリ問題分析
中渡瀬竜二, ○八田真児, 上田裕子（MUSCATスペース・エンジニアリング）, 斉藤賢爾（早稲田大学）, 花田俊也, 馬奈木俊介（九州大学）

11:45～13:00 昼休み

13:00 パネルディスカッション 2
「法政策的見地からのデブリ対策に対する産学官の役割」
モデレーター：竹内悠（JAXA）

パネリスト： 新谷美保子（TMI総合法律事務所）
大塚聡子（NEC）
渡邉亜希子（スカパーJSAT）
吉田良太（JAXA）

14:30～14:50 休憩

司会: 日南川英明（JAXA）

14:50 B06. アストロスケールが取組むRPO技術 - 低軌道デブリ除去から静止軌道での軌道上サービスまで -
○岡田光信（アストロスケールホールディングス）

15:10 B07. 最近のスペースデブリをめぐる規制とSTMの最近のグローバルな議論について
○岩本彩（アストロスケール）

15:30 B08. 低軌道デブリ光学観測システム
○柳沢俊史, 神谷浩紀, 黒崎裕久（JAXA）

15:50 B09. 日豪2地点からの低軌道物体光学観測実証
○中道達也, 篠原流, 泉山卓（IHI）, 柳沢俊史, 神谷浩紀, 黒崎裕久（JAXA）

16:10～16:20 休憩

司会: 泉山卓（IHI）

16:20 B10. 静止衛星の測光・分光同時観測
○藤原智子, 奥村真一郎, 西山広太, 二村徳宏（日本スペースガード協会）

16:40 B11. ライトカーブ観測とH-2A R/Bモデルを用いた再現実験
○黒崎裕久, 柳沢俊史, 林正人, 河本聡美（JAXA）

17:00 B12. 微小デブリ軌道上観測データの統計的解析手法
○古本政博, 佐原宏典（東京都立大学）

17:20 B13. デブリの軌道・回転運動把握のためのSLR反射器（Mt.FUJI）の開発
○秋山祐貴, 嘉生幸代, 坂本拓史, 日南川英明, 松本岳大, 吉川和宏, 渡邊優人, 中村信一（JAXA）

2月26日（金）10:00 ～ 17:40

司会: 平子敬一（慶応義塾大学）

10:00 C01. 衛星用複合材推薬タンクの再突入安全性評価モデル
〇清水隆三, 松本純, 藤本圭一郎, 足立寛和, 池田博英（JAXA）

10:20 C02. 高忠実な物理モデルによるリエントリ安全評価法 LS-DARC の開発:
第2報 熱流束モデル検証プロセス
〇藤本圭一郎, 根岸秀世, 飯塚宣行, 清水隆三, 沖田耕一（JAXA）

10:40～10:45 換気休憩

司会: 赤星保浩（九州工業大学）

10:45 C03. デブリ衝突損傷リスク解析ツール TURANDOT の現状と改修計画
〇中渡瀬竜二, 上田裕子, 八田真児（MUSCAT スペース・エンジニアリング）, 河本聡美（JAXA）

11:05 C04. 次世代型宇宙用デブリモニタ BBM の開発
〇松﨑乃里子, 松本晴久, 永松愛子, 神谷浩紀（JAXA）

11:25 C05. 耐 AO コーティングによる CFRP からのイジェクタの低減
〇西田政弘, 高原秀征（名古屋工業大学）, 古田尚正, 岩瀬賢明（東亞合成）, 東出真澄, 石田雄一（JAXA）

11:45～13:00 昼休み

13:00 ポスターセッション（オンライン中継）

P01. 東京大学木曽観測所モザイク CMOS カメラ「トモエゴゼン」による高速移動天体サーベイ
〇大澤亮, 酒向重行, 紅山仁, 諸隈智貴（東京大学）, 浦川聖太郎, 奥村真一郎（日本スペースガード協会）, 渡部潤一（国立天文台）, 柳沢俊史, 黒崎裕久, 吉川真（JAXA）, Tomo-e Gozen プロジェクト

P02. 東京大学木曽観測所モザイク CMOS カメラ「トモエゴゼン」による人工天体の検出効率と性質について
〇満田和真（デロイトトーマツリスクサービス）, 酒向重行（東京大学）, Tomo-e Gozen プロジェクト

P03. 低軌道 NEO 観測小型衛星
〇平子敬一, 柳沢俊史, 黒崎裕久, 神谷浩紀（JAXA）

P04. 超高分子量ポリエチレン繊維複合材／アルミニウム合金デブリバンパーからの イジェクタの低減
〇正木聖広, 西田政弘（名古屋工業大学）, 野村幸弘（東洋紡）, 東出真澄（JAXA）

P05. 電気推進噴出流の照射による宇宙デブリの脱軌道技術の研究とその実証超小型衛星 OSU4 の開発
〇田原弘一, 山本拓海, 島田貴久, 水出蒼真, 三村篤史（大阪産業大学）, 池田知行（東海大学）

P06. スペースデブリ除去装置への応用を目指した帯電薄膜による抗力増大装置の開発研究
〇村中崇信（中京大学）, 奥村哲平（JAXA）, 上野一磨, 大塚俊輔（中京大学）, 大川恭志（JAXA）

P07. EDT を用いた PMD デバイスにおけるテザー伸展についての初期検討
〇坂元洋輝, 渡部武夫, 佐藤強, 大﨑一樹, 佐藤洸輔（神奈川工科大学）, 蒲池康, 岡島礼奈（ALE）

P08. スペースデブリ捕獲に向けたデブリ模擬構造への金属銛撃込みに関する数値解析
田中宏明, 〇玉置悠人（防衛大学校）

P09. Streaks Detection Algorithm in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory
〇Manuel Cegarra Polo, YANAGISAWA Toshifumi, KUROSAKI Hirohisa (JAXA), OHSAWA Ryou, SAKO Shigeyuki (University of Tokyo, Tomo-e Gozen Team)

13:35～13:40 換気休憩

司会: 岡本博之（JAXA）

13:40 C06. ELSA-d, ADRAS-J プロジェクト及び将来サービスのための地上システムと運用について
〇小堀加奈絵（アストロスケール）

14:00 C07. ELSA-d プロジェクト ステータス - 打ち上げにむけて-
飯塚清太, 〇岡本章（アストロスケール）, ELSA-d プロジェクトチーム

14:20 C08. ADRAS-J プロジェクト概要 - 世界初大型デブリ除去実証技術とは -
〇藤田勝，浅葉薫，足木研介（アストロスケール），ADRAS-J プロジェクトチーム

14:40～14:50 休憩

司会: 田原弘一（大阪産業大学）

14:50 C09. デブリ環境改善に対する MHI の取り組み
〇小早川豊範，木村友久，志村康治，渥美正博（MHI）

15:10 C10. 衛星搭載パルスレーザーによる軌道離脱サービス
〇福島忠徳，平田大輔，足立数馬，山田淳，板谷優輝（スカパーJSAT），津野克彦，小川貴代，和田智之，戎崎俊一（理化学研究所）

15:30 C11. スペースデブリ発生防止用導電性テザーシステムとその実証
〇江川雄亮，蒲池康，鈴木大輔，岡島礼奈（ALE），河本聡美，大川恭志（JAXA），佐藤強，渡邊武夫（神奈川工科大学），佐藤悠司，栗原聡文（東北大学）

15:50 C12. デブリ除去に向けた 1kW 級ホールスラスタシステムの研究開発
〇張科寅，渡邊裕樹，松永芳樹，大川恭志（JAXA）

16:10～16:15 換気休憩

司会: 大川恭志（JAXA）

16:15 C13. ADR 作業の為の非協力的ターゲット捕獲・把持機構の検討
〇中西洋喜，川口直毅，林輝明，増田雄斗，多賀啓介（東京工業大学）

16:35 C14. ロバスト性の向上を目指したデブリ捕獲機構のコンセプトと開発状況
〇谷嶋信貴，岡本博之，壹岐賢太郎，渡邊惠佑，奥村哲平（JAXA）

16:55 C15. 動ターゲット捕獲検証プラットフォーム（SATDyn）の開発
〇岡本博之（JAXA）

17:15 C16. ADR 用銛機構の性能向上に向けた日本刀技術導入の検討
〇渡部武夫（神奈川工科大学），坂本武司（有明高専），佐藤強（神奈川工科大学）

17:35 **閉会挨拶** 第 9 回デブリワークショップ実行委員会

9th Space Debris Workshop Program

Wednesday 24 February 10：00 ～ 18：10

10:00 **Opening Remarks** HARIGAE Masatoshi (JAXA)

Chairperson: HORIKAWA Yasushi （former JAXA）

10:05 A01. **Space Debris Related Activities at JAXA**
○YAMANAKA Koji (JAXA)

10:35 A02. **Current Activities on Space Situational Awareness at STCC, JAXA**
○WATANABE Masato, UEMOTO Arimi, HATAKEYAMA Takuya, NAKAMURA Shinichi, IKEDA Saori and HINAGAWA Hideaki (JAXA)

10:55～11:00 **Break**

11:00 A03. **Latest Updates on JAXA Commercial Removal of Debris Demonstration (CRD2)**
○YAMAMOTO Toru (JAXA)

11:20 A04. **Status on JAXA Space Debris Mitigation Standard JMR-003**
○SATO Kenichi, NITTA Kumi, YOSHIHARA Toru (JAXA)

11:40～13:00 **Luncheon**

13:00 **Panel Discussion 1**
The Challenges for Commercializing Space Debris Solutions in Japan
Moderator: UENO Hiroshi (JAXA)

Panelist: KURAMOTO Jun (ALE)
TAJIME Nobuyasu (Astroscale)
NAKAMURA Yuya (Axelspace)
IZUMIYAMA Taku (IHI)
KUBOTA Nobuyuki (KHI)
HATTA Shinji (MUSCAT Space Engineering)
FUKUSHIMA Tadanori (SKY Perfect JSAT)
KANAZAWA Mac (Space BD)

14:30～15:00 **Break**

Chairpersons: YANAGISAWA Toshifumi and HINAGAWA Hideaki（JAXA）

15:00 A05. **Space Debris Related Activities in Russia**
○Vladimir Agapov (Astronomical Scientific Center)

15:45 A06. **New Space and the Need for Space Debris Mitigation**
○Stijn Lemmens (ESA)

16:30～16:40 **Break**

Chairperson: TAKEUCHI Yu（JAXA）

16:40 A07. **Space Traffic Management at IAA-IAF Level**
○Christophe Bonnal (CNES)

17:10 A08. **Latest Developments on Space Debris Modelling Activities at CNES**
○Juan-Carlos Dolado-Perez (CNES)

17:40 A09. **Modeling the Space Debris Environment - Latest Improvements and Updates**
○Carsten Wiedemann, A. Horstmann (TU Braunschweig), S. Hesselbach (DLR), V. Braun, H. Krag (ESA), S. Flegel (unaffiliated), M. Oswald (Airbus Defence & Space), E. Stoll (TU Braunschweig)

Thursday 25 February 10：00 ～ 17：40

Chairperson: HANADA Toshiya（Kyushu University）

10:00 B01. **Orbital Debris Modeling in Kyushu Univ.**
MARUYAMA Takahiro, YOSHIMURA Yasuhiro, ○HANADA Toshiya (Kyushu Univ.), KAWAMOTO Satomi (JAXA)

10:20 B02. **Study of the Orbit Insertion Capacity Tolerance of the Spacecraft Using the Orbital Debris Evolutionary Model**
○NAGAOKA Nobuaki, KAWAMOTO Satomi, KITAGAWA Yasuhiro (JAXA), HANADA Toshiya (Kyushu Univ.)

10:40 B03. **Development of JAXA's Original Baseline File for Debris Evolutionary Model**
○KAWAMOTO Satomi, NAGAOKA Nobuaki, KITAGAWA Yasuhiro, YANAGISAWA Toshifumi, UENO Hiroshi (JAXA), NAKAWATASE Ryuji, UEDA O. Hiroko, HATTA Shinji (MUSCAT Space Engineering), HANADA Toshiya (Kyushu Univ.)

11:00～11:05 **Break**

Chairperson: NAGAOKA Nobuaki（JAXA）

11:05 B04. **Analysis on Attitude Motion of ADR Target in LEO**
○MATSUSHITA Yuri (Kyushu Univ.), ITAYA Yuki (SKY Perfect JSAT), YOSHIMURA Yasuhiro (Kyushu Univ.), FUKUSHIMA Tadanori (SKY Perfect JSAT), HANADA Toshiya (Kyushu Univ.)

11:25 B05. **Overview of Space Debris from Economics**
NAKAWATASE Ryuji, ○HATTA Shinji, UEDA O. Hiroko (MUSCAT Space Engineering), SAITO Kenji (Waseda Univ.), HANADA Toshiya, MANAGI Syunsuke (Kyushu Univ.)

11:45～13:00 **Luncheon**

13:00 **Panel Discussion 2**
Law and Policy Perspectives of the Roles of Industry, Academia and the Government for Space Debris Issues
Moderator: TAKEUCHI Yu (JAXA)

Panelist: SHINTANI Mihoko (TMI Associates)
OTSUKA Akiko (NEC)
WATANABE Akiko (SKY Perfect JSAT)
YOSHIDA Ryota (JAXA)

14:30～14:50 **Break**

Chairperson: HINAGAWA Hideaki（JAXA）

14:50 B06. **Updating Astroscale's Business Plan on Orbit Servicing and Global Footprint**
○OKADA Nobu (Astroscale Holdings)

15:10 B07. **Global Trends in Regulations on Space Debris and STM**
○IWAMOTO Aya (Astroscale Japan)

15:30 B08. **Optical Observation System for LEO Debris**
○YANAGISAWA Toshifumi, KAMIYA Kohki, KUROSAKI Hirohisa (JAXA)

15:50 B09. **Optical Observation Demonstration of LEO Objects from Japan and Australia**
○NAKAMICHI Tatsuya, SHINOHARA Ryu, IZUMIYAMA Taku (IHI), YANAGISAWA Toshifumi, KAMIYA Kohki, KUROSAKI Hirohisa (JAXA)

16:10～16:20 **Break**

Chairperson: IZUMIYAMA Taku（IHI）

16:20 B10. **Simultaneous Photometry and Spectroscopy of GEO Satellites**
○FUJIWARA Tomoko, OKUMURA Shin-ichiro, NISHIYAMA Kota, NIMURA Tokuhiro (JSGA)

16:40 B11. **Light Curve Observation and Reproduction Experiment Using Model of H-2A R/B**
○KUROSAKI Hirohisa, YANAGISAWA Toshifumi, HAYASHI Masato, KAWAMOTO Satomi (JAXA)

17:00 B12. **Statistical Analysis on In-situ Measurements of Small Space Debris**
○FURUMOTO Masahiro, SAHARA Hironori (Tokyo Metropolitan University)

17:20 B13. **Development of SLR Reflector (Mt.FUJI) for Grasping Orbital and Rotational Motion of Debris**
○AKIYAMA Yuki, KASHO Sachiyo, SAKAMOTO Takushi, MATSUMOTO Takehiro, HINAGAWA Hideaki, YOSHIKAWA Kazuhiro, WATANABE Yuto, and, NAKAMURA Shinichi (JAXA)

Friday 26 December 10：00 ～ 17：40

Chairperson: HIRAKO Keiichi（Keio University）

10:00 C01. **Re-entry Survivability Analysis Model of Spacecraft Composite Propellant Tank**
○SHIMIZU Ryuzo, MATSUMOTO Jun, FUJIMOTO Keiichiro, ADACHI Hirokazu, IKEDA Hirohide (JAXA)

10:20 C02. **Development of High Fidelity Model-based Re-entry Safety Analysis Tool LS-DARC: Part 2 Validation Process for Heat-flux Model**
○FUJIMOTO Keiichiro, NEGISHI Hideyo, IIZUKA Nobuyuki, SHIMIZU Ryuzo, OKITA Koichi (JAXA)

10:40～10:45 **Break**

Chairperson: AKAHOSHI Yasuhiro（Kyutech）

10:45 C03. **Present Status and Improvement Plans of Tactical Utility for Rapid ANalysis of Debris on Orbit Terrestrial (TURANDOT)**
○NAKAWATASE Ryuji, UEDA O. Hiroko, HATTA Shinji (MUSCAT Space Engineering), KAWAMOTO Satomi (JAXA)

11:05 C04. **Development of JAXA Space Debris Monitor BBM**
○MATSUZAKI Noriko, MATSUMOTO Haruhisa, NAGAMATSU Aiko, KAMIYA Koki (JAXA)

11:25 C05. **Reduction in Ejecta from CFRP by AO Coating**
○NISHIDA Masahiro, TAKAHARA Hideyuki (Nagoya Institute of Technology), FURUTA Naomasa, IWASE Yoshiaki (Toagosei), HIGASHIDE Masumi, ISHIDA Yuichi (JAXA)

11:45～13:00 **Luncheon**

13:00 **Poster Session**

P01. **Survey of Fast Moving Objects with a CMOS Mosaic Camera, Tomo-e Gozen, at Kiso Observatory**
○OHSAWA Ryou, SAKO Shigeyuki, BENIYAMA Jin, MOROKUMA Tomoki (University of Tokyo), URAKAWA Seitaro, OKUMURA Shin-ichiro (JSGA), WATANABE Jun-ichi (NAOJ), YANAGISAWA Toshifumi, KUROSAKI Hirohisa, YOSHIKAWA Makoto (JAXA), Tomo-e Gozen Project

P02. **Detection Efficiency and Properties of Artificial Bodies Observed with a CMOS Mosaic Camera, Tomo-e Gozen, at Kiso Observatory**
○MITSUDA Kazuma (Deloitte Tohmatsu Risk Services), SAKO Shigeyuki (University of Tokyo), Tomo-e Gozen Project

P03. **Small Satellite for NEO Observation from LEO**
○HIRAKO Keiichi, YANAGISAWA Toshifumi, KUROSAKI Hirohisa, KAMIYA Kouki (JAXA)

P04. **Reduction in Ejecta from Ultra-high Molecular Weight Polyethylene Fiber Composites/ Aluminum Alloy Debris Bumper**
○MASAKI Masahiro, NISHIDA Masahiro (Nagoya Institute of Technology), NOMURA Yukihiro (Toyobo), HIGASHIDE Masumi (JAXA)

P05. **Study on Non-Contact Space Debris Deorbit Technology by Using Irradiation of Electric Thruster Exhaust Flows and Development of the 4th Osaka Sangyo University Nano-Satellite for Its Practical Experiment in Space**
○TAHARA Hirokazu, YAMAMOTO Takumi , SHIMADA Takahisa, MIZUIDE Soma, MIMURA Atsushi (Osaka Sangyo Univ.), and IKEDA Tomoyuki (Tokai Univ.)

P06. **Study on Drag Force Intensifier Applying Charged Membrane for Space Debris Removal**
○MURANAKA Takanobu (Chukyo Univ.), OKUMURA Teppei (JAXA), UENO Kazuma, OTSUKA Shunsuke (Chukyo Univ.), OHKAWA Yasushi (JAXA)

P07. **Initial Study on Tether Deployment in PMD Device Using EDT**
○SAKAMOTO Hiroki, WATANABE Takeo, SATO Tsuyoshi, OSAKI Kazuki, SATO Kohsuke (KAIT), KAMIMACHI Koh, OKAJIMA Lena (ALE)

P08. **Numerical Simulations on Harpooning Metal Anchors for Capturing Space Debris**
TANAKA Hiroaki, ○TAMAKI Yuto (National Defense Academy of Japan)

P09. **Streaks Detection Algorithm in Astronomical Images from the Tomo-e Gozen Camera at Kiso Observatory**
○Manuel Cegarra Polo, YANAGISAWA Toshifumi, KUROSAKI Hirohisa (JAXA), OHSAWA Ryou, SAKO Shigeyuki (University of Tokyo, Tomo-e Gozen Team)

13:35～13:40 **Break**

Chairperson: OKAMOTO Hiroyuki（JAXA）

13:40 C06. **Ground Systems and Operations for ELSA-d, ADRAS-J and Future Debris Removal Services**
○KOBORI Kanae (Astroscale Japan)

14:00 C07. **The ELSA-d End-of-Life Debris Removal Mission: Preparing for Launch**
IIZUKA Seita, ○OKAMOTO Akira (Astroscale Japan), ELSA-d Project Team

14:20 C08. **Towards the Observation and Removal of an Upper Stage Rocket Body – the JAXA-Astroscale ADRAS-J Mission**
○FUJITA Sho, ASABA Kaoru, ASHIKI Kensuke (Astroscale Japan), ADRAS-J project team

14:40～14:50 **Break**

Chairperson: TAHARA Hirokazu（Osaka Sangyo University）

14:50 C09. **MHI's Activity for Improving Space Environment**
○KOBAYAKAWA Toyonori, KIMURA Tomohisa, SHIMURA Koji, ATSUMI Masahiro (MHI)

15:10 C10. **End-of-Life Deorbit Service with a Pulsed Laser Onboard a Small Satellite**
○FUKUSHIMA Tadanori, HIRATA Daisuke, ADACHI Kazuma, ITAYA Yuki, YAMADA Jun (SKY Perfect JSAT), TSUNO Katsuhiko, OGAWA Takayo, WADA Satoshi, EBISUZAKI Toshikazu (RIKEN)

15:30 C11. **Electrodynamic Tether System for Space Debris Prevention and its Demonstration**
○EGAWA Yusuke, KAMACHI Koh, SUZUKI Daisuke, OKAJIMA Lena (ALE), KAWAMOTO Satomi, OHKAWA Yasushi (JAXA), SATO Tsuyoshi, WATANABE Takeo (KAIT), SATO Yuji, KUWAHARA Toshinori (Tohoku Univ.)

15:50 C12. **Research and Development of 1-kW Class Hall Thruster System for Active Debris Removal**
○CHO Shinatora, WATANABE Hiroki, MATSUNAGA Yoshiki, OKAWA Yasushi (JAXA)

16:10～16:15 **Break**

Chairperson: OKAWA Yasushi（JAXA）

16:15 C13. **A Study of Target Capture Device for Active Debris Removal**
○NAKANISHI Hiroki, KAWAGUCHI Naoki, HAYASHI Teruaki, MASUDA Yuto, TAGA Keisuke (Tokyo Institute of Technology)

16:35 C14. **Concept and Development Status of Robustness Improved Debris Gripper**
○TANISHIMA Nobutaka, OKAMOTO Hiroyuki, IKI Kentaroh, WATANABE Keisuke, OKUMURA Teppei (JAXA)

16:55 C15. **The Development of the Rendezvous and Capture Dynamics Hybrid Simulator: SATDyn**
○OKAMOTO Hiroyuki (JAXA)

17:15 C16. **A Study on Applying of Japanese Sword Technology for Improvement of the Performance of Harpoon Mechanisms for ADR**
○WATANABE Takeo (Kanagawa Institute of Technology), SAKAMOTO Takeshi (National Institute of Technology, Ariake College), SATO Tsuyoshi (Kanagawa Institute of Technology)

17:35 **Closing Address** 9th Debris Workshop Executive Committe

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