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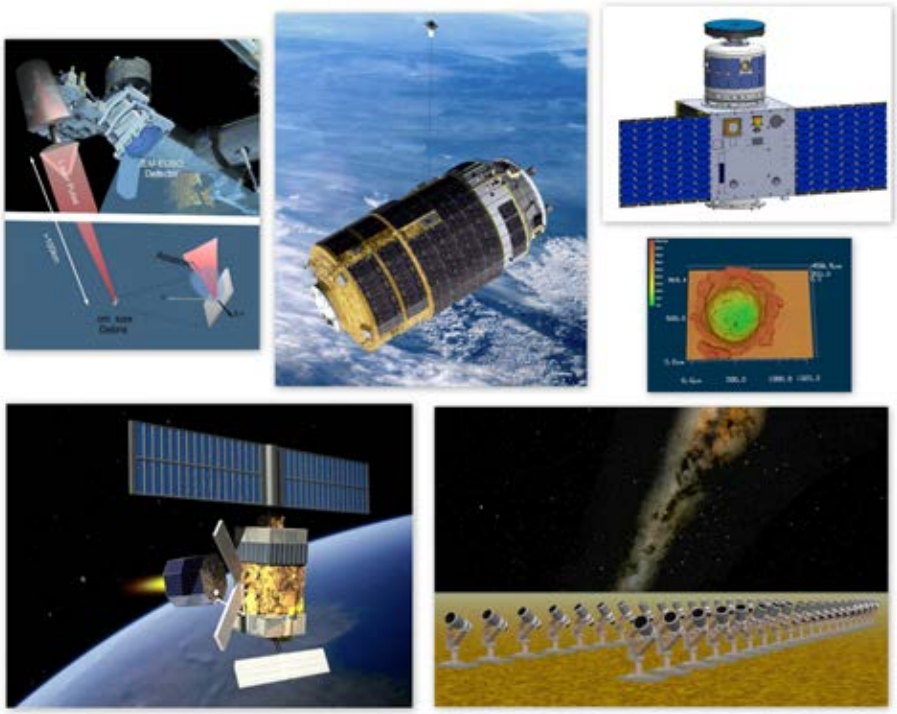
第6回「スペースデブリワークショップ」講演資料集

Proceedings of the 6th Space Debris Workshop



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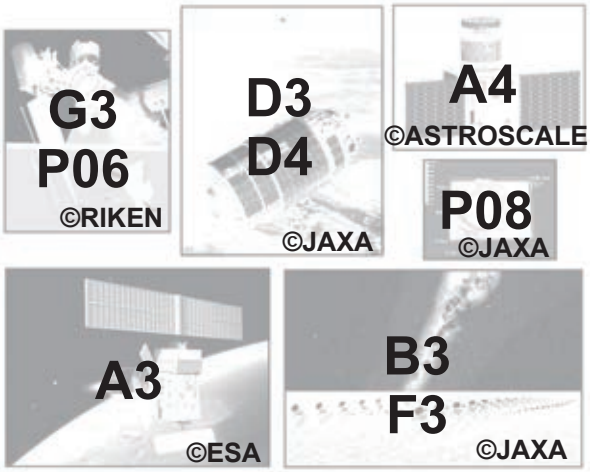

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巻頭言

大西　充　（研究開発本部 未踏技術研究センター）

Mitsuru Ohnishi
Director, Innovative Technology Research Center,
Aerospace Research and Development Directorate

2002 年に始まったスペースデブリワークショップは今回で６回を数え、スペースデブリ問題解決に特化した、国内で唯一の研究発表・技術的議論を行う場として定着してきている。回を追う毎に参加してくださる方が増加しており、世界的なデブリ問題解決向けた活動に、国際的に協調しつつも、我が国が主体的に参加するにあたって必須の ALL-JAPAN 体制構築に重要な役割を果たしていると自負している。

今年は、ESA の Holger Krag 博士や起業家の岡田光信氏を初めとする 40 件の口頭講演をお願いした他、初めての試みとして、ポスター講演を公募し、14 件の発表をいただき、また、総計 200 人以上の方に参加していただいた。全く新しく、あるいは久しぶりに参加された方が約 100 人に上っている。初期のワークショップの状況とは隔世の感があり、デブリ問題に関する関心の高さを痛感したところである。

デブリ問題は、世論の関心の高さが上がっていることに合わせ、マスコミに取り上げられることも多くなっているが、対応に苦慮する事柄も多々発生している。典型的なのが大ヒットした映画「ゼロ・グラビティ」である。この作品によりデブリ問題の認知度が一気に向上した一方で、誤解と思われる情報が広く発出されてしまったことも否めない。このような時に、デブリ対策の専門家の間で共通認識となるデブリ問題および対策の状況を共有しておき、誤解を招くことが無いよう尽力することが重要になると思われる。本ワークショップは、そのような情報共有の役目も負っていると考える。他方、広く門戸を開いて斬新的なアイディアを募ることも、国際的な地位向上を計る上で重要である。

また、ALL-JAPAN 体制構築には、技術的な議論だけでは無く、実際に機能するプログラムへの橋渡しが重要となるが､本ワークショップにはプログラム遂行を使命とする JAXA 関係者が多数参加しており、この間の連携を計る場としても重要な機能を担っていると考える。

今や人類共通の課題となっているデブリ対策を推進する場として、本ワークショップが、ますます重要となり、参加・協力していただいた皆さんが広く活躍されることを祈念している。

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A1

宇宙利用の長期持続性と宇宙空間平和利用委員会の役割

Long Term Sustainability of Outer Space Activities and Role of UNCOPUOS

堀川 康（宇宙空間平和利用委員会前議長、JAXA 技術参与）

Yasushi Horikawa, Former Chair of UNCOPUOS
and Technical Counselor of JAXA

In recent years, the utilization of space has seen an increasing number of States, non-governmental organizations, private sector entities and even universities expanding their presence. In an era where we are seeing space becoming increasingly crowded with new players, the need to show strong commitment to sharing responsibilities and acting responsibly in space to help prevent misperceptions, miscalculations and mistrust has never been greater. The proliferation of space debris and the increased possibility of a collision interfering with or causing damage to space objects raises concerns about long term sustainability of space activities, particularly the low-Earth orbit and geostationary orbit environment. With regard to the long term sustainability of outer space, the role of UNCOPUOS and the current and updated status of discussions on the long term sustainability of outer space activities will be presented.

Biography

Yasushi HORIKAWA (Japan)

Dr. Horikawa, as a technical counselor of Japan Aerospace Exploration Agency (JAXA), provides advices to international relations and application satellite development and utilization programs of JAXA. He is also the Chair of the United Nations Committee on Peaceful Use of Outer Space (UNCOPUOS) for 2012- 2013. During his carrier, he has assumed various executive and leadership positions. From 2005 to 2009, he served as an executive director of JAXA responsible for the development of application satellites such as Earth observations, communications, broadcasting and global positioning satellites as well as the operation and utilization of these satellites. He contributed to the development of the International Space Station as Japanese Program Manager and to the successful implementation of Japanese meteorological satellite programs and Earth observation programs.

A graduate of the University of Tokyo and received PhD from the University of Tokyo on Electronics Engineering.

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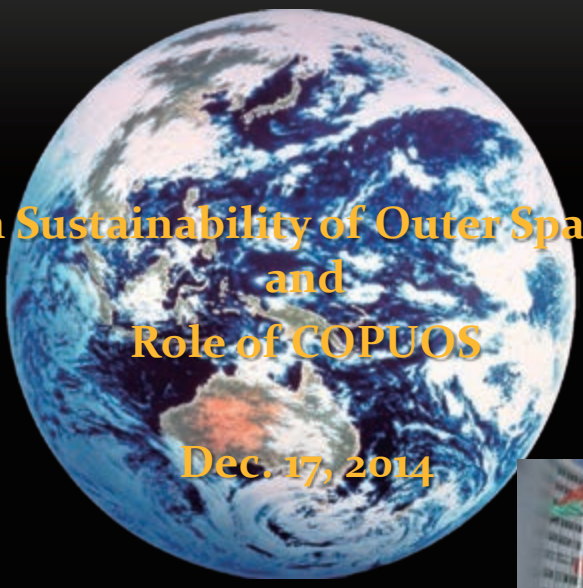
Space Debris Symposium
@ JAXA Chofu



Long Term Sustainability of Outer Space activities and Role of COPUOS

Dec. 17, 2014

Yasushi Horikawa
Former Chair of UNCOPUOS
Technical Councelor of JAXA

UN COPUOS – Overview

- UN COPUOS (Committee on the Peaceful Uses of Outer Space) is the primary international forum for the development of laws and principles governing activities in outer space
- A standing committee of the UN, founded in 1959 by 24 Member States
  - Currently 77 Member States and a large number of permanent observers
  - The technical work of COPUOS is carried out by two subcommittees.
    - Scientific and Technical Subcommittee (STSC)
    - Legal Subcommittee (LSC)
  - Decisions are reached by absolute consensus
  - Secretariat is the UN Office for Outer Space Affairs (Vienna)

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UN COPUOS – Member States

Albania, Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Belgium, Belarus, Benin, Bolivia, Brazil, Bulgaria, Burkina Faso, Cameroon, Canada, Chad, Chile, China, Colombia, Costa Rica, Cuba, Czech Republic, Ecuador, Egypt, France, Hungary, Germany, Ghana, Greece, India, Indonesia, Iran, Iraq, Italy, Japan, Jordan, Kazakhstan, Kenya, Lebanon, Libya, Luxemburg, Malaysia, Mexico, Mongolia, Morocco, Netherlands, Nicaragua, Niger, Nigeria, Pakistan, Peru, Philippines, Poland, Portugal, Republic of Korea, Romania, the Russian Federation, Saudi Arabia, Senegal, Sierra Leone, Slovakia, South Africa, Spain, Sudan, Sweden, Switzerland, Syrian Arab Republic, Thailand, Tunisia, Turkey, the United Kingdom of Great Britain and Northern Ireland, the United States of America, Ukraine, Uruguay, Venezuela & Viet Nam

UN COPUOS – Key Achievements

- **5 treaties on outer space**: peaceful use, registration, liability, astronaut return and moon
- **10 sets of Legal principles, guidelines or frameworks** governing activities of States, including remote sensing, space debris mitigation, nuclear power source, etc
- **Over 110 General Assembly resolutions and recommendations** on outer space matters
- **3 UN space conferences (1968, 1982, 1999)**
- **UN program on space applications**
  - Many workshops each year
  - Regional Centres for Space Science and Technology Education
  - SPIDER (Disaster Management)
  - International Committee on GNSS
- **Activities relating to space security/sustainability**
  - UN COPUOS space debris mitigation guidelines
  - UN COPUOS/IAEA safety framework for nuclear power source applications in outer space
  - WG on long-term sustainability of outer space activities of the STSC
  - In recent years, tendency to non-binding decisions, rather than treaties. (Non-binding does not mean non-legal)

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Space Treaty, Principle and Guideline

Outer Space Treaty	
1967	Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (102states)
1968	Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (92states)
1972	Convention on International Liability for Damage Caused by Space Objects (89states)
1976	Convention on Registration of Objects Launched into Outer Space (60states)
1984	Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (15states)
Principle and Guideline	
1963	Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space
1982	Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting
1986	Principles Relating to Remote Sensing of the Earth from Outer Space
1992	Principles Relevant to the Use of Nuclear Power Sources in Outer Space
1996	Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries
2004	Application of the concept of the "launching State"
2007	Recommendations on enhancing the practice of States and international intergovernmental organizations in registering space objects
2007	Space debris mitigation guidelines of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space
2012	Recommendations on national legislation relevant to the peaceful exploration and use of outer space
Framework	
2009	Safety Framework for Nuclear Power Source Application in Outer Space

UNCOPUOS – Agenda (2014)

COPUOS Main Committee

- General Exchange of Views
- Ways and means of maintaining outer space for peaceful purposes
- Report of STSC
- Report of LSC
- Space and sustainable development
- Spin-off benefits of space technology
- Space and water
- Space and climate change
- Review of current status: Use of space technology in the UN system
- Future role of the Committee

STSC

- UN Programme on Space Application
- Remote sensing
- Space debris
- Space-system-based disaster management support
- Recent developments in global navigation satellite systems
- Space weather
- Near-Earth objects
- Use of NPS in outer space
- Long term sustainability
- Use of GEO

LSC

- Application status of UN space treaties
- Information on the activities of IGO and NGO relating to space law
- Definition and delimitation of outer space and the character and utilization of the geostationary orbit
- National legislation on peaceful uses of space
- Review of principles on use of NPS in space
- International Interests in Mobile Equipment on Matters Specific to Space Assets
- Capacity building in space law
- National mechanisms relating to space debris
- International mechanisms on international cooperation

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Highlights and main results of COPUOS and its two Subcommittees

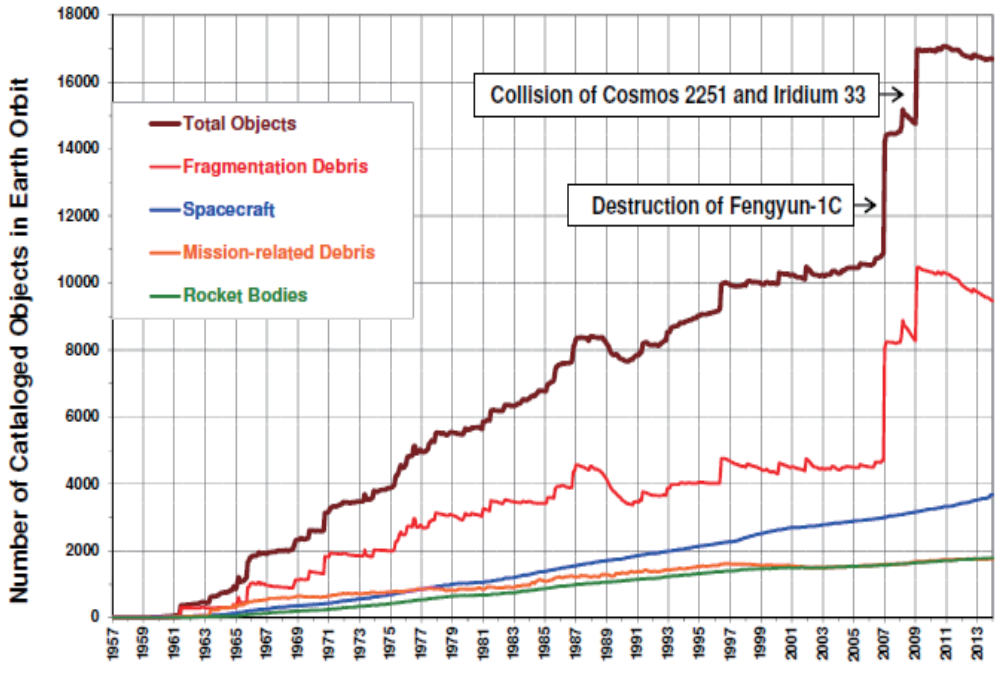
Recent achievements:

- Establishment of the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER) (2006)
- Establishment of the International Committee on Global Navigation Satellite Systems (ICG) (2006)
- Space Debris Mitigation Guidelines (2007)
- GA Resolution on enhancing the practice of States and international intergovernmental organizations in registering space objects (2007)
- Safety Framework for the Use of Nuclear Power Sources in Outer Space (2009)

Current issues - Space Agenda Today:

- Space applications for developing nations
- Space debris
- Long-term sustainability of space activities
- Near-Earth objects
- Space and climate change
- National space legislation
- Definition and delimitation of outer space
- Use of Geospatial Data for Sustainable Development
- International mechanisms on international cooperation

Trend of Space Debris



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Needs of Space Sustainability

- All humanity can use space for peaceful purposes and for socioeconomic benefits.
- Space technology is a critical tool to support sustainable development.
- The Earth's orbital space environment and Radio-Frequency Spectrums are limited natural resources.
- Access for Education and Capacity Building Purposes are Increasing.

Threats in Orbit

Threats for Outer Space Activities

- Orbital Debris
- Radio Frequency Interference
- Near Earth Objects

Factor of Threats

- Emerging Space Actors (New Emerging Countries and Non-Governmental Entities such as Private Sectors or Universities)
- Spontaneous Increase of Space Debris
- Difficulties of Active Removal
- Lack of Transparency and Confidence Building Measures
- Difference of Priorities and Funding Levels on Outer Space activities
- A-SAT Testing for Security Reasons
- Space Based Military Systems

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Urgent Needs of Coordination for Outer Space Activities

- Limited nature of some space resources will require governance challenges to ensure equitable access for entities.
- International cooperation will support in the transfer of expertise and technology for the access to, and use of space, by emerging space actors.
- Space industry will lead to decreasing costs for space access and use, and may increase the accessibility for a wider range of space actors.
- Military space sector may be an important driver in the advancement of capabilities to access and use space, but may be source of friction.

Coordination Mechanisms

Coordination Mechanisms for International Cooperation

- Long Term Sustainability Working Group (LTSWG) established in the Scientific and Technical Subcommittee of UNCOPUOS----Voluntary based Best Practice Guideline
- International Code of Conduct (ICoC) for Outer Space Activities initiated by European Union----Voluntary based Politicaly Binding
- Report from UN Group of Governmental Experts (GGE)----Selected by UN Secretary General
- Treaty on Prevention of the Placement of Weapons in Outer Space and the Threat of the Use of Force against Outer Space Objects (PPWT) ----Leagally Binding
- Conference of Disarmament (CD) is still deadlocked

Various Approach

- Consensus vs Voting
- National vs Multilateral
- Voluntary Base vs Politically or Leagally Binding

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WG on Long-Term Sustainability of Space Activities

Objective

- The objective of the Working Group is to examine and propose measures to ensure the safe and sustainable use of outer space for peaceful purposes, for the benefit of all countries

Terms of Reference

- The Working Group will examine the long-term sustainability of outer space activities in the wider context of sustainable development on Earth
- The work will take into consideration current practices, operating procedures, technical standards and
- The Working Group will take as its legal framework the existing United Nations treaties and principles

Outcomes by 2014 (changed to by 2016)

- Prepare a report on the long-term sustainability of outer space activities
- Produce a set of voluntary recommended guidelines

Organization of works

- Four Expert Groups (sustainable space utilization, space debris, space weather, regulatory regime)
- Inputs received from international organisations (e.g. IAA, IADC, CCSDS, etc.) and non-governmental organisations

Clustering

A. Expert group on sustainable space utilization supporting sustainable development on Earth
Co-Chairs: Filipe Duarte Santos (Portugal) and Mr. Enrique Pacheco Cabrera (Mexico)

B. Expert group on space debris, space operations and tools to support collaborative space situational awareness
Co-chairs: Claudio Portelli (Italy) and Dick Buenneke (USA)

C. Expert group on space weather
Co-Chair: Takahiro Obara (Japan) and Mr. Ian Mann (Canada)

D. Expert group on regulatory regimes and guidance for actors in the space arena
Co-Chair: Sergio Marchisio (Italy) and Michael Nelson (Australia)

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(Next 4charts are excerpts from WG chair's presentation materials.)

Topics for Discussion: 1/4

Expert Group A: Sustainable space utilization supporting sustainable development on Earth

co-CHAIRS: FILIPE DUARTE SANTOS (PORTUGAL), ENRIQUE PACHECO CABRERA (MEXICO)

* The contribution of space science and technology to sustainable development on Earth
* The concept of sustainable development extended to the domain of outer space
* Equitable access to the limited resources of outer space benefits of space activities
* International cooperation in peaceful uses of outer space as a means of enhancing space sustainability and supporting sustainable development on Earth

23 States
5 IGOs

→ 7 candidate guidelines
4 topics for future consideration

Topics for Discussion: 2/4

Expert Group B: Space Debris, Space Operations and Tools to Support Collaborative Space Situational Awareness

co-CHAIRS: RICHARD BUENNEKE (USA), CLAUDIO PORTELLI (ITALY)

Space debris:
* Collection, sharing and dissemination of data on space objects
* Techniques to improve accuracy of orbital data on space objects
* Implement space debris mitigation measures

Space operations:
* Conjunction assessment during orbital phases of flight
* Limit for the risk to people and property from controlled re-entry

Tools to support collaborative space situational awareness:
* Provision of appropriate contact information
* Common standards for sharing information
* Provision of Registration information in the identification of space objects

23 States
4 IGOs

→ 8 candidate guidelines
3 topics for future consideration

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Topics for Discussion: 3/4

Expert Group C: Space Weather
co-CHAIRS: TAKAHIRO OBARA (JAPAN), IAN MANN (CANADA)

* Collection, sharing and dissemination of data and forecasts
* Capabilities to provide a comprehensive and sustainable network of sources of key data in order to observe and measure phenomena related to space weather in real or near-real time
* Open sharing of established practices and guidelines to mitigate the impact of space weather phenomena on operational space systems
* Coordination among States on ground-based and space-based space weather observations in order to safeguard space activities

27 States
5 IGOs

→

5 candidate guidelines
2 topics for future consideration

Topics for Discussion: 4/4

Expert Group D: Regulatory Regimes and Guidance for Actors in the Space Arena
CO-CHAIRS: SERGIO MARCHISIO (ITALY), MICHAEL NELSON (AUSTRALIA)

Regulatory regimes:

* Adherence to existing treaties and principles on the peaceful uses of outer space
* Review of the regulatory framework and the tools for the use and transfer of space technologies within international cooperation and international turnover of controlled space-related goods
* National regulatory frameworks for space activities

Guidance for actors in the space arena:

* International cooperation as a means to promote LTS
* Sharing of experiences relating to LTS, such as technical standards, best practices and lessons learned
* Technical and legal capacity-building for emerging space actors countries

25 States
6 IGOs

→

11 candidate guidelines
5 topics for future consideration

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Emerging Candidate Guidelines

- The Expert Groups have produced 31candidate guidelines for consideration by the WG and 2 additional guidelines was proposed by WG chairman.
- The candidate guidelines of the EGs are necessarily thematically oriented and some address cross-cutting issues from a thematic perspective.
- These guidelines can be broadly grouped into implementation-oriented categories, such as:
  - ✓ Policy, regulatory, and organiztional,
  - ✓ Scientific and Technical,
  - ✓ International Cooperation and Capacity building
- In June 2014, the Working Group began its consideration of the candidate guidelines, 3-additional guidelines, 2 from Russia and 1 from Switzerland were added and agreed on a framework for the consolidation of the candidate guidelines to eliminate duplication (currently 19 guidelines in total) and to harmonise terminology.
- The WG will also address definitional and translation issues to ensure clarity of the guidelines.
- New guidelines and/or amendments are also being proposed by the Member States.
- Provision is made for implementation mechanisms and for updating of guidelines in future.

Time is not on our side. The WG will need to find a balance between issues where consideration is mature enough to reach consensus on guidelines and issues requiring further consideration in COPUOS.

Consolidated Guidelines (1)

33 guidelines are consolidated to 19 guidelines. Following 19 titles of guidelines are under consideration. (These are not guidelines themselves but just titles due to limitation of space)

Policy, regulatory and organizational

- Supervising national space activities
- Registration information on space objects
- Contact information and information on space objects and orbital events
- Spectrum protection
- Adoption of national regulatory frameworks
- Elements to be taken into consideration when developing national regulatory frameworks
- States and international intergovernmental organizations should develop and implement criteria and procedures for the preparation and conduct of space activities aimed at the active removal of space objects from orbit (Russian Proposal)

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Consolidated Guidelines (2)

- Respect the security of foreign space-related ground and information infrastructures （Russian Proposal)
- Awareness of space activities

Scientific and technical

- Research on and development of ways to support sustainable exploration and use of outer space
- Data on space objects
- Perform conjunction assessment during orbital phases of controlled flight
- Promotion of research on orbital debris and sharing of space debris monitoring information
- Development of space weather models and tools and collection of established practices on the mitigation of space weather effects
- Sharing operational space weather data and forecasts
- Investigation and consideration of new measures to promote the sustainability of outer space activities in the medium and long term （Swiss Proposal)

Consolidated Guidelines (3)

International cooperation and capacity-building

- International cooperation in support of the long-term sustainability of outer space activities
- Sharing of experience related to the long-term sustainability of outer space activities and procedures for information exchange
- Capacity-building

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Timeline

2011 WG adopts Terms of Reference and three-year work plan
WG establishes four expert groups to consider topics in TOR
2012 First COPUOS Long-Term Sustainability Workshop
Practices of States to promote LTS
Expert Groups commence work and refines list of topics to discuss
2013 Second COPUOS Long-Term Sustainability Workshop
Practices and experiences of non-State actors
Candidate guidelines proposed by expert groups
2014 WG begins consideration of draft guidelines during STSC
Presentation by Chair of WG to COPUOS Legal Subcommittee of COPUOS
Begin consideration of consolidated guidelines and review work plan
2015 Submit proposals on new elements, structual change or additional guidelines
WG coinsolidates the updated draft guidelines
2016 Agree on the form of guidelines to be presented to General assembly
Consider topics for future discussion

CONCLUSIONS

- Space utilization activities under the framework of United Nations should be conducted focusing on resolving the issues of humankind through international cooperation.
- Specifically, in the field of application satellite program, the significance of technological advancement and continuous utilization of satellites for the improvement of the daily lives for humankind is essential.
- Coordination for international cooperation and capacity building for developing countries is vital.
- It would be important to look into the overall role in meeting the needs for long-term space utilization by appropriately identifying the synergies of common interest issues with related countries.

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Thank you for your attention!

Visit UNOOSA Website :

http://www.oosa.unvienna.org/oosa/COPUOS/copuos.html

Initiatives Proposed by COPUOS Chair

The three main ideas targeting space research and utilization in response to the 50th Anniversay Declaration

1. To promote the role of the Committee and its Subcommittees as a unique platform at the global level for international cooperation in space research and long-term space utilization;
2. To promote dialogue between the Committee and regional and inter-regional cooperation mechanisms in space activities for the benefit of global development; and
3. To strengthen the relevance of space science and technology and their applications in meeting the outcomes of the United Nations Conference on Sustainable Development (Rio+20)

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UN GGE on TCBMs

- UN Group of Govt Experts on Transparency and Confidence Building Measures (TCBMs) for Outer Space Activities
- UN General Assembly Resolution A/Res/65/68 of 2010
- 15 Experts selected for geographical balance & knowledge
- The GGE is to conduct a study on outer space transparency and confidence-building measure
  - making use of relevant reports of the UN Secretary-General
  - without prejudice to the substantive discussions on the prevention of an arms race in outer space within the framework of the CD
  - and to submit to the General Assembly at its sixty-eighth session (in 2013) a report with an annex containing the study of governmental experts
- TCBMS are meant to be voluntary and not legally binding

Code of Conduct

- Proposed by EU
- Principles
  - freedom for all to use outer space for peaceful purposes
  - preservation of the security and integrity of space objects in orbit
  - due consideration for the legitimate security and defence interests of States
- All-encompassing in scope
- Focuses on establishing norms of behaviour and proscribing irresponsible behaviours
- Not legally-binding, a political commitment

EU lacks a multilateral mandate. Process needs to be “multilateralised”

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Conference on Disarmament (CD)

- Some States believe that conflict in outer space would have such terrible consequences that they would like to ban the use of weapons in space through a legally binding treaty
  - However, there are definitional problems
- CD has discussed Prevention of an Arms Race in Outer Space (PAROS) for a number of years
- However, CD is deadlocked because States cannot agree on its agenda, so there has been no progress on PAROS
- In 2008 China and Russia introduced draft Treaty on Prevention of the Placement of Weapons in Outer Space and of the Threat or Use of Force against Outer Space Objects (PPWT)
- PPWT has support of many States, but not all, because of definitional issued and verification concerns of the PPWT

International Space Law

- **International space law contains several obligations for States carrying out space activities (registration, responsibility, liability...)**
- **Privatization, commercialization of space activities as well as international cooperation have increased in recent years**
- **Private/commercial/non-governmental entities are not bound by international (space) law**
- **Implementation of international space law is needed to ensure that international space law is complied with at all levels.**

Obligations of States under International Space Law

(1) **Registration of space objects**
(2) **Liability of the launching States(s)**
(3) **Duty of authorization and supervision**
(4) **Others :**
- **no placement of weapons of mass destruction in Earth orbit,**
- **facilitate and encourage international cooperation,**
- **paying due regard to the interests of other countries....**

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Concluding Remarks

- To succeed world-class mission:

  Firm advanced mission requirements, high reliability and assured quality, operational life, and low life cycle cost

- Advancement of technical capability:

  Well structured development process, standardization, incorporation of lessons learned, and thorough review

- Advanced launch notification and information exchange of the space objects for sustainable use of outer space

- Coordination for international cooperation and capacity building for the long term sustainability of outer space

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A2

宇宙航空研究開発機構のスペースデブリ関連研究について

Overview of JAXA's Space Debris related Research Activities

伊東康之（宇宙航空研究開発機構）
Yasuyuki ITO, JAXA

Space debris is a risk factor for all the countries and organizations who perform space activities. For example, multiple collision damages are possible in a year for satellites with projected areas exceeding 10 m2. Efforts are required for mission assurance against debris. The protection design for critical components of a spacecraft, adding functions to complete self-disposal actions, etc.are considered. Almost all the debris experts in the world agree that the number of existing debris would continue to grow and the environment would go worse. Therfor, in addition to the mitigation efforts, more positive measures to remedy the environment should be globally discussed and implemented. In order to develop measures to remove debris, technology development is needed as well as international cooperation. Considering the above mentioned situation, JAXA's debris related research activities are introduced in this presentation.

スペースデブリは宇宙開発利用活動を行うすべての国、機関にとってリスクとなっており、ミッションの成功を保証するために努力が必要である。一例として、高度 1000km を周回する断面積 $1m^2$ の衛星には 1mmφのデブリが３年で１回の頻度で衝突すると推定されており、当たり所が悪いと人工衛星の機能の一部を喪失することとなる。より大きいデブリが衝突すれば衛星自体の喪失、破砕に至る。デブリは継続的に増加しており、その状況悪化の加速度を緩和するために、デブリ発生防止対策を徹底しなければならない。多くの対策は既に世界的に合意されているが、用済み後のシステムの除去や、落下時の地上安全の確保には更に徹底・配慮が必要な状況である。軌道上物体同士の衝突は近年現実的な脅威となっており、現状のデブリ発生防止対策を超えて、分布密度の高い高度域から使用済み衛星・ロケットを相当数除去する活動が、近い将来必要になるという認識が共有されつつある。この様な状況を踏まえ、宇宙航空研究開発機構におけるデブリ関連研究を概観する。

Biography

ITO, Yasuyuki
Associate Director General, JAXA

Place of birth : Osaka, Japan
Ms. and Bs. degree in Electrical Engineering
at Kyoto University

1980 - 2003: National Space Development Agency (NASDA)
2003 - : JAXA
< R & D Career >
Earth Observation Instrumentation at R&D Directorate: Synthetic Aperture Radar, Microwave Radiometer
Conceptual study of ENVISAT/AMI at ESA/ESTEC as Research Fellow
Earth Observation Satellite Project : ADEOS-II, Aqua/AMSR-E
< Administration/Management Career >
Strategic Planning Dept., Human Resources Dept., Audit & Evaluation Office, Earth Obs. Science Team Management

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OVERVIEW OF JAXA'S SPACE DEBRIS RELATED RESEARCH ACTIVITIES

December 2014

6th Space Debris Workshop, Chofu, Tokyo

Yasuyuki ITO, JAXA

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1. about Space Debris
2. about Japan's space policy and JAXA
3. Goals and Topics of JAXA Research activities

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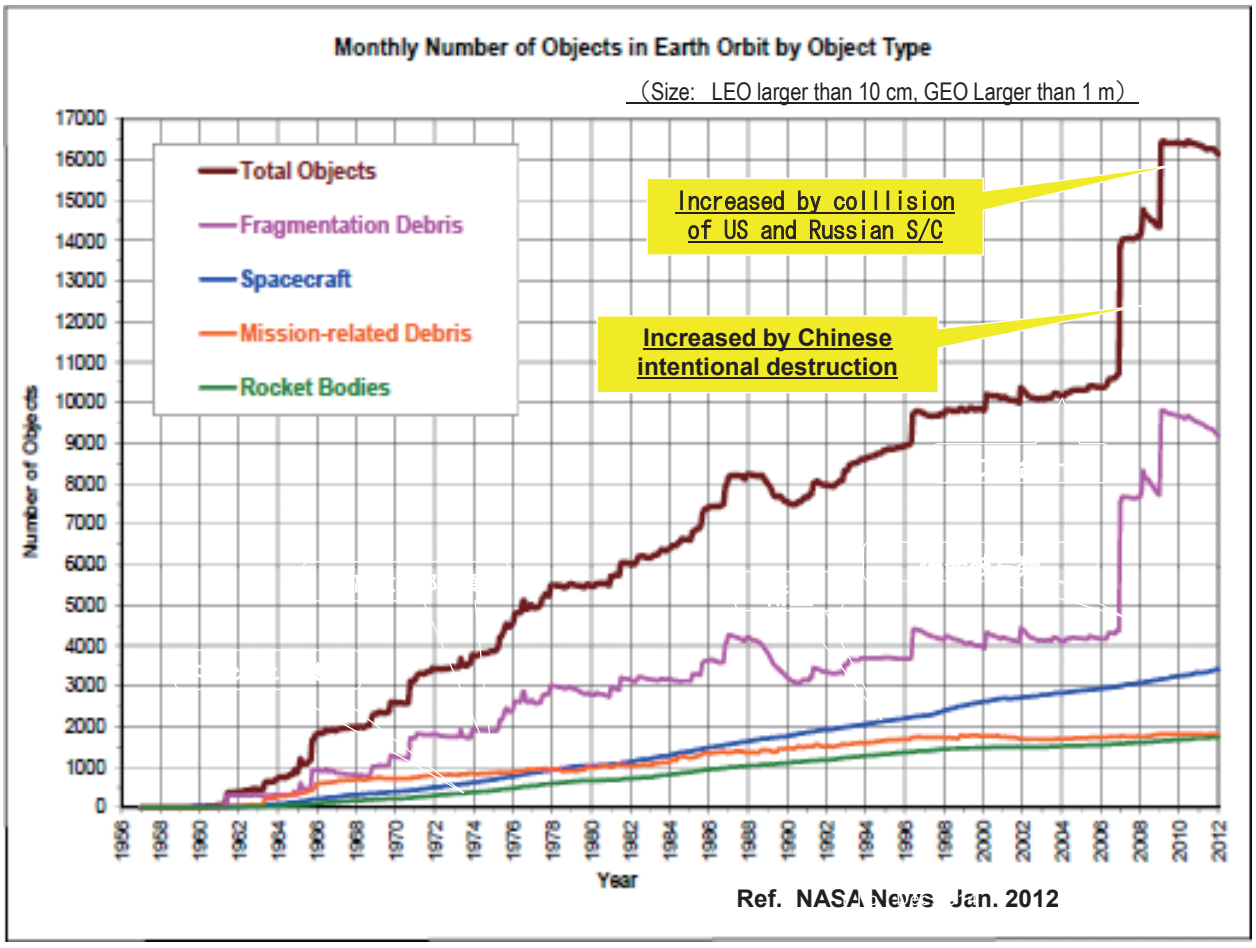

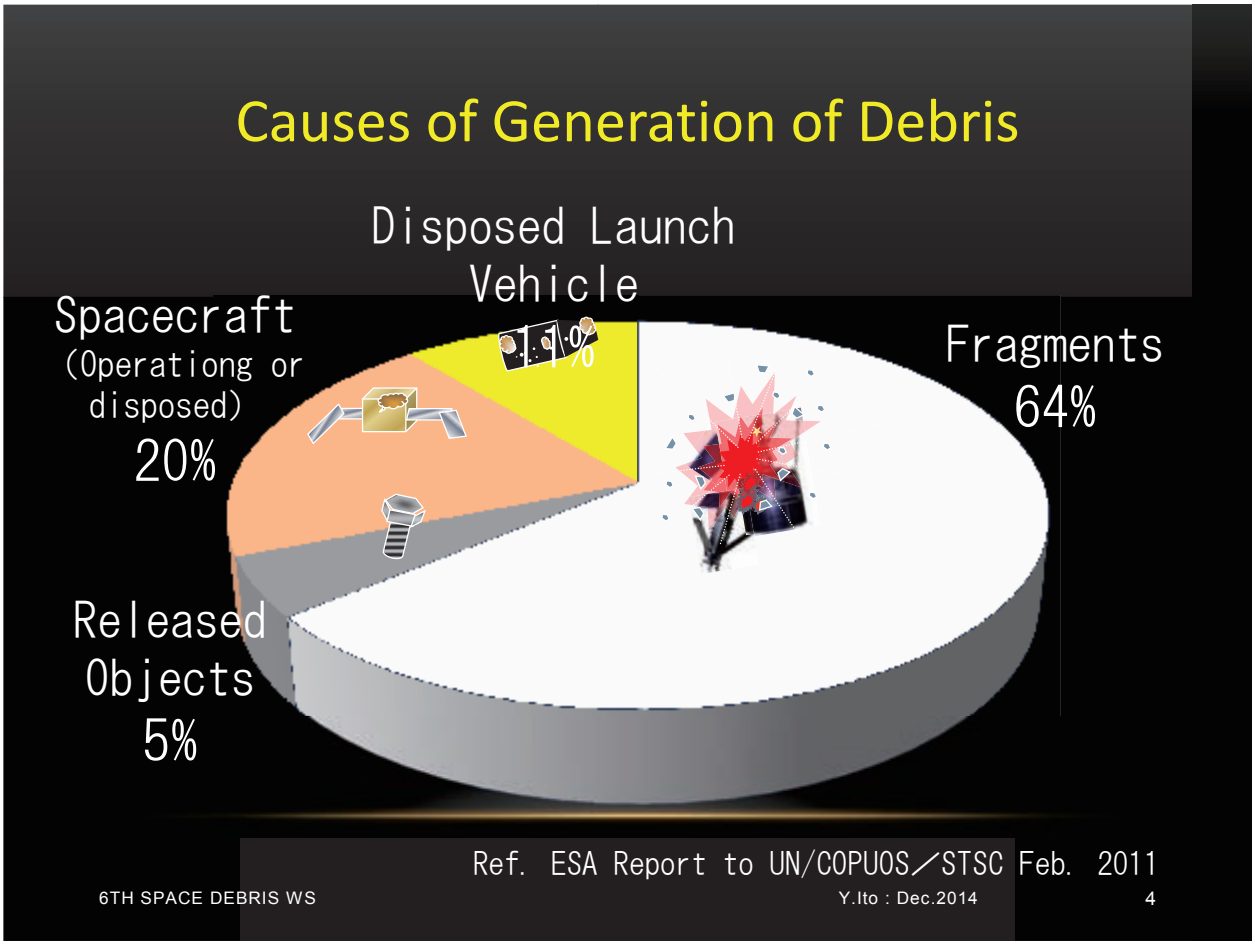

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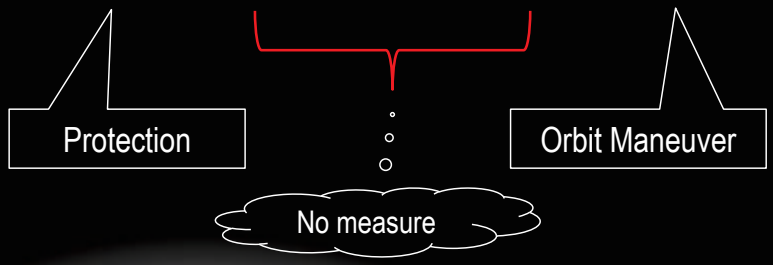
Estimated Annual Collision of Small Sized Debris to a Operating Satellite (1m^2 cross section at 800km altitude orbit)

Debris SIZE	0.1~1mm	1~10mm	1~10cm	10cm over
Estimated Annual Collision (times)	100	0.01*	0.0001	0.00001

Measures for Mission Assurance



* NASA analysis shows 0.1

Ref. :Analysis using ESA tool "MASTER"

Basic Plan on Space Policy, Second Issue : January 2013 (First Issue : June 2009)

JAXA has been positioned as the core organization that provides technical support for the entire governmental development and utilization of space projects.

Basic Policy

- Expanding the utilization of space
- Ensuring autonomy

Priority Subjects

- National Security and Disaster Management
- Industrial Development
- Progress in Frontier Areas including Space Science

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Basic Plan on Space Policy, Draft for New Issue : for Public Comment in November 2014

Provisional Translation

Table of Contents

0. Introduction
1. Current circumstances
2. Goals
3. Basic Policy
4. Measures that the Government should take

Description about Space Debris in the New Basic Plan Draft

Provisional Translation

4. Measures that the Government should take

(1) Systems of Governmental Measures for the Goal

① Ensuring Security in Space

ｉ）Sustainable Development and Utilization of Space

Space Situational Awareness (SSA) system acquisition and development of the capability

Capability for collision avoidance

Realize/strengthen the rule of law in space

Development of technologies for debris removal

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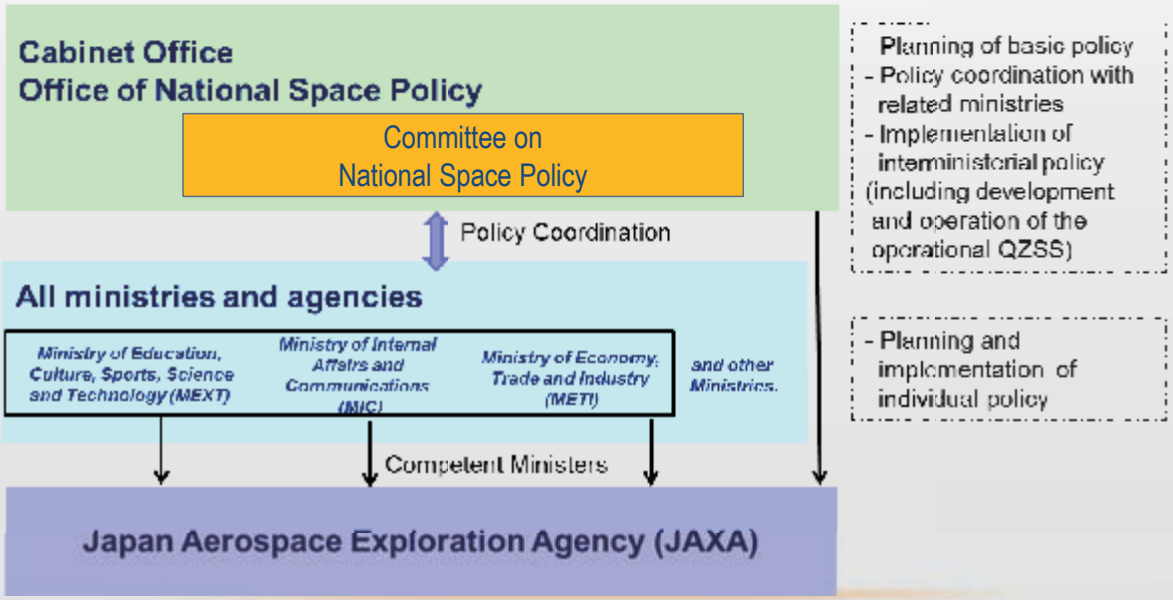
Organization chart
(Space related ministries in Japan)



Ref.: Presentation by Office of National Space Policy, CAO

6TH SPACE DEBRIS WS Y.Ito : Dec. 2014 9

JAXA ORGANIZATION CHART

Naoki Okumura

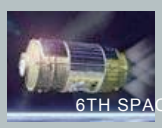
President

Senior Vice-President

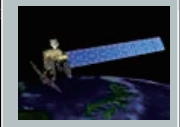
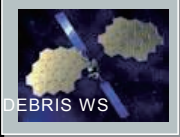
Kiyoshi Higuchi
IAF President

Policy Coordination | Admin. Management | Technical Management

Space Transportation Mission Directorate

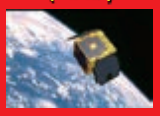


Satellite Applications Mission Directorate I

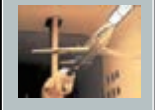
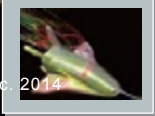
Human Spaceflight Mission Directorate

Aerospace Research & Development Directorate (ARD)

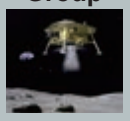


Institute of Space & Astronautical Science

Institute of Aeronautical Technology

Lunar & Planetary Exploration Program Group



6TH SPACE DEBRIS WS Y.Ito : Dec. 2014 10

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ISAS NAL NASDA

1996 : NASDA first Debris Standard

1999 : Japan proposed a specific committee to UNCOPUOS for debris issue

1995 : NASA first Debris Standard

1999 ~ 2007 : CNES first Debris Standard
European Code of Conduct

2002 : IADC released the IADC Debris Mitigation Guidelines

2003

JAXA First Mid-Term

2006 : JAXA Debris Committee

2007 : UN adopted the COPUOS Debris Mitigation Guidelines

2008

JAXA Second Mid-Term

2011 : ISO released “Debris Mitigation Requirements”

2012 : (Japan’s New Law)

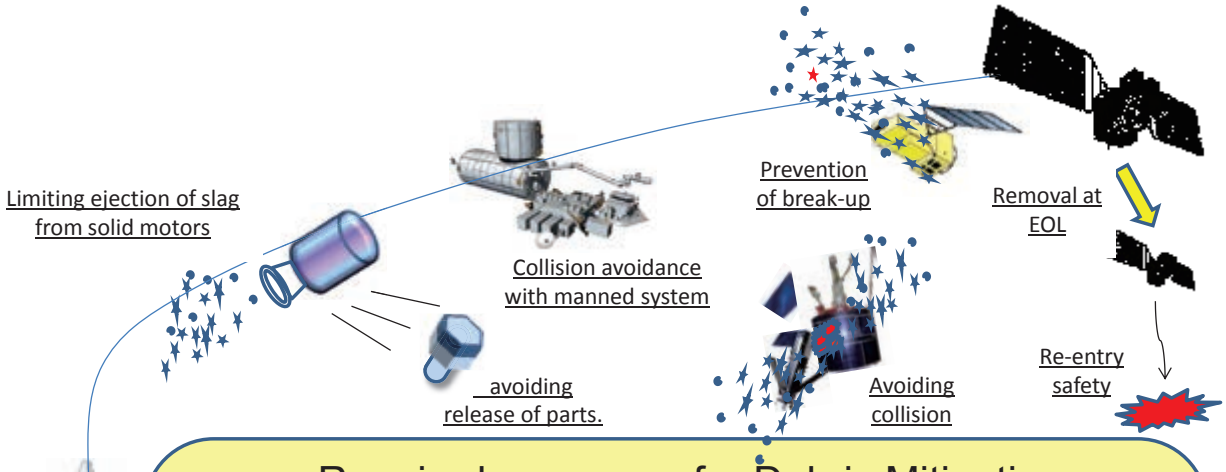
2013

JAXA Third Mid-Term

< 6th Debris Workshop >

History of JAXA and World Debris Activities

6TH SPACE DEBRIS WS Y.Ito : Dec. 2014 11



Required measures for Debris Mitigation

- Avoiding release of objects
- Collision avoidance at new launch
- Protection from impact of debris
- Collision avoidance with observable large objects
- Protection from impact of tiny debris
- Prohibition of intentional destruction, prevention from break-ups
- Removal form protective region at EOL
- Ensuring re-entry safety

Y.Ito : Dec. 2014 6th Space Debris WS 12

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Major Elements of Strategy

Mission Assurance

Sustainable Development

Preventive Action
- Risk Identification ⇒ Observation, Modeling, Risk Analysis
- Protection measures ⇒ Protection Design STD

Detection
- Conjunction Assessment & Warning ⇒Monitoring, Conjunction Analysis
- Impact & Failure detection ⇒ On-Board Detector

Counter Actions
- Collision Avoidance ⇒ Avoidance Maneuver
- Damage Reduction ⇒ Separation of Function. etc.

Corrective Actions
- Preservation & Ground Safety ⇒ Mitigation Design & Operation Re-entry Safety Analysis
- Prevention of Chain Reaction ⇒Technology for Removal

Red : Primary R&D items,
Blue : Vehicles and spacecraft projects team will promote.

Mission Assurance: Ground Observation

Goals in next 5-year-plan

1. Objects smaller than 10 – 20 cm in GEO can be observed.
2. Conjunction with debris can be assessed by domestic facilities in sufficient precisions to support avoidance maneuver.

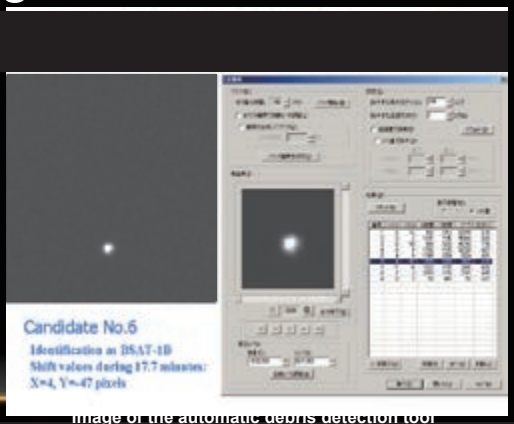

Image of the automatic debris detection tool

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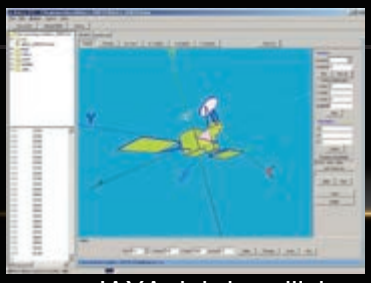
Mission Assurance: Modeling

Goals in Modeling

1. Future debris population can be prospected, and adequate policy can be implemented in advance.
2. Collision risk management will be conducted by analyzing the impact probability, damage estimation, and protection design.



JAXA debris collision risk analysis tool, TURANDOT

Mission Assurance: Protection Design

Goals in next 5-year-plan

1. Establishment of a Protection Design Standard
   - It enables adequate design depending on the mission characteristics.

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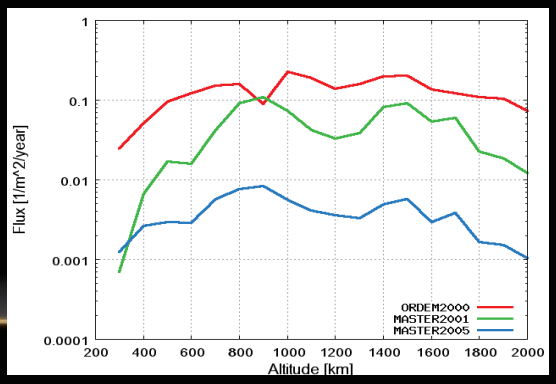
Mission Assurance: Debris Detector

Goals in Debris Detector

1. The debris detector will be launched to confirm orbital debris distribution.
   1. The debris larger than 100μm will be detected with its size
   2. The data will contribute to the world debris models.



Disagreement in MASTER and ORDEM

Ground Safety

Goals in Ground Safety after deorbit

1. More reliable re-entry risk analysis can be done with improved database (material properties, human distribution, etc.)
2. Risky devices that survive re-entry will be minimized.

Titanium casing of the STAR-48B solid rocket motor found in northeastern Argentina.

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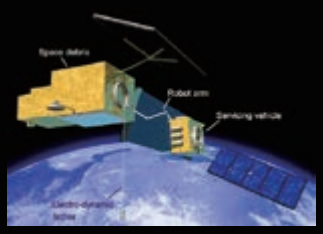
Preservation and improvement of the environment

Goals in Active Debris Removal

1. First step: Key technology demonstration such as electro-dynamic tether (EDT) as economical deorbit devices.
2. Final Step : large intact debris such as rocket upper stages will be removed by international project.

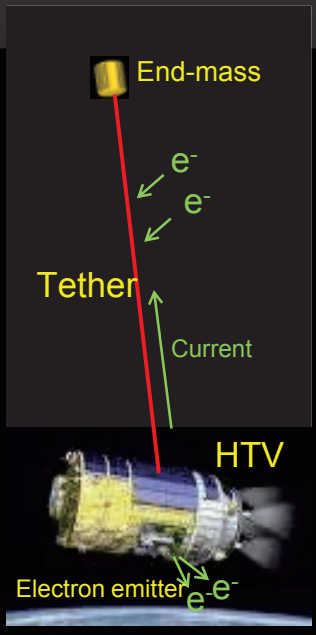


EDT Demonstration using HTV

EDT on HTV (H-II Transfer Vehicle)

- Objective
  - Demonstration of EDT key technologies
    - Deployment of bare tether
    - Electron collection by bare tether
    - Electron emission by field emission cathode
    - Current loop formation via plasma
    - Autonomous current control operation
- Flight Sequence
  - HTV leaves ISS and lowers altitude
  - Tether deployment
  - EDT operation
  - HTV re-enters atmosphere

7 days for EDT mission



Tether length	700 m
Max. tether current	10 mA

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A3

The latest space debris related research and technology activities in the European Space Agency

Holger Krag, ESA

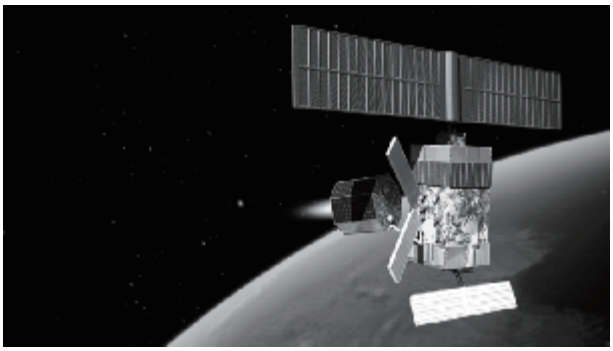
This talk will address ESA's progress in space debris research and technology in 4 domains:

1. ESA operates a conjunction analysis system and currently monitors 10 satellites. The system uses the JSpOC CDM data. A number of novel techniques have been developed including automation in the processing of the data, new algorithms for low delta-v approaches and independent manoeuvre screening. ESA's conjunction assessment system and related statistics and highlights will be presented.

2. Since many years, ESA develops object databases, as well as risk assessment and mitigation analysis software. Methods for the verification of the compliance to on-ground risk and orbital lifetime assessment have been developed. ESA, as an operator of objects in very unusual orbits such as high-eccentric and Lagrange Point orbits has developed novel disposal options which have been validated with these new means. The means and related technology will be presented along with recent examples.

3. Further, ESA runs an ambitious SSA program, for which a system architecture has been designed and a demonstrator phased-array radar has been developed. In addition to this, it operates its own 1m-telescope on Tenerife which has discovered a population of high area/mass objects. Recent radar and optical as well as laser ranging measurements concentrate on the identification of the attitude motion of uncontrolled objects, like Envisat. An overview over the current measurement systems and recent results will be presented.

4. Finally, ESA has been investing in the technology for rendez-vous and capture of uncontrolled objects. Various solutions have been scrutinized in system studies. In parallel, the effect of active removal and the criticality of a given objects in LEO orbit has been studied. This presentation will show ESA's analysis results and the recent plans for the e.Deorbit mission for the controlled removal of an uncontrolled target in LEO.



ESA's e.Deorbit mission

ESA's SSA demonstrator radar

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Biography

Dr. Holger Krag

Title: Head of Space Debris Office
Division: Ground Segment Engineering Department
Company: ESA/ESOC
Email: holger.krag@esa.int

Dr. Holger Krag has been a Space Debris Analyst in the Space Debris Office of ESA/ESOC located in Darmstadt, Germany, since 2006. He has worked on the operational conjunction event analysis for various ESA missions, debris risk assessment, mitigation analysis and the Surveillance and Tracking Segment of the European SSA system. Since 2014, he is head of the Space Debris Office. He represents ESA in the IADC (Inter Agency Debris Coordination Committee) and is involved in the development of an ESA mission for the active removal of a non-cooperative space objects from orbit.

From 2002 – 2006 Dr. Holger Krag has served as a System Engineer in the Navigation Business Unit of Thales ATM, responsible for development of a test bed for the ground mission segment of Galileo with permanent collocation in Toulouse, France.

From 1998 – 2002 Dr. Holger Krag was a project scientist at the Technical University of Braunschweig, Germany and conducted more than 4 years of detailed research in the area of space debris environment and observation modeling.

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The latest space debris related research and technology activities in the European Space Agency

Holger Krag
ESA/ESOC

6th Space Debris Workshop
JAXA Chofu Aerospace Center, December 17-19, 2014

Outline

- *Collision Avoidance*
- *DISCOS Database*
- *Compliance Analysis*
- *Mitigation Technology and Re-entry Assessment*
- *Space Situational Awareness and Measurements*
- *Space Debris Modelling*
- *Attitude Measurements of uncontrolled objects*
- *Active Removal (e.Deorbit)*

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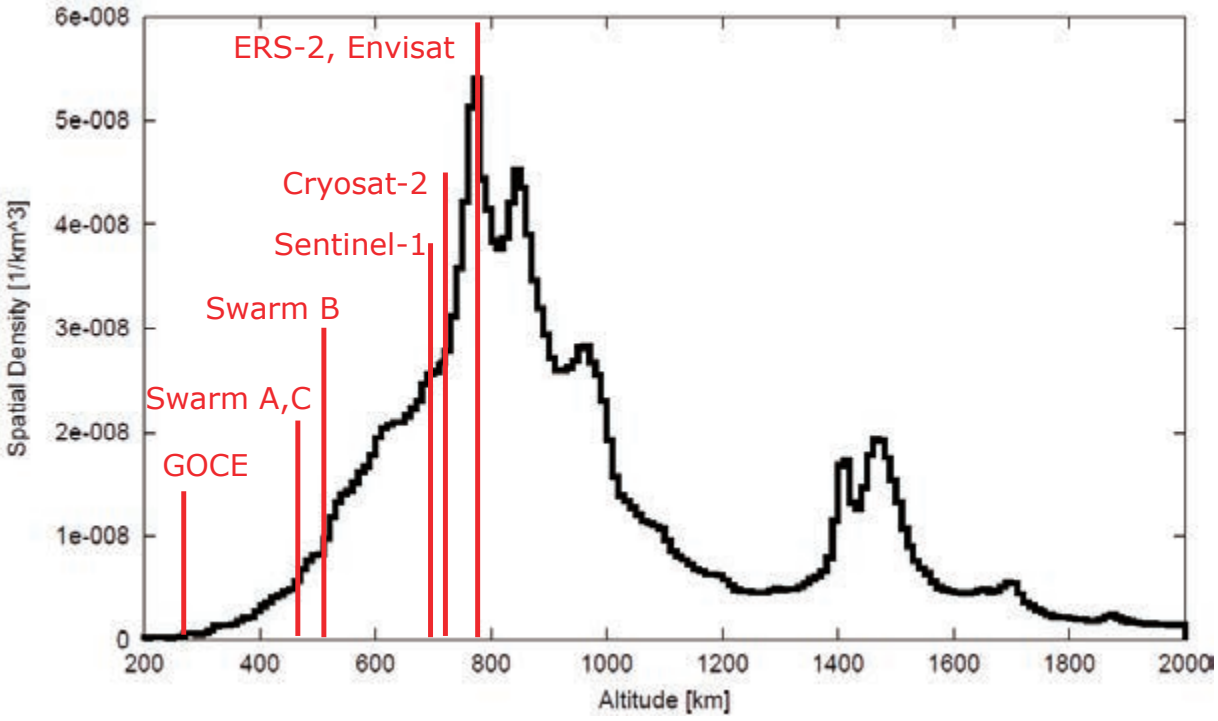
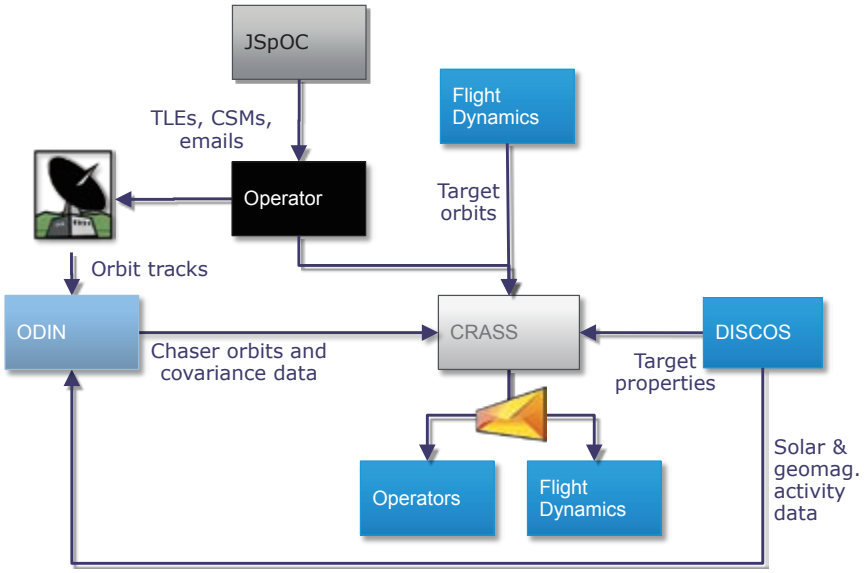
Monitored Missions



Collision Avoidance System (2004-2013)



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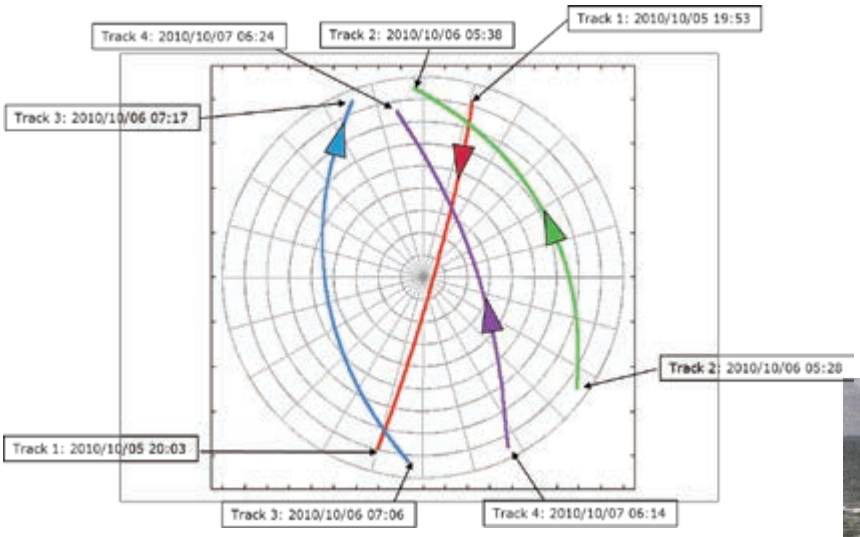
Orbit Refinement by Tracking



Tracking and Imaging Radar

Monge tracking ship

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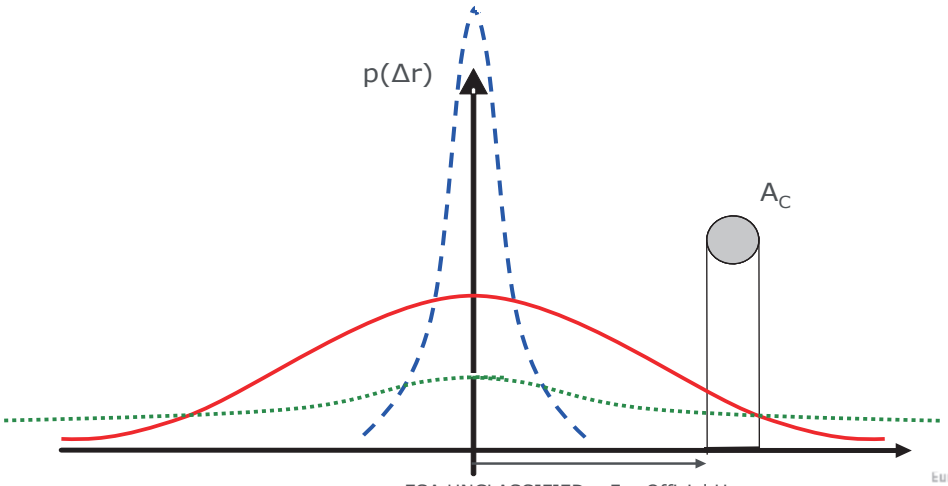
Impact of Orbit Accuracy on Conjunction Analysis

- Establish new Collision Avoidance Procedures based on the CSM:
  - New threshold collision probability
  - Additional minimum (geometry-dependent?) fly-by distance



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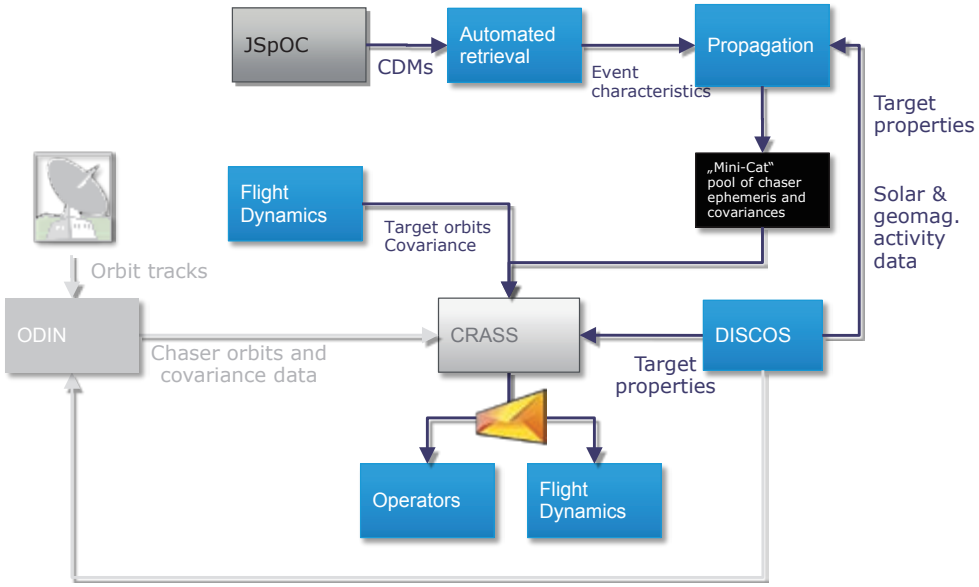
Collision Avoidance System (since 2014)



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CORAM

Features:

•Several Collision Probability Algorithms:

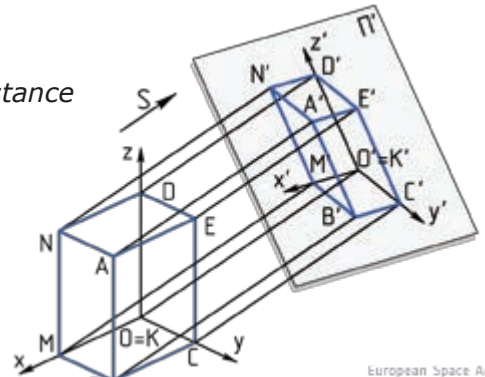
- *Alfriend Akella*
- *Maximum Probability*
- *Algorithms for low delta-v approaches*
- *Monte-Carlo*

•Cross-sectional projections

•Manoeuvre planning:

- *Sampling of several desired radial fly-by distance*

•Covariance scaling



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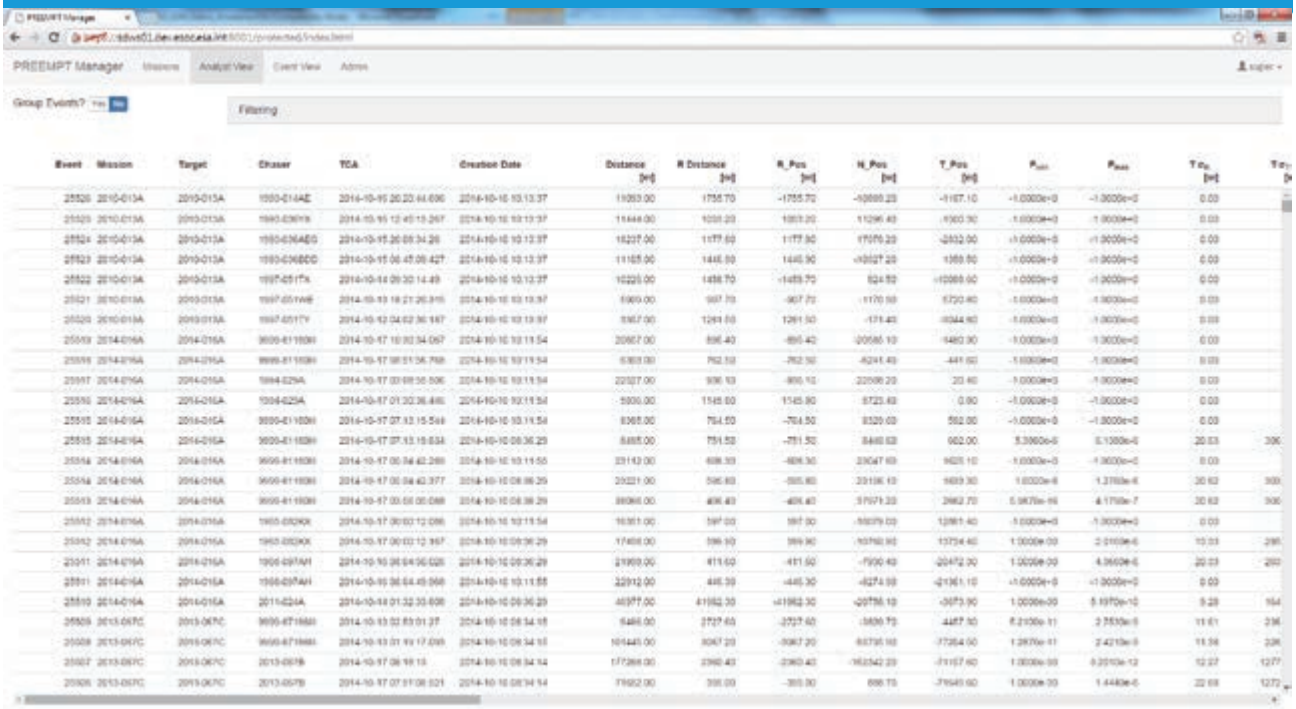
PREEMPT



PREEMPT

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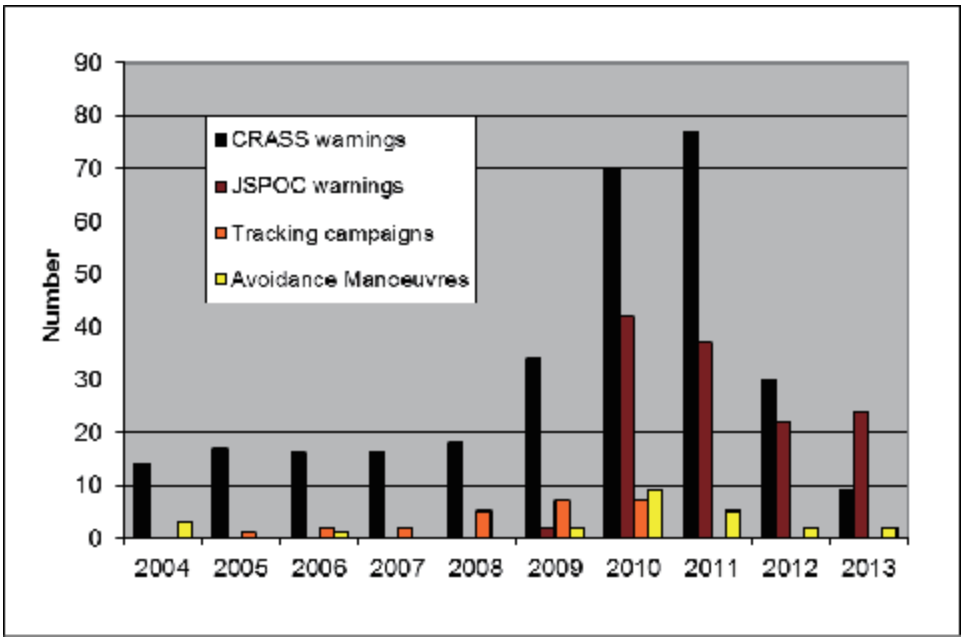
Statistics for ESA Satellites



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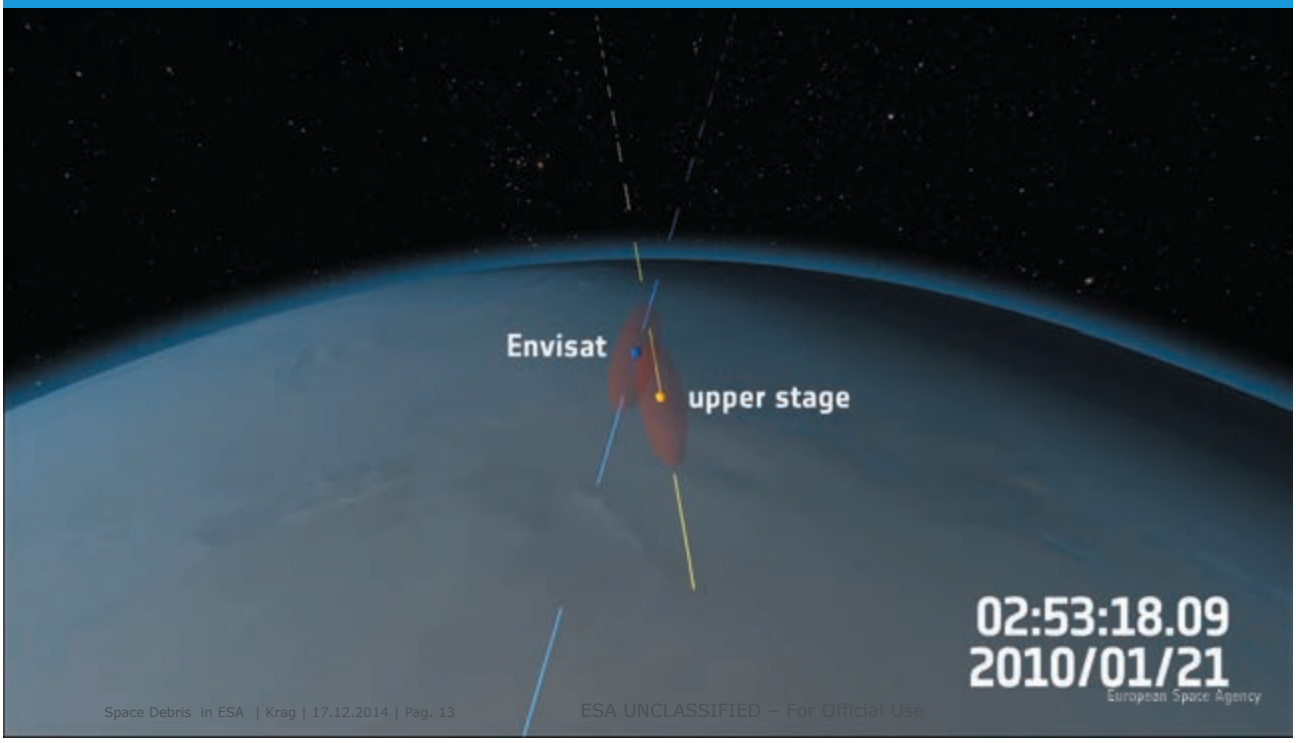
Envisat Conjunction Jan. 21st, 2010



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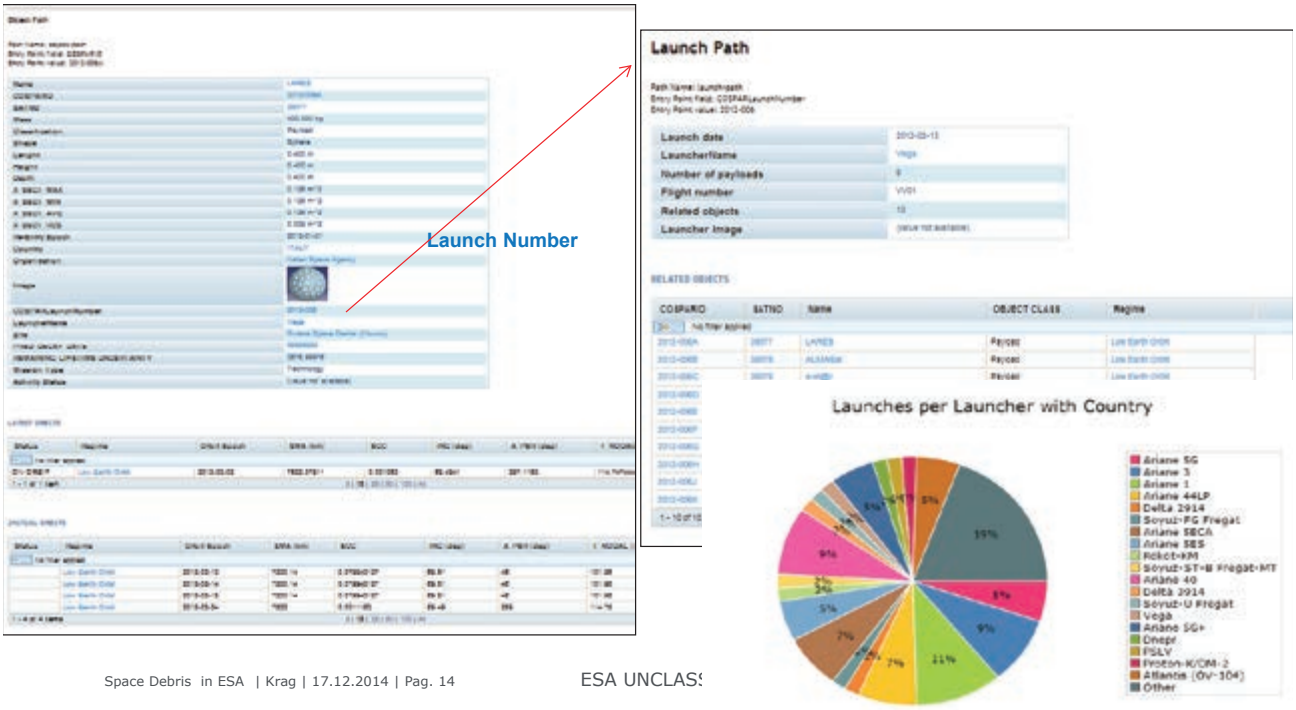
The new DISCOS Web Frontend



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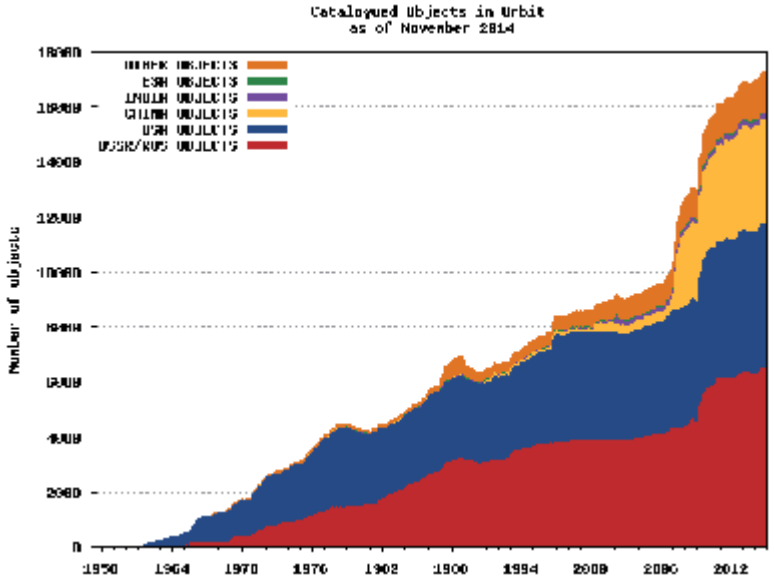
Catalogued objects in orbit

- December 2014: ca. 40000 Objects have been catalogued, of which about 17000 are in orbit



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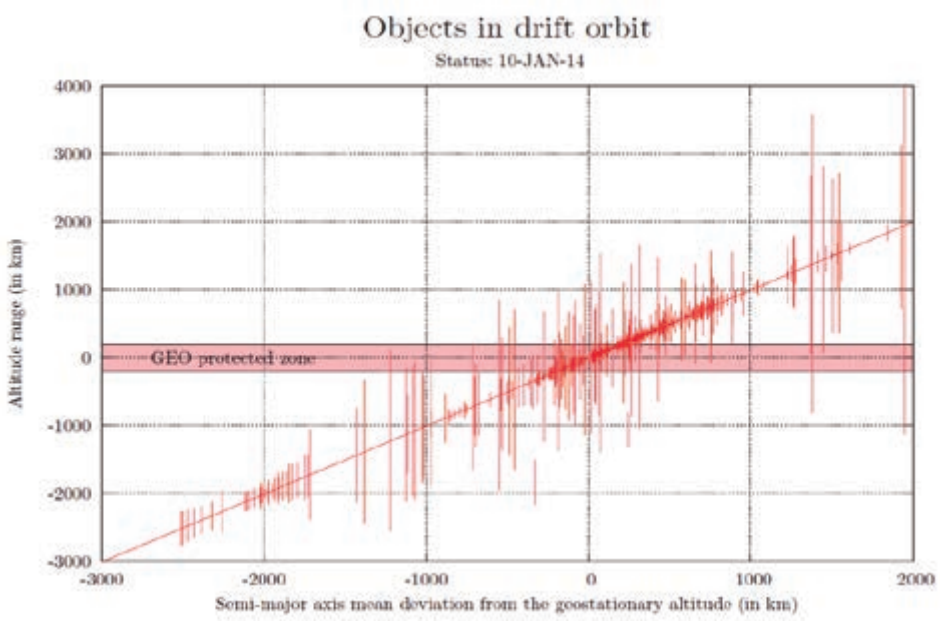
Distribution of drifters
(TLE only)



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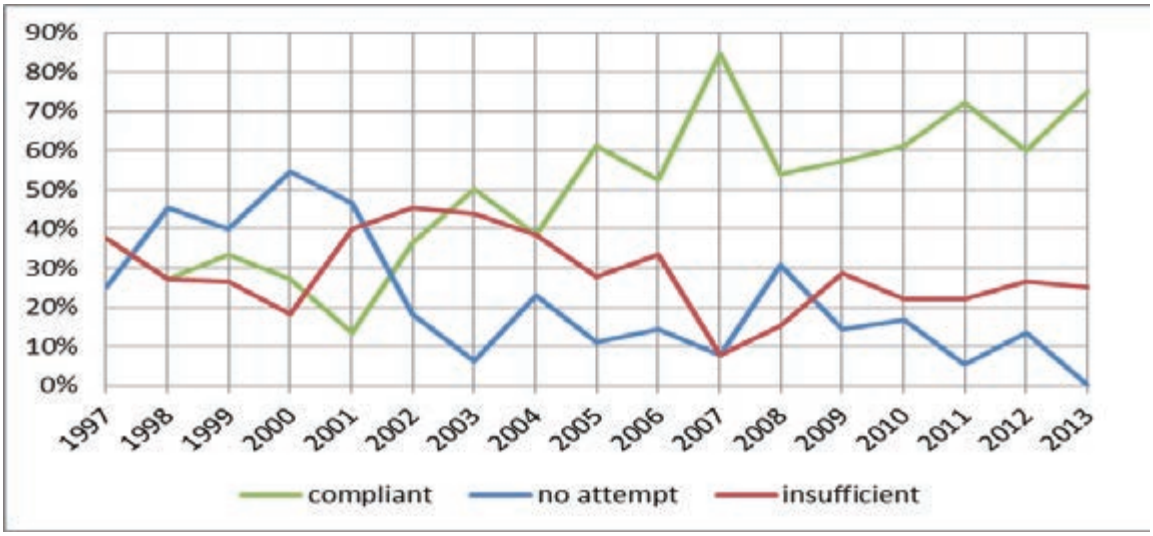
EoL statistics

- Average of 16 annual disposals



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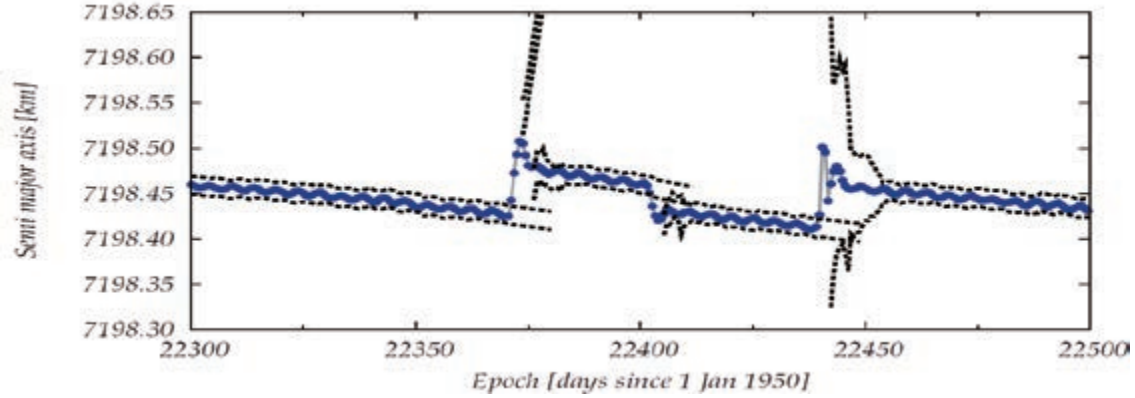
Manoeuvre Detection from TLEs

METOP-A between 21/1/2011 and 9/8/2011



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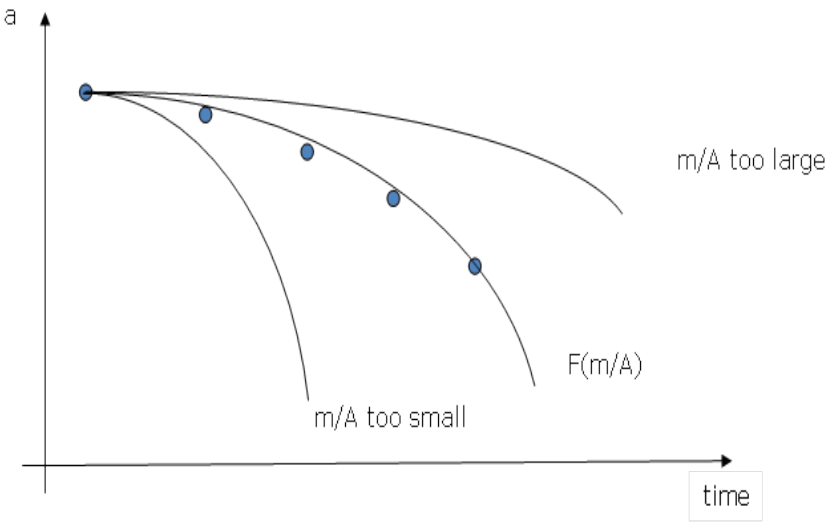
Orbital Lifetime Prediction from TLEs



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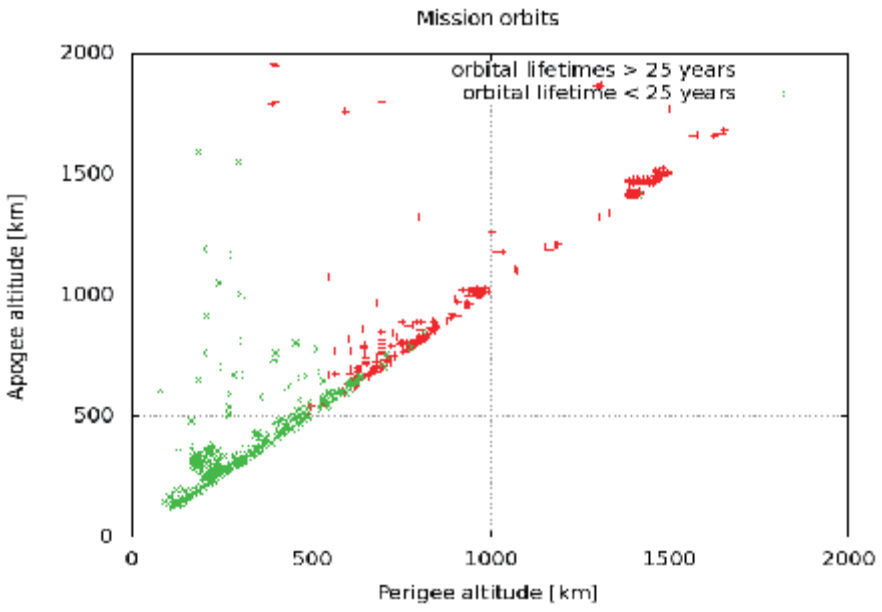
Destination orbits of spacecraft



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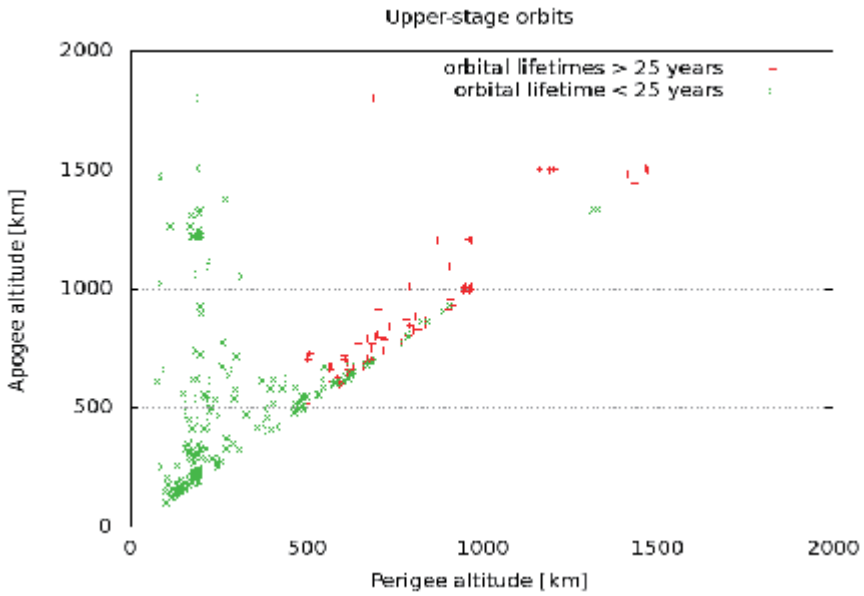
Destination orbits of upper-stages



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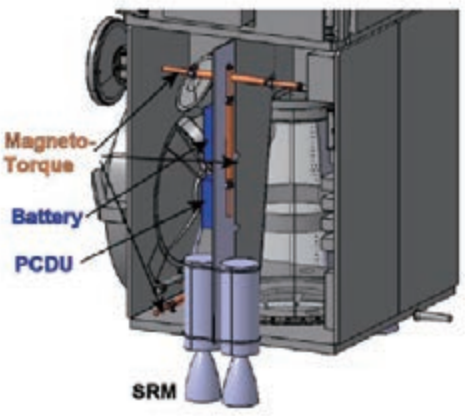
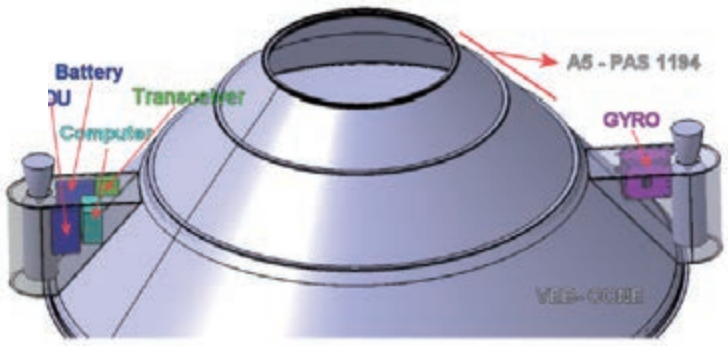
SPADES



Solid **P**ropellant **A**utonomous **De**-orbit **S**ystem

← Accomodation on LEO Satellite

Accomodation on Ariane 5 GTO state →



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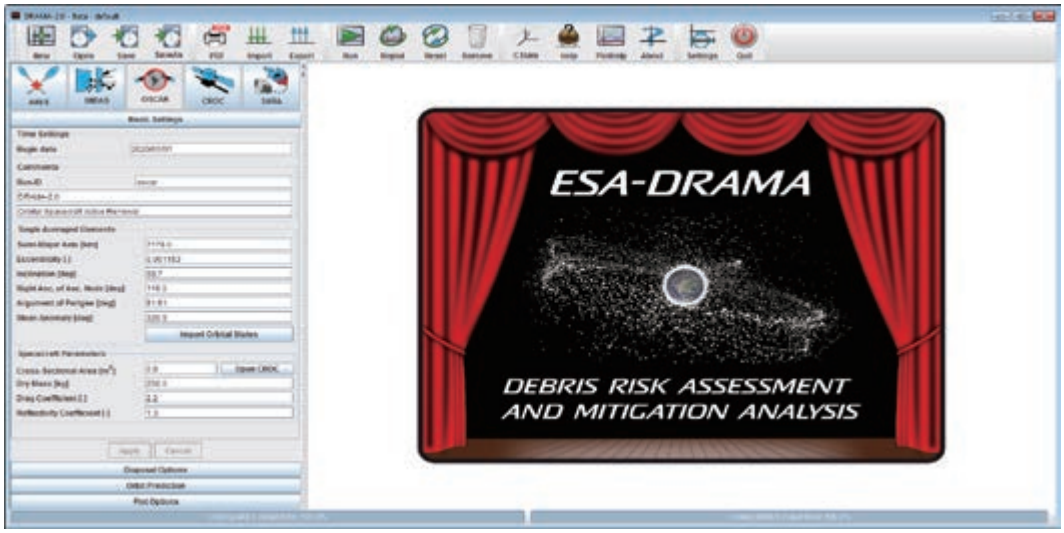
V2.0 Graphical User Interface

- Windows, Linux, ~~Solaris,~~ **Mac-OS**



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The DRAMA 2.0 software suite

ARES: Assessment of Risk Event Statistics:
To consider the possible requirements for collision avoidance manoeuvres during a mission.

MIDAS: MASTER (-based) Impact Flux and Damage Assessment Software: To model the collision flux and damage statistics for a mission.

OSCAR: Orbital Spacecraft Active Removal: To analyse the disposal manoeuvre performed by a space system at the end of its useful lifetime.

CROC: Compute projected cross-sectional areas of complex bodies

SARA: Spacecraft Entry Survival Analysis Module (SESAM):
To model the re-entry of a space system into the Earth's atmosphere.
Spacecraft Entry Risk Analysis Module (SERAM):
To assess the risk on ground of objects surviving re-entry.

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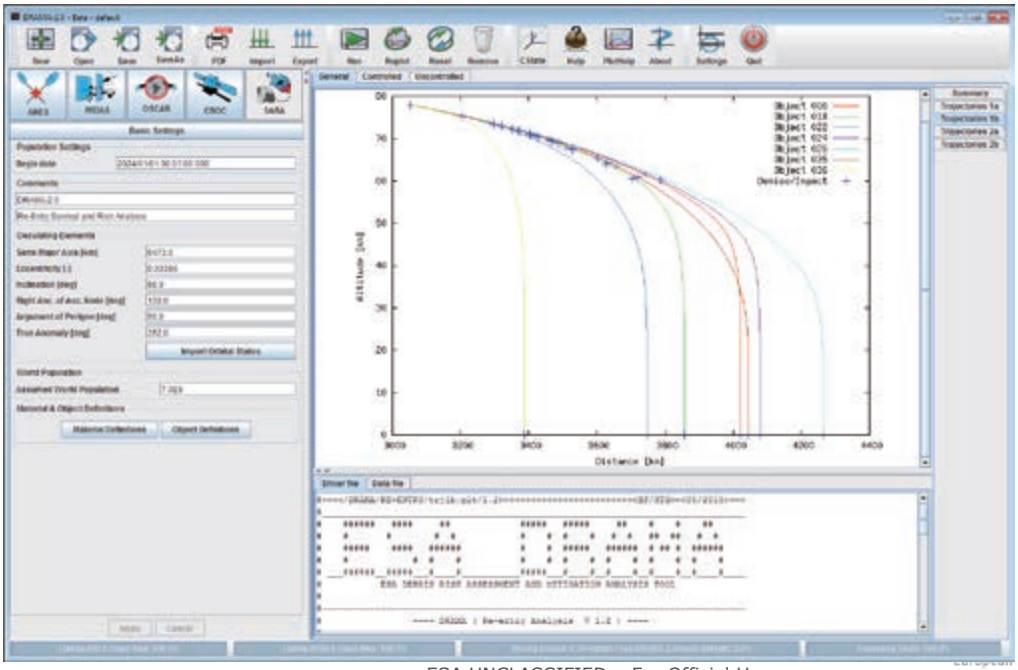
New Presentation of Results



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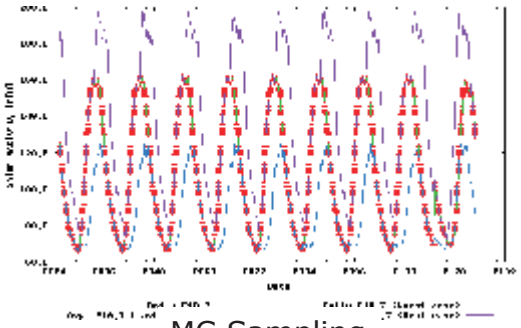
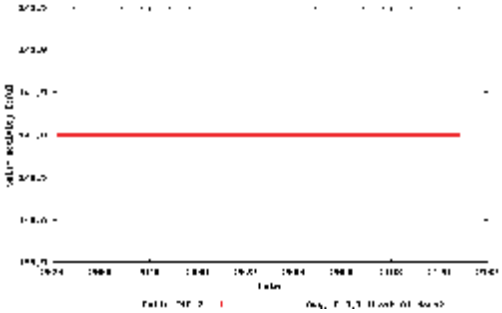
Task #2: Solar Flux Prediction Methods

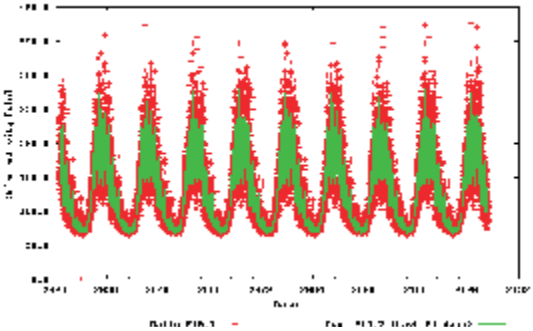
Nominal and Confidence interval



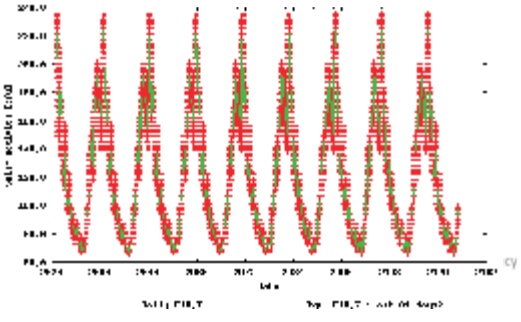
Specific Constant (STELA)



MC Sampling



ECSS Reference Cycle



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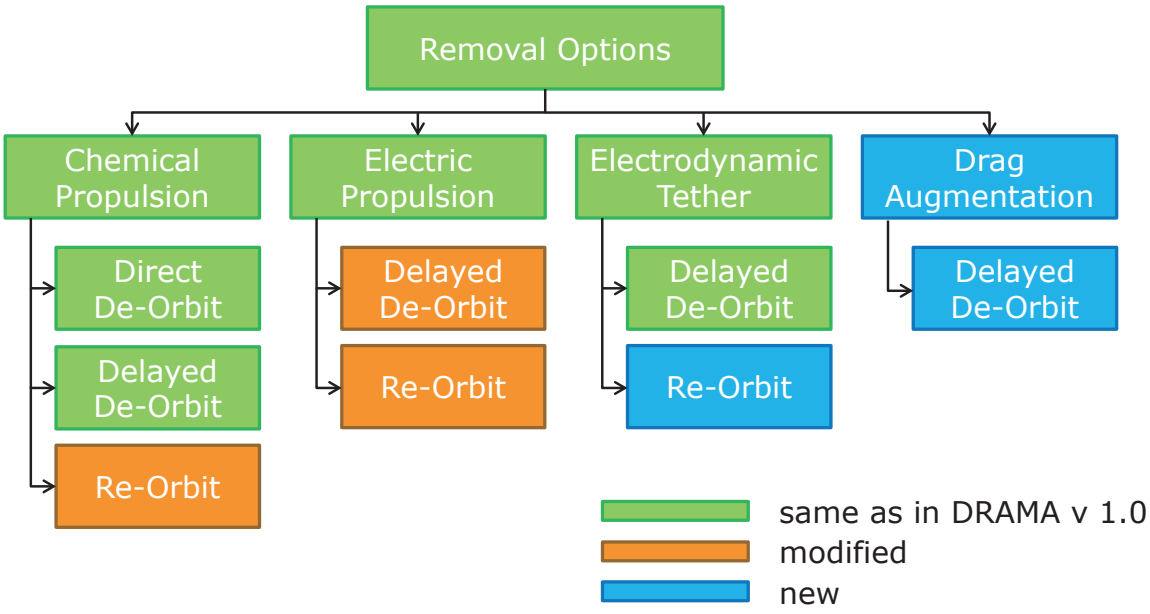
Removal Options Analysed by OSCAR



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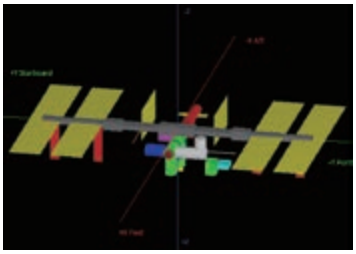
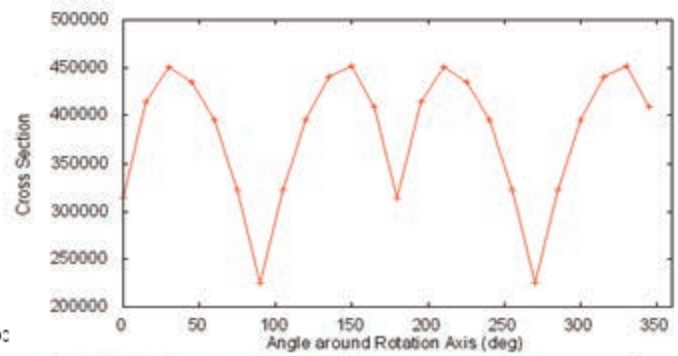
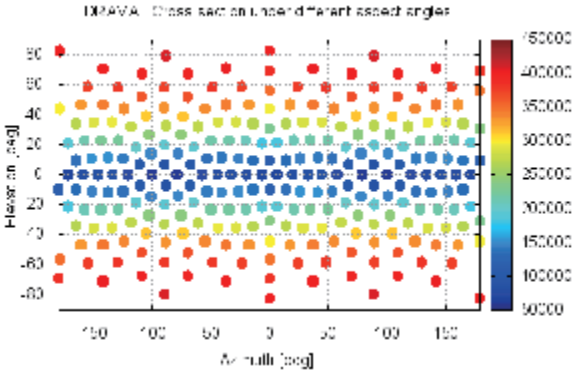
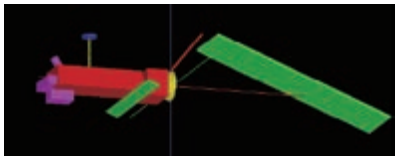
Cross-Section Computation









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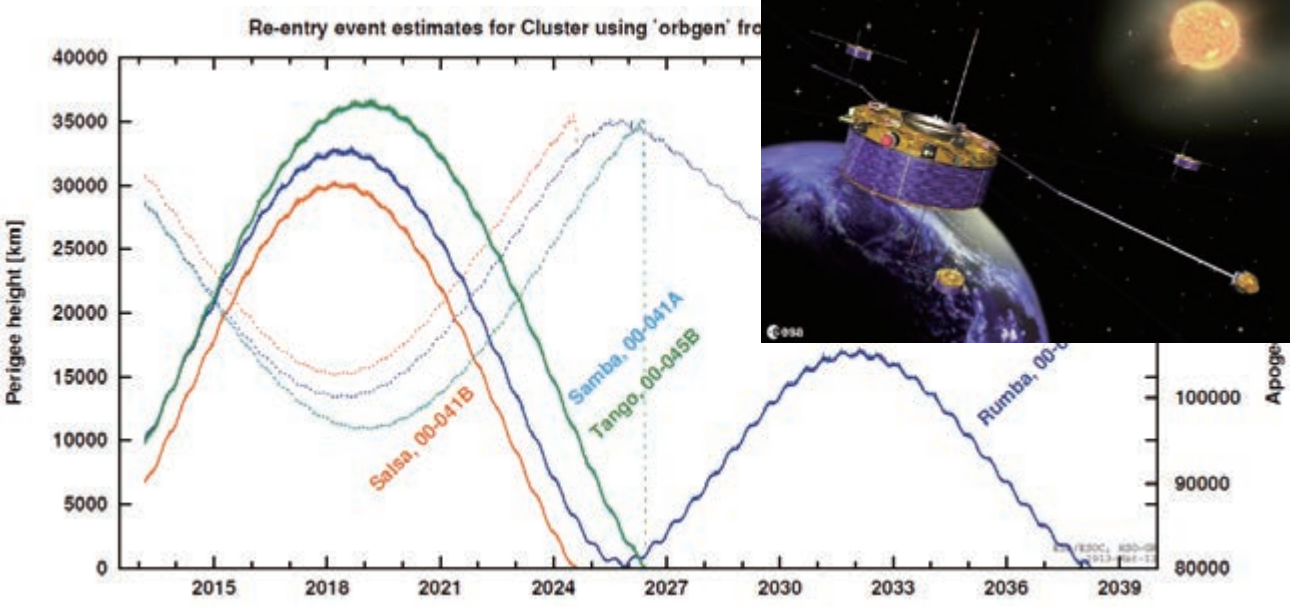
Cluster-II Re-entry



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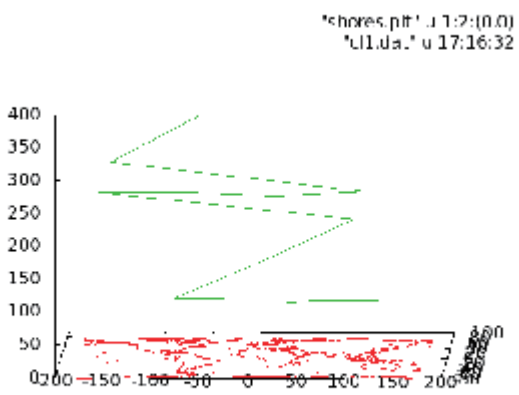
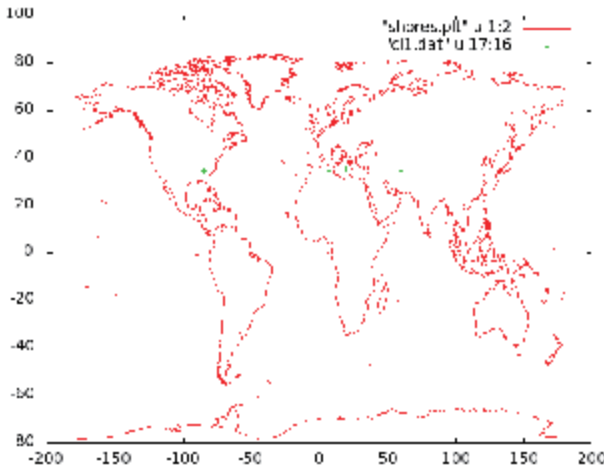
Cluster-II S/C 1





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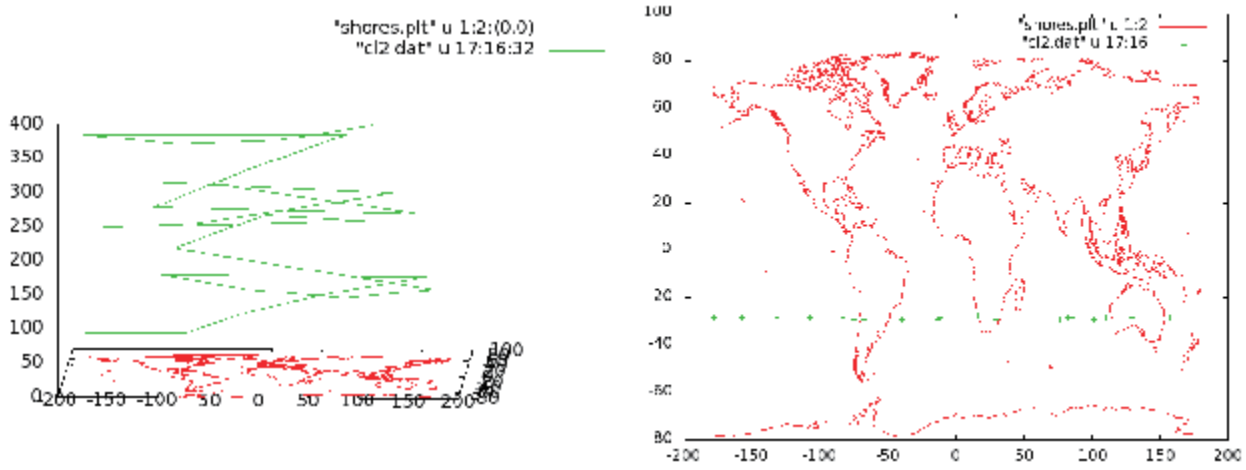
Cluster-II S/C 2



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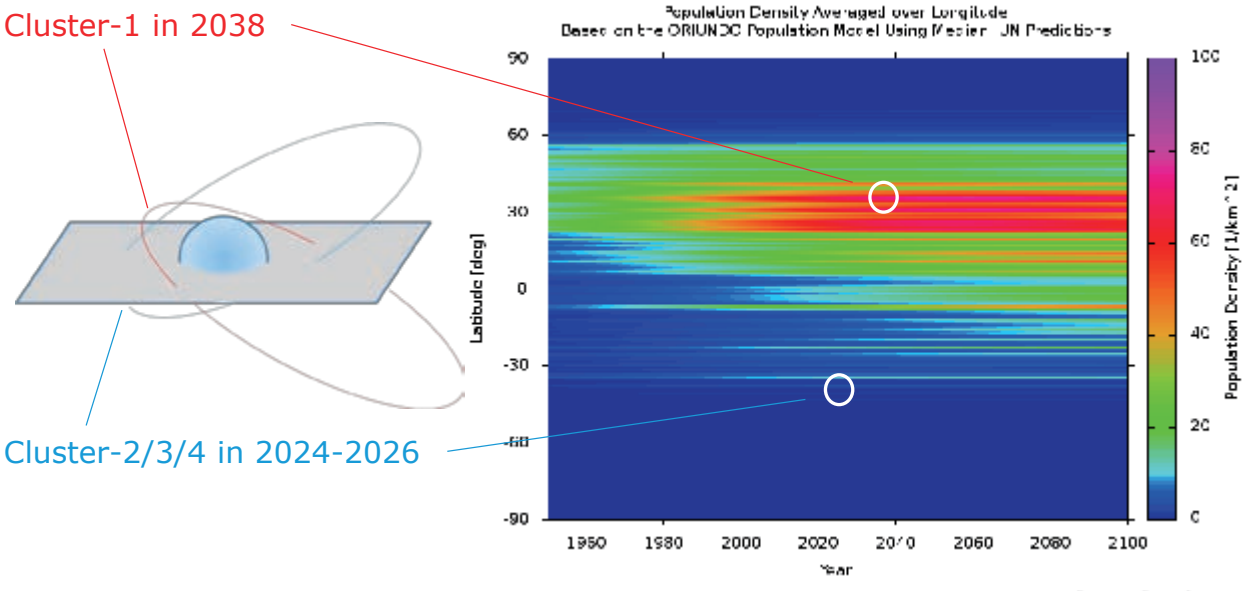
Cluster-II Line of Apsides and On-ground Risk



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Determining Break-Up process and Survivability

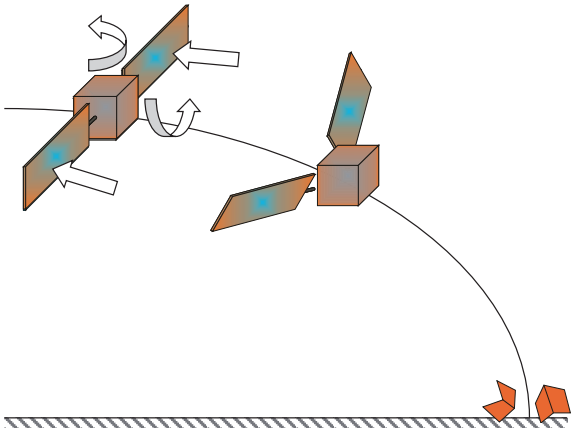
S/C modeling
→ simplified model

Aerodynamic analysis
→ forces and torques

Dynamic analysis
→ trajectory and attitude motion

Aerothermal analysis
→ heating and melting

Fragmentation analysis
→ structural fracture and separation due to melting



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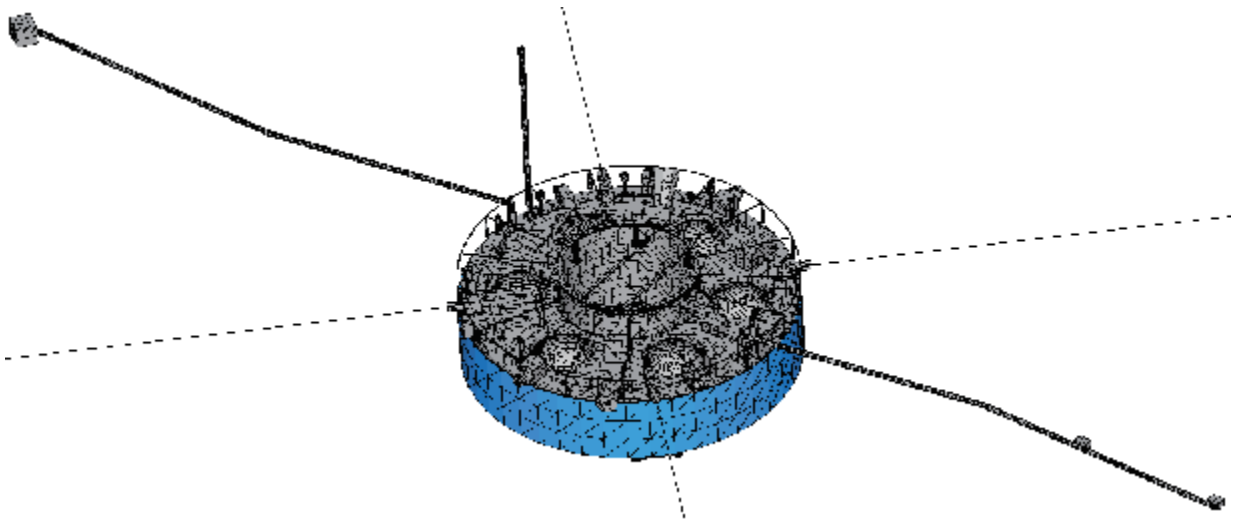
Modelling
Cluster-II – SCARAB Model



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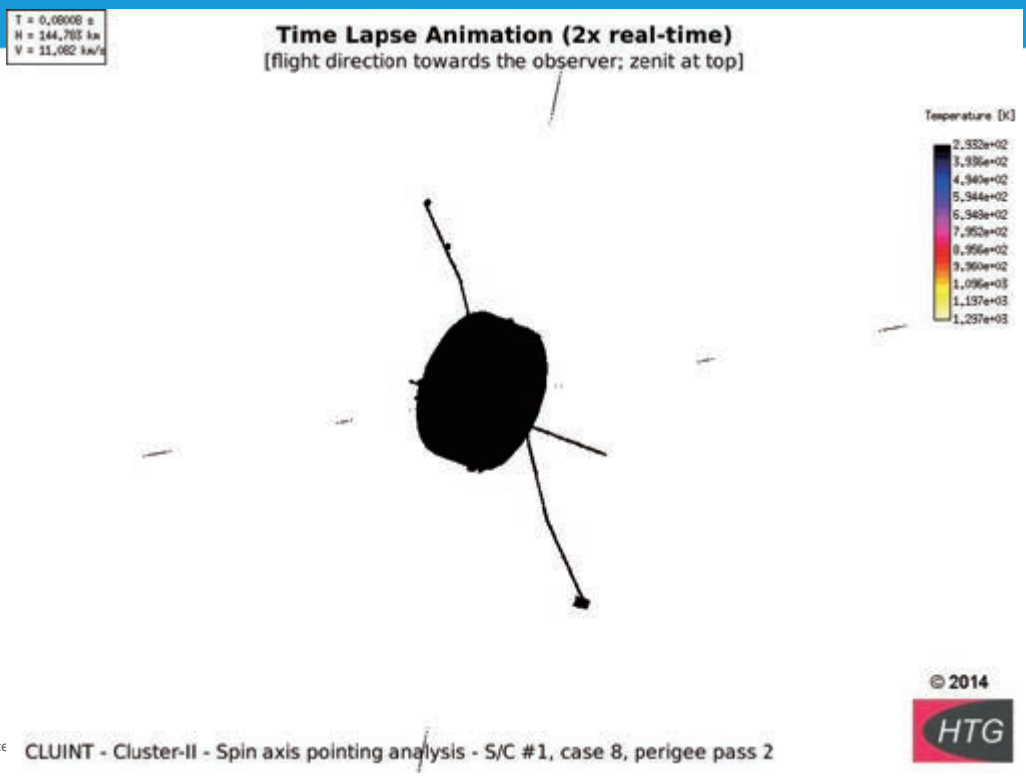
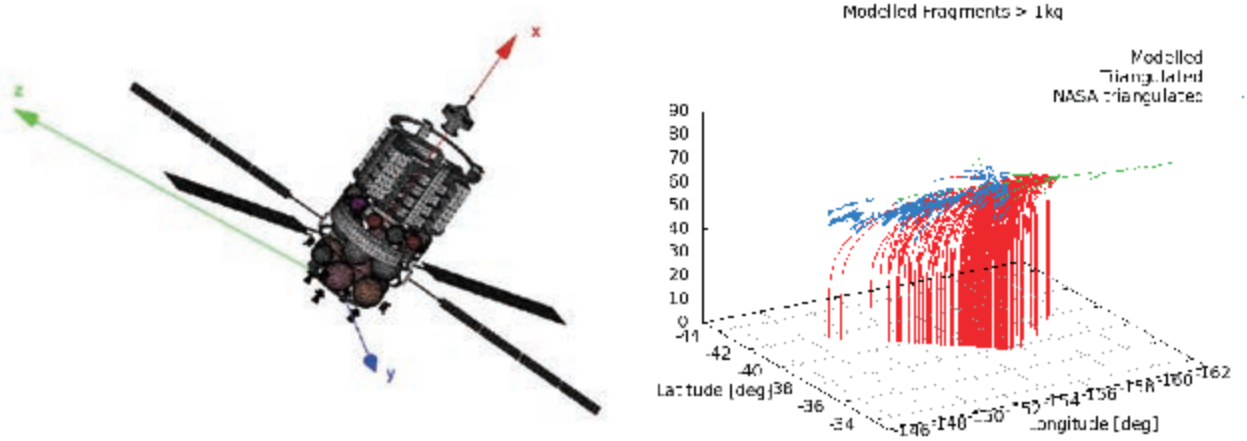
Simulation for Cluster-II Spacecraft 1



Observations of the ATV-5 Shallow Re-entry

- Re-entry Trajectory: 190km x 75km (normal trajectory: 400km x 0km)

Observation results of ATV-1



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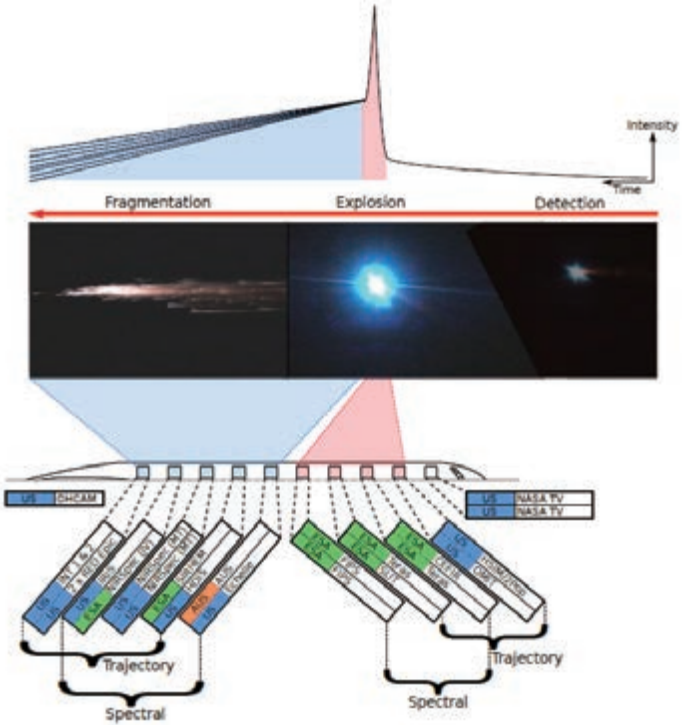
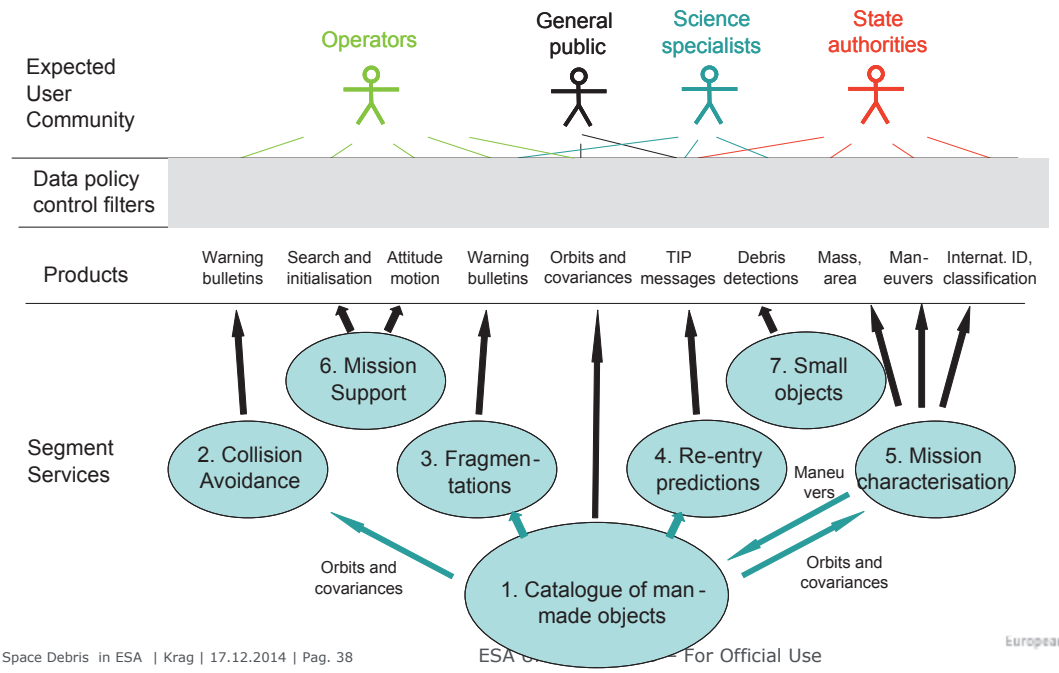
ATV: Re-entry observations (1/3)

NASA DC-8 Research Aircraft



Surveillance and Tracking Services (as per ESA program)



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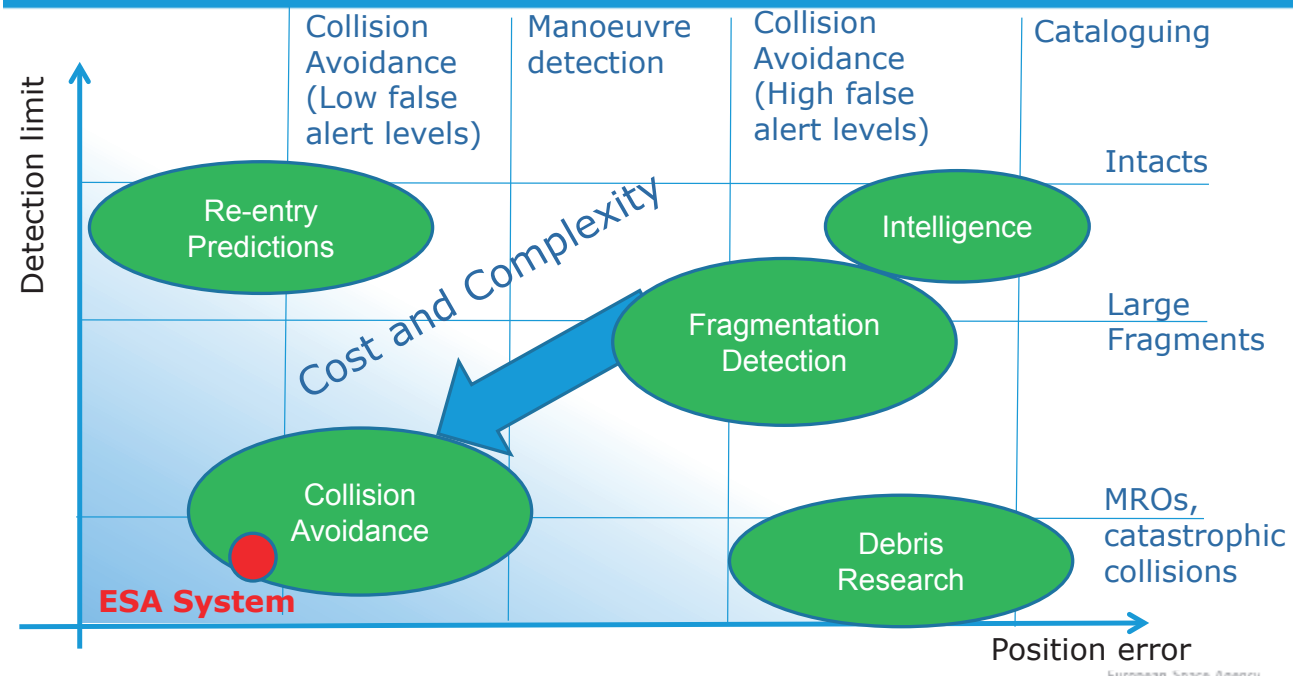
Surveillance Performance (LEO)



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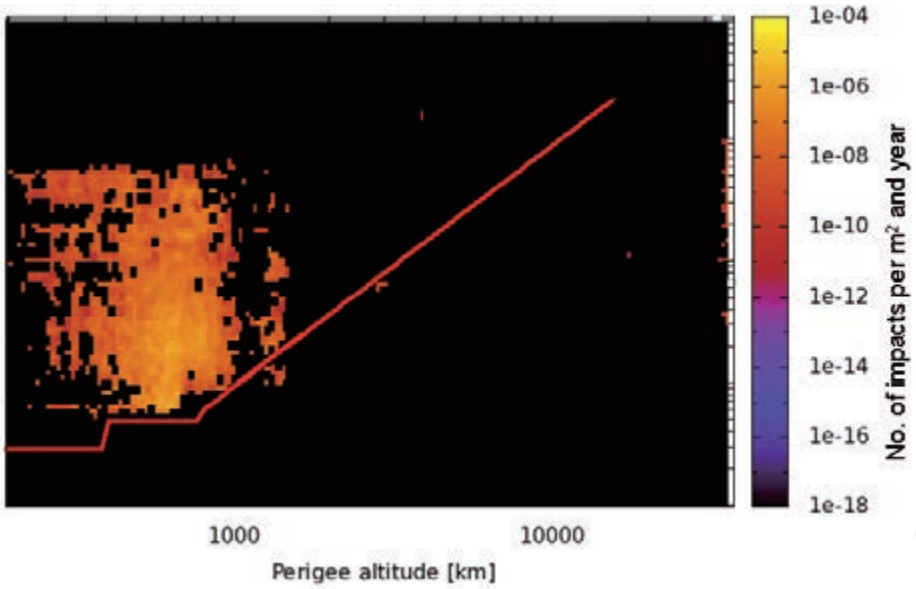
Required System Sensitivity (2/2)

- 98% coverage correspond to the follow radar performance envelope:
  - 32cm @2000km altitude, 8cm @1000km altitude



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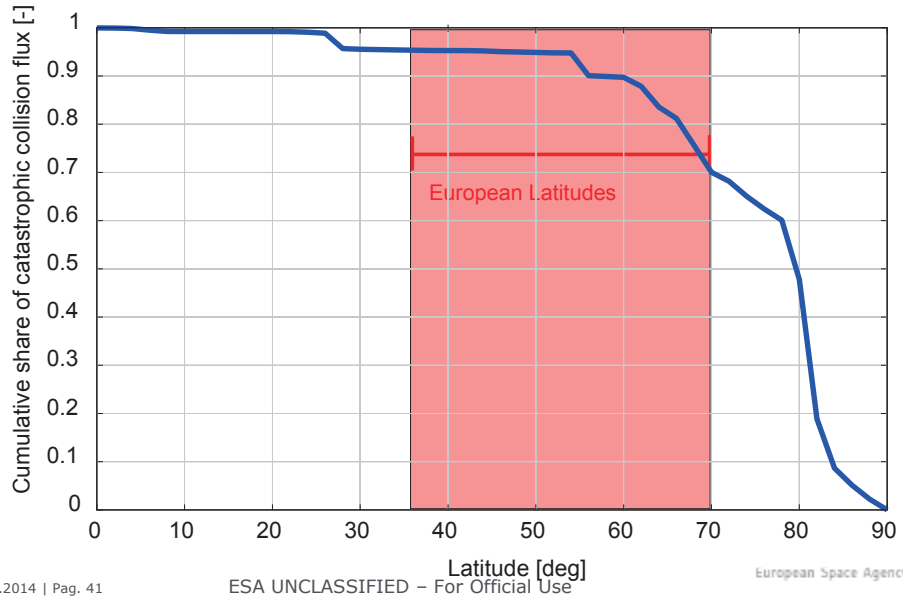
Loss due to Selected Sensor Latitude

– Loss of another at least 5% due to selection of a site on European mainland



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Demonstrator radar in Santorcaz (Spain)

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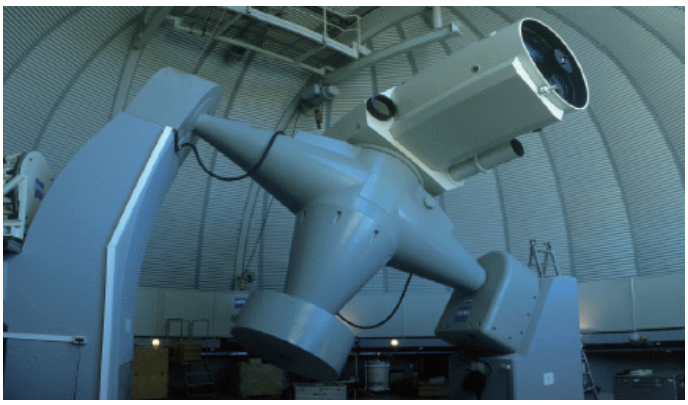
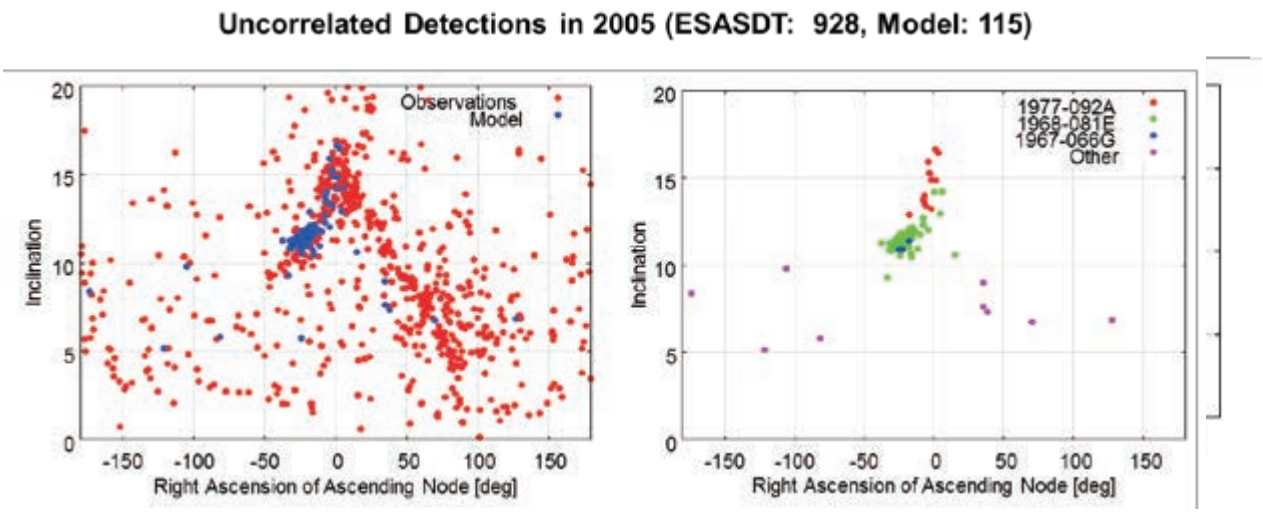
ESA Space Debris Telescope Tenerife/Spain (EU)

- Zeiss telescope of 1m aperture and 0.7º field-of-view, Tenerife (lat = 28.17º N, long = 16.30º W)
- Detection threshold: mag 19 - 21 (~ 15 cm objects in GEO), 120º of GEO ring visible



ESA Space Debris Telescope Tenerife/Spain (EU)



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Beampark experiments

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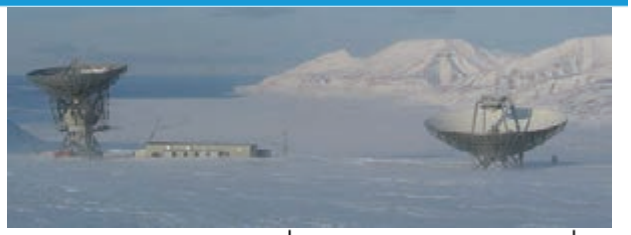
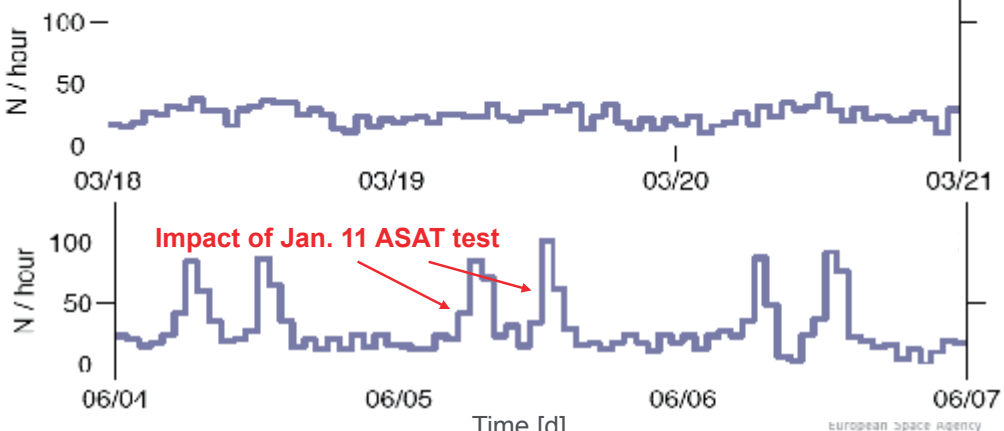
FY-1C ASAT (2/2)

EISCAT Svalbard radar (lon: 16.029° , lat: 78.153°)
(42m and 32m UHF antennas)



March 2006,
18th-21st

June 2007,
4th-7th



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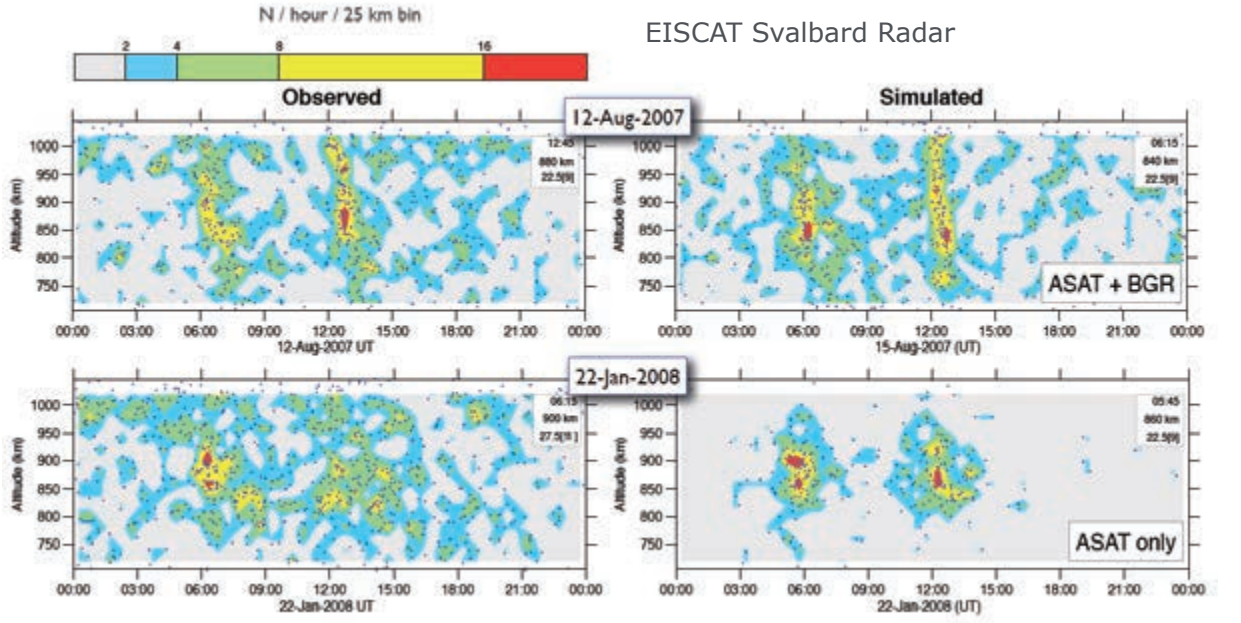
Comparison to measurements (2/2)



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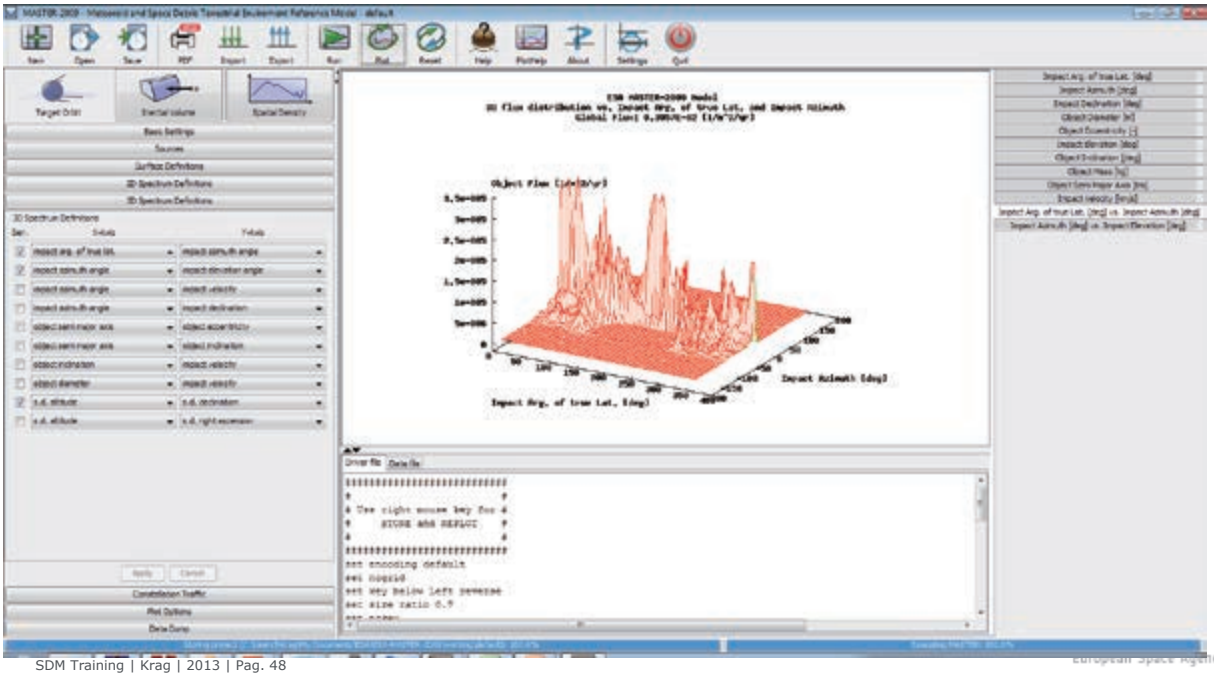
MASTER-2009 Application



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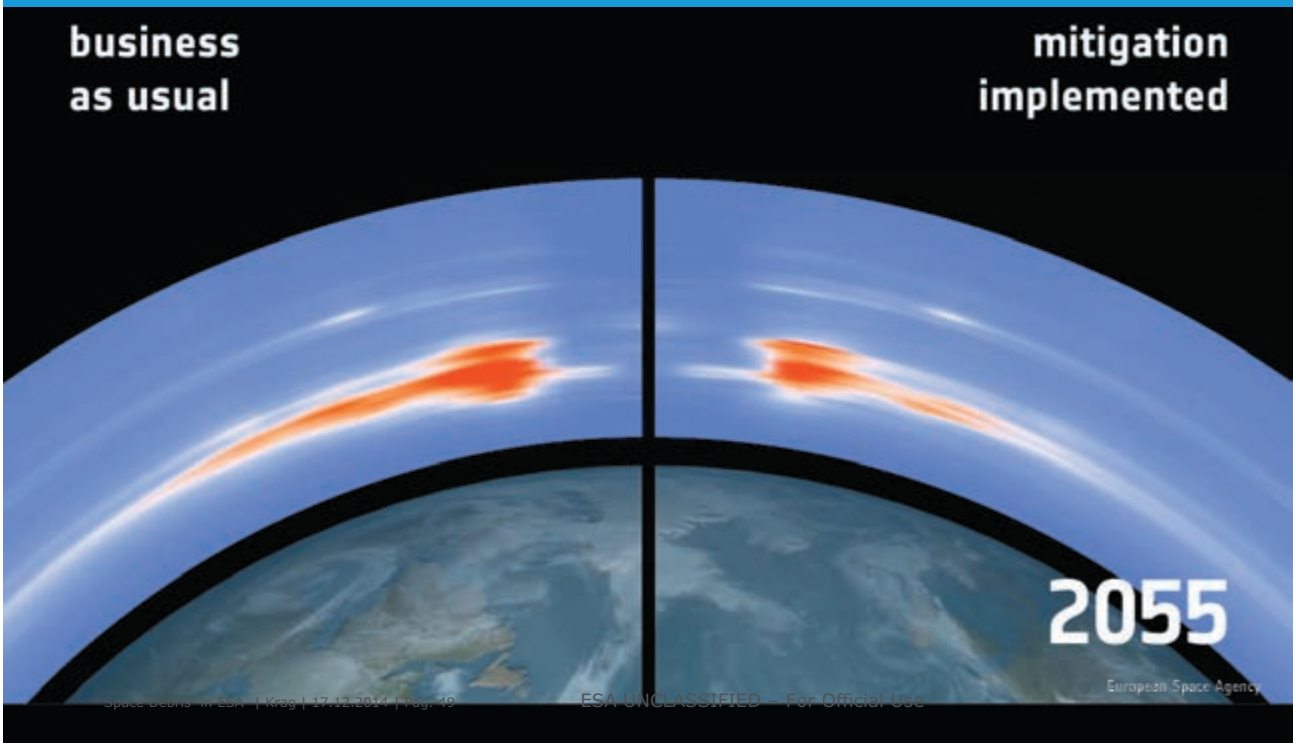
Target orbits



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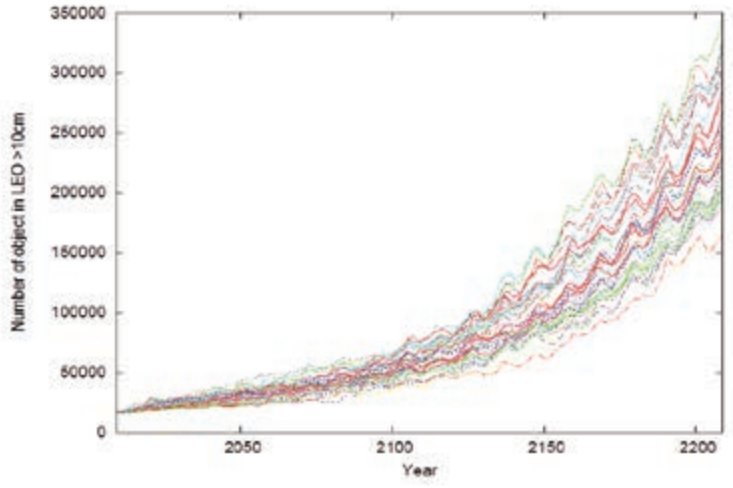
Environment Projections

- DELTA
  - Debris Environment Long-Term Analysis
  - 3-D time dependant semi-deterministic model
  - Traffic models (launch cycle of th past 8 years)
  - Debris mitigation measures
  - Simulation of environment response to active debris remova



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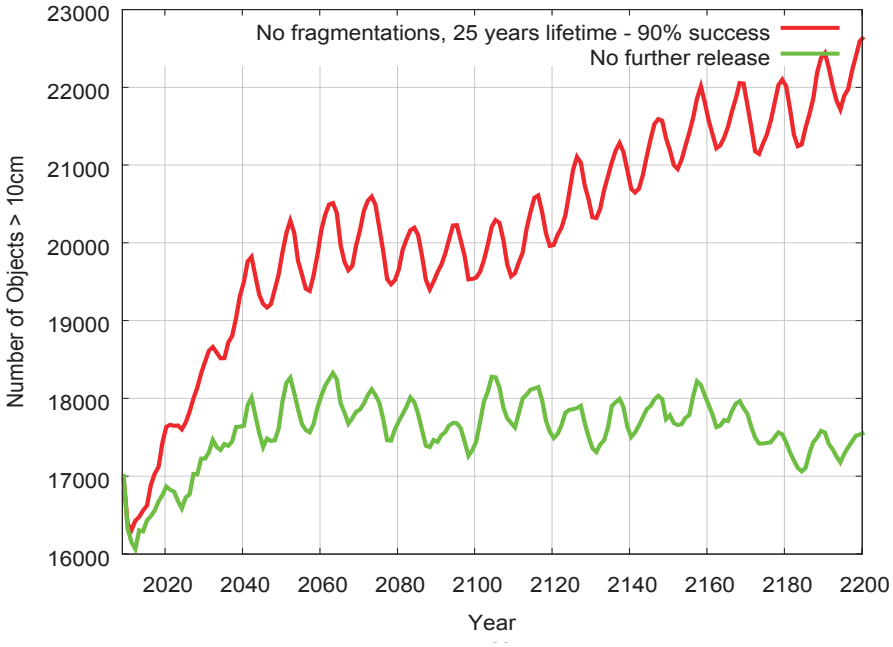
DELTA results: Future evolution of the environment



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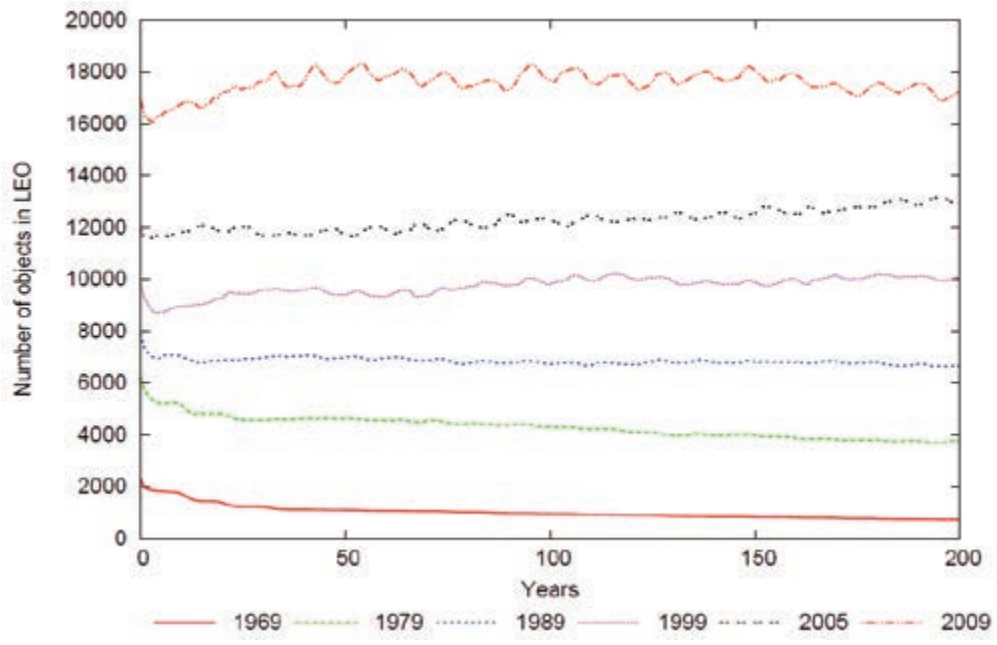
Analysis of different historical populations

No further release:

- No launches
- No explosions



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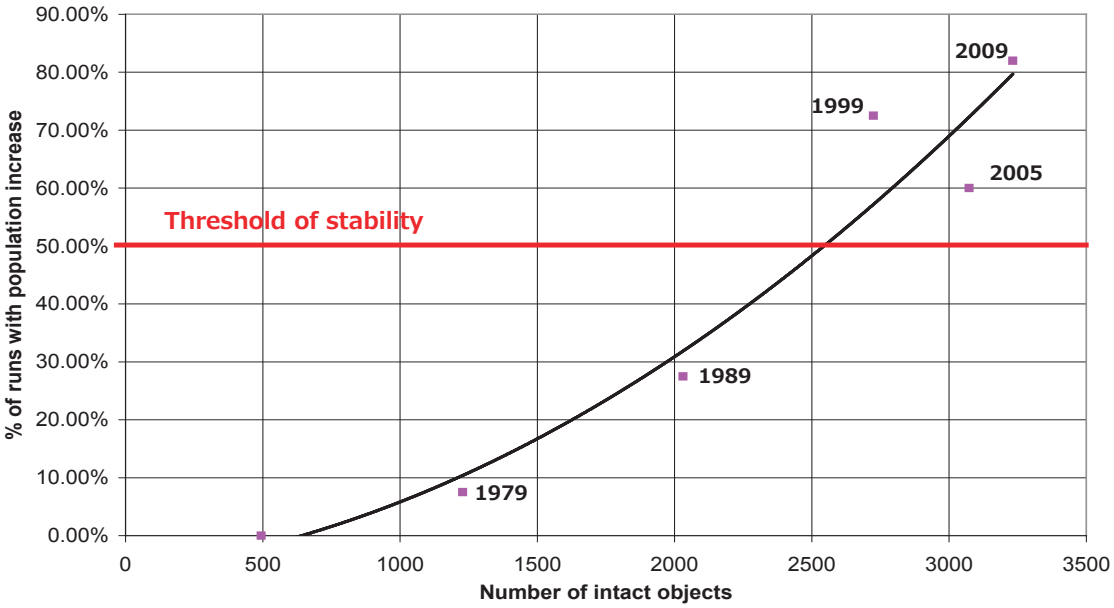
Stability of historical populations



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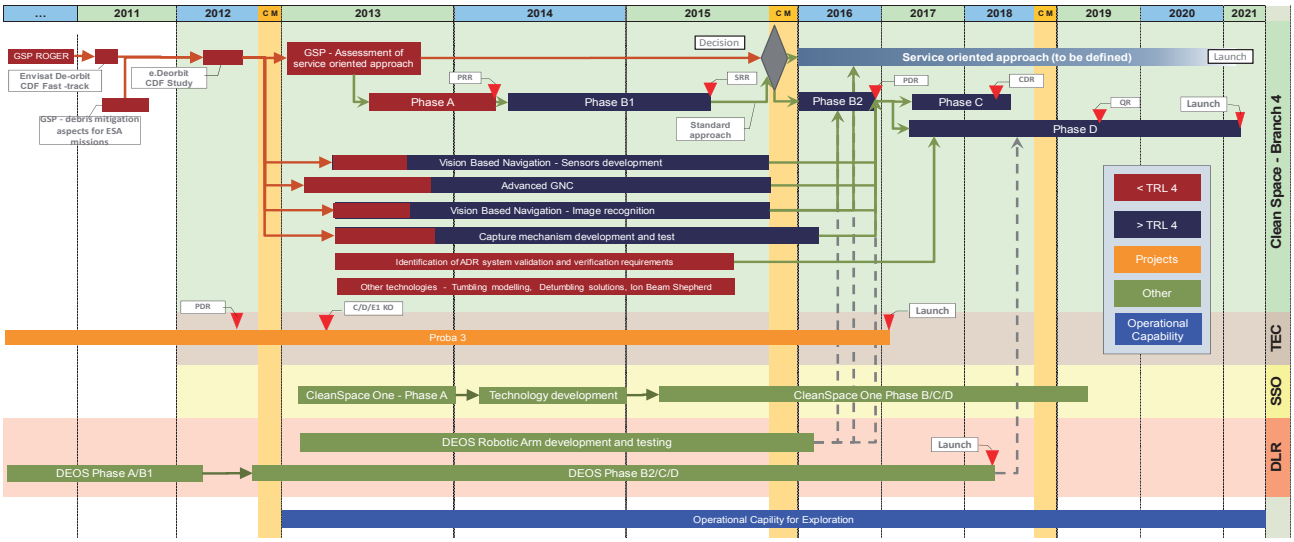
Branch 4 Space Debris Remediation
Roadmap



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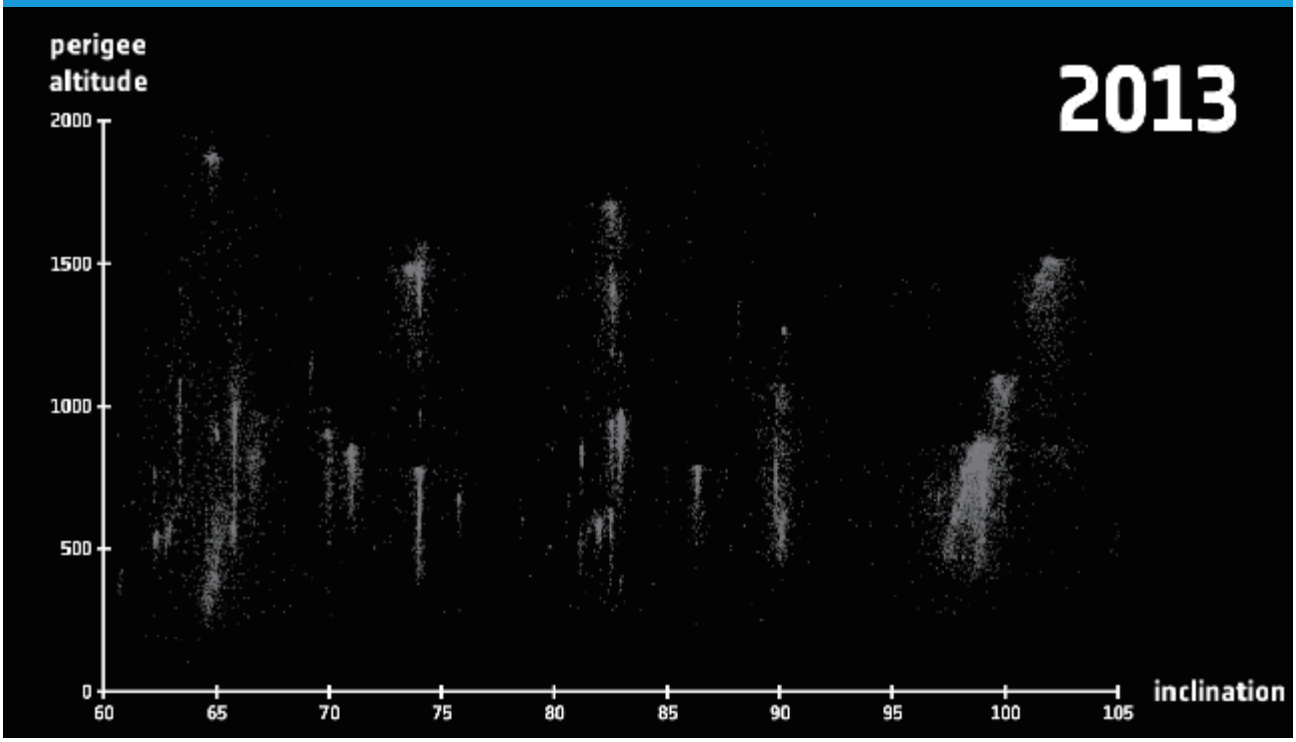
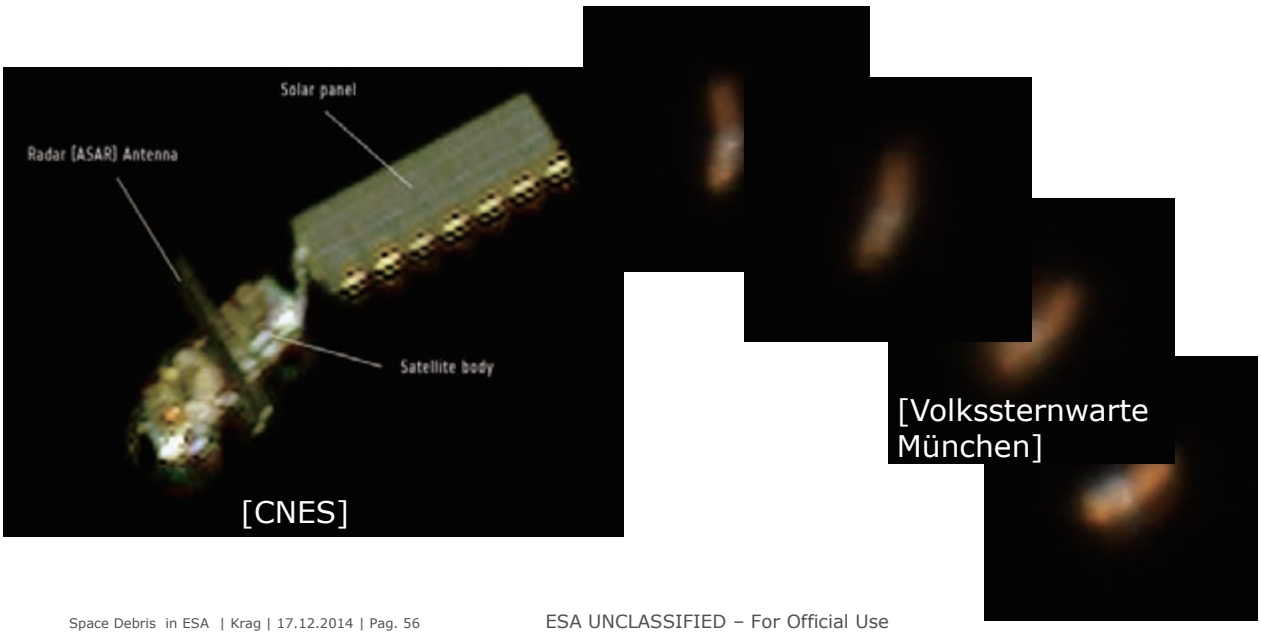
Orbital regions of interest (1/2)



Attitude Measurements



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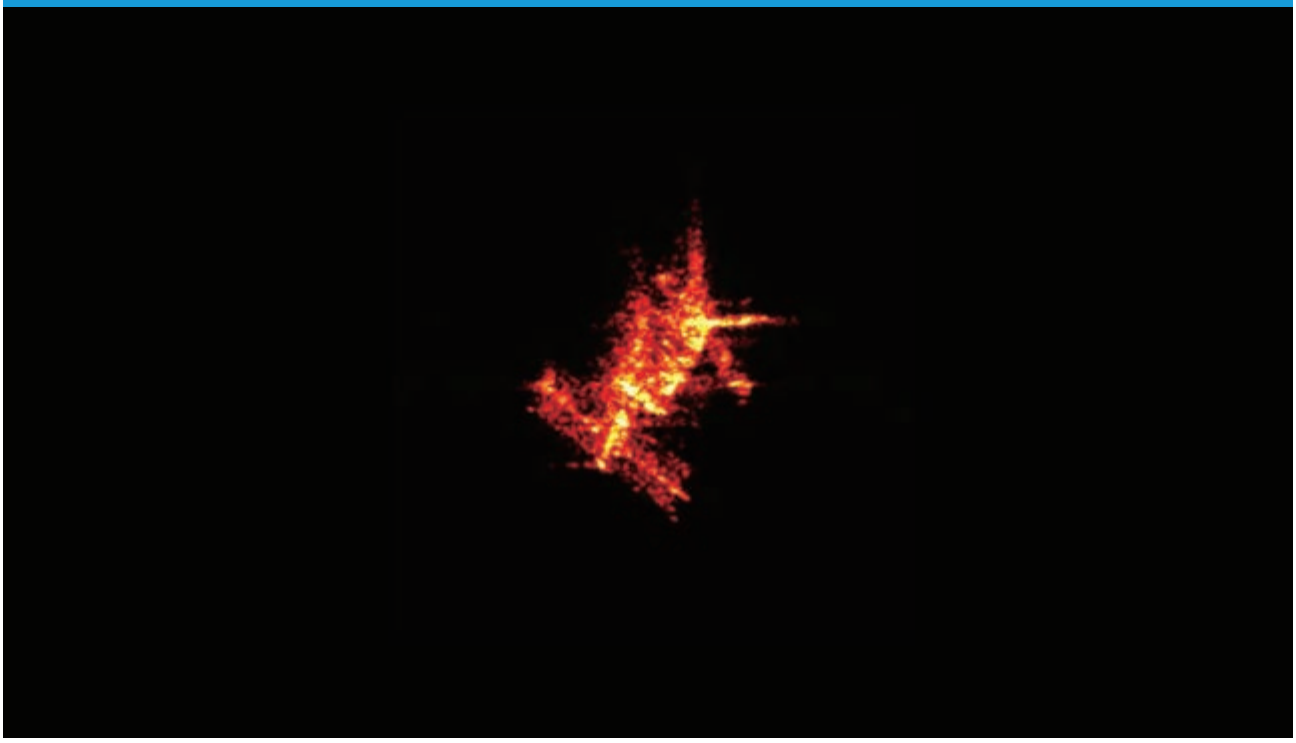
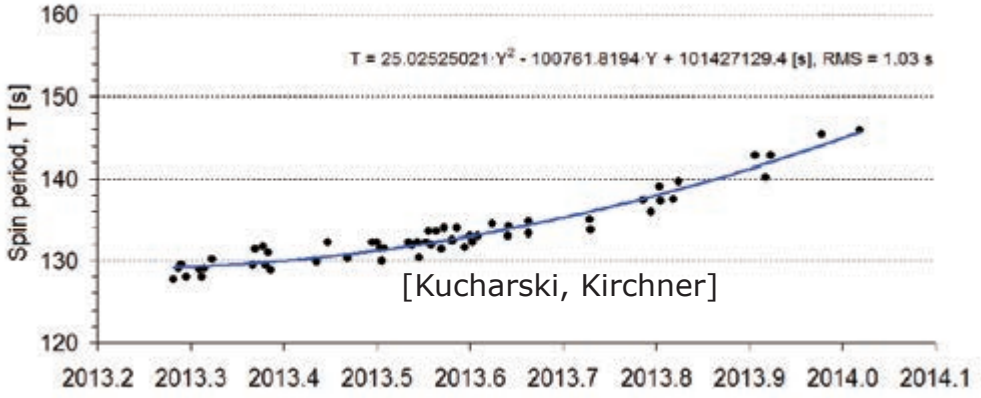
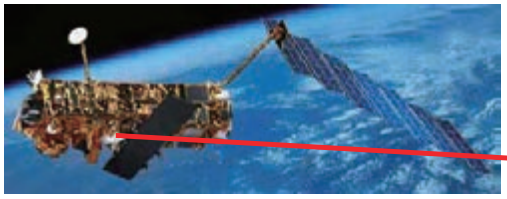
Identification of attitude motion from ground (TIRA imaging radar)



Laser Ranging for Attitude Measurements





Laser Retroreflector

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ESA U

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Capture (controlled re-entry): Robotic Arm

Capture (controlled re-entry): Tentacles

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Capture (controlled re-entry): Net

Back-Up Slides

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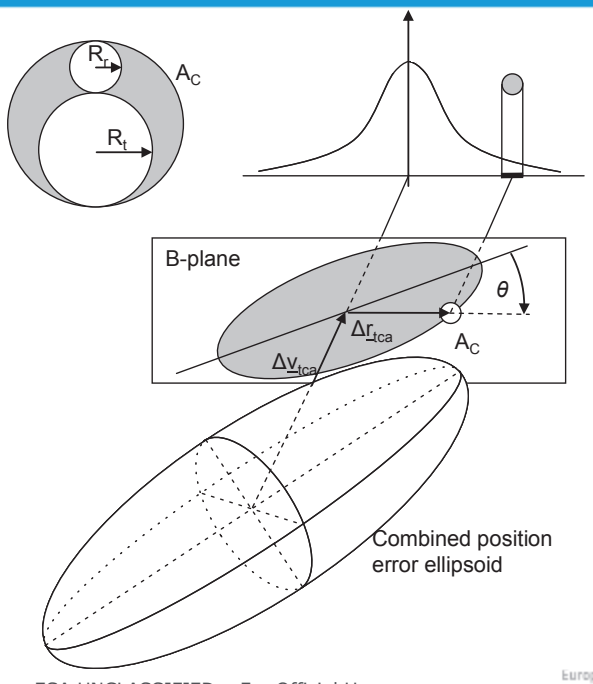
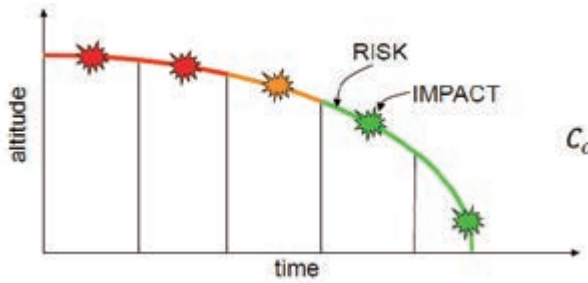
Collision Probability Algorithm

1. Determination of combined target+chaser cross section
2. Combination of the two error covariance matrices into a single one (3D ellipsoid)
3. Projection of ellipsoid onto the B-plane
   a. ∣ distance vector
   b. ⊥ relative velocity vector
4. Integration of projected probability over cross-section = collision probability



Approaches to describe criticality

ESA approach considers:
•the risk of this object to collide with other objects,
•the impact a fragmentation of this object would have on the overall population



$$C_{crit} = c_{risk} \cdot c_{impact}$$

$$C_{crit} = \sum_{t=t_{start}}^{t_{end}} [c_{risk,t} \cdot \int_{\tau_{frag=t}}^{\tau_{end}=t_{end}} (\Delta p)\, d\tau]$$

Other approaches:

Figure-Of-Merit: FOM = flux * A * $m^{0.75}$ * ROL

- flux [1/m^2/yr]: Debris flux in the target's orbit
- A [m^2]: Geometrical cross-section area
- $m^{0.75}$ [kg]: Mass of target raised to the power of 0.75
- ROL [yrs]: Remaining orbital lifetime of the target object

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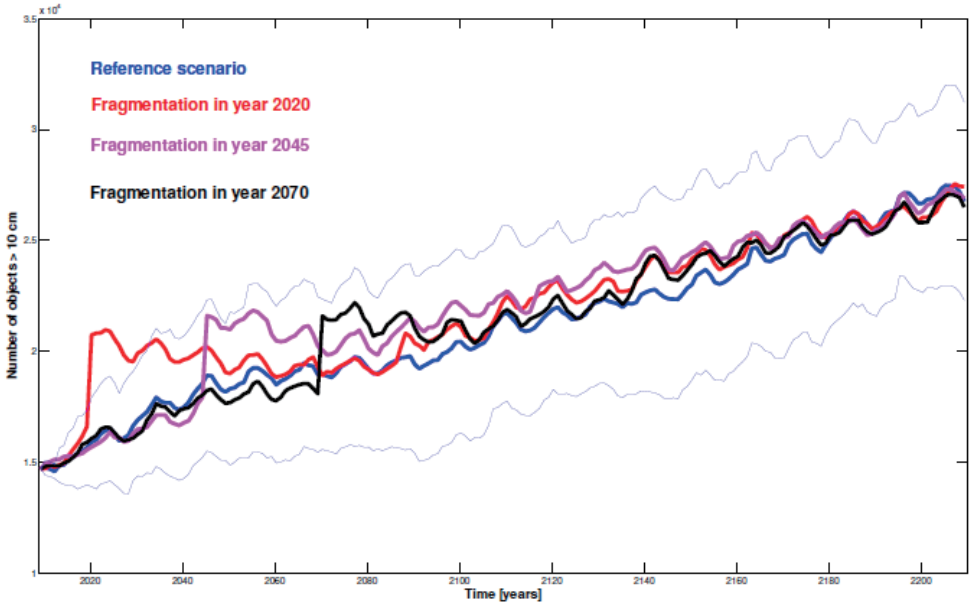
Envisat Break-Up Consequences



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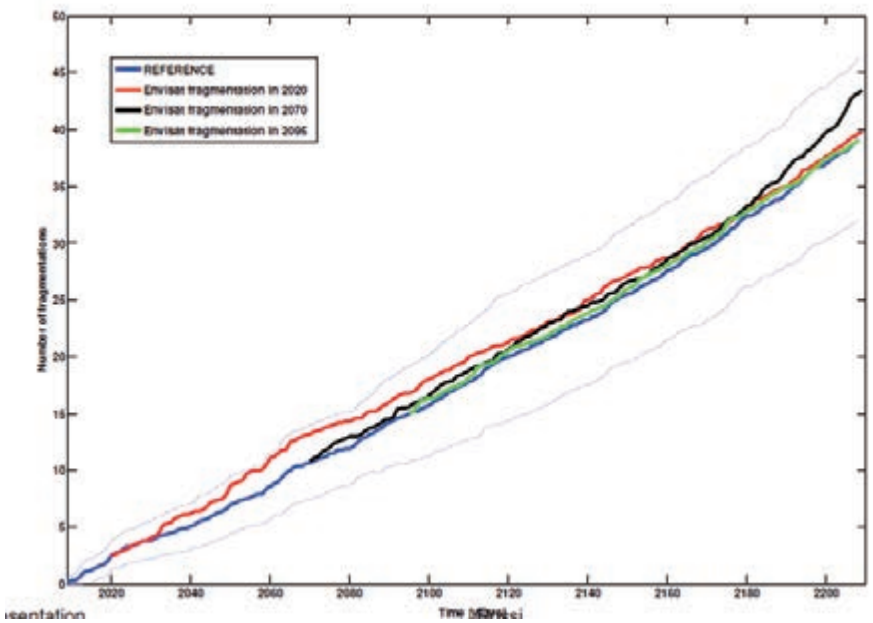
Envisat Break-Up Consequences



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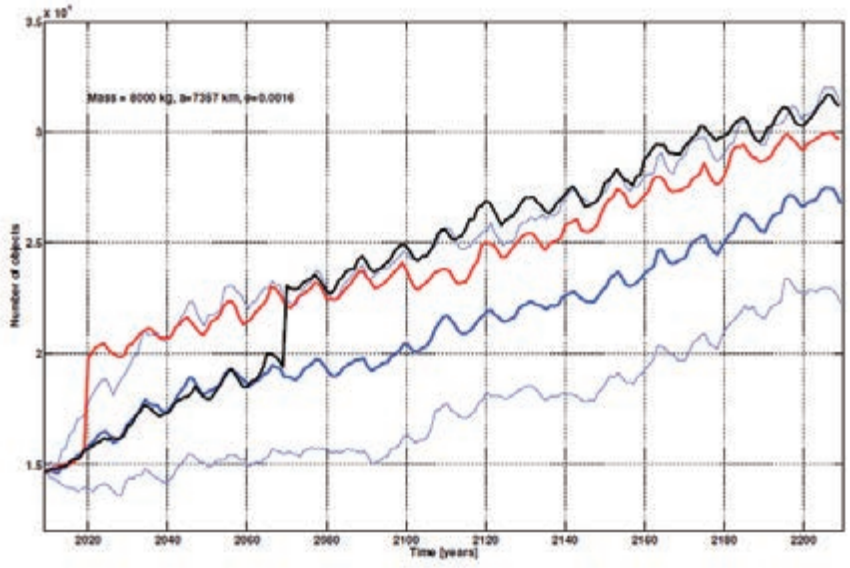
Zenith Break-Up Consequences



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Technology Required for Remediation

Object	Norad Designator	a [km]	e [-]	Incl [°]	-log(crit)	Changed*	
SL-16 R/B	25400	7190.04	0.001194708	98.32	0.37	↗	2
SL-16 R/B	25407	7223.23	0.000427786	71.01	0.37	↗	3
SL-16 R/B	17590	7219.87	0.001134369	71.00	0.37	↑	9
SL-16 R/B	19120	7211.76	0.001566885	71.02	0.37	↑	15
ENVISAT	27386	7148.48	0.00113031	98.40	0.43	↘	-4
METOP-A	29499	7202.59	0.001121819	98.68	0.92	↑	60
COSMOS 2360	25406	7234.58	0.000468583	70.81	0.98	↑	22
RESURS O1-N4	25394	7192.94	0.001076055	98.39	1.11	↑	17
COBE	20322	7260.29	0.001874581	99.00	1.15	↑	58
ARGOS	25634	7210.65	0.001504719	98.78	1.16	↑	34
SPOT 3	22823	7211.21	0.001397824	98.78	1.30	↑	45
ARIANE 40+ R/B	23561	7150.34	0.001092256	98.66	1.41	↑	21
ARIANE 40 R/B	25261	7164.84	0.001233803	98.39	1.41	↑	22
ARIANE 40 R/B	21610	7140.48	0.001878068	98.75	1.41	↑	46

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Re-entry Removal List

OBJ. TYPE	IDYR	IDN	IDP	OWNER	OBJECT NAME	MASS [tonnes]	A-SECT. [sqm]	H_APO [km]	H_PER [km]	INC [deg]	LIFETIME [years]	10cm FLUX [1/sqm *year]	COLL. RATE [1/year]	#	Σ # %	COLL. SEVERITY [kg/year]	#	Σ # %	COLL. CONSE-QUENCES [kg]	#	Σ # %
DC	2002	9	A	ESA	Envisat	8111	63.0467	786.039878	783.403991	98.5491	223.3147	2.22E-05	1.40E-03	1	100%	1.14E+01	1	100%	2.54E+03	20	46%
RB	1998	51	B	RU	Zenit-2 second stage	8226.97	33.4262	842.420994	839.496076	70.9916	747.3423	1.96E-05	6.61E-04	6	46%	5.36E+00	2	47%	4.02E+03	2	73%
RB	1999	43	G	RU	Zenit-2 second stage	8226.97	33.4262	818.783209	800.410411	99.33	474.4788	1.91E-05	6.37E-04	5	46%	5.24E+00	3	46%	2.49E+03	21	48%
RB	2002	6	B	RU	Zenit-2 second stage	8226.97	36.1642	854.645796	838.434309	70.9966	896.0166	1.79E-05	6.31E-04	7	46%	5.13E+00	4	46%	3.61E+03	5	66%
RB	1998	48	B	RU	Zenit-2 second stage	8226.97	33.4262	844.917217	836.303482	71.2115	714.9631	1.84E-05	6.18E-04	8	44%	5.06E+00	5	44%	3.62E+03	4	66%
RB	1988	102	B	SU	Zenit-2 second stage	8226.97	33.4262	849.612987	831.452151	70.9988	687.7599	1.83E-05	6.11E-04	9	44%	5.02E+00	6	44%	3.45E+03	11	63%
RB	1994	77	B	RU	Zenit-2 second stage	8226.97	33.4262	844.92155	840.094128	70.9764	775.0091	1.83E-05	6.10E-04	10	43%	5.02E+00	7	44%	3.56E+03	3	70%
RB	1995	55	B	RU	Zenit-2 second stage	8226.97	33.4262	852.096752	833.413696	71.021	764.5923	1.80E-05	6.00E-04	11	43%	4.94E+00	8	43%	3.45E+03	9	63%
RB	1990	46	B	SU	Zenit-2 second stage	8226.97	33.4262	866.30672	833.433179	70.998	896.8942	1.77E-05	5.92E-04	12	42%	4.87E+00	9	43%	3.39E+03	12	61%
RB	1988	39	B	SU	Zenit-2 second stage	8226.97	33.4262	843.661263	814.700526	71.0124	571.8422	1.72E-05	5.74E-04	14	41%	4.72E+00	10	42%	2.70E+03	19	49%
RB	1987	41	B	SU	Zenit-2 second stage	8226.97	33.4262	847.175881	824.376581	71.0072	662.6458	1.71E-05	5.70E-04	15	41%	4.69E+00	11	41%	3.10E+03	15	56%
RB	1987	37	B	SU	Zenit-2 second stage	8226.97	33.4262	841.455573	833.068617	71.0005	703.5773	1.70E-05	5.69E-04	16	41%	4.68E+00	12	41%	3.29E+03	13	60%
RB	1985	97	B	SU	Zenit-2 second stage	8226.97	33.4262	845.625457	832.419493	71.002	694.0896	1.70E-05	5.67E-04	17	40%	4.66E+00	13	41%	3.24E+03	16	59%
RB	1984	23	B	RU	Zenit-2 second stage	8226.97	33.4262	847.186476	841.033119	70.9968	766.6691	1.68E-05	5.62E-04	18	40%	4.62E+00	14	41%	3.54E+03	7	64%
RB	1992	93	B	RU	Zenit-2 second stage	8226.97	33.4262	848.489199	838.883473	71.0301	784.1832	1.67E-05	5.59E-04	19	40%	4.60E+00	15	40%	3.47E+03	10	63%
RB	1983	16	B	RU	Zenit-2 second stage	8226.97	33.4262	850.911879	838.984396	71.0102	709.1643	1.67E-05	5.58E-04	20	40%	4.60E+00	16	40%	3.26E+03	14	59%
RB	1993	59	B	RU	Zenit-2 second stage	8226.97	33.4262	850.780307	823.336878	70.9912	692.0008	1.68E-05	5.61E-04	21	39%	4.63E+00	17	40%	2.95E+03	18	54%
RB	1982	76	B	RU	Zenit-2 second stage	8226.97	33.4262	847.383131	829.386908	70.9987	666.8037	1.63E-05	5.44E-04	22	39%	4.48E+00	18	39%	3.07E+03	17	56%
RB	2007	29	B	SU	Zenit-2 second stage	8226.97	36.1642	847.014601	843.987898	70.979	926.0499	1.49E-05	5.24E-04	23	37%	4.31E+00	19	39%	3.56E+03	6	66%
RB	2004	21	B	RU	Zenit-2 second stage	8226.97	36.1642	848.49523	843.344478	71.0029	816.1111	1.48E-05	5.20E-04	24	37%	4.28E+00	20	39%	3.49E+03	8	63%
DC	2002	56	A	JP	MIDORI-2 (ADEOS 2)	3650	60	805.17955	803.615067	98.6223	205.1914	1.90E-05	1.14E-03	2	51%	4.20E+00	21	37%	5.61E+02	22	16%
RB	2001	56	F	RU	Zenit-2 second stage	8226.97	36.1642	1007.91194	995.423199	99.1949	1535.8615	1.94E-05	3.89E-04	25	28%	3.00E+00	22	28%	5.51E+03	1	100%
DC	2006	44	A	EUM	METOP-A	4085	34.2012	820.953254	819.591237	98.67	274.6389	1.93E-05	6.60E-04	3	47%	2.70E+00	23	34%	7.41E+02	23	13%
RB	1999	39	B	RU	Zenit-2 second stage	8226.97	33.4262	850.40694	829.364118	97.7447	78.213	9.71E-06	3.26E-04	26	23%	2.67E+00	24	23%	2.09E+02	26	4%
RB	2002	56	E	JP	H-2A second stage	4000	31.4276	841.45484	736.903416	98.558	121.9933	2.29E-05	6.58E-04	4	47%	2.63E+00	25	23%	3.21E+02	24	6%
RB	1994	74	B	RU	Zenit-2 second stage	8226.97	33.4262	849.680283	840.304433	98.0807	88.798	9.67E-06	3.20E-04	27	23%	2.63E+00	26	23%	2.34E+02	25	4%
DC	2006	2	A	JP	DAICHI	4000	31.7611	698.469766	693.623784	98.1519	43.6674	1.13E-05	3.87E-04	13	42%	2.36E+00	27	21%	1.49E+02	27	3%

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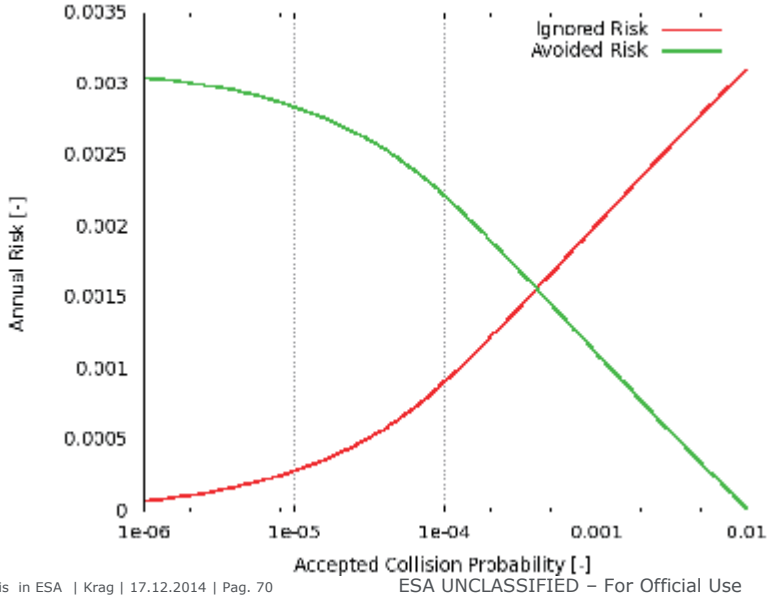
Situation before CSM

- Example: Envisat: 26m span, 8t mass, initial covariance ca. 10m x 56m x 14m
- TLE screening (initial chaser covariance ca. 225m x 750m x 195m)



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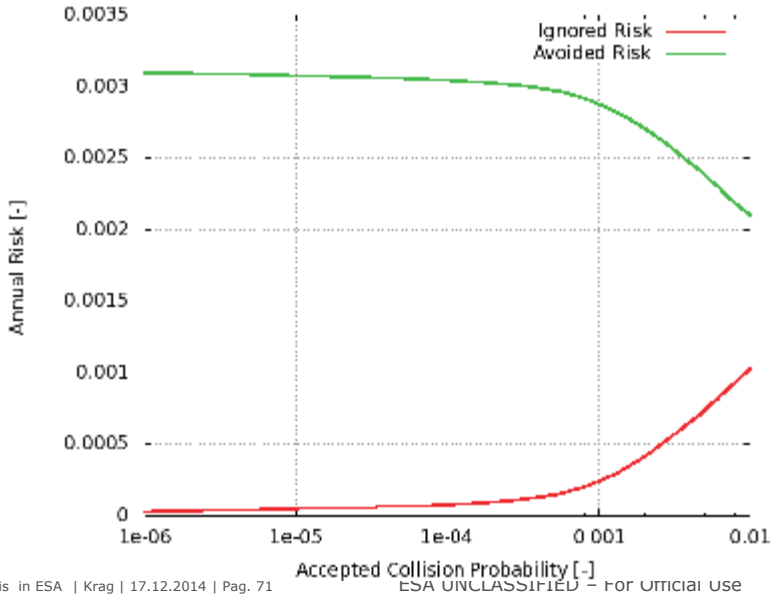
Situation with the new CSM

- Example: Envisat: 26m span, 8t mass, initial covariance ca. 10m x 56m x 14m
- JSPOC screening (CSM chaser initial covariance ca. 23m x 75m x 20m)



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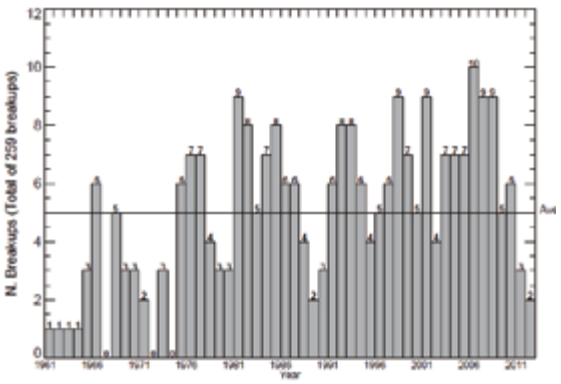
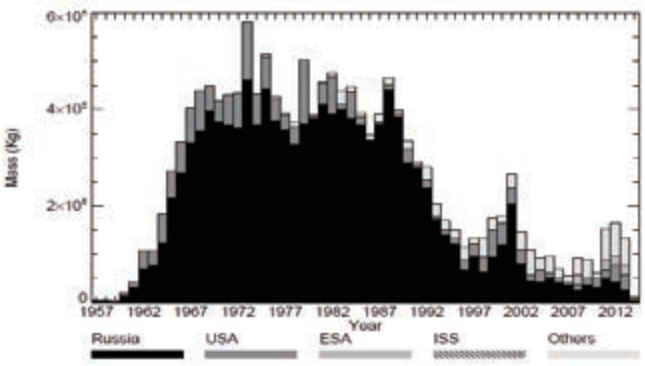
Analyses with DISCOS

Number of events per year



Re-entering mass per year (uncontrolled)



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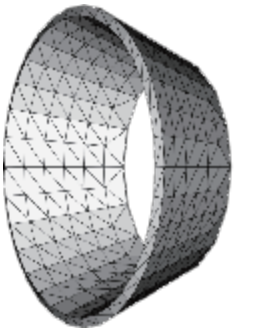
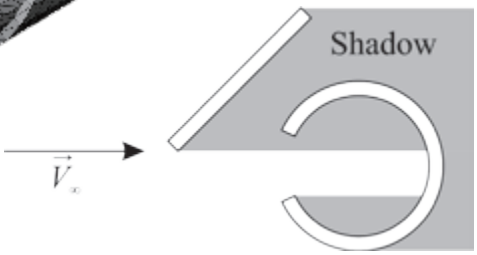
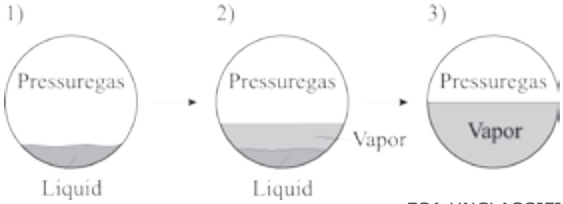
SCARAB modelling principles

- Model built from “primitive shapes”
- Modelling approachare subject to a shadow analysis based on geometric area projections in flow direction.
- No flow expansion behind shadowing panels (Ma∞, S∞ → ∞)
- Tank bursting analysis







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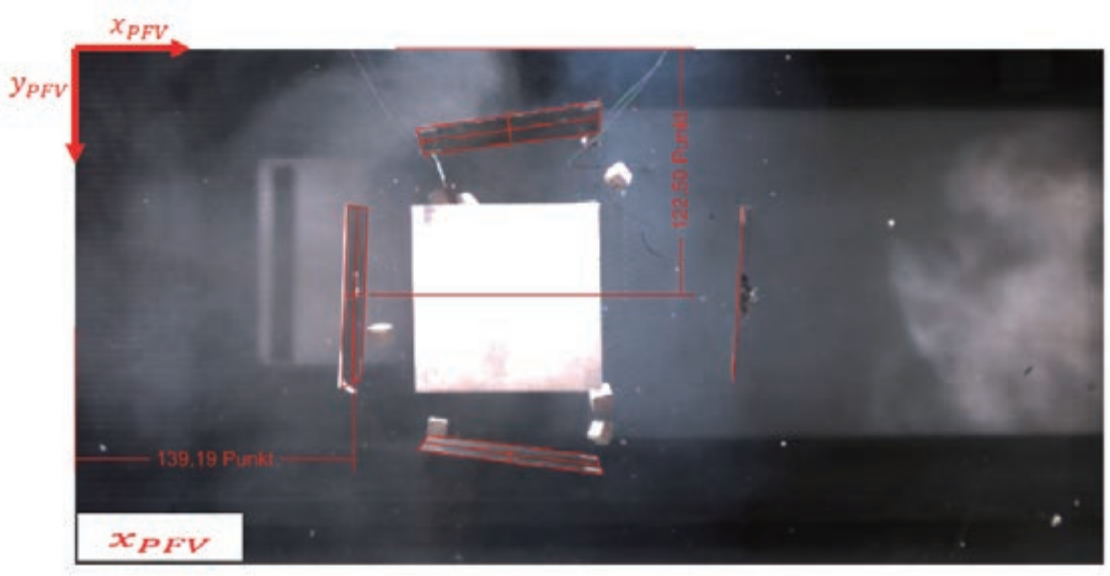
Understanding catastrophic break-up



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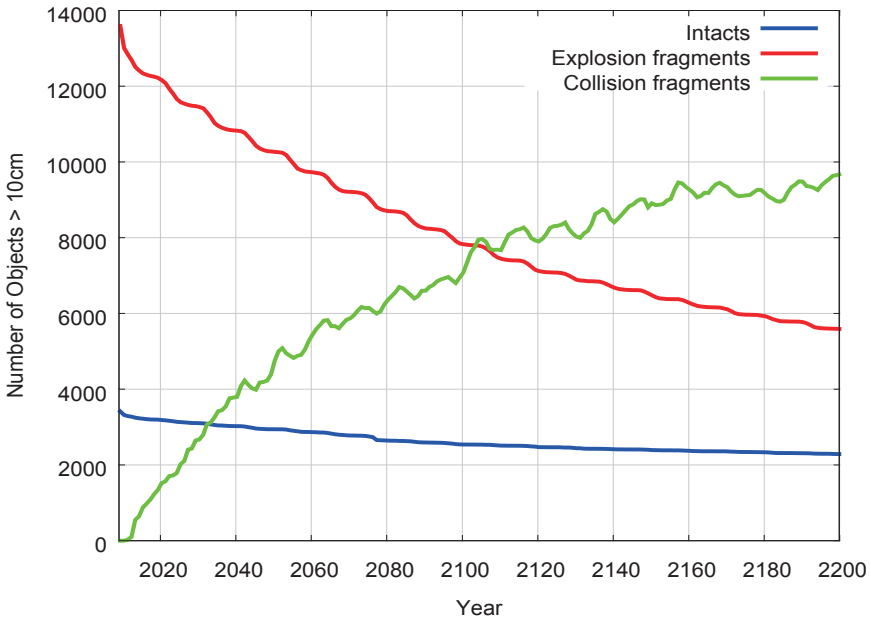
No further release scenario



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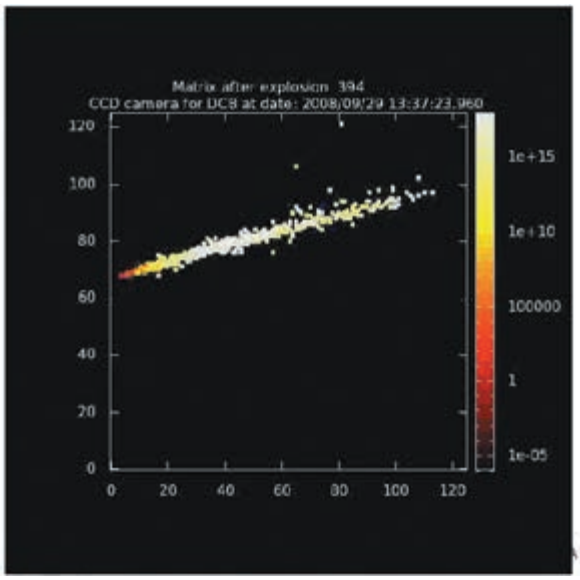
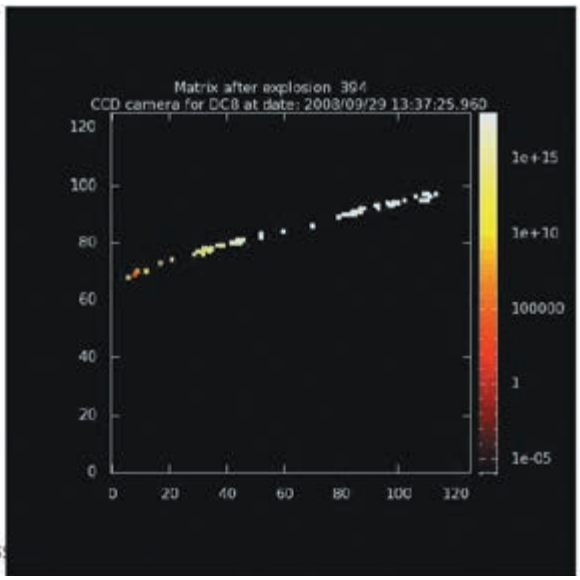
ATV-1 DC-8: different fragmentation model

DC8 airplane, Camera mounting: AZ=100deg, El=0deg.
Camera properties: FOV=40deg, Lpix=0.02mm, D=0.3m, Npix=125
Solar panel break-off altitude = 95km. Explosion altitude = 78km.

Evolve Model



ACTA Model



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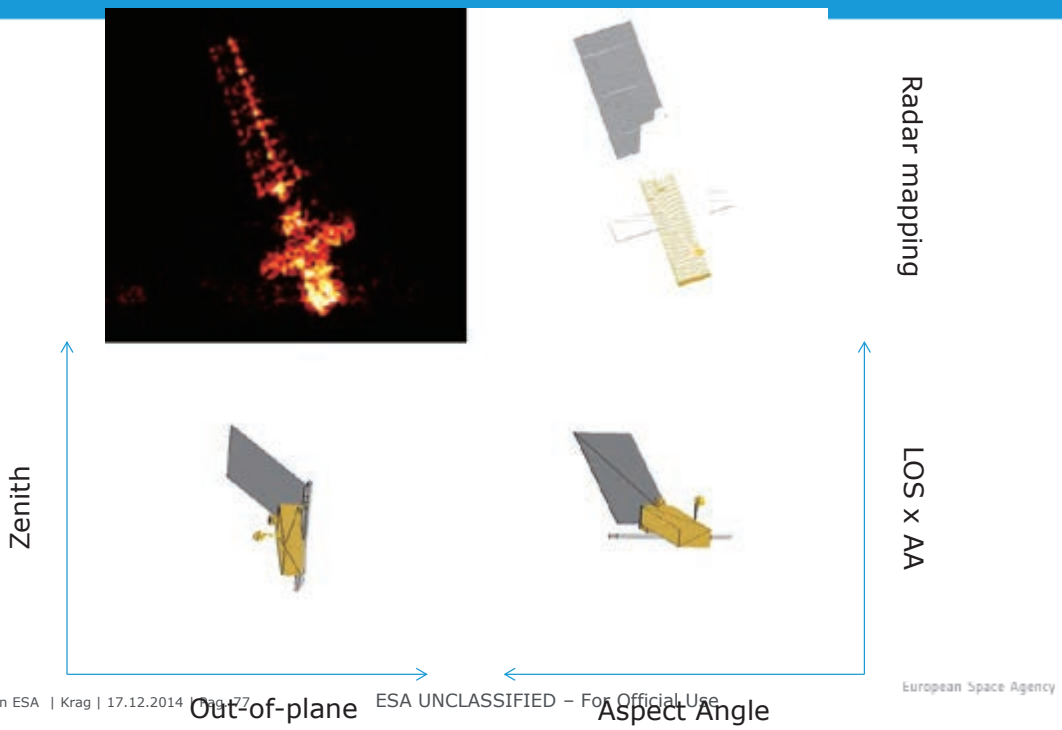
Latest Envisat ISAR observation



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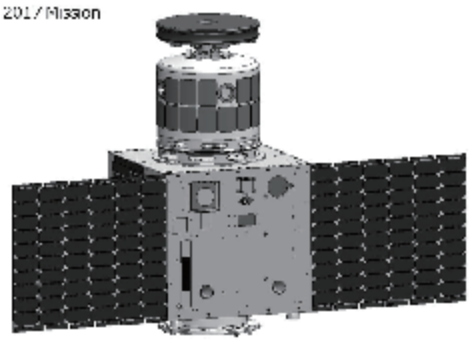
A4

民間企業による ADR サービス実現の具体的方法

A private company's solution to implement space debris removal service

岡田光信（ASTROSCALE CEO）
Nobu Okada, ASTROSCALE, CEO

Currently, the national space agencies around the world are investigating the active space debris removal technologies. There are numbers of the space debris which all vary in its materials, sizes and orbit, therefore, the removal technology must be affordable and sustainable. ASTROSCALE aims to provide affordable space debris removal service for medium to large scale space debris. The company targets to launch its first mission towards the end of 2017. In this session, the presentation focuses on the company's strategy for the team structure, technological development, fund raising, structuring the business model, and regulatory compliance. The company aims to provide sustainability to the space environment by establishing itself as a supplementary position to the existing space agencies.



スペース・デブリ除去の技術は現在各国の宇宙機関で検討されているが、スペース・デブリは数も多く、種類も大きさも軌道も多様であるため、安価で、持続的な除去技術の構築が必要である。ASTROSCALE は民間として独自の技術で中型～大型デブリの除去サービスを安価に提供することを考えており、2017 年後半に初号機を打上げる予定である。チーム作り、技術開発、資金調達、ビジネスモデル構築、コンプライアンス遵守をどのように進めているのかを説明する。宇宙機関の補完的な役割を担うことによって、持続的な宇宙環境を維持できることを期待している。

Biography

岡田 光信（おかだ みつのぶ）
1973 年生まれ。兵庫県出身。シンガポール在住。東京大学農学部卒業。Purdue University MBA 修了。宇宙ゴミ（スペース・デブリ）を除去することを目的とした宇宙ベンチャー、ASTROSCALE PTE. LTD. のＣＥＯ。大蔵省（現財務省）主計局に勤めたのち、マッキンゼー・アンド・カンパニーにて経営コンサルティングに従事。自身で経営を行いたいとの思いが募り、ＩＴ会社ターボリナックス社を皮切りに、SUGAO PTE. LTD. ＣＥＯ等、ＩＴ業界で 10 年間、日本、中国、インド、シンガポール等に拠点を持ちグローバル経営者として活躍する。幼少より宇宙好きで高校１年生時にＮＡＳＡで宇宙飛行士訓練の体験をして以来、宇宙産業への思いが強く、現在は宇宙産業でシンガポールを拠点として世界を飛び回っている。

Mr. Nobu Okada founded ASTROSCALE PTE. LTD. in Singapore in 2013 to address growing threat of space debris by incubating removal technologies while arousing a passion for space exploration among ordinary citizens. Prior to this, he managed IT companies in Japan, China, India and Singapore, one of which had a successful IPO. Before joining IT industry, Nobu worked for McKinsey & Company and the Japanese Ministry of Finance. Nobu received his Bachelors degree in Genetics from University of Tokyo in 1995 and an MBA in Krannert School of Business, Purdue University in 2001. Braunschweig, Germany and conducted more than 4 years of detailed research in the area of space debris environment and observation modeling.

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ASTROSCALE

CEO Nobu Okada

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Can I remove space debris by myself?

Yes, most probably, we can do it.

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Who we are

How we do

2017 Mission

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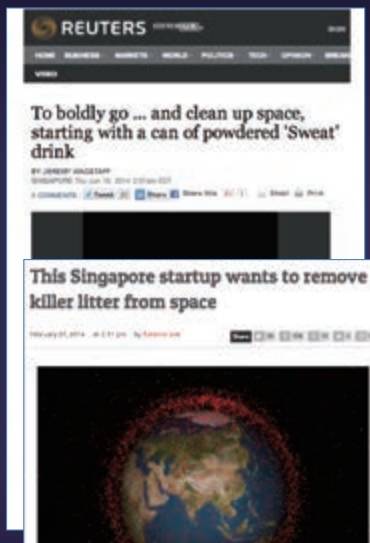
Awards/Conferences

Web news


REUTERS

To boldly go ... and clean up space, starting with a can of powdered 'Sweat' drink

This Singapore startup wants to remove killer litter from space

TV, Magazines

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Lunar Dream Capsule Project

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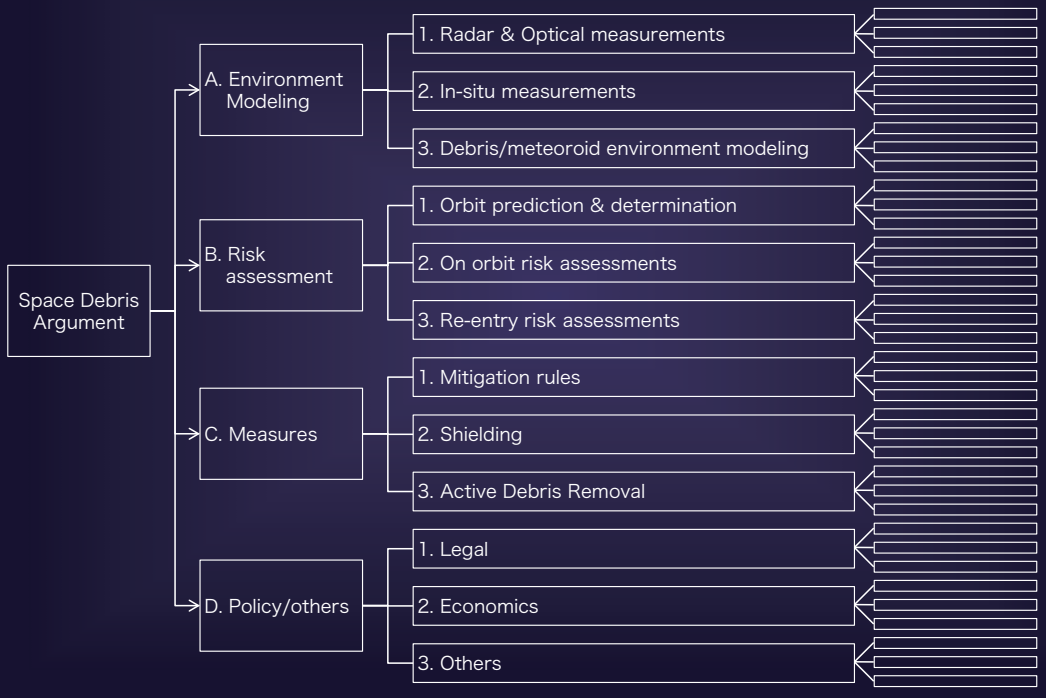
SPACE DEBRIS ARGUMENT



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Technologies

Fund

Rules/laws

Someone needs to crack the code for sustainable ADR.

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WHY PRIVATE SECTOR?

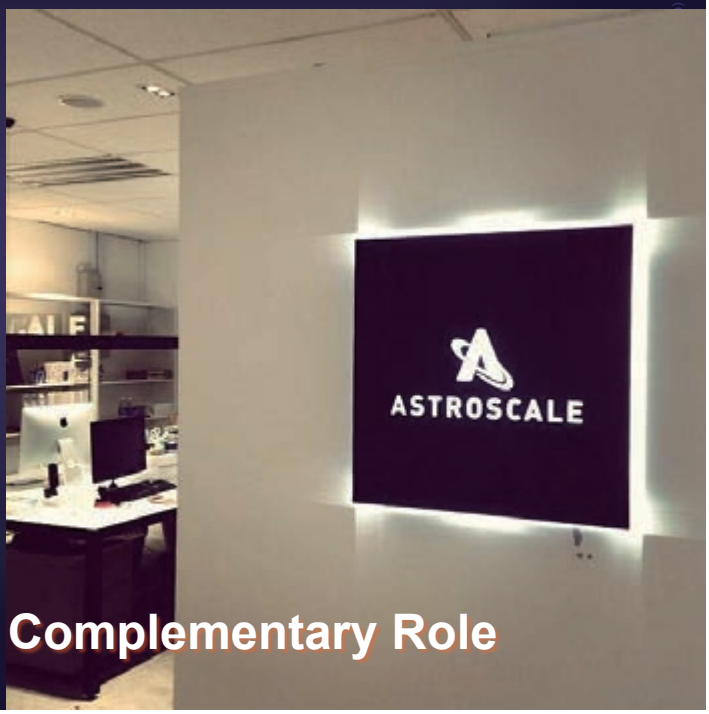
Cost effective

Quick try and error

No border

Biz model

Pure business



Breakthrough & Complementary Role

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Team

Goal & Solution

Initial Money

Biz model

Compliance

Space Sweepers

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Space Sweepers

	Who/Lab	Organization	Role
1	Prof Nakasuka Lab – Intelligent Space System	University of Tokyo	BUS Design, AOCS
2	Prof Kimura Lab	Tokyo University of Science	Unmated approach, C&DH
3	Prof Sahara	Tokyo Metropolitan University	Propulsion system
4	Assoc. Prof Koizumi Lab	University of Tokyo	Propulsion system
5	Mr. Nakano	Tokyo Metropolitan University	Propulsion system
6	Prof Hanada – Space Systems Dynamics Lab	Kyushu University	Orbital mechanics
7	Assoc. Prof Iwata – Micro satellite testing	Kyushu Institute of Technology	Space environment testing
8	Yuki Precision		Design and mfg of satellite parts
9	ASTROSCALE		Project management and coordination, and ALL

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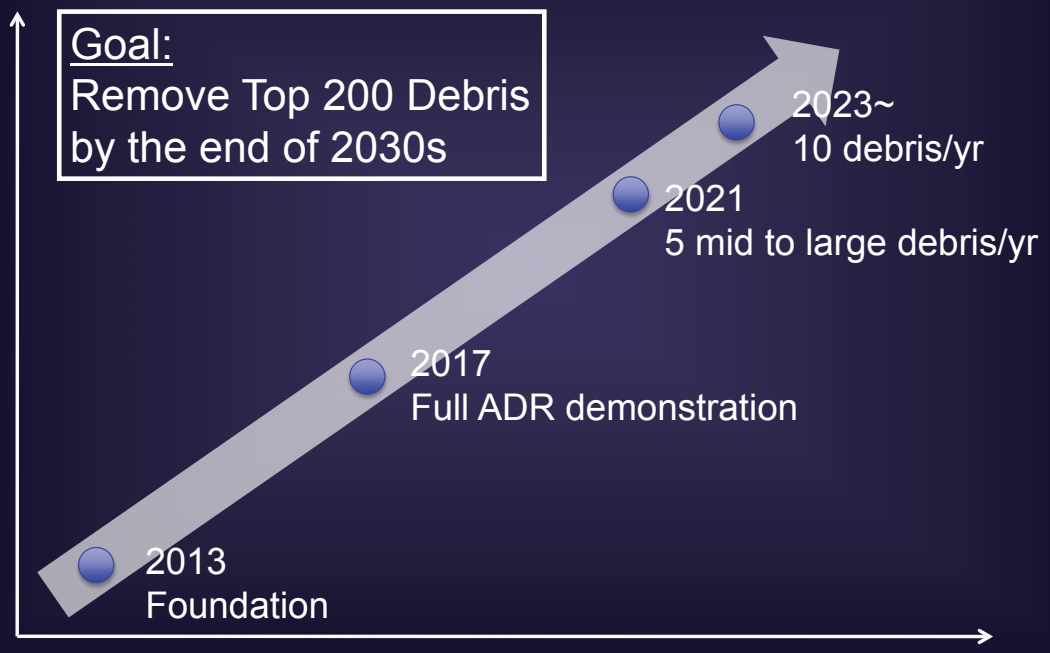
GOAL & TIMELINE



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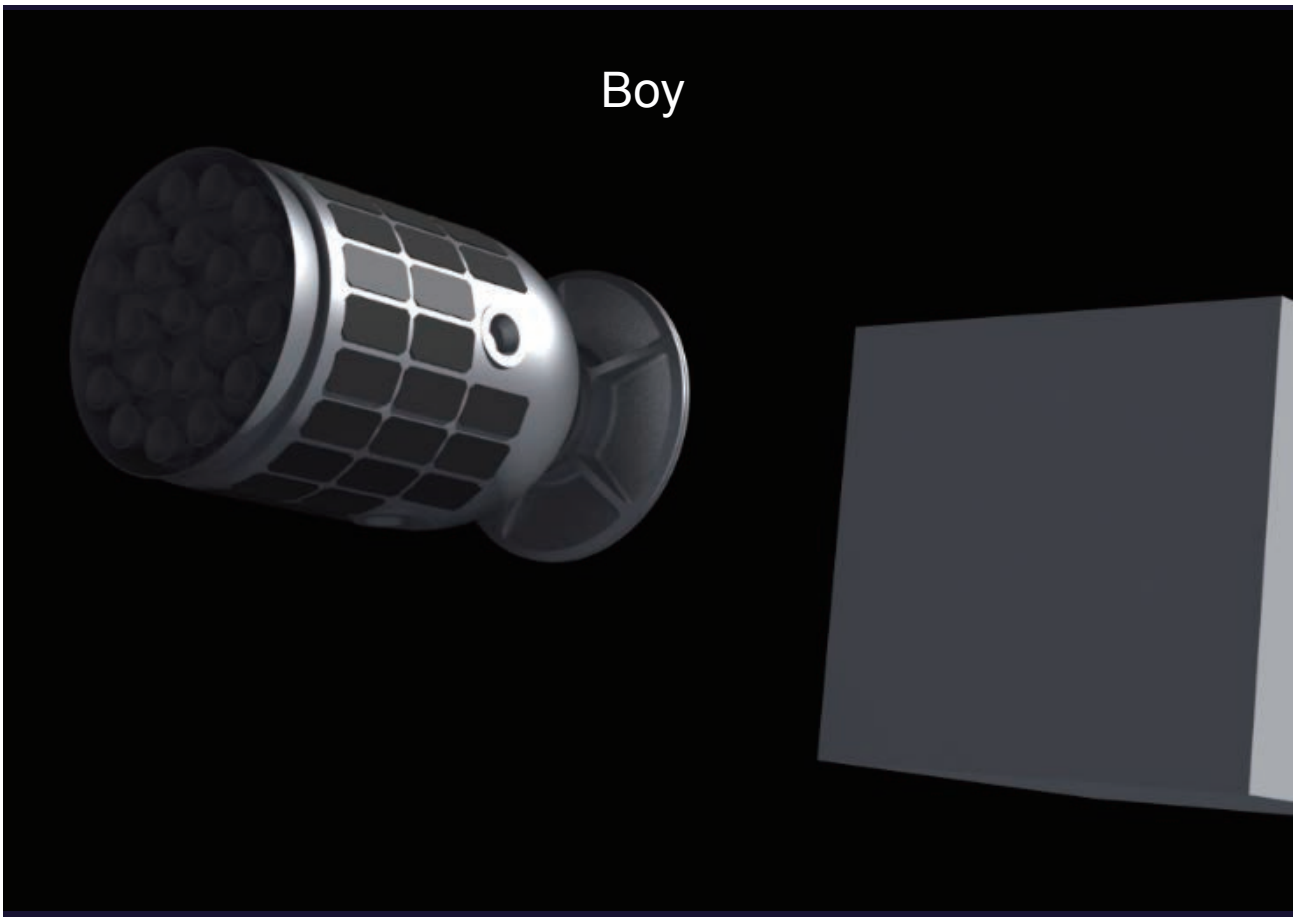

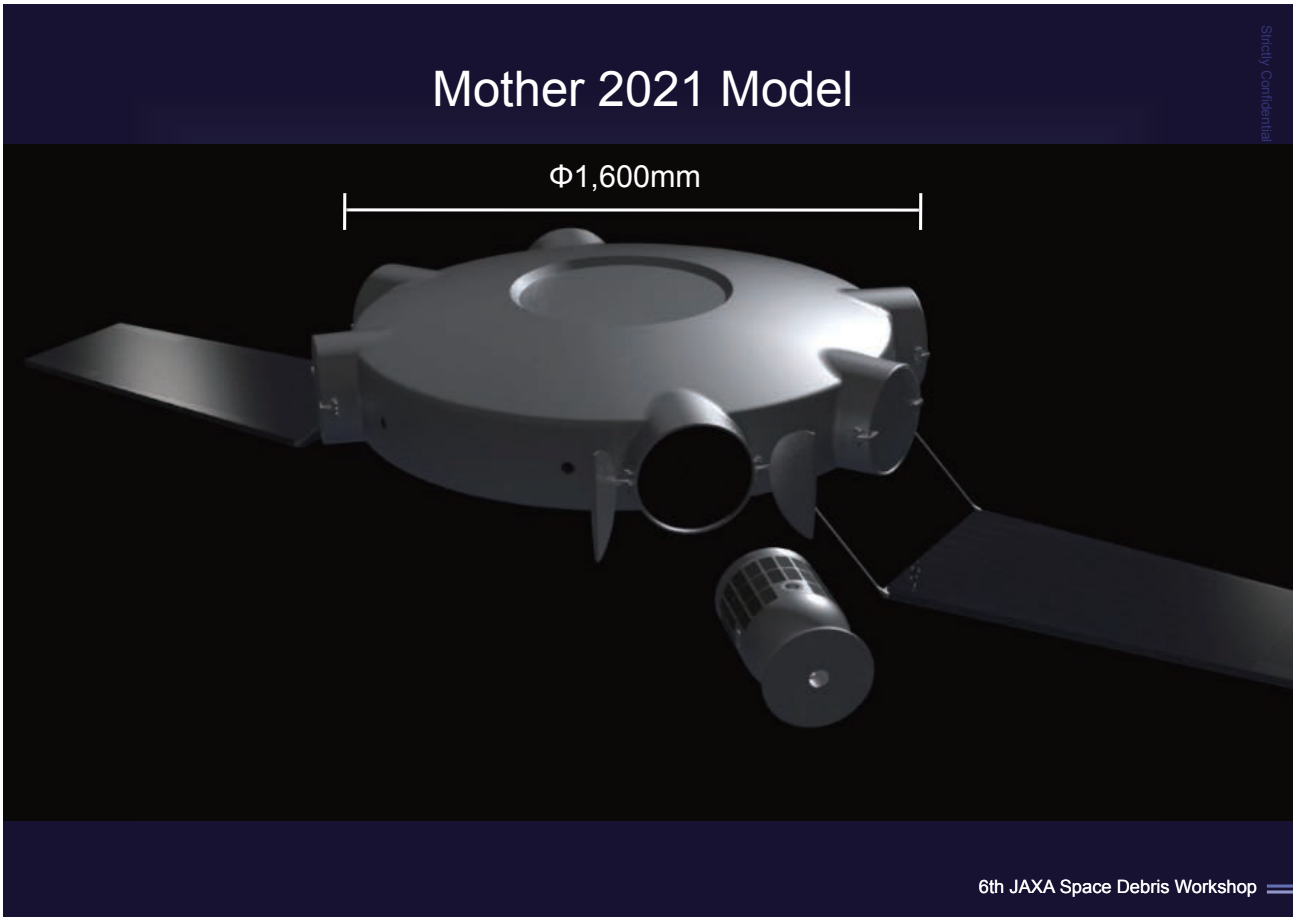

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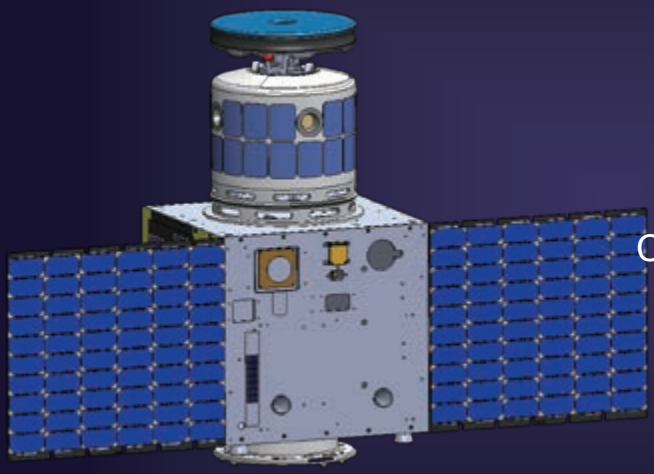
2017 Mission



Concept	1 Mother + 1 Boy
Size	50 x 50 x 90cm
Mass	<80kg
ACS	3 axis stabilization
Communication	X-band, S-band
Orbit Control	Xe-propelled Ion thruster
	H2O2-propelled RCS

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Mission Overview

	Missions
1	Launch & Commissioning
2	Unmated approach demonstration
3	Proximity operations demonstration
4	Diagnosis demonstration
5	Release & Capture demonstration
6	Tugboat demonstration
7	Partially controlled reentry demonstration

Full range of ADR

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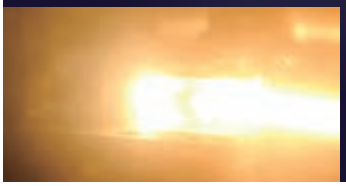
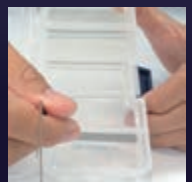
Boy 2017 Model

Concept	Small but powerful
Size	Φ300mm x 40cm
Mass	20kg+
Others	Adhesive compound
	Solid propellant
	37 nozzles
	Gimbal

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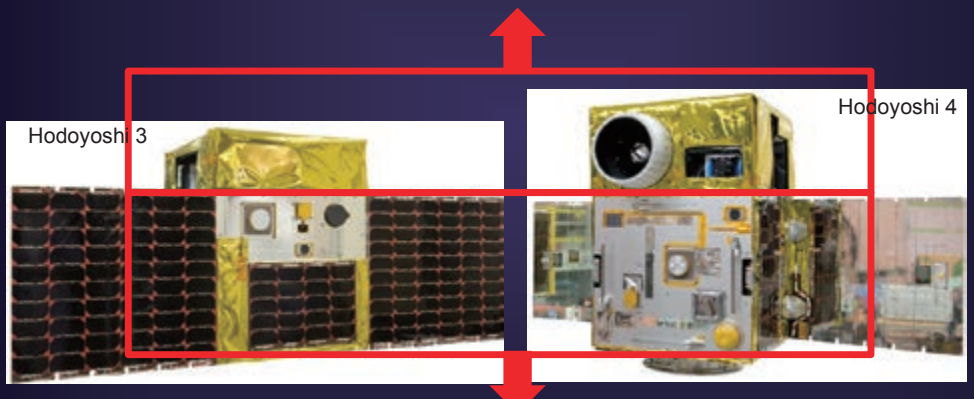
Heritage from Hodoyoshi

ASTROSCALE inherits Hodoyoshi core team to explore more Microsat applications

Application layer to Boy



ASTROSCALE Bus
+ RCS, Unmated approach capability, Release mechanism

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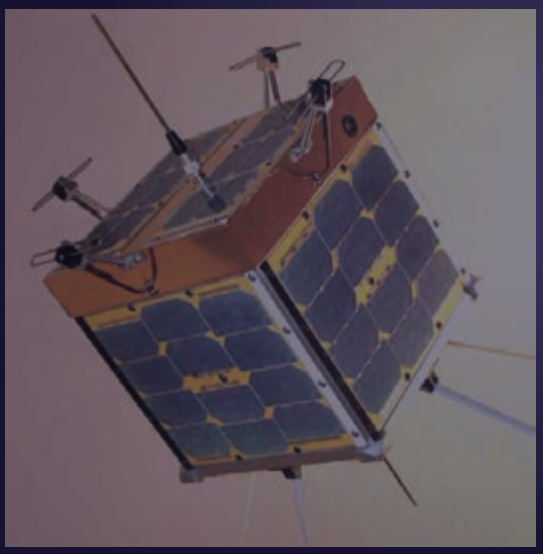
Target Debris

Free Launch Opportunity!



Bring with Mother/Boy in the same rocket.

- Satellite owner to pay development cost
- ASTROSCALE to pay launch cost
- 50 x 50 x 50cm or less
- <40kg
- Mission duration < 2 months
- Surface can be uneven

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UNMATED APPROACH (1)

Steps	0	1	2	3	4	5
Stage	Launch	Far range			Middle range	Near range
Distance		>10,000km → 10km			10km → 1km	1km → 50m
Orbital elements		Inclination, RAAN	Semi major axis	Phase		
Thruster		Xenon-propelled ion thruster 300μN			H2O2-propelled RCS, 350~500mN	
Duration		2~5 months			1~2 days	1~2 days
Chaser location		GPS			GPS	GPS
Target location		TLE			Optical camera	LIDAR
Comments					Angle-only approach, Batch processing	Real-time processing

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UNMATED APPROACH (2)

Steps	6	7	8	9	10
Stage	Fly-around	Proximity operation			Release & Capture
Distance	30-50m	→ 5m	5m	→20cm	20cm
Orbital elements	Final tuning		Rotation and target surface		
Thruster	--	RCS	RCS	RCS	
Duration			1 round		
Chaser location	GPS	GPS			
Target location	LRF	LRF/Optical camera			
Comments	Abort mode standby	3 Axis control w RW and RCS	--	3 Axis control w RW and RCS	

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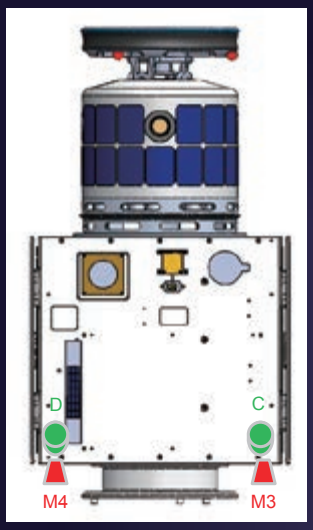
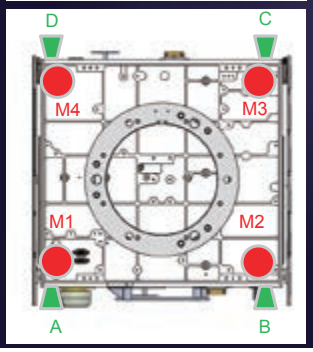
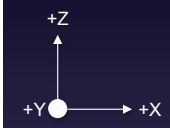
RCS







	Dtetails
Nozzles	Translation (M) 4 on –Z Attitude Control (A, B, C, D) : 4 on ±Y w 30° angle
Translations	+X Translation : No (Z axis 90° Rotation, +Y Translation) -X Translation : No (Z axis 90° Rotation, -Y Translation) +Y Translation : C+D+M3+M4 -Y Translation : A+B+M1+M2 +Z Translation : M1+M3 or M2+M4 or M1+M2+M3+M4 -Z Translation : A+B+C+D
Rotations	+X Rotation : C+D or M1+M2 -X Rotation : A+B or M3+M4 +Y Rotation : A+D or M1+M4 -Y Rotation : B+C or M2+M3 +Z Rotation : A+C -Z Rotation : B+D
Redundancy	Enough redundancy except –Z translation

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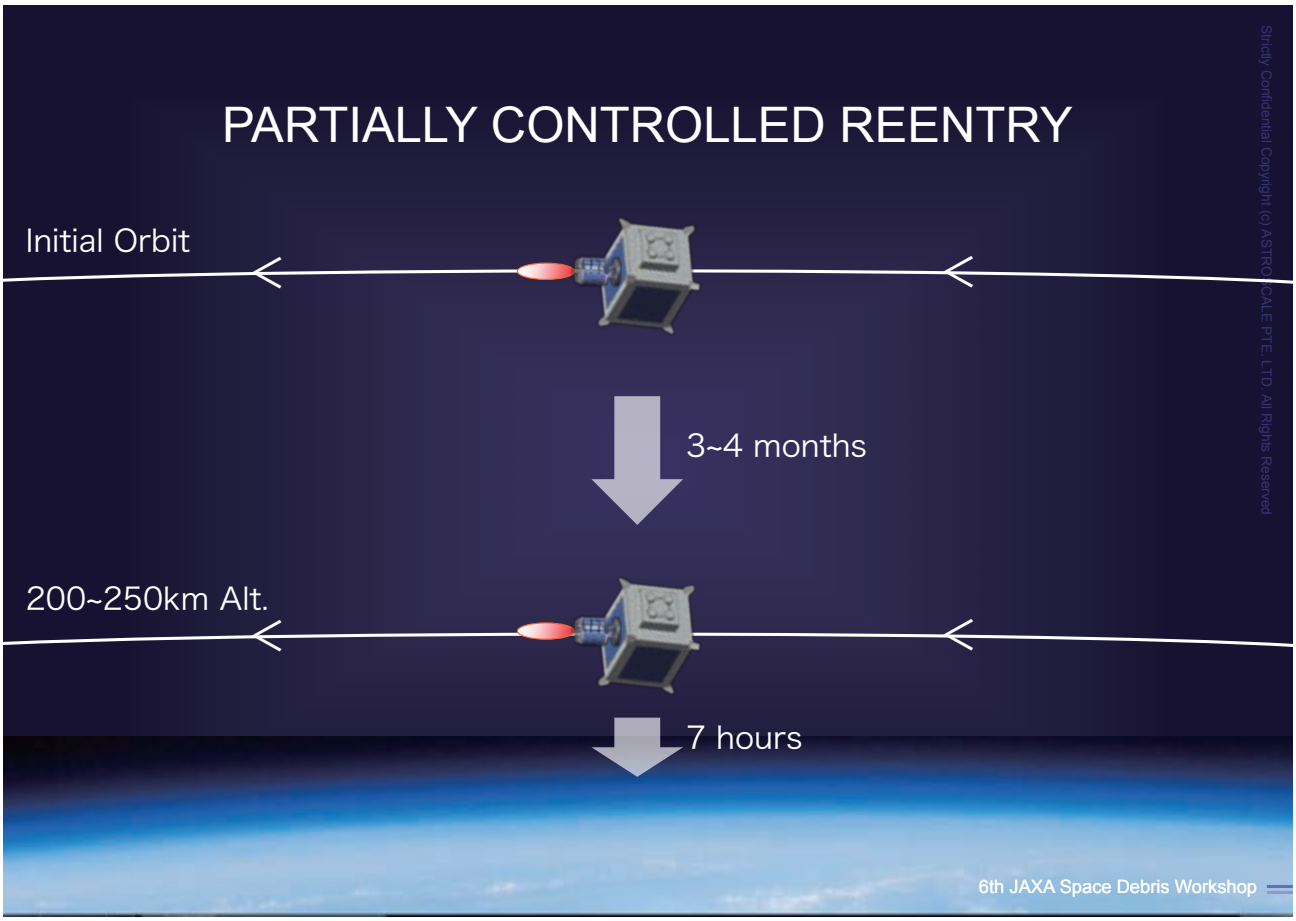

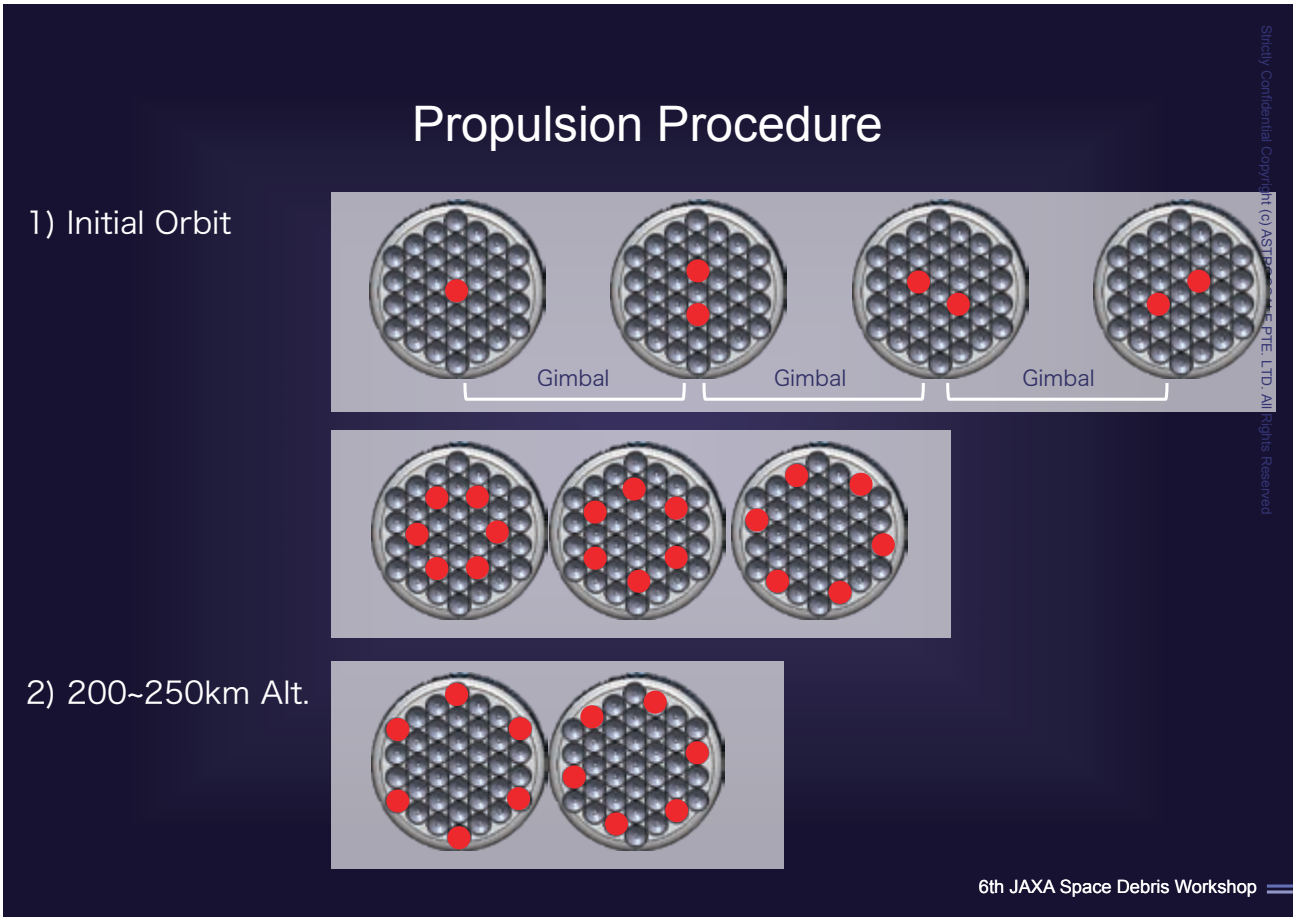

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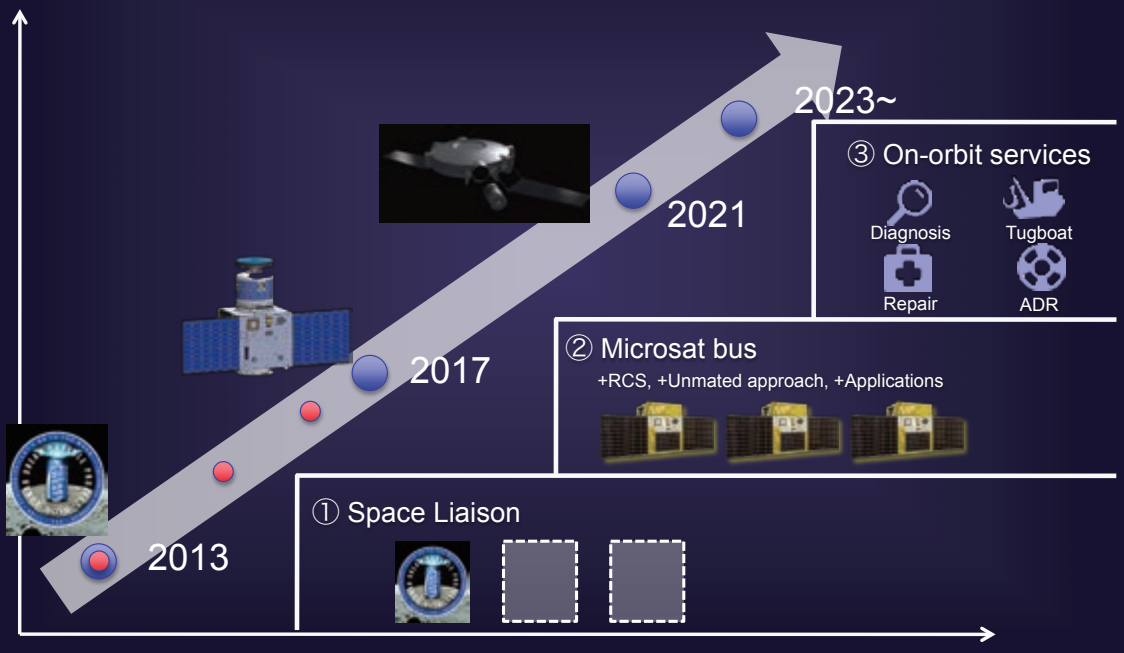
BUSINESS MODEL



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COMPLIANCE

	Regulation	Guidelines	
1	UN COPUOS Space Mitigation Guidelines	• Limit the probability of accidental collision in orbit • Limit the release of debris during operations • Compulsory post-mission disposal • Limit the long-term presence of spacecraft and launch vehicle orbital stages in LEO and GEO region after the end of mission	Compliant
2	UN Outer Space Treaty		
3	IADC Space Debris Mitigation Guidelines		
4	ISO 24113 Space Debris Mitigation Requirements		
5	European Code of Conduct for Space Debris Mitigation		
6	NASA Space Debris Mitigation Standards	If casualty risk to population on ground is greater than 10^-4, • Avoid uncontrolled reentry in atmosphere • Ensure pre-defined impact footprint over an ocean area with sufficient clearance of landmass and traffic routes	Compliant
7	ESA Space Debris Mitigation for Agency Projects		
8	French Space Operation Act	Components should be placed in an orbit that does not interfere with protected regions more than one year.	Compliant

	Transparency	Actions
1	Space industry	-Submit papers for technological progress to space conferences -Discuss at space debris communities
2	Ordinary people	- Proactively talk to media to increase awareness of debris issue

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POTENTIAL COLLABORATION WITH SPACE AGENCIES

	Collaborations (examples)	Details
1	Ground equipment	More ground stations. Need compatibility
2	Launch	Provide launch opportunity, while we provide navigation data etc
3	Others	Let's discuss

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CONCLUSIONS

Progress

- Team is there
- Mother/Boy undergoing design, EM to be completed by April 2016
- Fund raising in good progress
- Factory to open in April 2015
- Rocket contract to be made late 2015

2017 Mission Novelty

- First full range of ADR mission
- First small satellite on-orbit-service demonstration
- First private company's demonstration

Keep you updated at Space Conferences and HP

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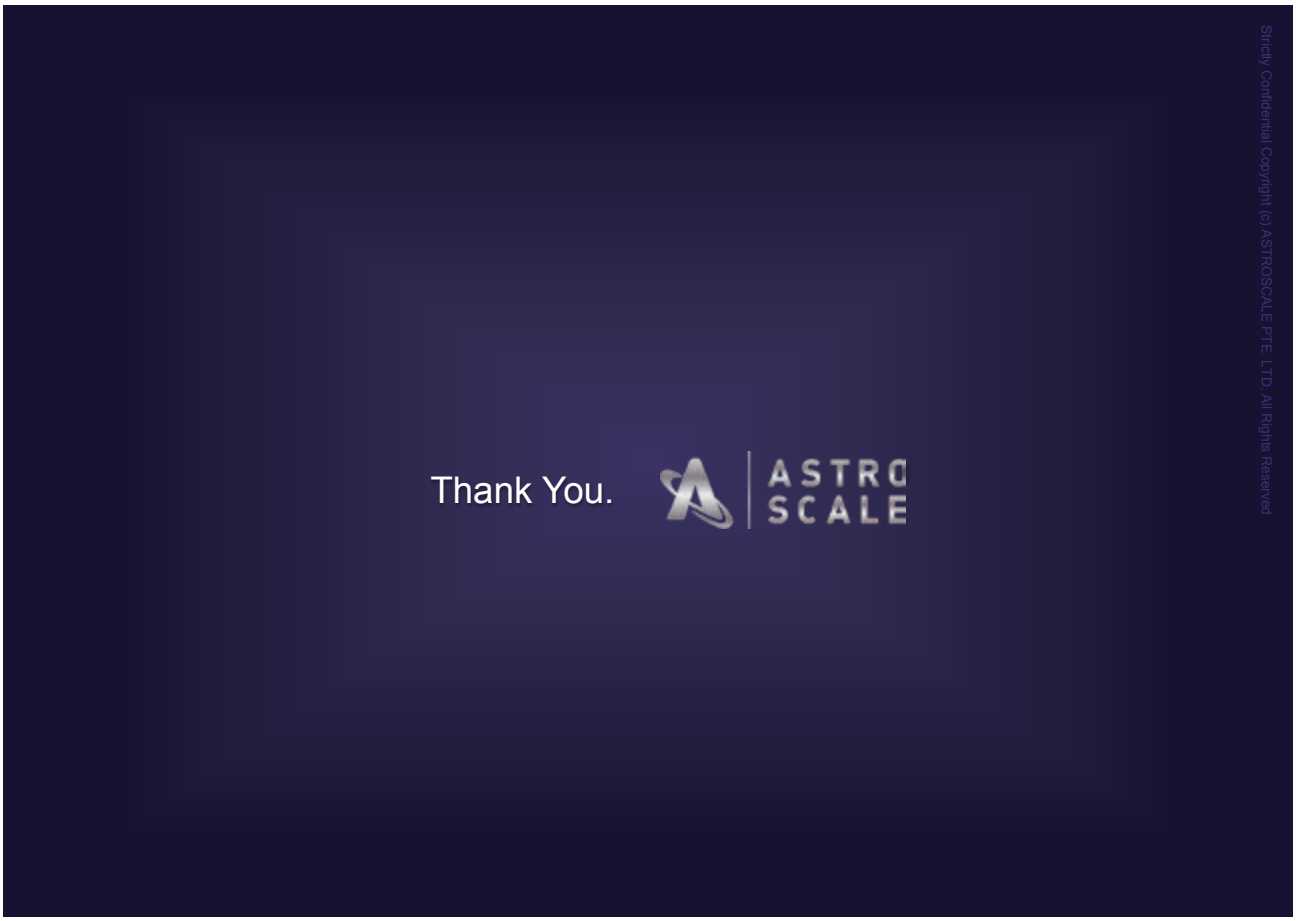

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一般セッション

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B1

世界のデブリ関連規制の動向

Current situation of the international space debris mitigation standards

加藤 明（宇宙航空研究開発機構）
Akira Kato (JAXA)

スペースデブリの発生の防止と衝突被害からの保護のための規格やガイドラインが様々な国際機関、国の政府、宇宙機関などから発行されている。国際標準化機構（ISO）でも種々の規格や技術レポートを発行し、現在も作成作業を続けている。これら規格の全貌を紹介し、他の世界の規格類と比較して紹介する。また、現在日本から提案し、制定作業中の「デブリ対策設計・運用マニュアル」の趣旨を説明する。このアニュアルにて ISO のデブリ対策活動の全貌が把握でき、システムレベルからコンポーネントレベルまでのデブリ対策活動の要点が包括的に理解できることを願っている。

Several debris mitigation standards and guidelines have been developed in the international organizations, the administrations of national governments, and national space agencies. The international organization for standardization (ISO) has also developed and being developed various debris related standards and technical reports. This presentation will introduce them and show the comparison among them. Also the current work to develop the “Space Debris Mitigation Design and Operation Manual” for spacecraft and launch vehicle orbital stages, which were submitted from Japan, will be introduced. This manual will support the space engineers to understand the total concept of the debris mitigation measures in ISO, and present recommendable activities with the hardware oriented manners for design and operation of the spacecraft subsystems and components.

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世界のデブリ関連規制の動向
Current situation of the international space debris mitigation standards

JAXA研究開発本部第6回スペースデブリワークショップ
JAXA Space Debris Work Shop

17-19 December 2014, Tokyo, Japan

加藤　明 [JAXA 安全・信頼性推進部、(併)研究開発本部]
Akira Kato, JAXA
Dr. ENG and P.E. Jp（Aerospace System）

1

内容
Contents

1. 軌道環境とデブリ衝突リスク
   Orbital Environment and Risk of Debris Impact
2. デブリの発生要因
   Major factors of debris generation
3. 世界のデブリ低減規格／ガイドライン
   Global Debris Mitigation Standards and Guidelines
4. 国際標準化機構(ISO)における取組み
   Activities in ISO

2

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1.軌道環境とデブリ衝突リスク
Orbital Environment and Risk of Debris Impact

3

Figure 1 Number of Objects Newly Observed or Decayed (or Escaped) Every Year
(Ref. Data from Satellite Situation Report / Space-Track / USSTRATCOM, @June 25, 2012) (processed by A. Kato)

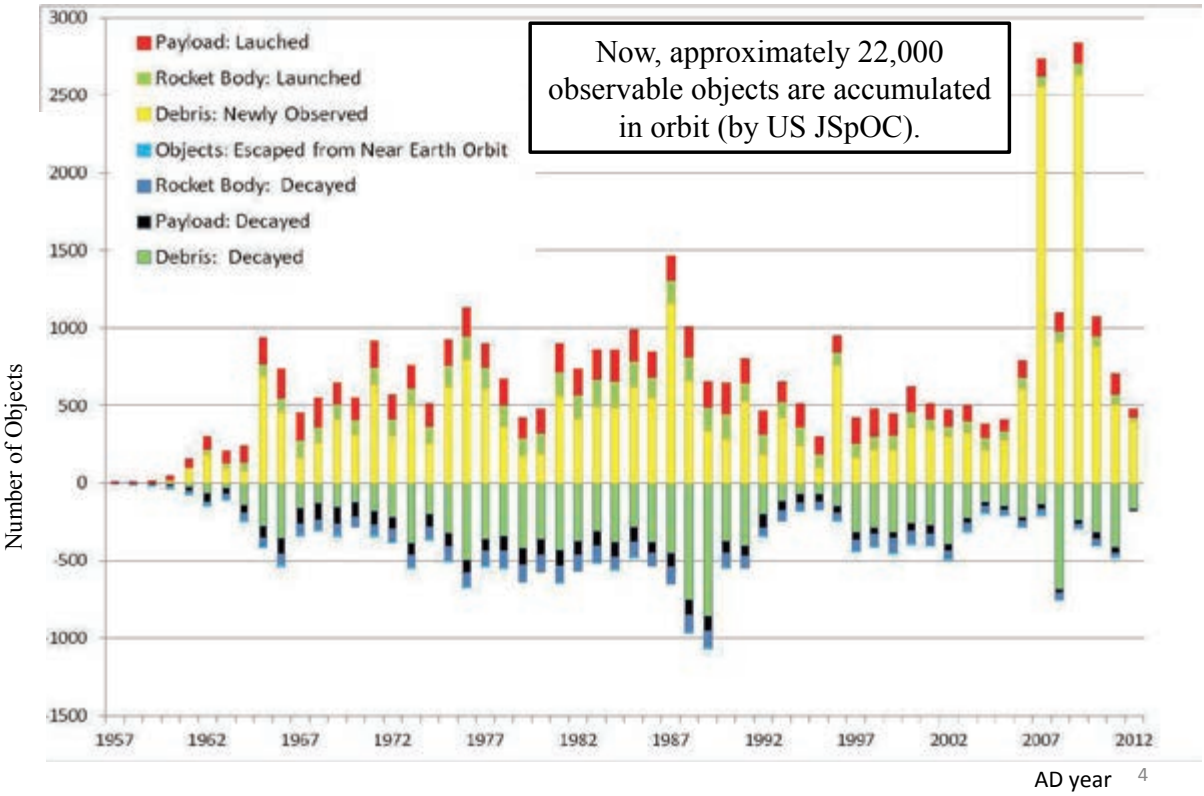

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Fig.-2 Number of Orbital Objects observed from the ground by US

(size > 10 cm in LEO, size > 1 m in GEO) @2014-9-3

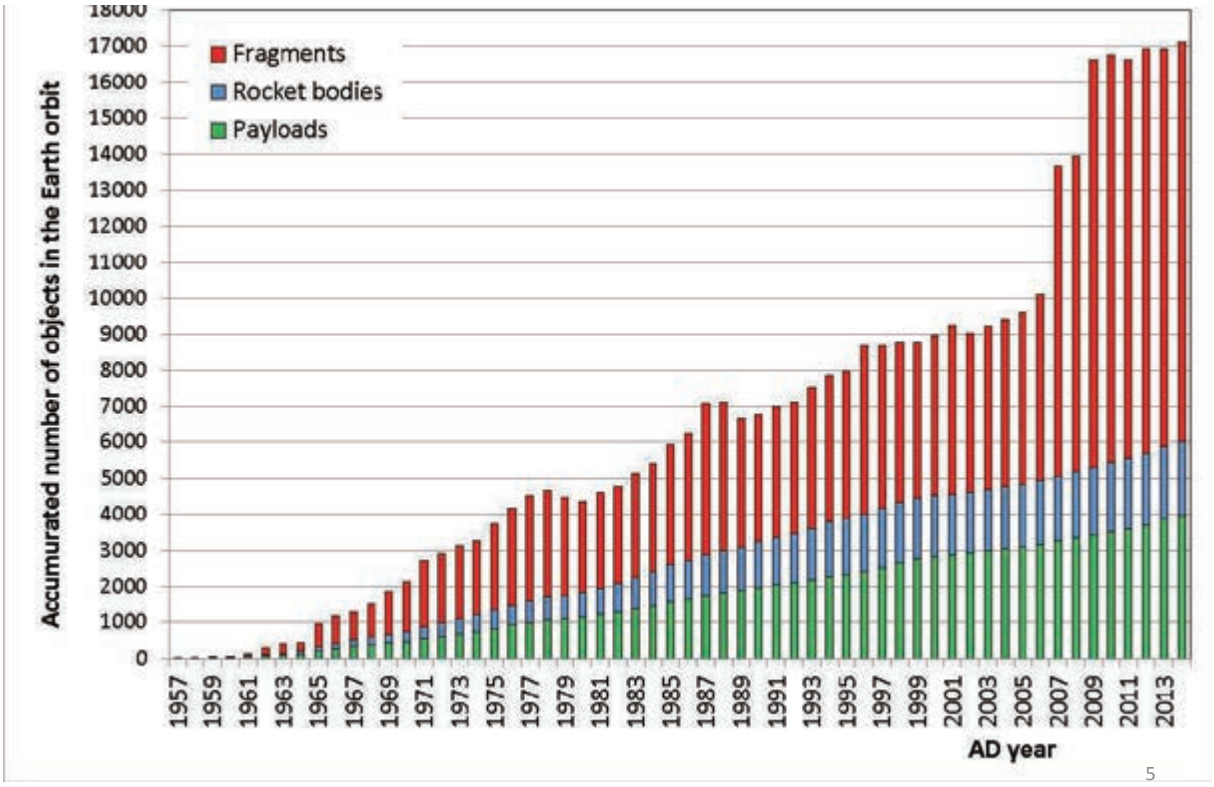
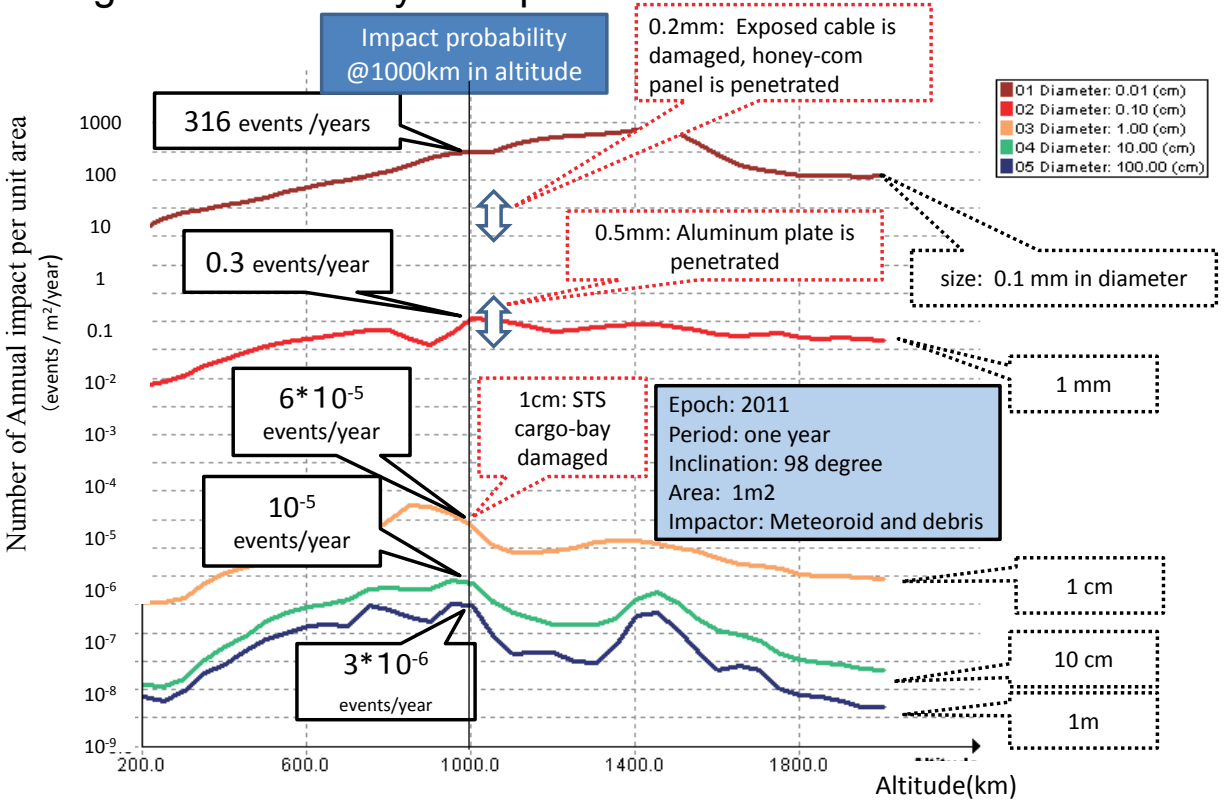


Fig.-3 Probability of Impact



Number of annual Impact according to Altitude (Analyzed by DAS-2/NASA) 6

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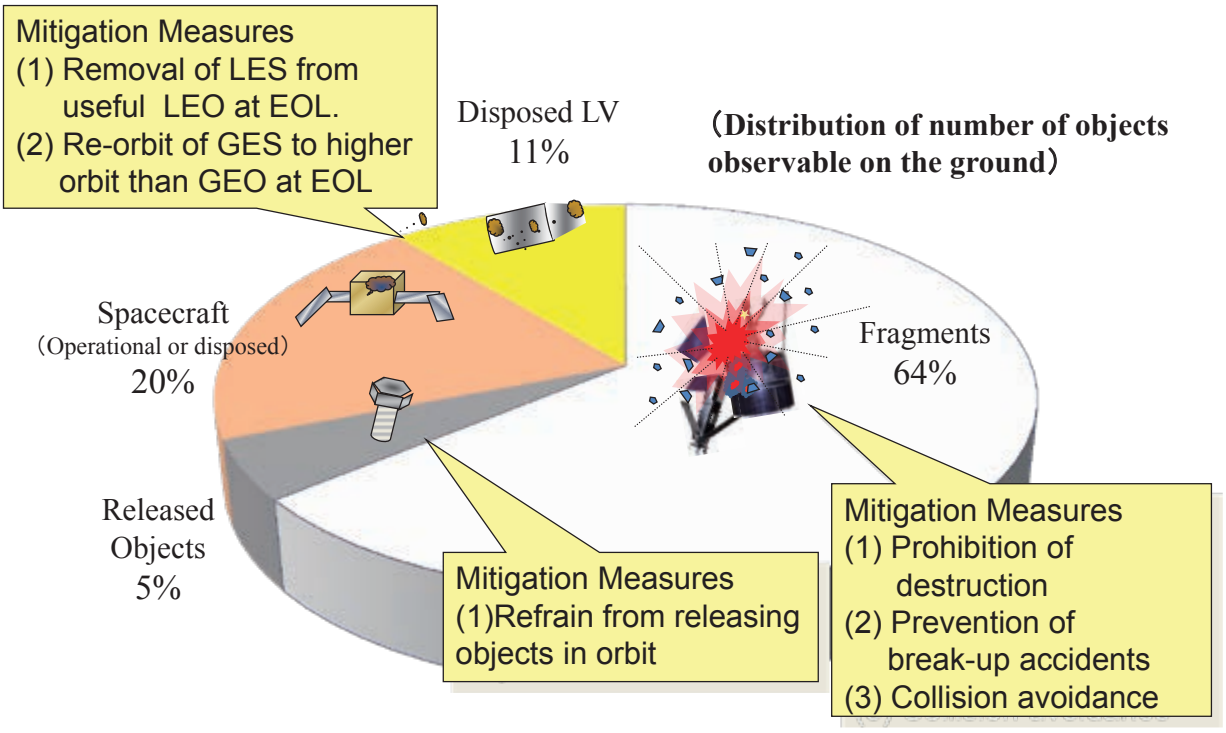
2. デブリの発生要因
Major factors of debris generation

7

Fig.-5 Causes of Debris Generation and Mitigation Measures



Data from a report of ESA presented at UNCOPUOS/STSC Conference held in February, 2011

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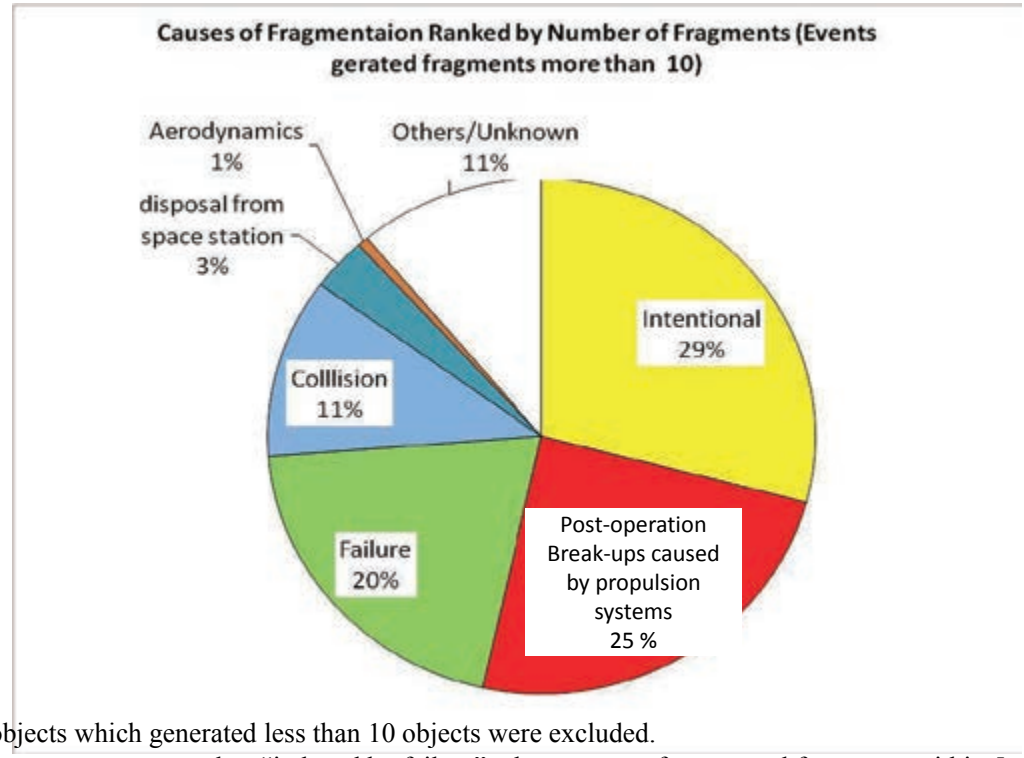
Fig. 7: Distribution of Causes of Debris According to the Number of Fragments



The objects which generated less than 10 objects were excluded.
The events were assumed as “induced by failure” when spacecraft generated fragments within 5 years after launching, or the launch vehicles caused break-ups on the same day of launching.

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3.世界のデブリ低減規格／ガイドライン
Global Debris Mitigation Standards and Guidelines

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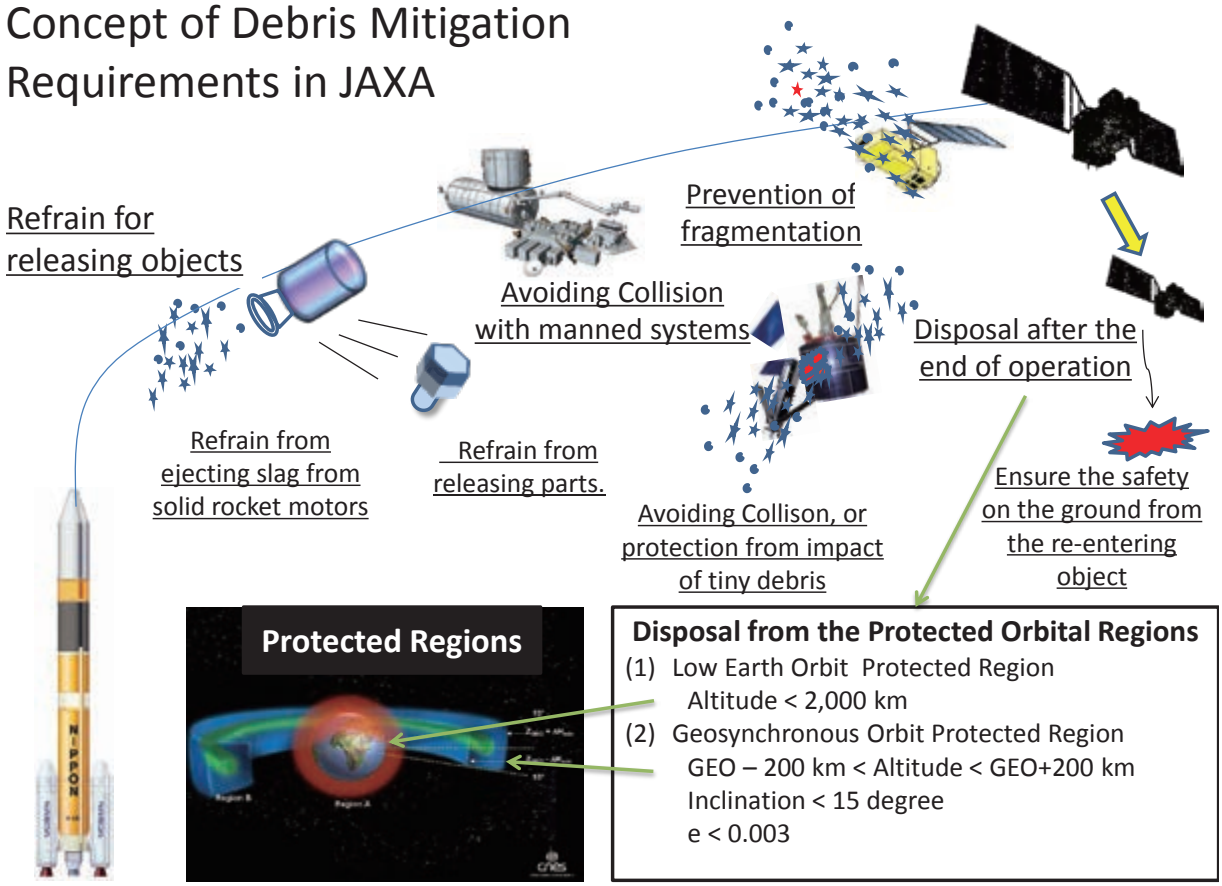
Concept of Debris Mitigation Requirements in JAXA

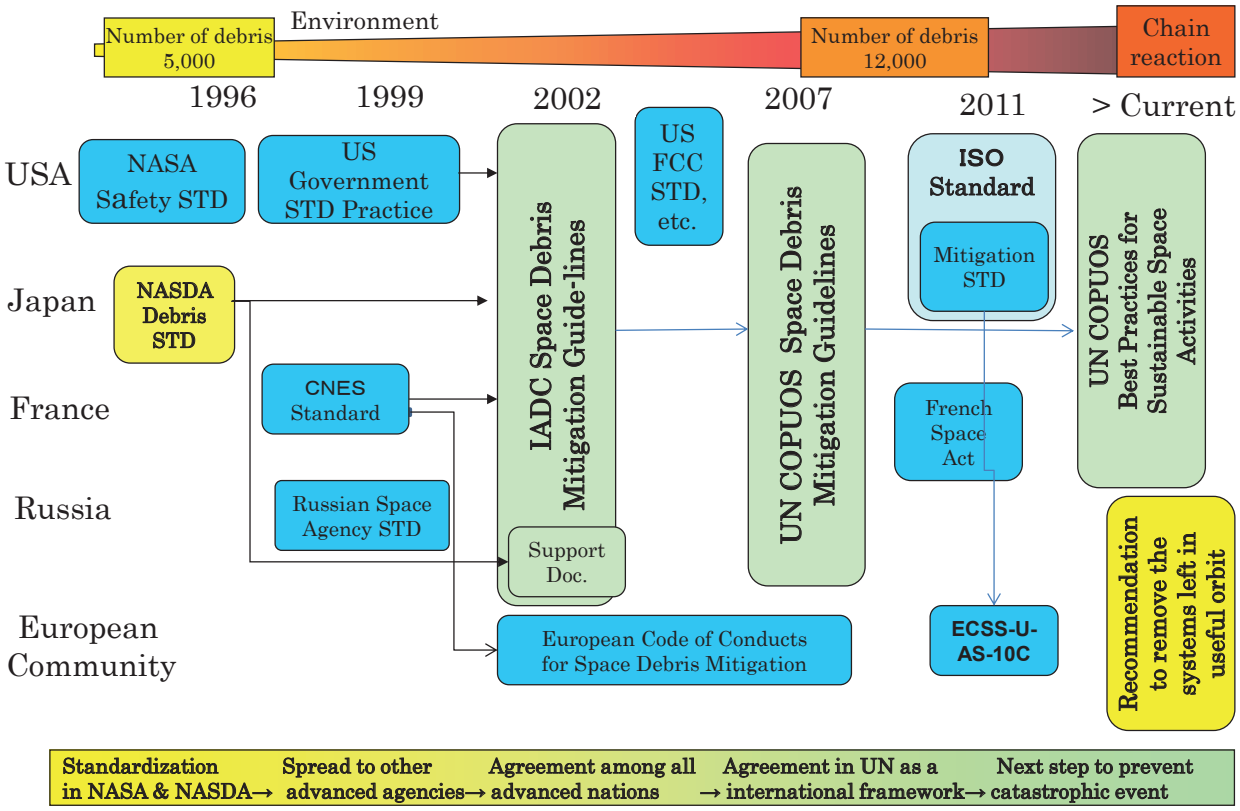


Disposal from the Protected Orbital Regions

(1) Low Earth Orbit Protected Region
Altitude < 2,000 km

(2) Geosynchronous Orbit Protected Region
GEO – 200 km < Altitude < GEO+200 km
Inclination < 15 degree
e < 0.003

History of the Regulation for Debris Mitigation



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Global debris mitigation rules and JAXA standard

The requirements are almost common including other various standards and guidelines.

		Measures	ISO Standards (or Technical Reports)	JAXA (JMR-003B)	IADC Guidelines [g]
Limiting Debris Generation	*Released Objects*	General idea to refrain from releasing objects	**ISO-24113 / § 6.1.1**	Required	§ 5.1
		Slag from Solid Motor	**ISO-24113 / § 6.1.2.2, § 6.1.2.3**	Required	--
		Combustion Products from Pyrotechnics	**ISO-24113 / § 6.1.2.1** (Combustion Products < 1 mm)	Combustion products < 1 mm	--
	On-orbital Breakups	Intentional Destruction	**ISO-24113 / § 6.2.1**	Required	§ 5.2.3
		Accident During Operation	**ISO-24113 / § 6.2.2** (Probability < 10^{-3})	Required (Monitoring) (Probability < 10^{-3})	§ 5.2.2 (Monitoring)
		Post mission Breakup (Passivation, etc.)	**ISO-24113 / § 6.2.2.3 (Detailed in ISO-16127)** (Probability < 10^{-3})	Required	§ 5.2.1
Disposal at End of Operation	*GEO*	Reorbit at EOL	**ISO-24113 / § 6.3.2 (Detailed in ISO-26872)** § 6.3.2.2: 235 km+ (1,000・Cr・A/m), e < 0.003 § 6.3.1: Success Probability > 0.9	235 km+ (1,000・Cr・A/m) e < 0.003 Success Probability >0.9	§ 5.3.1 235 km+ (1,000・Cr・A/m), e < 0.003
	LEO (MEO)	Reduction of Orbital Lifetime	**ISO-24113 / § 6.3.3 (Detailed in ISO-16164)** § 6.3.3.1: EOL Lifetime < 25years § 6.3.1: Success Probability >0.9	EOL Lifetime < 25years Success Probability > 0.9	§ 5.3.2 (Recommend 25 years)
		Transfer to Graveyard	**ISO-24113 / § 6.3.3.2 (f)** (guarantee 100 years' non-interference)	Required	Mentioned in recommendation-6
		Other manners	**ISO-24113 / § 6.3.3.2 (a) ~ (e)**	--	§ 5.3.2
Re-entry		Ground Casualty	**ISO-24113 / § 6.3.4 (Detailed in ISO-27875)**	Controlled with Ec	§ 5.3.2
Collision Avoidance with Large Debris			**ISO-16158**	Required (CAM, COLA)	§ 5.4
Protection from Impact of Tiny Debris			**ISO-16126**	Required	§ 5.4 13

4.国際標準化機構(ISO)における取組み
Activities in ISO

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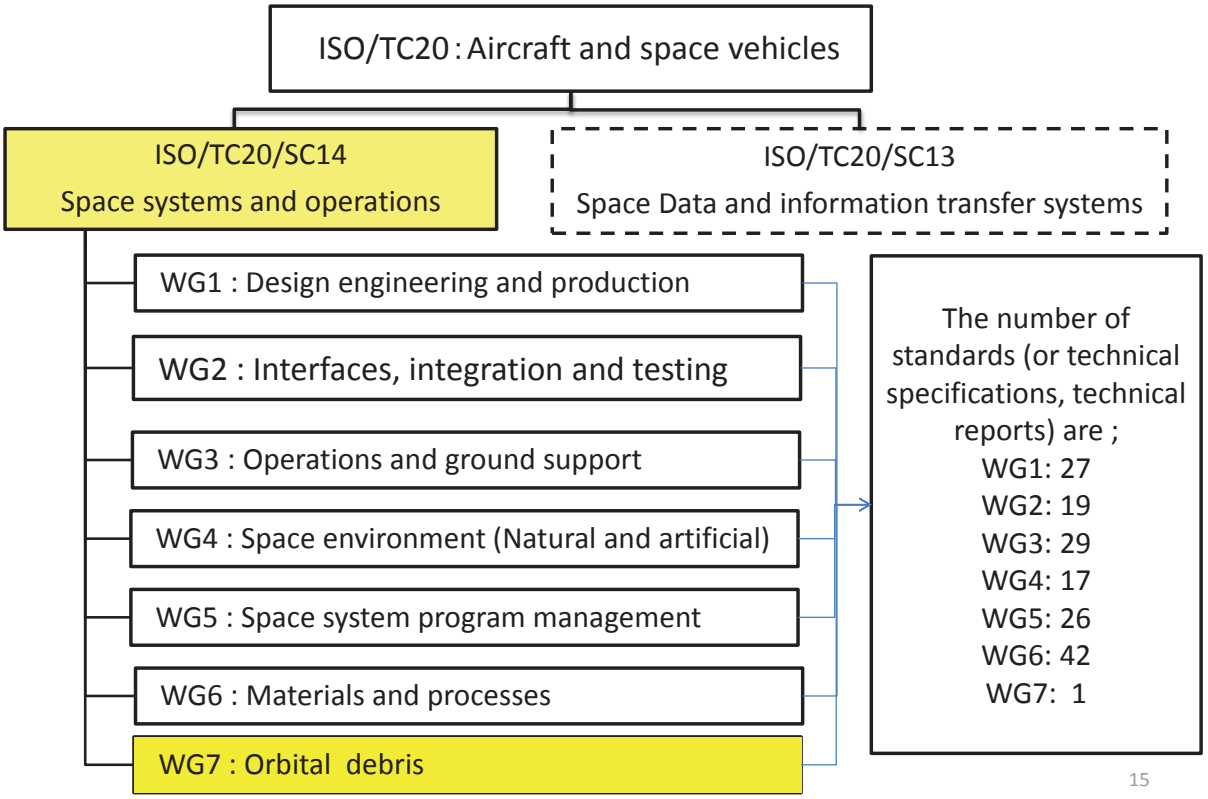
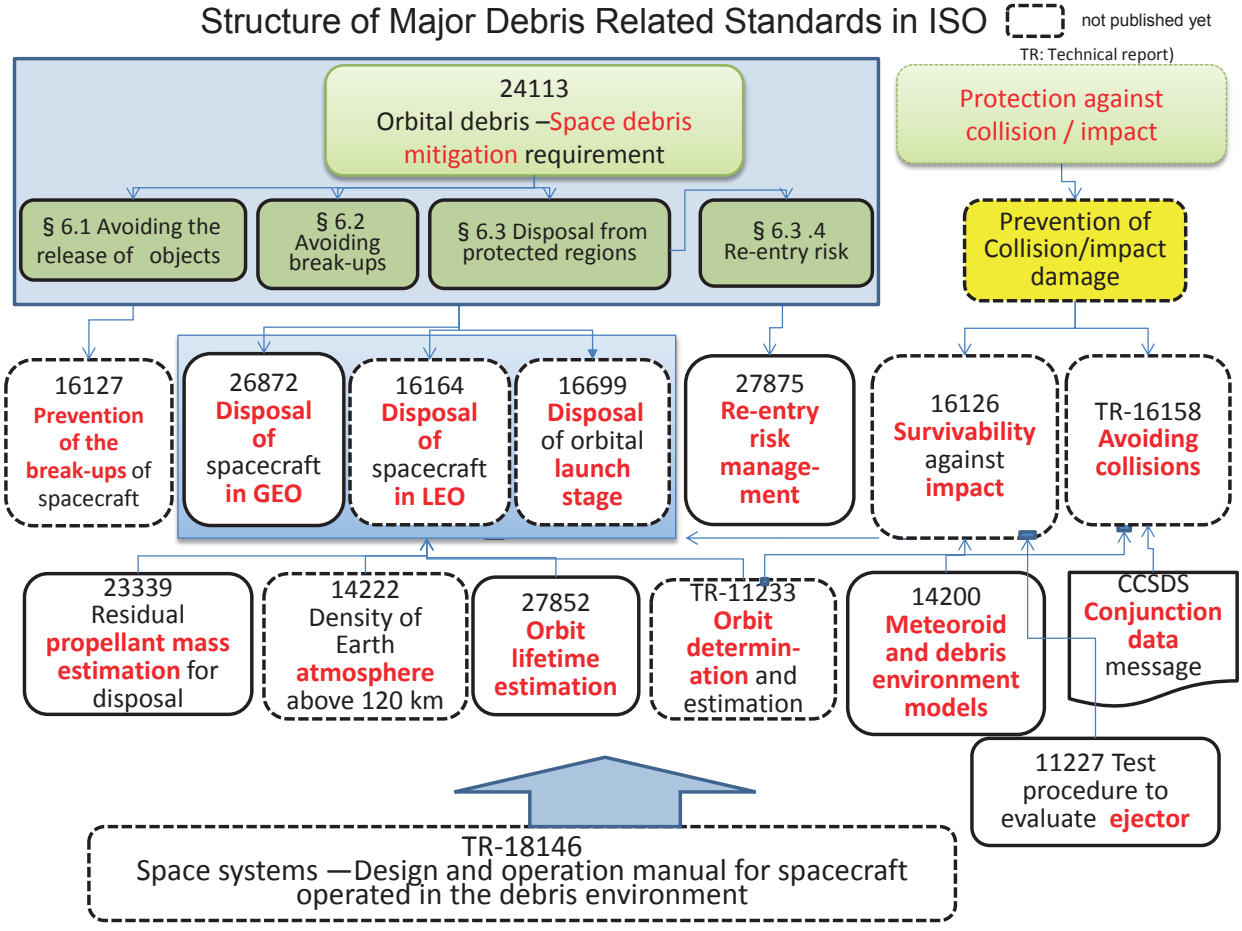
Set of standards in ISO／TC20／SC14

as support tools for transferring space technologies to ensure the Quality, Reliability and Safety



Structure of Major Debris Related Standards in ISO



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1. 宇宙機用デブリ低減設計・運用マニュアルの趣旨
Scope of TR-18146

(1) デブリ関連規格の増加への対処

Since there are so many debris related standards, engineers must refer many of them, and pick up the requirements for their responsible work from them.

Need a catalogue of standards and comprehensive linkage among them

(2) フェーズドプランニングへの適時対応

Since the some debris mitigation requirements should be take into consideration from the early phase,

Need a table to encourage the timely practices along the phased plan.

(3) 具体的作業への展開

High level standard (ISO-24113) presents requirements simply, and various medium level standard present what should be done. Need practical guidance but not in strict requirements rather as informative and soft –document as a Technical Report.

(4) サブシステム・機器設計者への推奨作業

Since high level requirements in ISO-24113 and medium level requirements are presented in objective oriented manner, while engineers need to be shown in hardware oriented manner.

Need integration of requirements and help to convert them into design specifications and allocate them to the lower subsystems and components

[Detail requirements are not imposed in this manual, but soften informative recommendable practices are provided to support sub-system engineers.]

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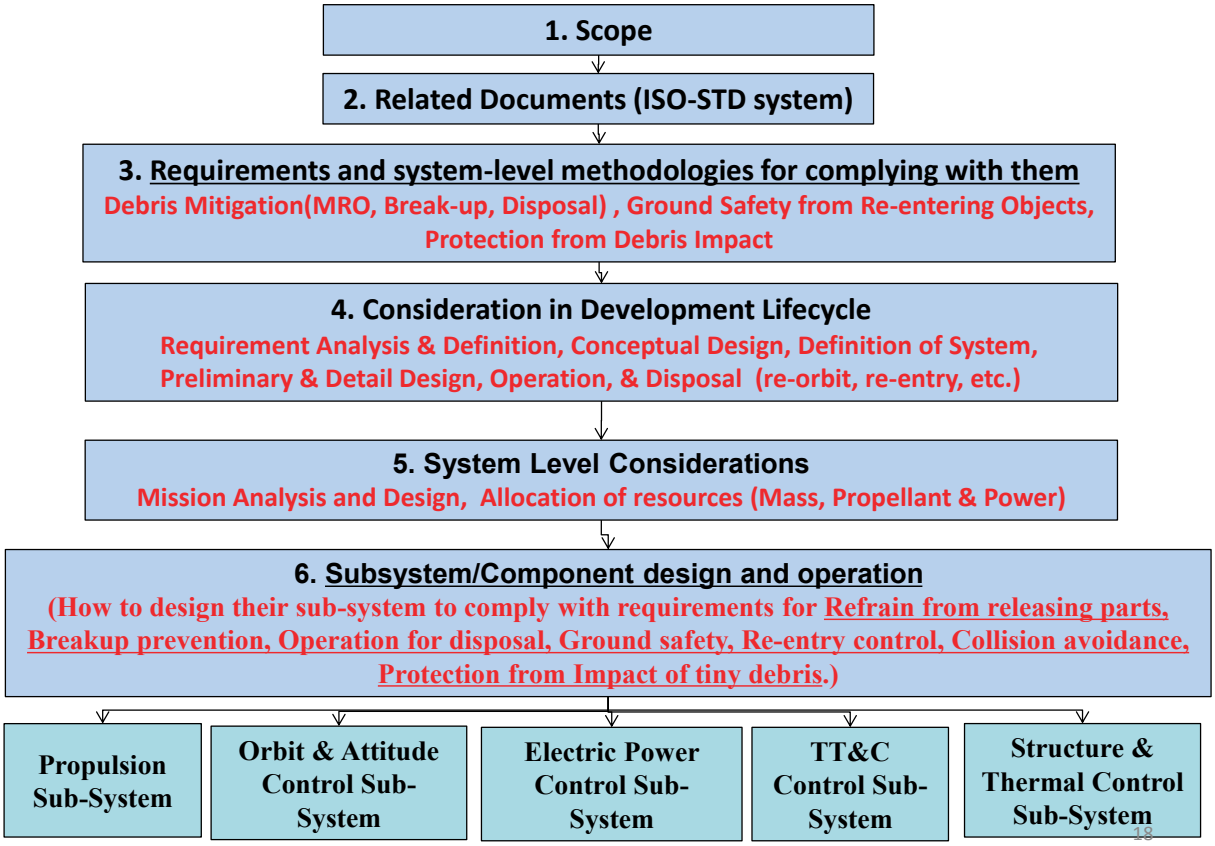
記述内容 Structure of TR-18146



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Requirements and system-level methodologies (Clause-3 in TR-18146*)*

(1) rationale or justification of requirements in high level standards (24113, etc.) as a support document for them, and

(2) what should be done, and work break-down for that,

Typically, works are broken-down and presented as following table.

Low level STDs will be introduced to see the detail. (Linkage will be cleared.)

Example: Table-1 Work breakdown for preventing orbital break-ups

Process	Subjects	Major works
Preventive measures	Identification of sources of breakup	Identify components that may cause fragmentation during or after operation. **(ISO-16127)**
	Design measures	(1) Prevent accidental break-up during operation. Provide functions to monitor symptoms of break-up. (2) Provide functions for depleting stored energy sources at the end of operation (3) Prohibit intentional break-up. **(ISO-16127)**
	Limiting the probability of B/U	Limit the probability of break-up by reliability design. **(ISO-24113)**
Risk detection	Monitoring during operation	Periodically monitor critical parameters. Take immediate actions if the symptom of a malfunction that could lead to a breakup is detected. **(ISO-16127)**
Counter measures	Preventive measures for break-up	If this kind of condition is detected, terminate the mission operation, and proceed to the disposal process Perform the disposal operations **(ISO-16164, -26872)**

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Consideration in Development Lifecycle (Clause-4)

Major works related to debris in each phase

Phase / Subjects	Pre-phase A: Mission analysis phase Phase A: Feasibility phase	Phase B: Definition phase Phase C: Development phase Phase D: Production phase	Phase E: Utilization phase	Phase F: Disposal phase
System-level work	1) Input debris related requirements 2) Clarify debris related design philosophy and input them to the system requirements & specification	1) Propellant allocation (including disposal, collision avoidance, controlled re-entry, etc.) 2) Mass allocation (including protection shields, propellants for debris issues, etc.)	1) Transfer debris-mitigation plan to operators. 2) Fix the procedure to determine the operation termination	1) Final determination for disposal action (including disposal maneuver, break-up prevention, controlled re-entry)
Quality Assurance	1) Clarify QA design philosophy 2) Define QA program including parts program	1) Ensure that the probability of successful disposal, non-break-up, and so on, are all high	1) Identify a disposal action for use in case of failure.	2) Ensure that the probability of successful disposal is high
Limiting of debris generation (ISO-24113/6.1)	1) Clarify debris-mitigation design philosophy	1) Fix the design to limit releasing objects, limit their orbital lifetime, etc. 2) Identify the energy sources of fragmentation, and design measures to prevent them.	1) Monitor critical parameters to check symptoms of critical malfunctions that lead to break-ups or prevent disposal actions.	1) Vent residual energy. 2) Terminate operation in the proper sequence.
Disposal (ISO-24113/6.3)	1) Clarify disposal concept 2) Estimate propellant for disposal	1) Design a propulsion subsystem for the planned disposal maneuver.	1) Monitor the residual propellant and identify the end-of-operation time in a timely manner.	1) Remove spacecraft to avoid interference with protected regions.
Re-entry safety (ISO-24113/6.5.4)	1) Clarify re-entry safety concept 2) Define re-entry survivability analysis method 3) Determine whether or not to apply controlled re-entry	1) Design a propulsion subsystem and attitude control system for controlled re-entry, if needed.		1) Conduct controlled re-entry.
Collision avoidance	1) Clarify avoidance procedures 2) Define debris population model and database to monitor the orbital objects	1) Design a propulsion subsystem for collision avoidance. 2) Allocate an amount of propellant for avoidance maneuvers	1) Perform periodic conjunction analysis, and determination of avoidance maneuvers, if needed.	
Impact protection	1) Clarify protection design philosophy 2) Define the debris population model and ballistic limit equations. 3) Estimate mass for shielding.	1) Protection design for vulnerable components to guarantee disposal function at least.		

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System Level considerations (Clause-5)

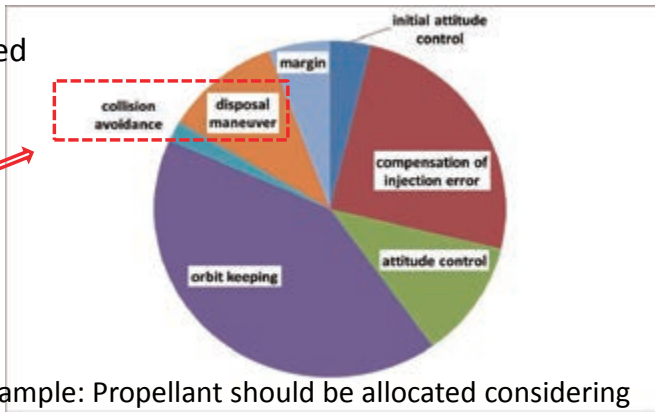
Debris mitigation measures effect on system design.
Clause 5 will present relation among mitigation works and following system design.

(1) Mission design
(2) Mass allocation
(3) Propellant allocation
(4) Power allocation

For example, followings are warned not to forget in allocation of propellant.

a. disposal operations
b. controlled re-entry, if it is planned
c. collision avoidance maneuvers

Debris mitigation design recommends not to forget those factors.



Example: Propellant should be allocated considering debris related consumption

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Subsystem/Component design and operation (Clause-6) (1/2)

Clause 6 will show how the debris mitigation requirements will be converted to design specifications and allocated to the lower sub-systems and components.
Sub-system engineers will grasp what they should do.

Table debris mitigation requirements and Linkage with functions allocated to sub-system

No	Debris-related items and practices	Necessity of subsystem-level functions					
		Propulsion RCS	AOCS /GNC	Power	TT&C	Structure	Thermal
1	Decrease (control) the number of separation/release items a) Parts released from fasteners, etc. b) slag from solid motors	Yes		Yes	Yes	Yes	
2	Prevent break-up in orbit after the end of operation due to: a) chemical explosion b) rupture of high-pressure vessels c) rotating devices	Yes Yes	Related	Yes			Yes
3	Monitor critical parameters to prevent break-up in orbit during operation	Yes	Related	Yes	Related		Related
4	Remove the spacecraft from protected orbital regions: a) Provide functionality for disposal maneuvers b) Measure residual propellant with high accuracy c) Choose an operation terminating sequence	Yes Yes	Yes	Yes	Related Related Related		
5	Ground safety from re-entering objects a) improvement of survivability b) prevention of pollution on the ground from toxic substance, etc. c) controlled re-entry	Yes Yes Yes	Yes		Yes	Yes Yes	
6	Collision avoidance for large objects a) conjunction assessment, and collision avoidance	Yes	Yes		Related		
7	Protection against the impact of micro-debris a) protection design	Yes	Related	Yes	Related	Yes	Related

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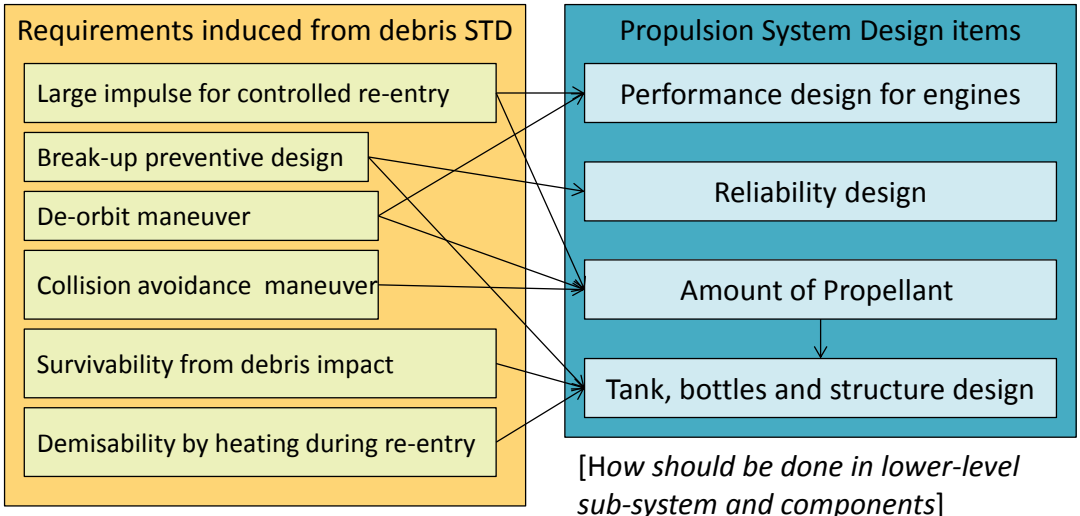
Subsystem/Component design and operation (Clause-6) (2/2)

Following is an example of the propulsion sub-system. Debris related standards present various requirements. Many of them are satisfied by propulsion engineers, but since they are not presented in hardware oriented manner, those engineers must pick-up related requirements from them and integrate them, and convert them into design specifications.



[*What shall be done in system-level*]

[*How should be done in lower-level sub-system and components*]

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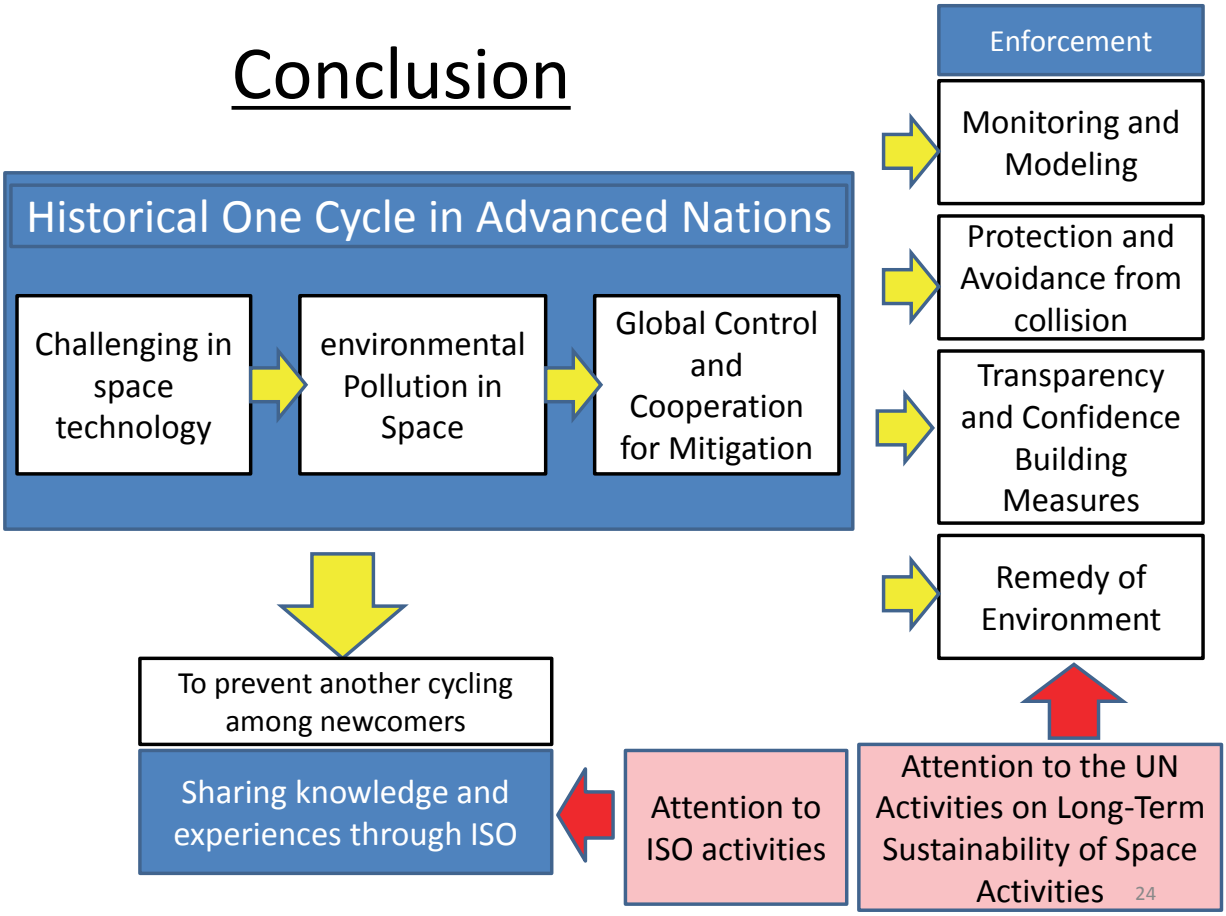
Conclusion



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B2

宇宙ごみのモデリングとその応用について
Orbital Debris Modeling and Applications

花田 俊也 (九州大)
Toshiya Hanada (Kyushu Univ.)

宇宙ごみのモデリングにより，現在および将来のデブリ分布を予測する推移モデルを構築し，どのようにすればデブリを低減できるか，あるいは環境を改善できるか，を議論することができる．また，宇宙ごみのモデリングにより，地上光学望遠鏡を用いてどのように観測すれば効率的に未知のデブリを探索することができるか，並びに，地上から追跡できない小デブリの計測を軌道上で実施する際の実用性を行かできる．別の応用として，環境改善のために除去すべき人工物の姿勢運動を推定することもできる．この講演では，九州大学で注力している宇宙ごみのモデリングとその応用について紹介する．

The orbital debris modeling can build evolutionary models as essential tools to predict the current or future orbital debris populations, and also to discuss what and how to do for orbital debris mitigation and environmental remediation. The orbital debris modeling can also devise an effective search strategy applicable for breakup fragments in the geostationary region using ground-based optical sensors, and to evaluate the effectiveness of space-based measurements of objects not tracked from the ground, both to contribute to space situational awareness. Another application of the orbital debris modeling is to estimate attitude motion of space objects to be removed for environmental remediation. This paper briefly introduces efforts into orbital debris modeling and applications.

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Orbital Debris Modeling and Applications

Toshiya HANADA
Kyushu University, Fukuoka, Japan

Orbital Debris Modeling

Orbital debris modeling describes:

- **Debris generation**
  - To characterize and predict physical properties of breakup fragments
- **Orbit propagation**
  - To characterize, track, and predict the behavior of individual or groups of space objects

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Applications

Orbital debris modeling can be applied to:

- **Future projections**
  - To investigate the stability of the current or future orbital debris populations
  - To discuss what and how to do for space debris mitigation and environmental remediation
- **Light curves**
  - To understand how space objects tumbles through their light curves in optical measurements
- **Measurements**
  - To devise an effective strategy for searching possible fragments from orbital anomalies in the geostationary region using small-aperture telescopes
  - To evaluate the effectiveness of in-situ measurements of objects not tracked from the ground

Debris Generation

To characterize and predict physical properties of breakup fragments

- Simulated spacecraft walls
  - To investigate low-velocity impacts on spacecraft
  - Outcome were all non-catastrophic, resulting in craters or holes on simulated spacecraft walls
- CANSAT
  - To investigate outcome of a catastrophic impact
- Micro satellites
  - To compare low-velocity and hypervelocity catastrophic impacts on identical micro satellites
  - To investigate the effects of impact directions on fragmentation
  - To investigate fragments originating from multi-layer insulation and solar panels

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Example and Result of Satellite Impact Fragmentation

Orbit Propagation

To characterize, track, and predict the behavior of individual or groups of space objects

- Numerical orbit integrators
  - To reproduce archived orbital history
  - Integrates the rate of change of the classical orbital elements in the Gaussian form of the variation of parameter equations
  - Integrates equations of satellite orbit motion in the Cowell's formulation
- Analytical orbit integrators
  - To be used in future projections using orbital debris evolutionary models
  - Calculates only the secular and long-term variations of the classical orbital elements

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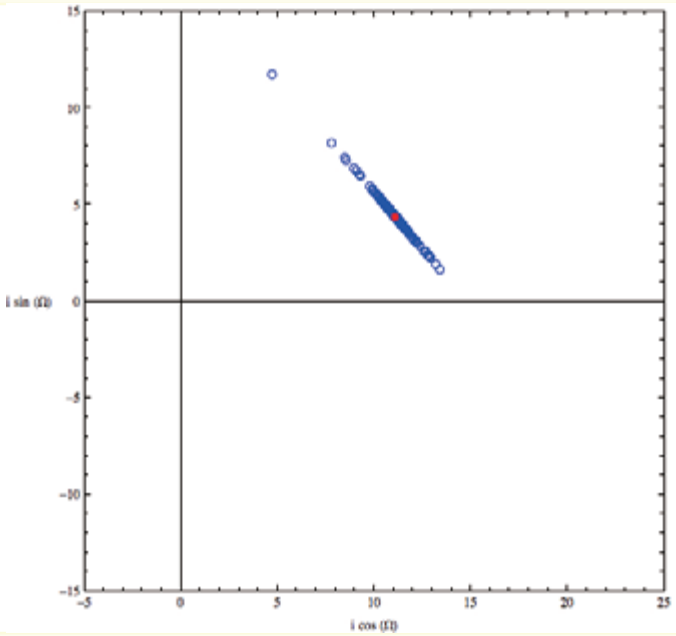
Example of Evolution of Explosion Fragments in the Geostationary Region



$x = i \times \cos(\Omega)$
$y = i \times \sin(\Omega)$

i = inclination
Ω = ascending node

• = US Titan IIIC Transtage
○ = explosion fragments

Future Projections

- Orbital debris evolutionary models
  - To investigate the stability of the current or future orbital debris populations
  - To discuss what and how to do for orbital debris mitigation and environmental remediation
- GEODEEM
  - To track objects in the geostationary region (or with eccentricity < 0.2, mean motion between 0.9 and 1.1 rev/day, and inclination < 70 deg)
- LEODEEM
  - To track objects in the low Earth orbit region (or with perigee altitude < 2000 km)
- NEODEEM
  - To track all objects orbiting around Earth

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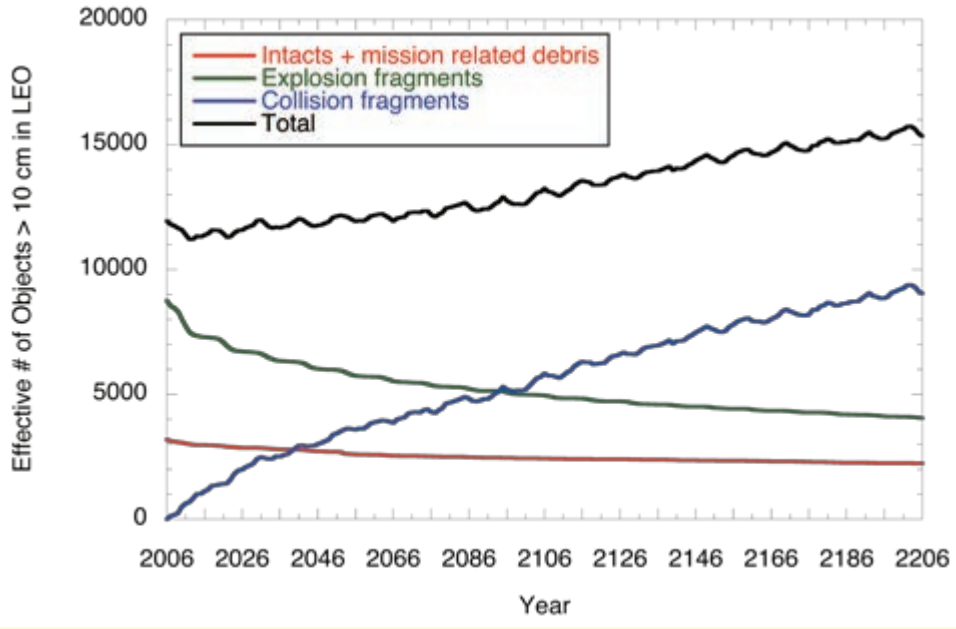
Projection Scenario

- Use the same initial population as of 1 January 2006
- Set the initial epoch to 1 January 2006
- Carry out future projection for 200 years
- Use the same solar flux table for drag calculation
- Allow no new launches beyond 1 January 2006
- Set future explosion to 0
- Allow no station keeping
- Include objects 10 cm and larger in collision consideration
- Use the NASA standard breakup model to predict the outcome of collisions
- Run as many Monte Carlo (MC) simulations as possible

LEO Population Growth



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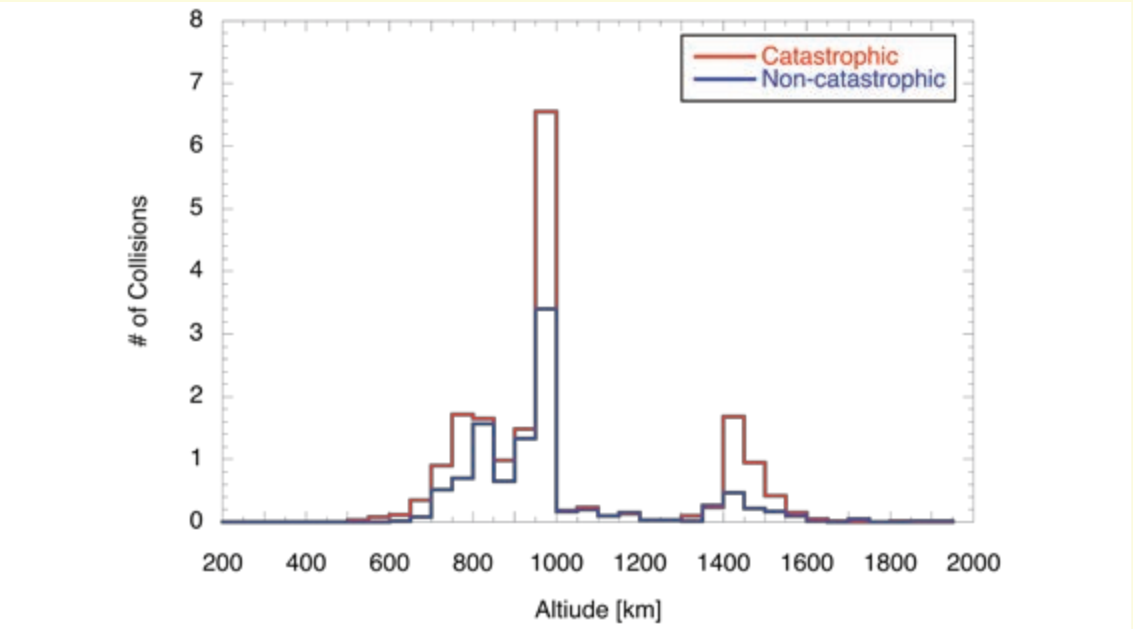
Collision Locations



Light Curves

- Active debris removal (ADR) is considered a necessary means to remediate the LEO environment
  - The majority of the potential ADR targets are large/massive intact objects (upper stages and payloads)
  - Limited data indicate that many of them have non-trivial tumble rates (faster than 1 rpm)
  - Fast tumble rates will be a major problem during ADR proximity and docking operations
- International collaboration on the characterization of the tumble motions of the potential ADR targets is key to guide the necessary technology development for future ADR operations
- The tumble motion can be characterized through **light curves**, change of brightness in optical measurements

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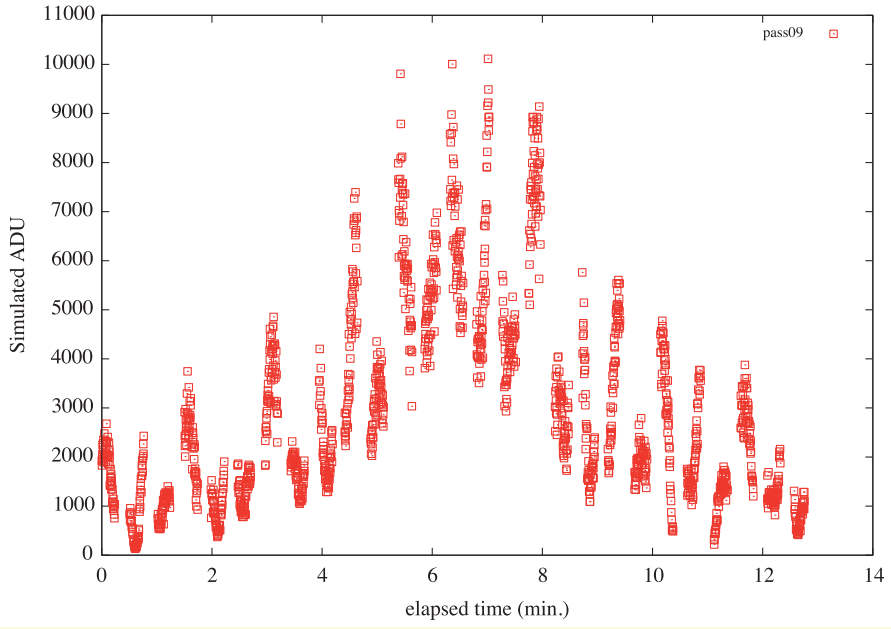
Efforts to Be Emphasized

- **Perturbed reference frame introduced** to define attitude
  - Reference frame rotates at $(0, -h/r^2, -rF_W/h)$, where h is angler momentum, r is radius, and **F_W is perturbing acceleration normal to orbital plane**
  - **Rotation about yaw axis** represents nodal regression mainly due to Earth's oblateness
  - Rotation about pitch axis is also subject to orbit perturbations because of non-conservative angular momentum in perturbed orbit motion
- **Orbit perturbation induced torques that vary attitude carefully modeled/considered**
  - Spacecraft modeled as **consisting of multiple facets**
  - Resultant perturbing forces and external torques evaluated after calculating on each facet

Example of Light Curves



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Optical Measurements

- Four very old Titan IIIC Transtages (1966-053J, 1667-066G, 1973-100D, 1978-113D) have experienced abrupt orbital changes for unknown reasons
  - Orbital changes have been equivalent to ΔV of only **a few meters per second**
  - **No debris clouds** have yet been associated with these Transtages
- ESA has listed six very old Titan IIIC Transtages (1966-053J, 1967-066G, 1968-081E, 1973-040B, 1975-118C, 1979-053C) as objects that have released fragments
  - **1968-081E observed as it fragmented**, but the others have not yet been identified
  - Archived orbital history not available for 1973-040B, 1975-118C, 1979-053C
- Confirmation which of Transtages have actually released fragments brings a better understanding of the present orbital debris environment
  - Effective strategy for searching possible fragments from orbital anomalies can be devised based on **orbital debris modeling**

Issues to Be Solved and Solutions

- Issues to be solved:
  - **Cost** of larger aperture (> 1 m) telescope
  - Uncertainty in **population**
  - Uncertainty in **motion**
  - Difficulty in detection of **low-luminosity** objects
- Solutions:
  - **Orbital debris modeling** enables **population prediction** and **motion prediction**
  - Population prediction enables **effective observation planning**
  - Combination of JAXA stacking method with motion prediction enables **sub-meter-sized aperture telescopes to detect fainter objects** by stacking successive images that have been shifted according to the predicted motion of the target object

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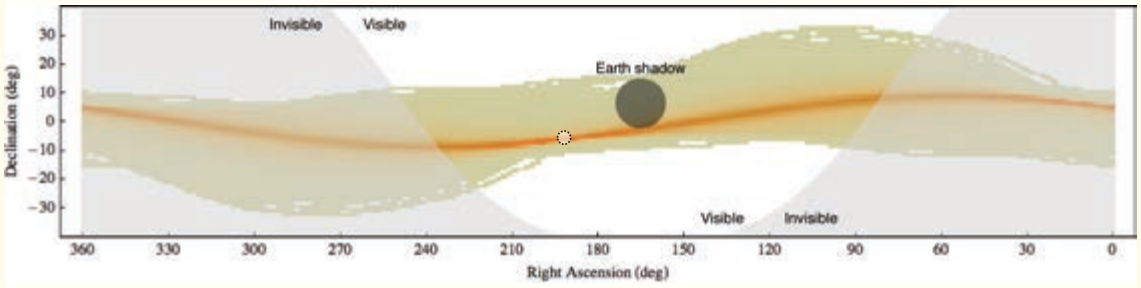
Example of Effective Observation Planning

- Use **population prediction**
- Mask **invisible region** from a given site
- Overlay **Earth shadow** at the nominal geostationary altitude
- Specify **the point where most fragments will be detected**
- Set **duration** to keep looking at the point



In-situ Measurements

- Current environment has not been defined well because
  - Measurements of micron-size debris are
    - Nearly impossible from the ground
    - **Quite limited** in terms of orbital regimes
    - **Not continuously** available
  - Latest information on micron-size debris may
    - **Not be enough regarding recent major breakups** such as
      - Chinese anti-satellite test using Fengyun-1C on 11 Jan. 2007
      - US Iridium 33 and Russian Cosmos 2251 accidental collision on 9 Feb. 2009
- Information should be dynamically updated based on measurements in the actual environment

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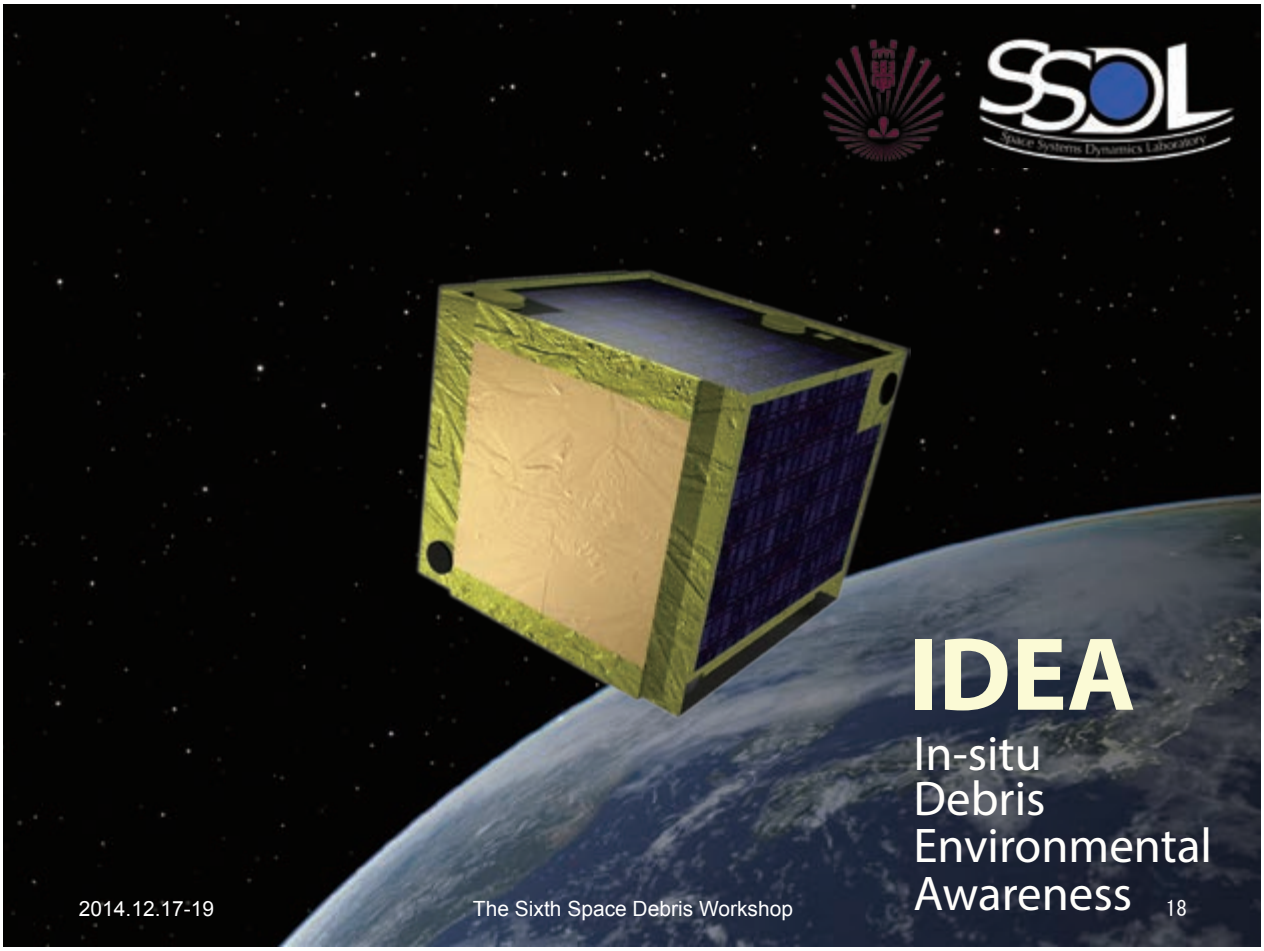

IDEA the project for In-situ Debris Environmental Awareness

- Aims at a **prompt and clear understanding** of micron-size debris environment
- Deploys a group of **micro satellites** conducting in-situ and real-time measurements of micron-size debris
- Realizes a **high temporal-spatial resolution**
- Defines and **dynamically updates** micron-size debris environment
- Identifies **environmental change** due to a breakup
- Estimates **impacts on the future** micron-size debris environment

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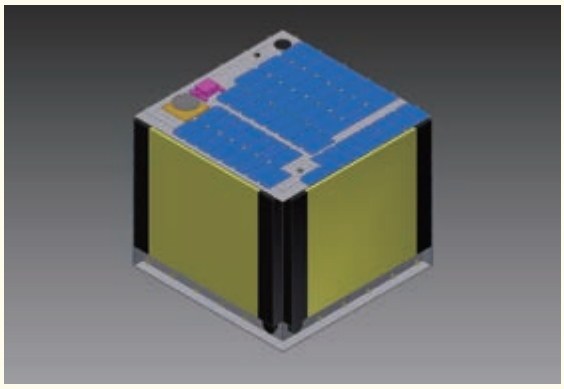
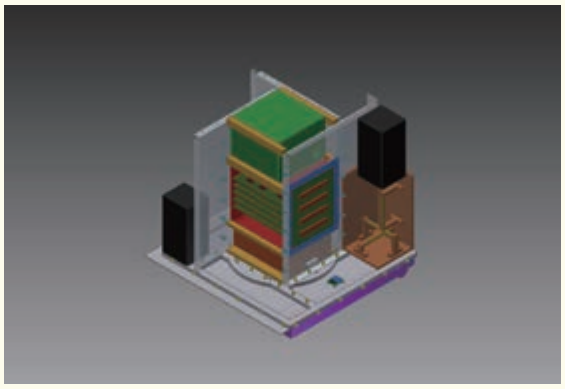
Schematic Design of IDEA Satellite



External View

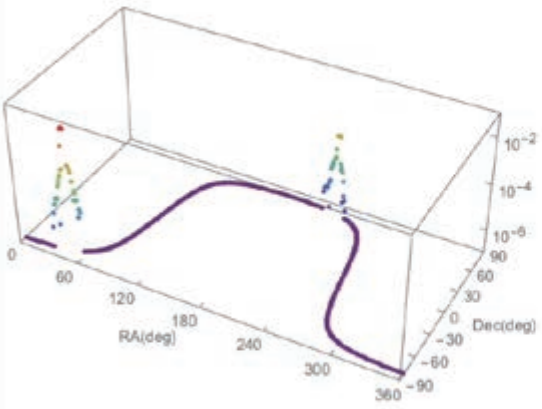


Inner Layout

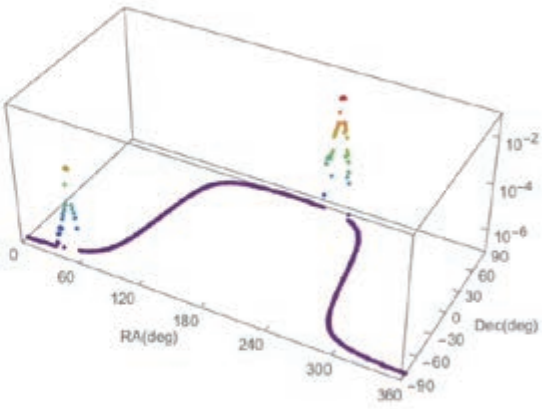
Dimension	**50 cm by 50 cm by 50 cm**
Mass	**25 kg**
Power	**31.5 W**

Example of Environmental Change in Collision Flux (1/m^2/year) Due to a Breakup

Left Sensor



Right Sensor



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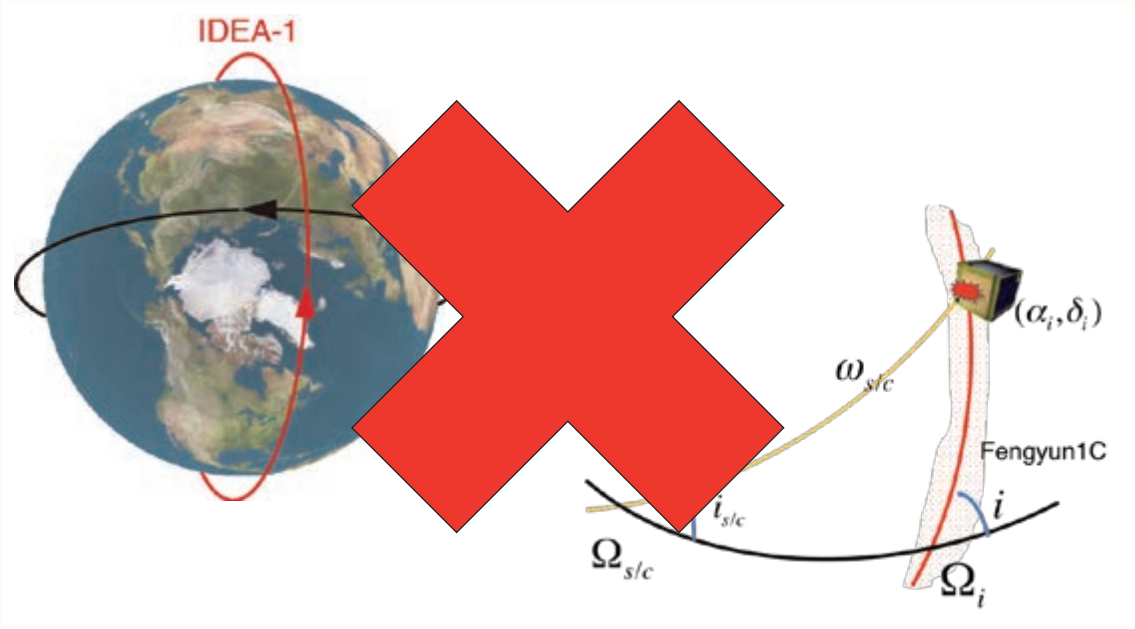
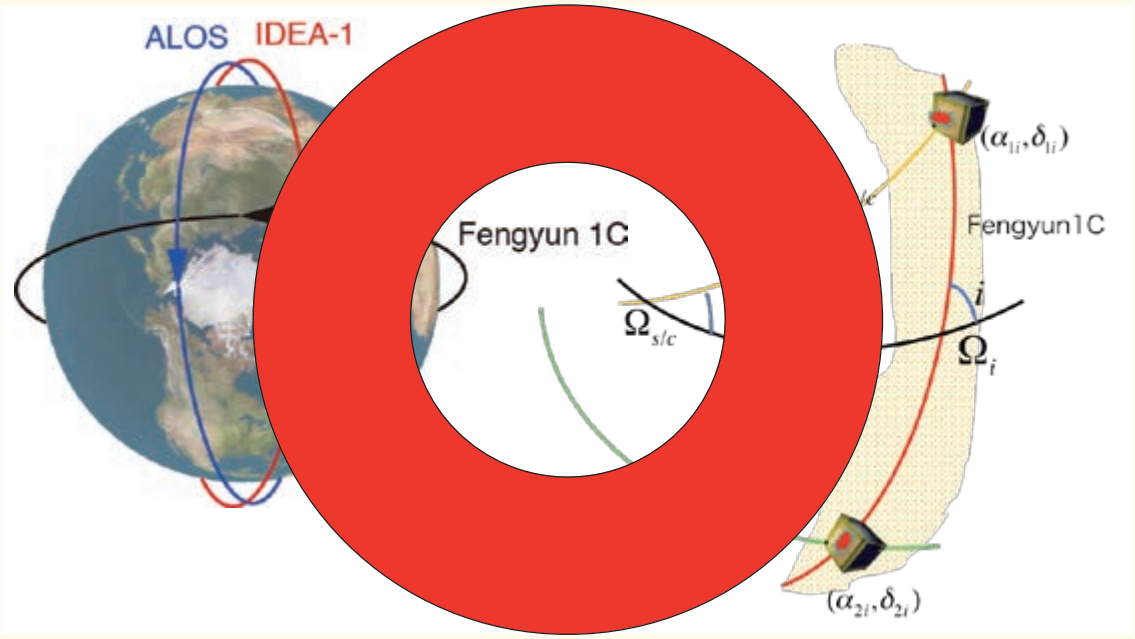
One Measurement Satellite



Two Measurement Satellites



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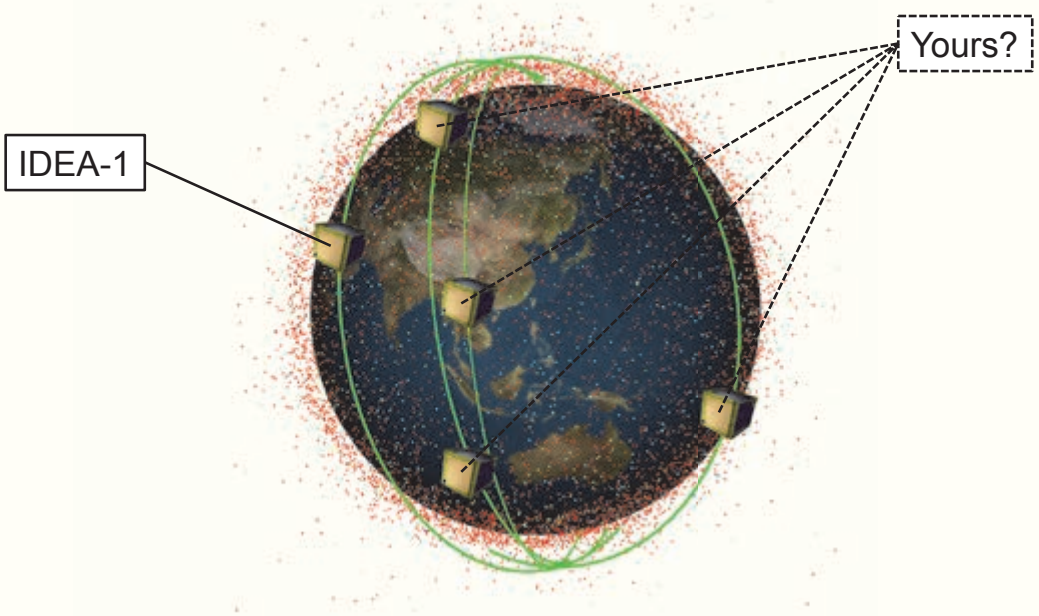
Future Vision of Collaboration Through IDEA



Summary

- Orbital debris modeling describes **debris generation** and **orbit propagation**, and can be applied:
  - To investigate the stability of the current or future orbital debris populations
  - To discuss what and how to do for space debris mitigation and environmental remediation
  - To understand how space objects tumbles through their light curves in optical measurements
  - To devise an effective strategy for searching possible fragments from orbital anomalies in the geostationary region
  - To evaluate the effectiveness of in-situ measurements of objects not tracked from the ground
- Research and development on orbital debris modeling and applications are essential to **long-term sustainability of space activities**

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B3

デブリ観測・防御技術の研究開発動向

Research and Development of Space Debris Observation and Protection Technologies

○柳沢俊史，東出真澄（宇宙航空研究開発機構）
○Toshifumi Yanagisawa and Masumi Higashide (JAXA)

デブリ問題解決のためのアプローチとしてデブリ観測及び防御技術があげられる。現在、低軌道デブリの観測能力は 10 ㎝であるのに対し宇宙機が防御できるサイズは数 mm といわれている。観測及び防御能力の向上によりこのギャップを埋めることはデブリ問題の解決に大きく貢献する。講演では世界でどのような観測、防御技術に関する研究開発が実施されているかを概観し、JAXA 未踏センター内で行われている最新の研究開発内容を紹介する。観測技術に関しては光学観測装置を利用した未カタログデブリの検出や軌道決定技術について、防御技術については 2 段軽ガスガンを利用した宇宙機構成物に対するデブリ衝突時の特性について説明する。

In order to cope with the space debris problem, improvements of observation and protection technologies must be considered. The main concern is that there is a gap between observable size (10cm) and protectable size (a few mm). Burying this gap by enhancing both observation and protection technologies will greatly contribute to solving the problem. I would like to outline what is currently going on the areas of space debris observation and protection in the world and introduce our activities in JAXA on these area.

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Research and Development of Space Debris Observation and Protection Technologies

Japan Aerospace Exploration Agency (JAXA)

Innovative Technology Research Center

T. Yanagisawa, M. Higashide

1

Abstract

In order to cope with the space debris problem, improvements of observation and protection technologies must be considered. The main concern is that there is a gap between observable size (10cm) and protectable size (a few mm). Burying this gap by enhancing both observation and protection technologies will greatly contribute to solving the problem. This talk outlines what is currently going on the areas of space debris observation and protection in the world and introduce our activities in JAXA on these area.

2

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U.S.A.

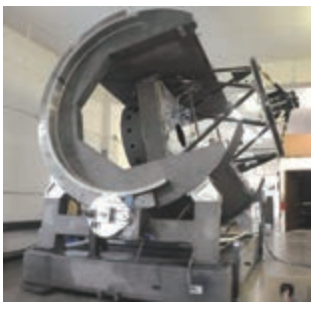
Improving Space Surveillance Network (SSN) to Space Fence System is underway. Space objects of about 10 times will be tracked. Joint Space Operations Center (JSpOC) is providing the conjunction assessment services to satellites' operators since 2009.

3

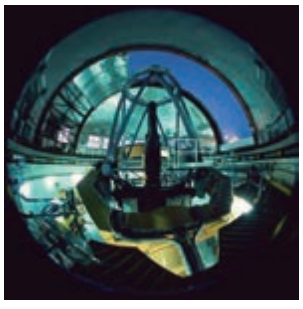
U.S.A.

61cm MODEST Telescope at CTIO in Chile

6.5m Magellan Telescope at CTIO in Chile



Meter Class Autonomous Telescope in Ascension Island



3.8m UKIRT Telescope in Hawaii

NASA is collecting GEO debris data using 61cm MODEST telescope in Chile under the collaboration with Michigan University since 2001. From 2011, 6.5m Magellan Telescope which can carry out spectroscopy is being used.

Meter Class Autonomous Telescope is being constructed in Ascersion Island. The telescope will be able to observe GEO and LEO with photometry and spectroscopy mode. It will also contribute SSA.

3.8m UKIRT Telescope for IR photometry and spectroscopy is also available.

4

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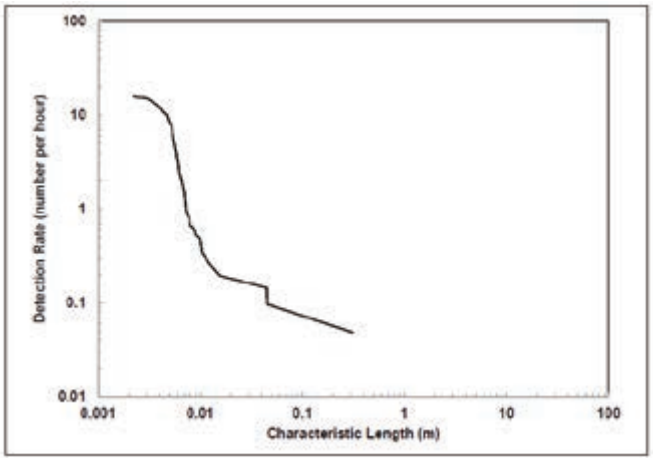
U.S.A.

Haystack radar in Lexington

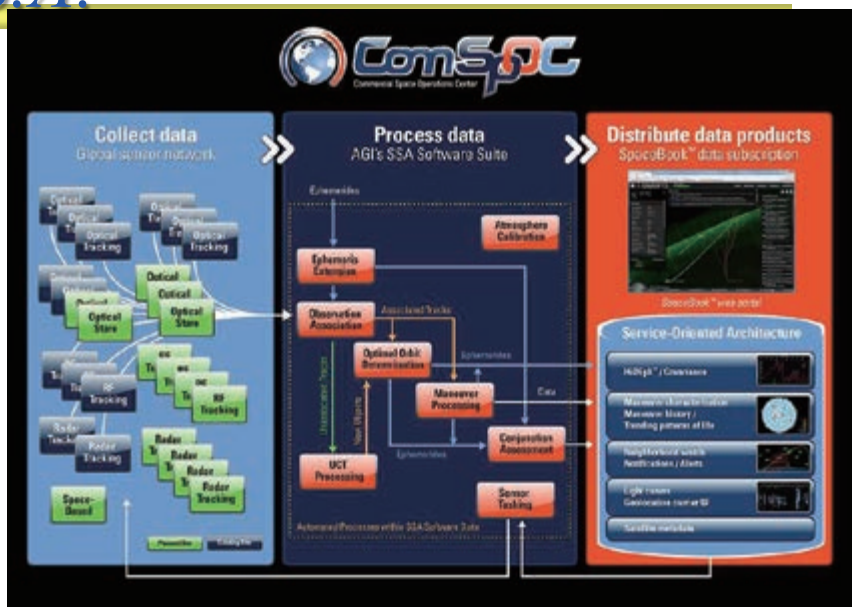


Size distribution of all objects detected by Haystack in 2008 campaign

NASA is monitoring LEO environment using Haystack radar and Haystack Auxiliary (HAX) radar in Lexington. Although they can't determine orbits of detected objects, it can detect LEO objects of a few mm in size.

5

U.S.A.



AGI established Commercial Space Operation Center (ComSpOC). By using world wide optical and radar sensors, ComSpOC provide satellites with variety of SSA services including conjunction analysis. Up to 100x reduction in uncertainty dramatically reduces the number of false alarms and warnings.

6

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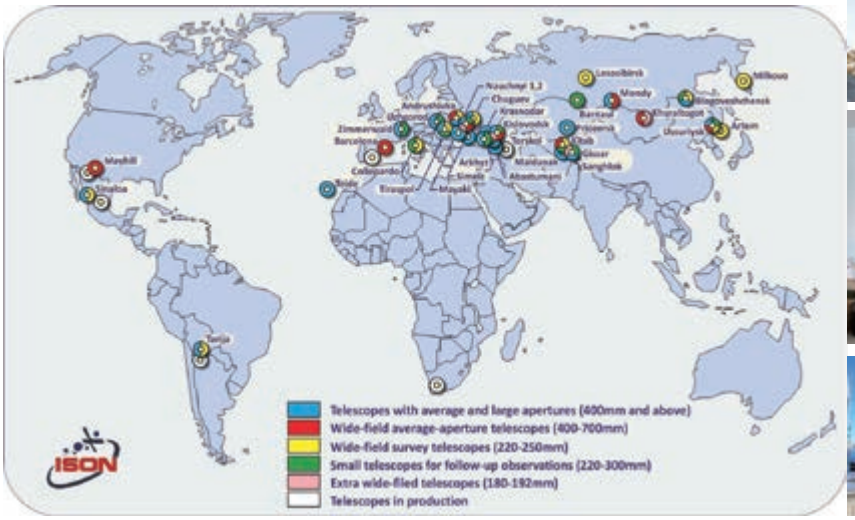
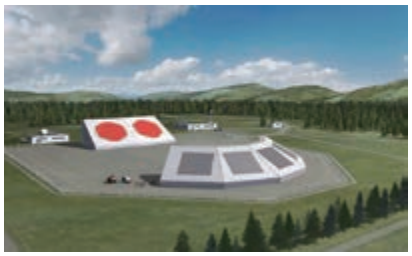
Russia



International Scientific Optical Network (ISON) started in 2005 has been adding new telescopes every year. Currently, 80 telescopes in 15 countries are joined. The main objective is GEO monitoring, but LEO observations are also planned. Most of the telescopes are ranging from 20cm to 40cm.

7

Europe



Future SSA radar system

1m telescope in Tenerife

TIRA radar

ESA started SSA program which will be funded 0.8 billion dollars in 10 years from 2009.

ESA is conducting GEO, GTO, MEO surveys using the 1m telescope in Tenerife. LEO environment is continuously monitored by TIRA radar . The data obtained both sites are reported in IADC every year.

Envisat rotation was investigated using radar and optical data. Rotation rate was jumped up to 3.5 degrees/s in 2013 from 0.4 degree/s in 2012.

8

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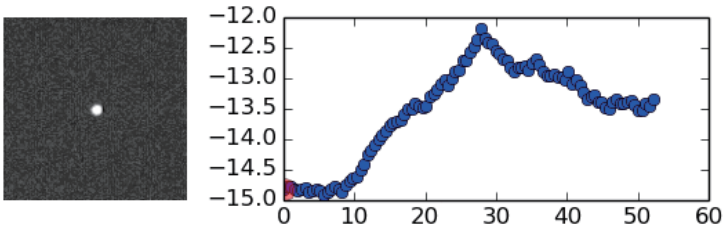
China



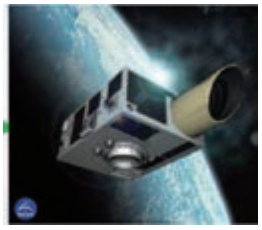
Light curve observation by CNSA

Laser ranging of space debris

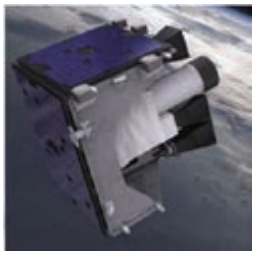
A lot of light curve observations were carried out to investigate rocket bodies' attitude in LEO region. Laser ranging toward space debris are being conducted using high power laser to get accurate orbital information.

9

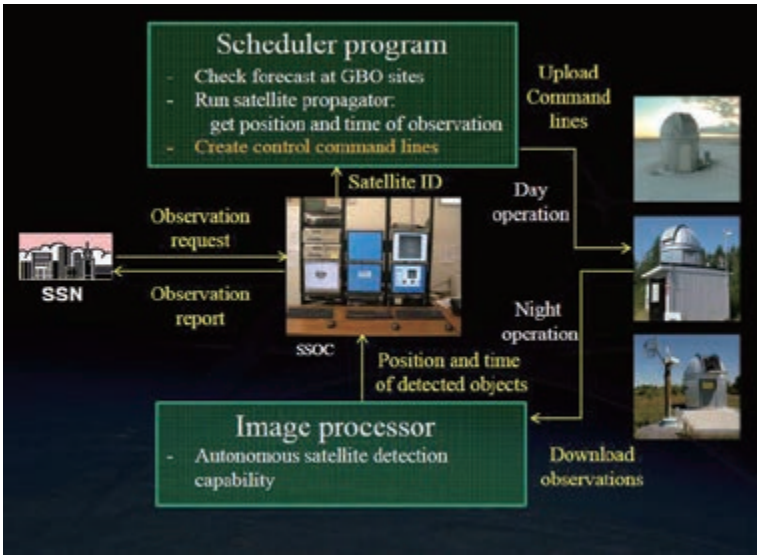
Canada



NEOSSat



SAPPHIRE



Two small satellites, NEOSSat for NEO observation and SAPPHIRE for GEO debris observation, were successfully launched. Ground-based optical automated observatories were constructed using 4 40cm-telescopes.

10

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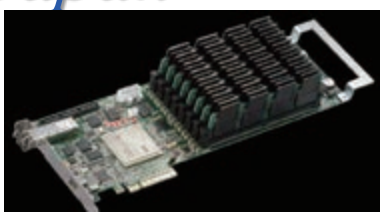
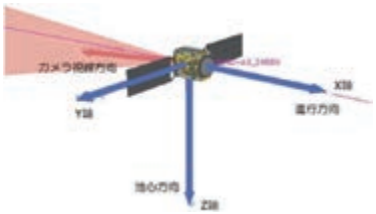
Japan



FPGA board developed for image-processing

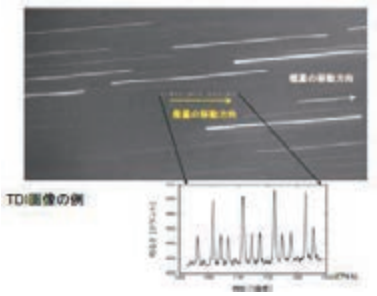
CMOS sensor for detection of LEO objects



Space based optical sensors for GEO debris

Phased array radar of Kamisaibara space guard center

Optical telescopes of Bisei space guard center

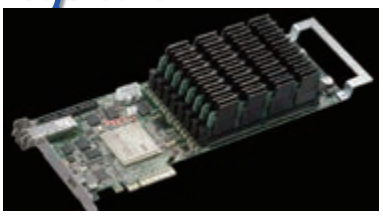


Light curve data taken with 1m telescope at Bisei space guard center

FPGA board for image-processing and CMOS sensor for detection of LEO were developed. Space based optical sensors for GEO debris are being considered. GEO and LEO are being monitored with both a phased array and optical telescopes in Japan.

11

Japan



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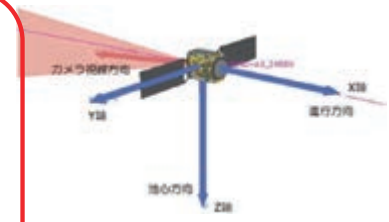

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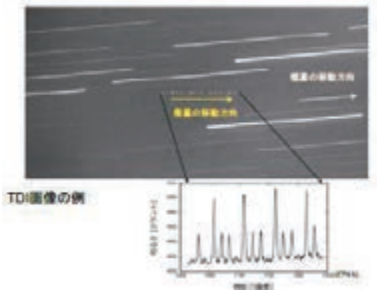

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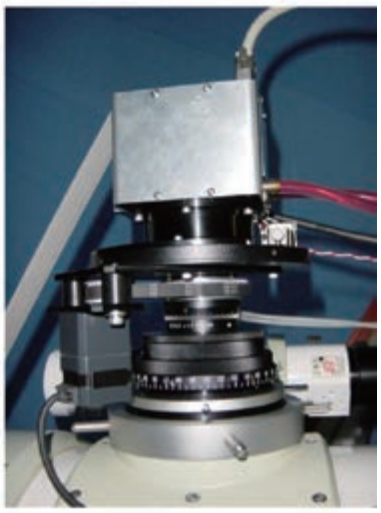
Optical Observational Facility of JAXA at Mt. Nyukasa

Overview of the facility

Observational equipment: 35cm telescope and 2K2K CCD camera

Telescope: Takahashi ε-350
D: 355mm f:1248mm (F/3.6)
Equatorial mount: Showa fork-type 25EF



CCD camera: N.I.L. CCD42-40
chip: 2K2K back-illuminated(e2v)
cooling: peltier device(-30°)
FOV: 1.27×1.27°

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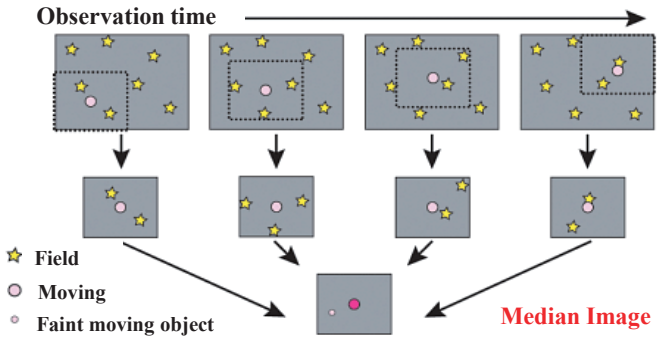
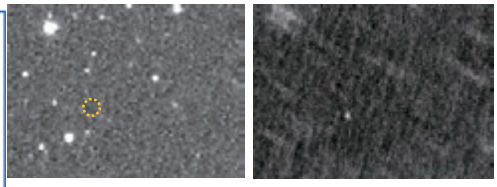
Data analysis process Ⅰ : Stacking method

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

Concept of the stacking method

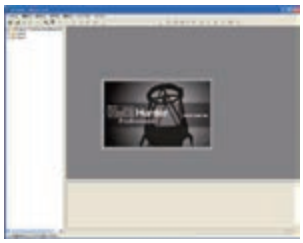




An asteroid detect with the stacking method. One CCD image (left) and the stacked image (right).

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

Many asteroids were discovered by the method.



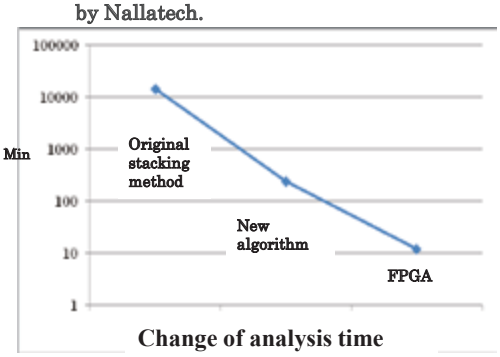
Stellar Hunter Professional: Commercial software for discovering asteroids and comets.

Development of the new algorithm

The algorithm is installed to the FPGA board for reducing analysis time.

FPGA board H101-PCIXM manufactured by Nallatech.

FPGA board system manufactured by iDAQs.



Change of analysis time

Analysis time is reduced one 1200th.

280 hours → 14 minutes

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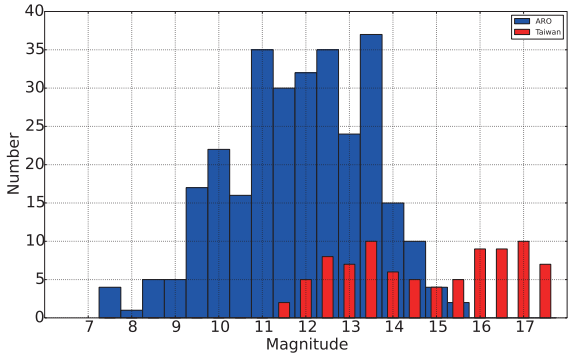
Remote observation in Australia

Remote observations using small telescope at Australia are being carried out. Weather condition there is much better than Japan.

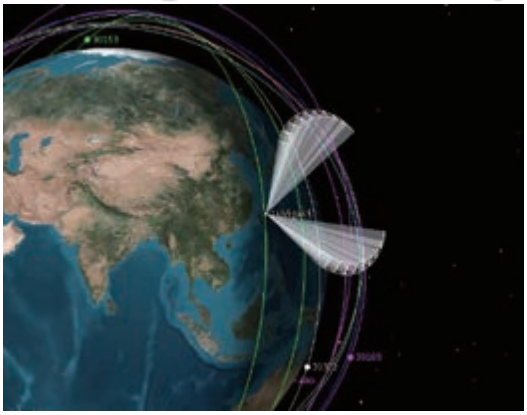
Australian Remote Observatory (Queensland , Oakey)



Brightness distribution of detected GEO objects using 50cm telescope in Taiwan(red) and 18cm telescope in Australia(blue).

17

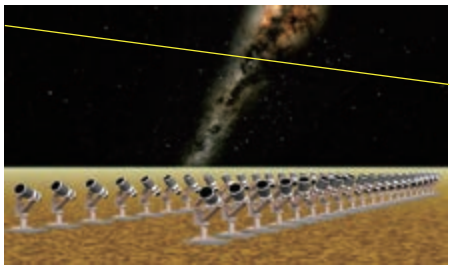
Optical Fence System for LEO objects

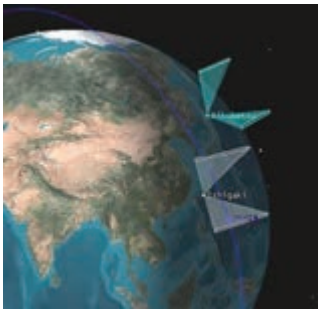


About 40 optical sensors are installed to one site.

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

2 consecutive passes should be observed for accurate orbital determination. For this reason, 2 longitudinally separated sites are considered.





Detection of identical object at 2 sites

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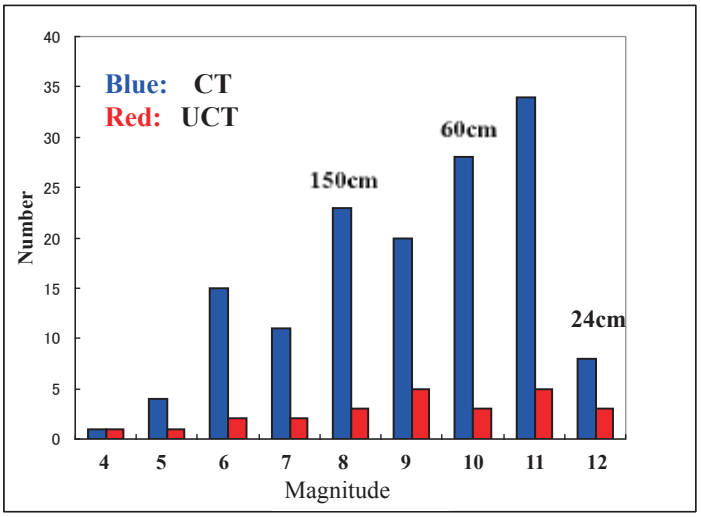
Detection abilities



Diffuse reflection with 90-degree phase angle and albedo 0.1

Result of 16 days' survey

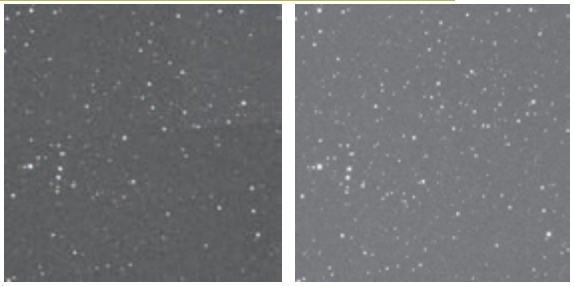
About 30cm LEO objects are detectable

About 15% of detected objects are un-cataloged

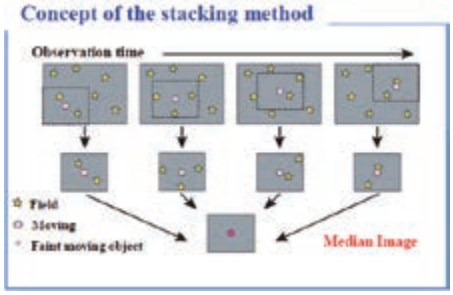
19

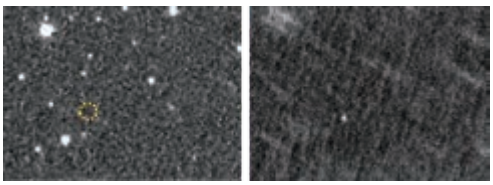
Future Works

CMOS sensor for LEO observation. Readout time is 60 times faster than that of CCD



Comparison between a CCD frame(left) and CMOS frame(right) in same condition





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

- Improve equipment: CMOS sensor will be used for the LEO survey observation
- Improve analysis method: Linear Motion Detection Algorithm → Stacking method

Aim to detect about 10cm LEO objects

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U.S.A.

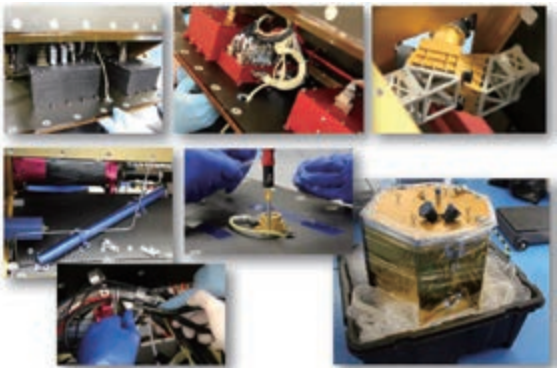
Ref. Rivero, M., et al., Proc. 65th IAC, 2014.

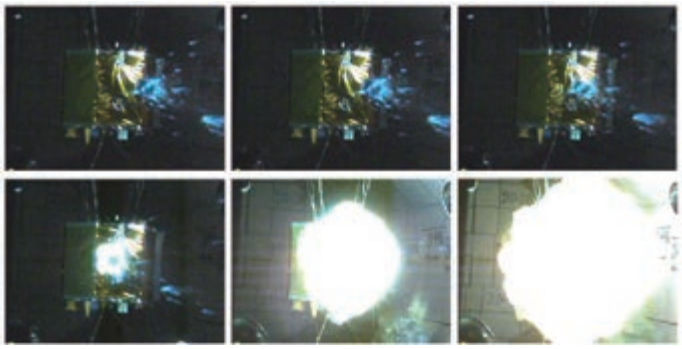
DebrisSat Project

NASA collaborates with University of Florida, The Aerospace Corp., and US Air Force

Design and fabricate a 60-cm/50-kg class satellite, including MLI and solar panels, to be representative of modern payloads in LEO

Perform hypervelocity impact test with sufficient kinetic energy to completely breakup DebriSat





Fragments were collected with foam panels

The collected fragments are characterized the physical properties

Analyze the data to improve NASA satellite breakup models

21

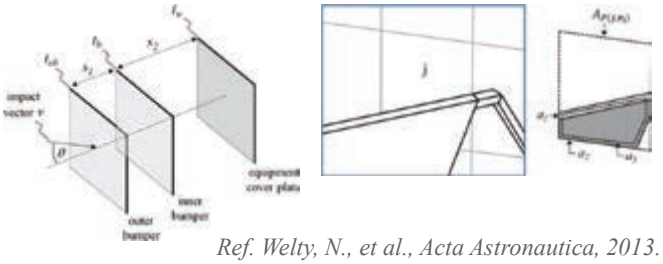
Europe

Risk Assessment of Satellite Internal Structure

Fraunhofer EMI conducted as a part of EU FP7 project P²ROTECT

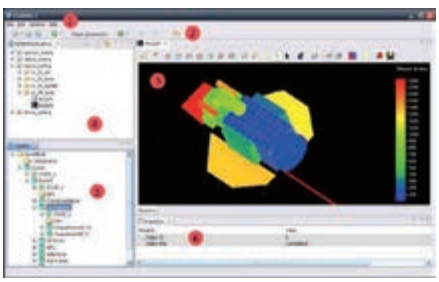
Estimate satellite internal structure damage by using a triple-wall ballistic limit equation

Investigate damage of electronics boxes from impact experiments



Ref. Welty, N., et al., Acta Astronautica, 2013.

Ref. Putzar, R.., et al., Proc. 56th IAC, 2005.



Ref. ESABASE2 HP

ESABASE2

MMOD impact risk assessment tool developed by ESA

Analyze impact risk against a satellite 3D model

22

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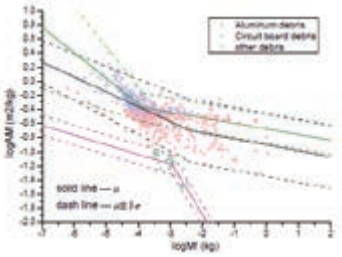
China

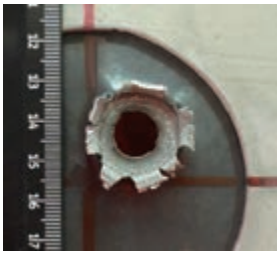
Ref. Liu, S., et al., Proc. 65th IAC, 2014.

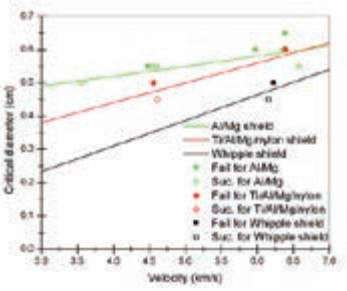
Spacecraft Breakup Model

Research by Hypervelocity Aerodynamics Institute of China Aerodynamics Research & Development Center

Develop the breakup model based on impact experiment results of dummy spacecrafts made of aluminum plates, filled with some simulated electronics boxes with a circuit board as the actual payload







Density-grade Bumper Shield

Research by China Academy of Space Technology

Develop new bumper made of density-grade material, Ti/Al/Mg/nylon and Al/Mg

Ref. Gong, Z., et al., Proc. 6th European Conference on Space Debris , 2013.

23

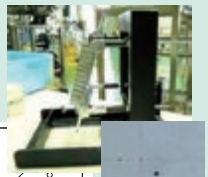
Japan

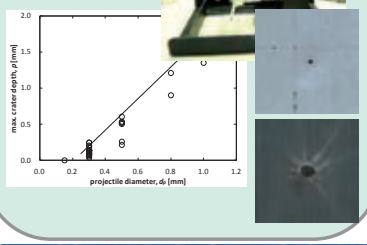
Protect spacecraft from space debris impacts

Investigate debris impact vulnerability of spacecraft components

- Honeycomb sandwich structures
- Wire harnesses
- MLI

etc.

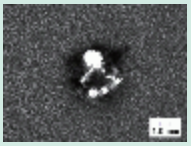


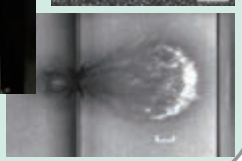


Propose debris bumper shields

- Light weight bumpers (CFRP, Porous metal)
- Flexible bumpers (High-strength fiber fabric)

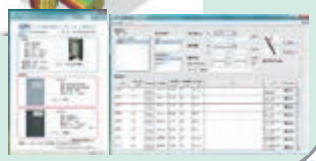
etc.





Develop tools to help space debris protective design

- Impact risk assessment tool (TURANDOT)
- Impact experiment & numerical simulation database



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Conclusion

The trend of research and developments on space debris observation and protection in the world was outlined. JAXA's activities on this field were also introduced. Strengthening observation and protection abilities against space debris is fundamental to solve the problem. We would like to bury the gap between observation and protection limit and contribute to solving the problem under the collaboration of other nations.

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B4

デブリ除去技術の概要と動向

Overview of studies on active debris removal

○河本聡美、大川恭志、壹岐賢太郎、青山順一、奥村哲平、片山保宏(JAXA)
○S. Kawamoto, Y. Ohkawa, K. Iki, J. Aoyama, T. Okumura, Y. Katayama (JAXA)

スペースデブリは近年急増しており、混雑軌道では今すでに軌道上にあるデブリ同士の衝突により数が増加していくとデブリ推移モデルにより予測されている。そのため、これから打ち上げる宇宙機のデブリ発生低減対策だけでは不十分で、衝突確率の高い大型デブリ(使用済み衛星やロケット上段)を能動的に除去する必要があり、世界でもデブリ除去の実現に向け検討が進められつつある。デブリ除去のためには非協力対象であるデブリに接近、推進系を取り付けて軌道を変換する必要がある。本発表では、デブリ除去の必要性、除去対象、必要な技術、非技術的課題、世界の動向等、デブリ除去技術に関する概要を報告する。

The amount of space debris has been increasing, and some evolutionary models predict that it would increase because of mutual collisions between existing objects. In such a case, debris mitigation measures will be inadequate and an active debris removal (ADR) will be needed to preserve the space environment. In order to realize ADR, a removal satellite that will rendezvous with non-cooperative debris object and attach propulsion system for de-orbiting, and recently many studies have been conducted for realizing ADR all over the world. This presentation introduces overview of ADR, such as the necessity of ADR, targets for removal, required technologies, non-technological issues to be solved, and so on.

This document is provided by JAXA.

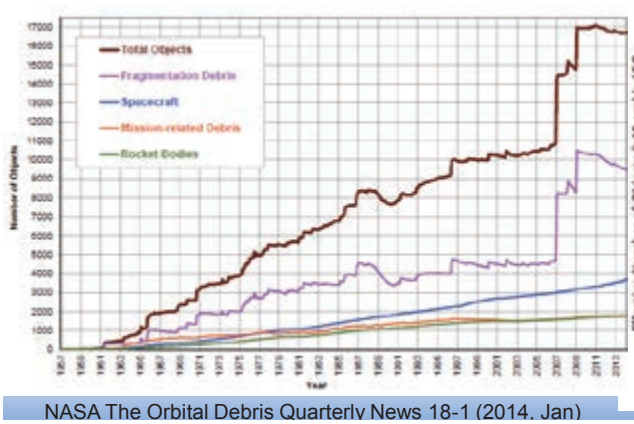
6th Space Debris Workshop
2014/12/17

Overview of Studies on Active Space Debris Removal

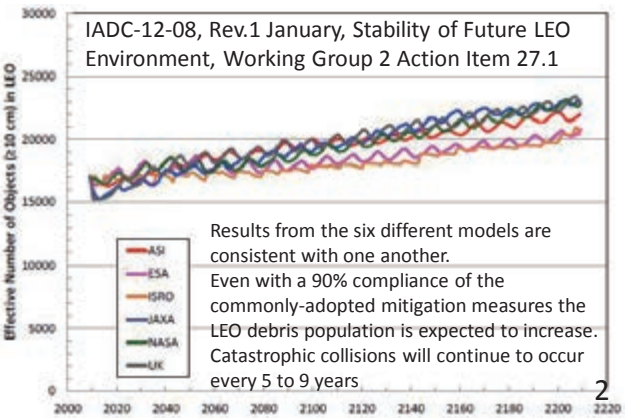
S. Kawamoto, Y. Ohkawa, K. Iki, T. Okumura,
J. Aoyama, Y. Katayama(JAXA/ARD)

Introduction : Necessity of Active Debris Removal (ADR)

- The amount of space debris has been increasing
  - Accidental collisions have been actually occurred
  - Debris countermeasures such as collision avoidance maneuvers (CAM) and debris protection design are indispensable
- Debris evolutionary models predict the amount of debris will continue to increase due to mutual collisions
- Active debris removal is necessary to reduce
  - Burden of CAM and debris protection design
  - Risks of unavoidable debris collisions



NASA The Orbital Debris Quarterly News 18-1 (2014, Jan)



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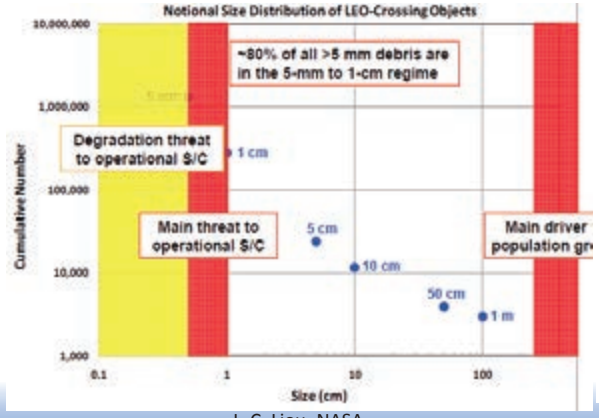
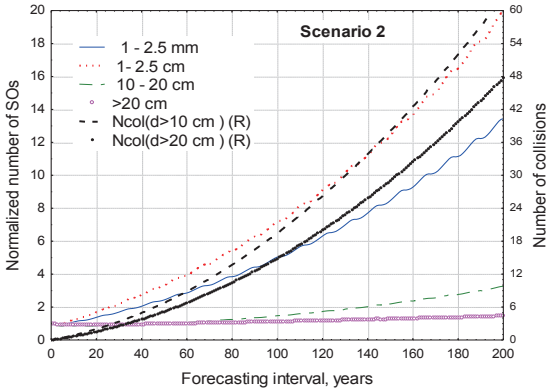
Targets of ADR: Size

- Burdens and risks of debris arise from small size debris
  - Burden of Collision Avoidance Maneuvers by fragments cataloged debris (~10 cm)
  - Burden of debris protection design by debris < 1mm
  - Risks of unavoidable debris collisions by debris a few mm < debris < some cm
- Removal of such small size objects is difficult
  - A huge amount of smaller debris exists, and these are spread over a vast area of space
  - A catastrophic collision between two pieces of large debris may generate numerous new small size objects at once
- We can remove large intact objects in crowded regions since they are a potential source of numerous smaller debris that pose direct risks



J.-C. Liou, NASA

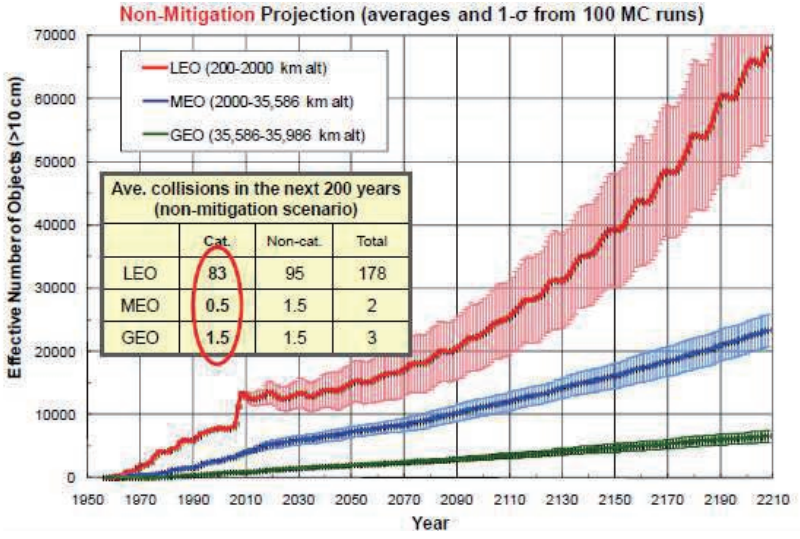


A. Nazarenko, IAC-11.A6.4.2, 2011

3

Targets of ADR: Orbit

- Non-linear increase predicted in LEO > GEO、MEO
  - Nearly all the economic activity in GEO
  - Specific debris objects that interrupt operation can be the targets of ADR in GEO



Ave. collisions in the next 200 years (non-mitigation scenario)

	Cat.	Non-cat.	Total
LEO	83	95	178
MEO	0.5	1.5	2
GEO	1.5	1.5	3

The Top 10 Questions for Active Debris Removal, J.-C. Liou (NASA), European Workshop on Active Debris Removal, 22 June 2010, CNES HQ, Paris, France

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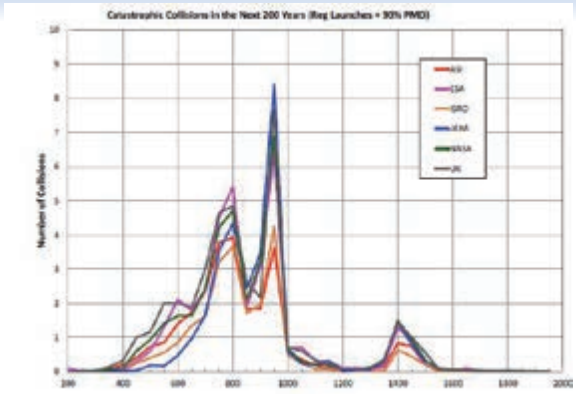
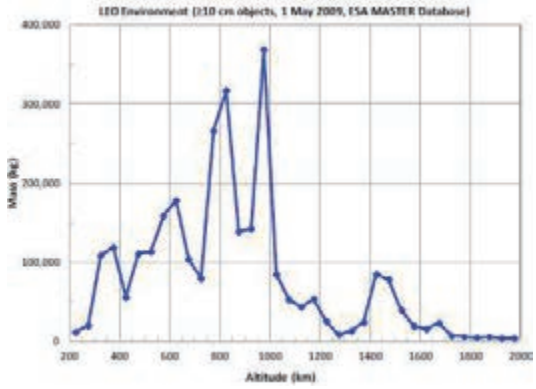
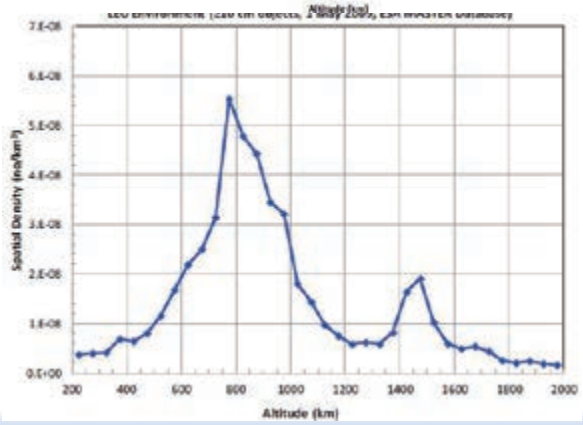
Targets of ADR: Orbit

- Collisions are predicted to occur in crowded regions such as 950-1000km, 700-800km altitude





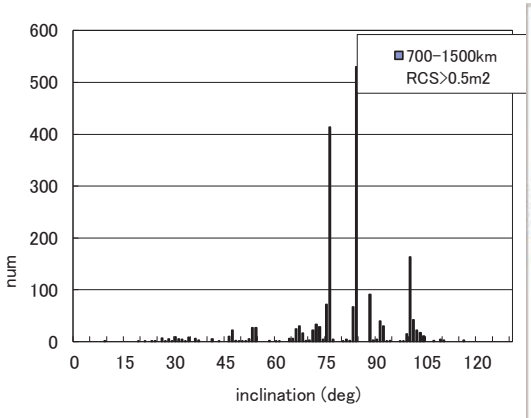


Stability of the Future LEO Environment IADC-12-08, Rev. 1 , 2013

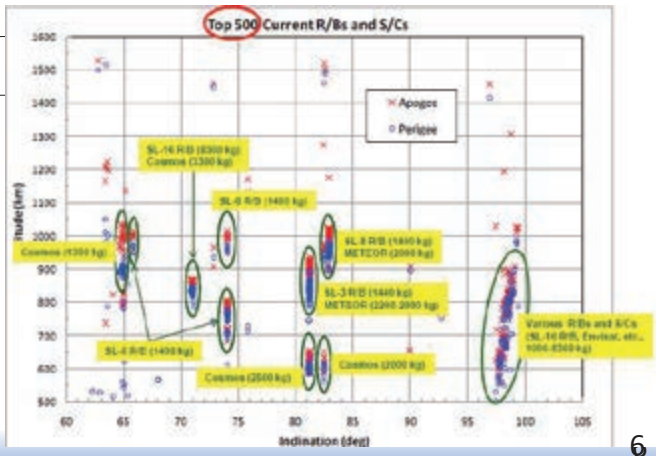
5

Targets of ADR: Orbit

- Sharp peaks exist such as 83 deg, 74 deg, 98-100deg inclination
- Mass x Pc (collision probability)
  - Evaluation using debris evolutionary model will be required considering realistic restrictions and long term effect



The number of objects in altitude of 700-1500 km with RCS > 0.5 m2 in each 1 deg inc. bin



J.-C. Liou, NASA 2010

6

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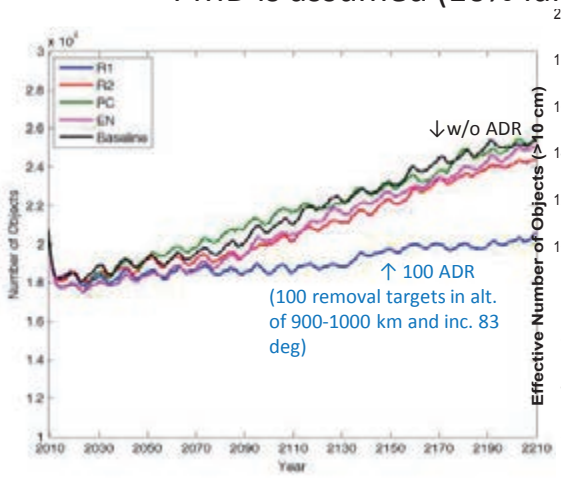
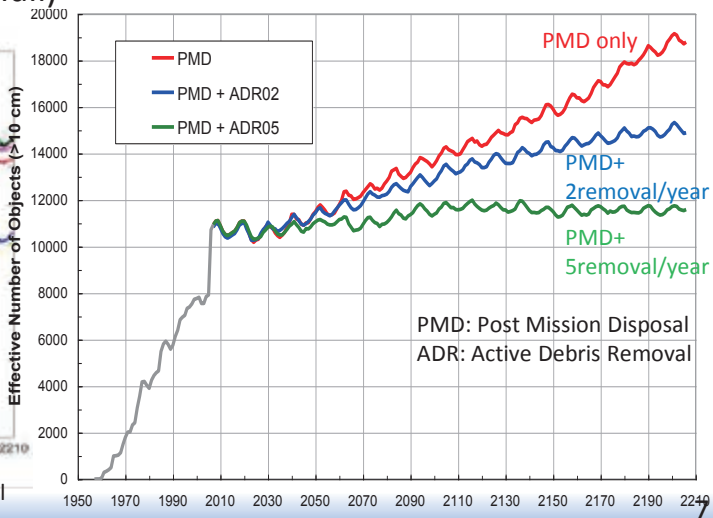
Effect of active debris removal

- Active Debris Removal of currently existing 100-150 debris objects or 5-10 debris objects/year is required in order to stabilize LEO environment
  - No need for removal of all 20000+ catalogued debris
  - Continuous removal will be needed because 90% compliance of PMD is assumed (10% fail)



Effect of removal using debris evolutionary model
Kyushu Univ./JAXA

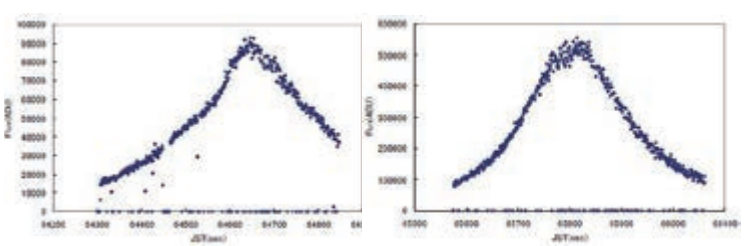


J.-C. Liou, NASA 2010

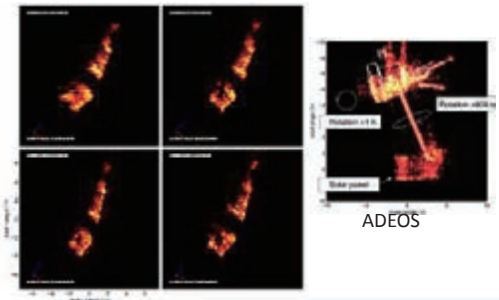
7

Targets of ADR: Type

- Removal of rocket upper stages may be both technologically and non-technologically less challenging compared with satellites debris
  - There is less variation in the shapes compared with satellites
  - Unlike some satellites they do not possess appendages such as solar paddles that pose a collision risk in proximity operations
  - Their axisymmetric shape means that their attitude motions are likely to be simple with no complicated tumbling
  - There exist some rocket bodies with almost stable attitude
  - Their design details are less confidential than satellites



Light curve of SL-8 rocket upper stage.
There exists no tumbling objects.



H-IIA rocket body observed by FHR (2006.10) TIRA RADAR

8

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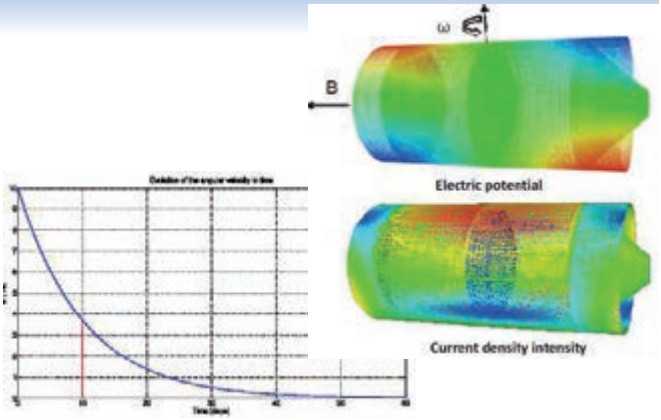
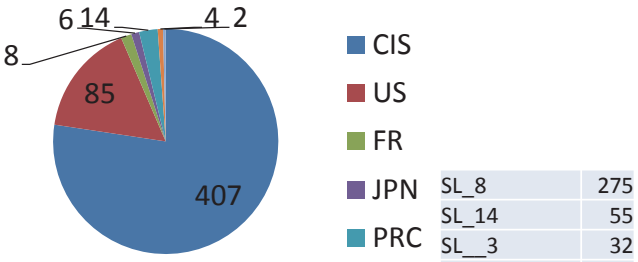
Targets of ADR: Type

- Need survey to understand the attitude motion of objects
  - Damping by eddy current interaction



N. Praly, Study on the eddy current damping of spin dynamics of space debris

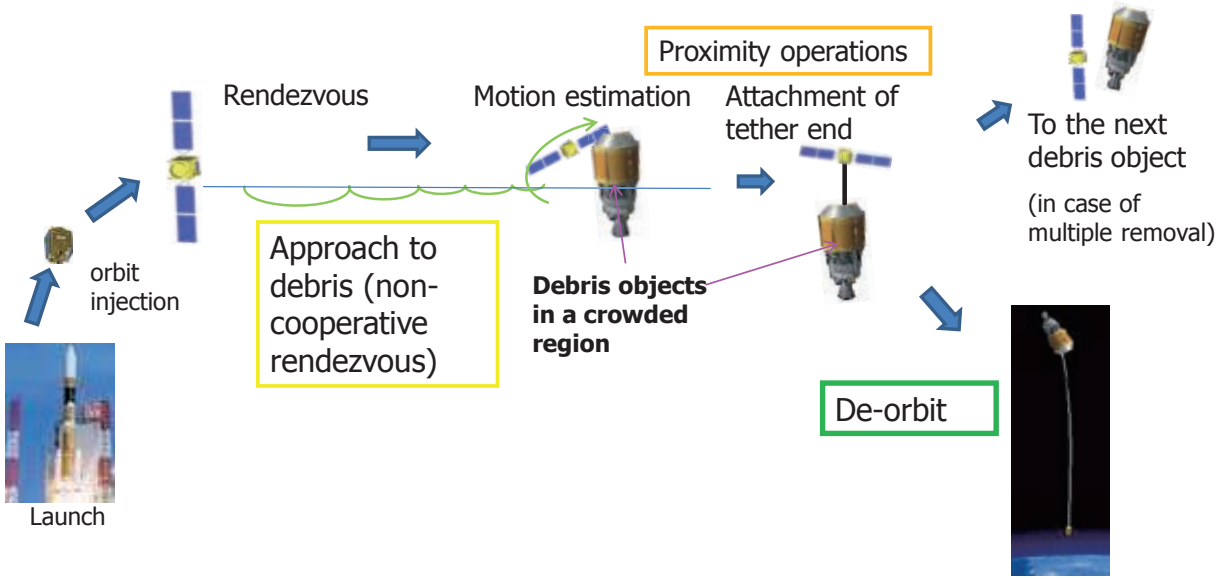
- Necessity of controlled reentry
  - Discussions within IADC
  - Some objects with low survival rate will be more appropriate for removal



SL_8	275
SL_14	55
SL__3	32
SL__16	20
DELTA_1_R/B	17

9

Operation Scenario for Active Debris Removal



10

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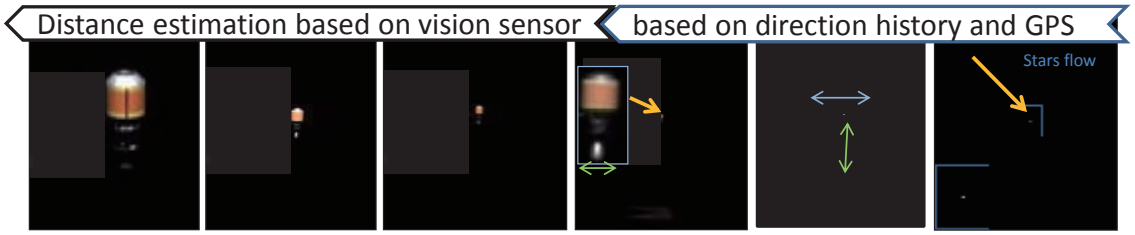
Non-cooperative rendezvous

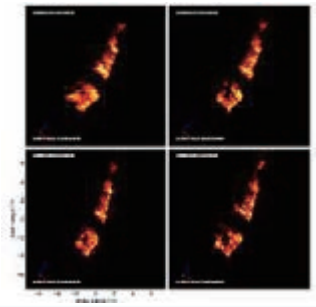
- Need to rendezvous with a non-cooperative target without colliding with it
- Predicted position accuracy based on ground observation: several kilometers
- Relative distance and attitude motion of debris without markers nor reflectors are needed
  - Radar without reflector is costly
- Optical environment changes drastically
  - Optical cameras observe target as a point in far range
  - No image obtained in eclipse
  - Optical environment is difficult to test on ground



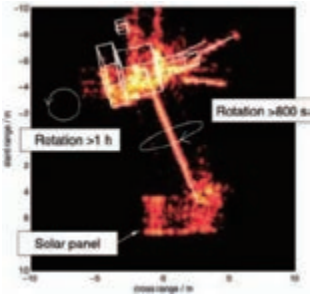
11

Proximity operations

- Need to capture and/or give thrust to a non-cooperative target
  - Attitude of debris is unknown as their attitude is no longer controlled
  - No handle nor grapple fixture
  - Angular momentum needs to be reduced before or after capturing if a target is tumbling
  - Short visibility time. Teleoperation is costly.
  - On-orbit environment such as no-gravity, large-scale are difficult to test on ground
- Attachment of propulsion is required to give dV > 100 m/s to debris with > some tons
  - e.g. 3000kg, 100m/s -> 1000N, 300sec
  - Firm fixation is required for some propulsion system



H-IIA rocket body observed by FHR (2006.10) TIRA RADAR



ADEOS

12

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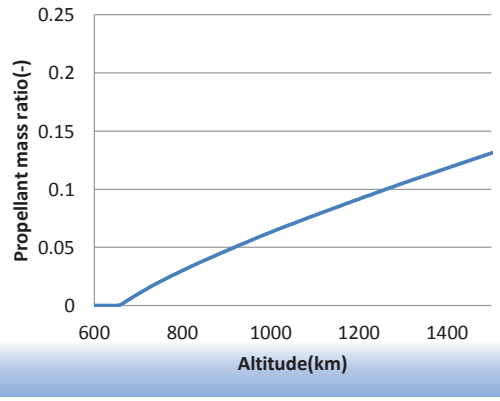
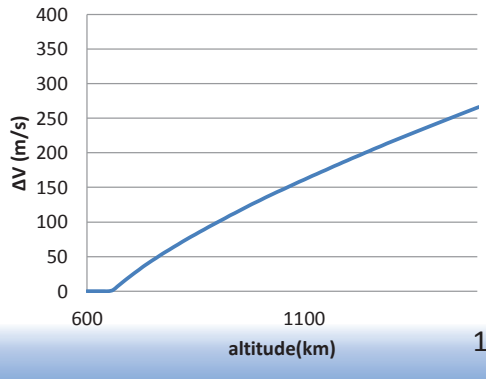
De-orbiting

- ΔV ~100m/s ~ 300m/s (depending on altitude, necessity of controlled reentry) required
- thrust vector control may be needed
  - Control of C.G. when removal satellite pushes debris, or stable pulling is required
- Multiple removal is preferred to reduce cost
- Heavy removal satellite becomes dangerous debris if it fails





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Non-technological issues of ADR

- Legal and policy issues
  - Ownership
  - Liability for damage caused by debris
  - No obligation of removal when it is launched
    - Will be changed when ADR becomes technologically feasible ?
- International frameworks
  - Transparency and Confidence Building
  - Which debris should be removed?
- Affordable cost
  - Who pays?
    - Alternative spacecraft is cheaper in the short term
  - Business model

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Worldwide Movement

- Conference/Workshop
  - 2009.12 NASA/DARPA　International Conference on Orbital Debris Removal
  - 2010.4 Russia ISTC（International Science & Technology Center）
  - 2010.6　CNES/ESA、European Workshop on Active Debris Removal
    - 2012.6 2nd WS, 2014.6 3rd
  - 2010.10 China/ISU/SWF、Beijing Orbital Debris Mitigation Workshop
    - 2011.10, 2012.11　Beijing Space Sustainability Conference
  - 2011.11 Mcgill Institute of Air and Space Law　International Interdisciplinary Congress on Space Debris Remediation
  - 2012.10 SWF European Conference on On-Orbit Satellite Servicing and Active Debris Removal: Exploring Commercial, Legal, and Policy Implications
  - 2013.2 SWF Singapore Conference on On-Orbit Satellite Servicing and Active Debris Removal
- IAA
  - initiated a comprehensive survey of techniques in 2006
  - published cosmic study on Space Debris Environment Remediation in 2013
- IADC
  - Discussion on Remediation Mission Guidelines

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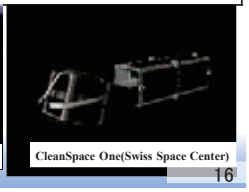
Worldwide Movement

	状況	実証計画	備考
ESA	CleanSpaceイニシアチブ（ADR€15-20M)の中で3年以内のデブリ除去ミッション設計を計画	2020年頃の実証を想定	出典: http://www.esa.int/Our_Activities/Space_Engineering/Clean_Space
EU	FP7でRemoveDEBRIS(Surrey大他、€13M）、BETs（導電性テザー、€1.8M）他多数の資金	RemoveDEBRISは2016年打上予定	出典: http://ec.europa.eu/enterprise/policies/space/research/fp7-projects/#h2-5 他
ロシア	2012年9月、ベルリンエアショーにてデブリ除去システム開発の計画を発表し国際協力を呼びかけ 2014年8月静止軌道の大型ﾃﾞﾌﾞﾘ除去iquidator報道	2020年代のデブリ除去機の打ち上げを想定	出典: http://en.rian.ru/russia/20120912/175923000.html http://rt.com/news/182060-space-scavenger-geostationary-orbit/
DLR	ロボット技術実証衛星DEOS開発のため2012年9月Astriumに€15Mの契約	2018年頃打上予定	出典: http://www.dlr.de/dlr/presse/en/desktopdefault.aspx/tabid-10172/213_read-5173/
CNES	ATV技術を活かしたミッションとしてデブリ除去をセレクト。Astrium社とTAS社に各35万€の研究業務発注	2020年頃のシステム実証を想定	出典: Current status of CNES studies related to Active Debris Removal, ADR Workshop, June 2012
カナダ	2011年10月デブリ除去のシステム検討に2社を選定	実証計画不明	出典: http://www.asc-csa.gc.ca/eng/media/news_releases/2011/1027.asp
スイス	キューブサットによるCleanSpace Oneを提案 S3による打上と15Mスイスフラン獲得	2016-17頃の実証を計画	出典: http://space.epfl.ch/page-61745-en.html
NASA	2011年12月よりデブリ除去の検討Phase Ⅱ。有望技術の絞り込みおよびロードマップを策定。2011年EDTを用いたデブリ除去システム”EDDE”の地上試験に$1.9M資金提供	実証計画不明	出典: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120011693_2012011338.pdf http://www.spacesafetymagazine.com/2012/03/13/electrodynamic-debris-eliminator-receives-funding/



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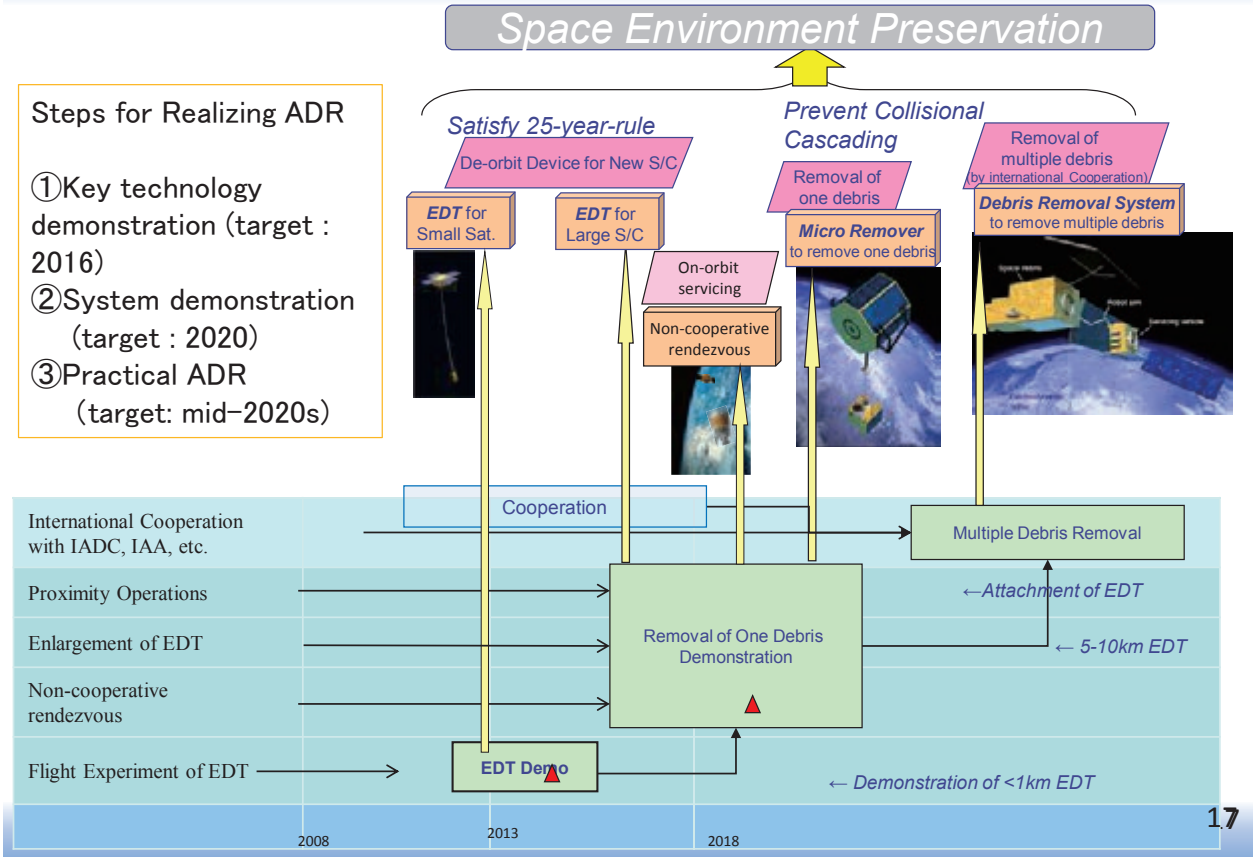
Roadmap for debris removal –JAXA's case



Conclusion

- Overview of ADR were introduced
  - Necessity
  - Targets of removal
  - Challenges of ADR
    - Technological challenges
    - Non-technological issues
  - Worldwide Movement
  - Roadmap for debris removal –JAXA's case

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C1

ロケットに対するデブリ対策の現状と取組み

Debris mitigation status for rocket upper stage in Japan

○齊藤 靖博, 沖田 耕一 (JAXA)
○Yasuhiro Saito, Koichi Okita (JAXA)

スペースデブリ問題は国連平和利用員会(COPUOS)で対策のガイドラインが示されるなど世界的に加速の流れがある中で、日本のロケットも先導的な立場で取組みを行っている。具体的な取り組みとしては、無害化に加え有用な軌道から早期に退避するなど、「デブリを発生させない」ことが基本方針であるが、ロケット（特に H-IIA など大型）はその大きさ故、再突入時の地上に対する安全性にも配慮する必要がある。本発表では、H-IIB のコントロールドリエントリに代表される H-IIA/B やイプシロンにおけるデブリ対策の現状と新型基幹ロケットや将来型イプシロンなど今後に向けた取り組みを紹介する。

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ロケットに対するデブリ対策の現状と取組み

2014年12月18日
JAXA 宇宙輸送ミッション本部
宇宙輸送系システム技術研究開発センター
○齊藤靖博、沖田耕一

はじめに

1. 要求

2. 各国の取組み状況

3. H-IIA/Bやイプシロンの現状と対応オプション

4. 将来ロケットに向けたデブリ対策に係る対応オプション

5. ロケット再突入データ取得システムによる解析精度向上の取組み

6. まとめ

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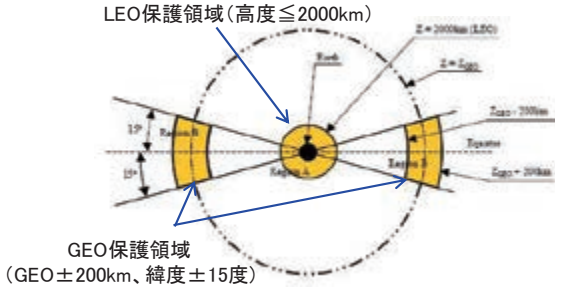
1. 要求

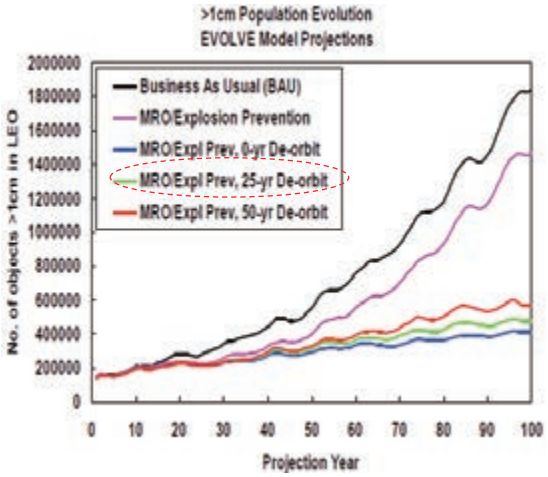
① デブリ低減のため、運用終了後可能な限り早く保護領域（右上図）から退避させる

- 国連のガイドライン（参考1）では「早く」に対する数字の明記はないが、IADCや各国の基準には右下図を理由に**「LEO25年」**
- 25年以下に相当する軌道高度は概算＜600km



② 再突入物体の地上安全のため、可能な限り安全にリエントリさせる

- 国連のガイドラインやIADCでは数字の明記はないが、欧米ではEc<10^{-4}を基準としている



なお、軌道上衝突や破砕は本資料の対象外

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2. 各国の取組み状況（概要）

1. 米国

（1）IADC 25年ルール

- EELV（Delta-IV, Atlas-V）に対し2020年までに25年ルールは100%遵守する方針。Falcon9の商業GTOは3回中2回で25年ルールを満足。
  - Atlas-Vのユーザーズマニュアルには「デブリ低減のための上段廃棄マヌーバを行う」と明記

（2）再突入リスク対応（傷害予測数<10^{-4}）

- EELVは制御再突入を命じる政策はない。ただし、EELVは9回（＋1回の引力圏脱出）/40（保護領域*に投入したミッション）、Falcon9も1回の制御落下実績がある
- オンボード判断の実施については調査中

2. 欧州

（1）IADC 25年ルール

- ロケットデブリを宇宙空間に残さない姿勢を示しており、今後のロケット（Vega, Ariane5ME, Ariane6）では制御再突入を要求し、それが不可能なことが明確なミッションでも25年ルールは遵守する方針
  - 現状のAriane5は、2段再着火できないためATVミッションを除き軌道変更は実施していない

（2）再突入リスク対応（傷害予測数<10^{-4}）

- （1）のとおり積極的に実施。
- Ariane5やVegaはオンボード判断（ただしテレメータは受信）により制御再突入している

[小型ロケットの動向]

- 上記のVegaが3回中2回の制御落下と1回の寿命短縮マヌーバを行っている以外は実績がない。（ミノタウルス、ドニエプル、ロコット(調査中)）

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2. 各国の取組み状況（一覧）

		ミッション／システム要求		実現方法	実績	計画	源泉
		①25年ルール	②制御再突入				
米国	Atlas5	全てのミッション（将来の話）	余剰能力があれば	?	9回の制御落下、1回の地球重力圏脱出	打上げ能力向上を行い、2020年までに25年ルールは遵守	・AIAA 2012-5333(Aerospace co.の論文) ・Atlas5ユーザーズマニュアル
	Delta-IV			?			
	Falcon9	?	?	?	2機のGTOミッションはいずれも25年ルール満足（再突入済） 1機の制御再突入	?	Space Track
欧州	Ariane5 ME	全てのミッション	機能へのシステム要求	LOXガスによる追加推進系	-	例外を除き制御再突入。例外でも25年ルールは遵守	・French space operation act (FSOA) ・JAXA/CNES輸送系共同研究
	Ariane6			TBD（同上が有力）	-		
	Vega			オンボード判断による主エンジン燃焼	3機のうち ・F1は25年ルール ・F2,3は制御再突入		

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3. H-IIA/Bやイプシロンの現状と対応オプション

- H-IIB/HTVの制御落下以外は、競合ロケットの実施状況や能力不足などを踏まえ、デブリ対策用軌道変更は行っていない。H-IIB/HTVは、定期的に打上げられる標準ミッションであり、従来ミッションよりリスクの度合いが高いことなどから制御落下を実施している。
- 要求①②への適合性を下表にまとめた

機体	ミッション	保護領域との干渉	要求①：デブリ低減	要求②：再突入リスク
H-IIA	従来GTO	250x3.6万km, 28.5deg	× 100~200年	×
	高度化GTO	2700x36000, 20deg	- （保護領域に干渉なく必要なし）	-
	SSO	500~800km	△ 10~300年	×
H-IIB	HTV	200x300km, 51.65deg	○ （90min）	○
イプシロン	1号機	950x1150km,31deg	× ∞	○

- もちろん、破砕防止の観点から残留推進薬の排出（イプシロンのヨータンブラ削除含）は行ってい

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3. H-IIA/Bやイプシロンの現状と対応オプション

- H-IIAによるコントロールドリエントリは、GTOでは最大2割／SSOでは最大1~2割程度の打上げ能力ロスとなり、これを許容しても開発と、打上げ費用増など影響がある。さらに能力ロスを回復させるには補助ブースタ開発と装着が必要。
- イプシロンは地球観測など高度600km以下のミッションは軌道寿命が短く（25年以内）、地上落下リスクも小さいことから必要ない。600km以上のミッションに対しては対応が難しい。

機体	ミッション	保護領域との干渉	能力（スペック）	コントロールドリエントリ実施について		
				能力ロス	能力ロスをさせない方法	開発期間
H-IIA 202（4S フェアリング）	従来GTO	250x3.6万km, 28.5deg	4ton	最大2割	SRB-A1本相当追加	3年
	高度化GTO	2700x36000, 20deg	2.9ton	保護領域と干渉しないため必要なし（行う場合、3割）	（SRB-A1本相当*追加）	（3年）
	SSO・LEO	500~800km	5ton@500km~3.9ton@800km	1~2割	SRB-A0.5本相当追加	1年
H-IIB	HTV	200x300km 51.65deg	16.9ton	対応済	-	-
イプシロン	SSO	500km	0.5ton	25年以内に落下し、地上落下リスクも低	-	-

4. 将来ロケットに向けたデブリ対策に係る対応オプション

- 世界の動向として25年ルールの厳守は必須となりつつある動向を踏まえ、以下の方針案を検討中

A) すべてのミッションで25年ルールを遵守する

B) 想定される主なミッションで再突入リスク（傷害予測数<10^{-4}）を満足する（機能要求）

これらのマヌーバをオンボード判断*により実施することについても併せて検討する

*）地上システム・運用が必要なくなり、コスト低減に繋がるため有効（欧州はオンボードにより実施している）

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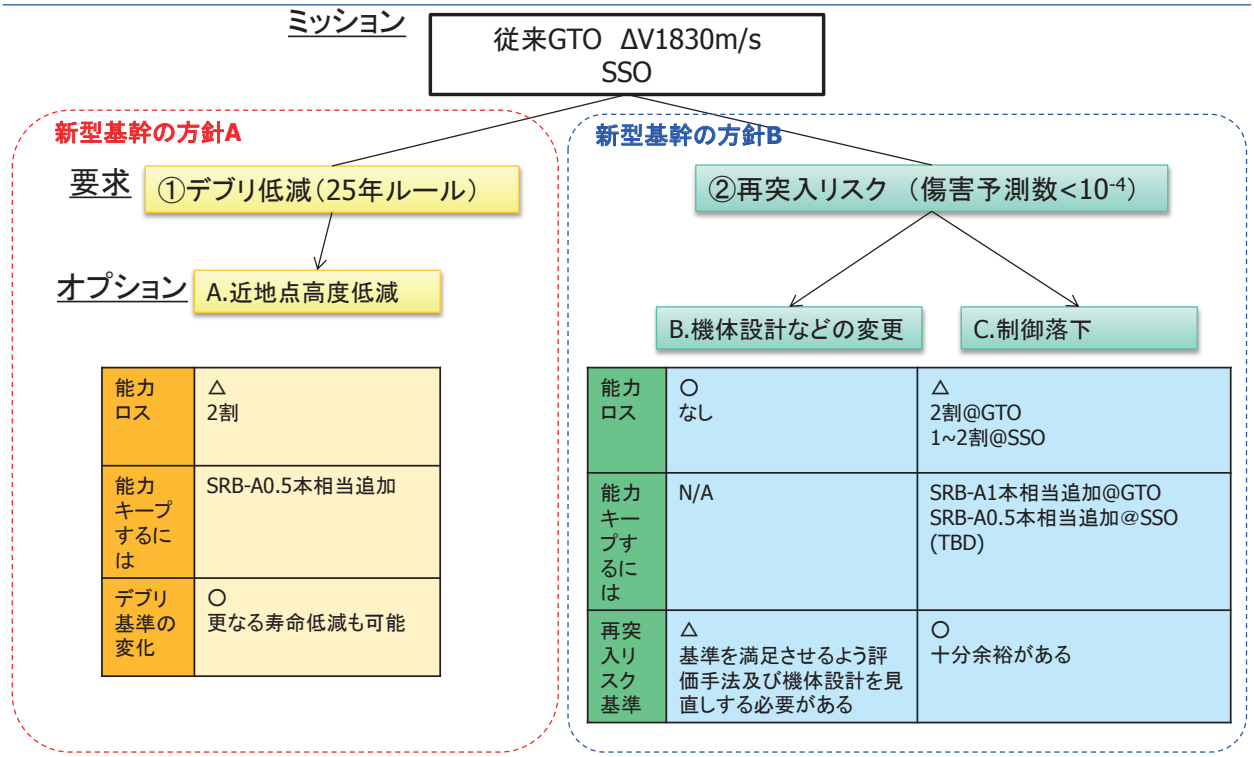
4. 将来ロケットに向けたデブリ対策に係る対応オプション



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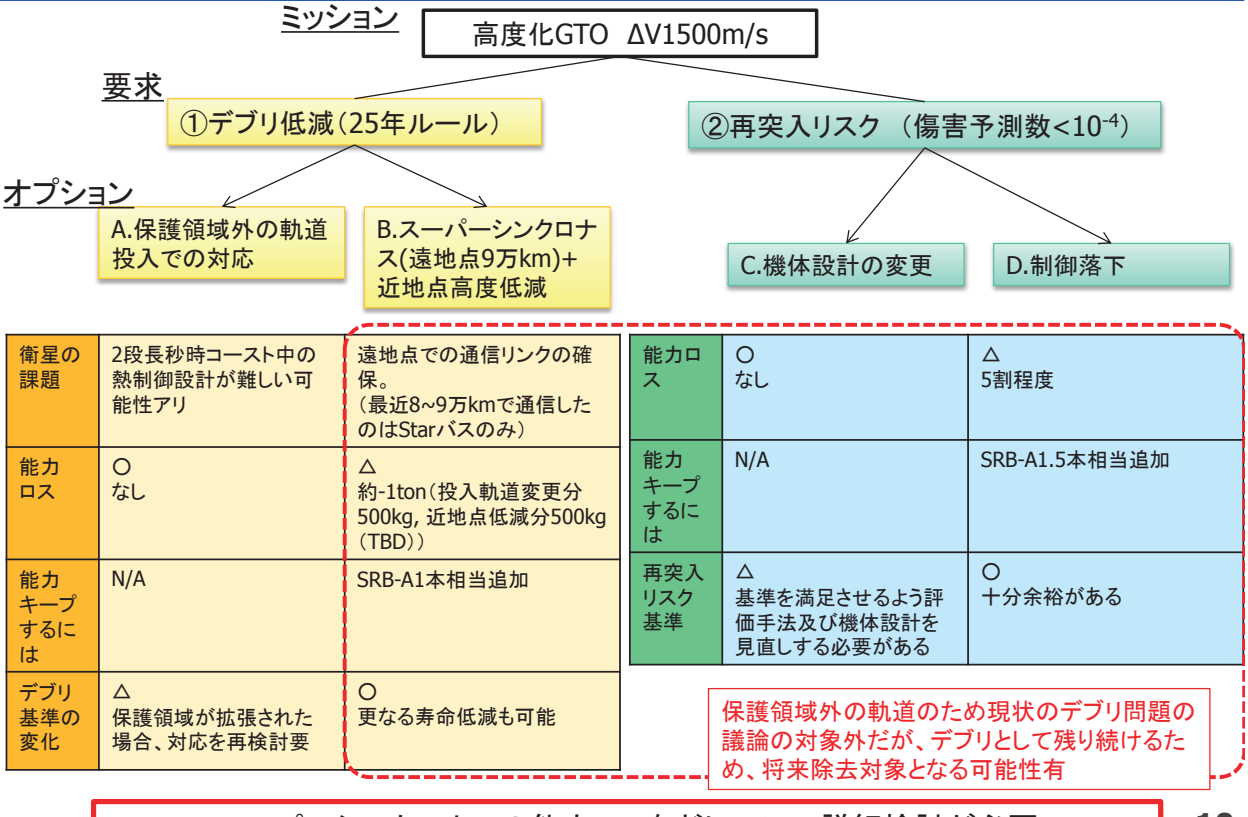
4. 将来ロケットに向けたデブリ対策に係る対応オプション



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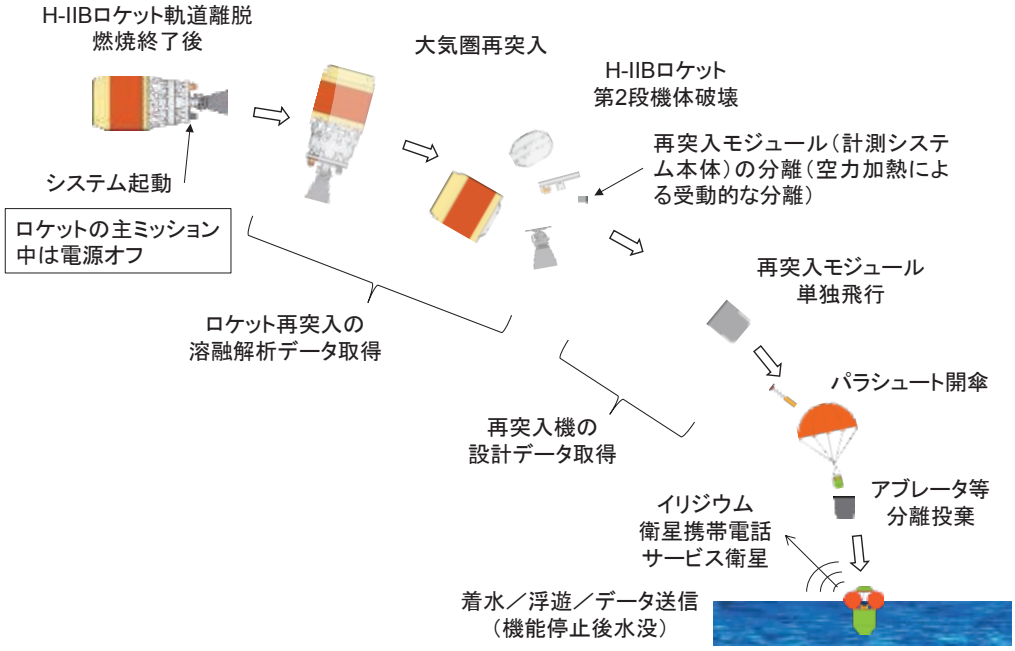
5. ロケット再突入データ取得システムによる解析精度向上の取組み

- ロケットの溶融解析精度向上や再突入技術データ蓄積を目的に"ロケット再突入データ取得システム"の研究を実施中
- ワイヤレスで温度・圧力などを計測し、着水後衛星電話でデータ伝送
- 2016年度に予定されているH-IIB6号機への搭載を目指している



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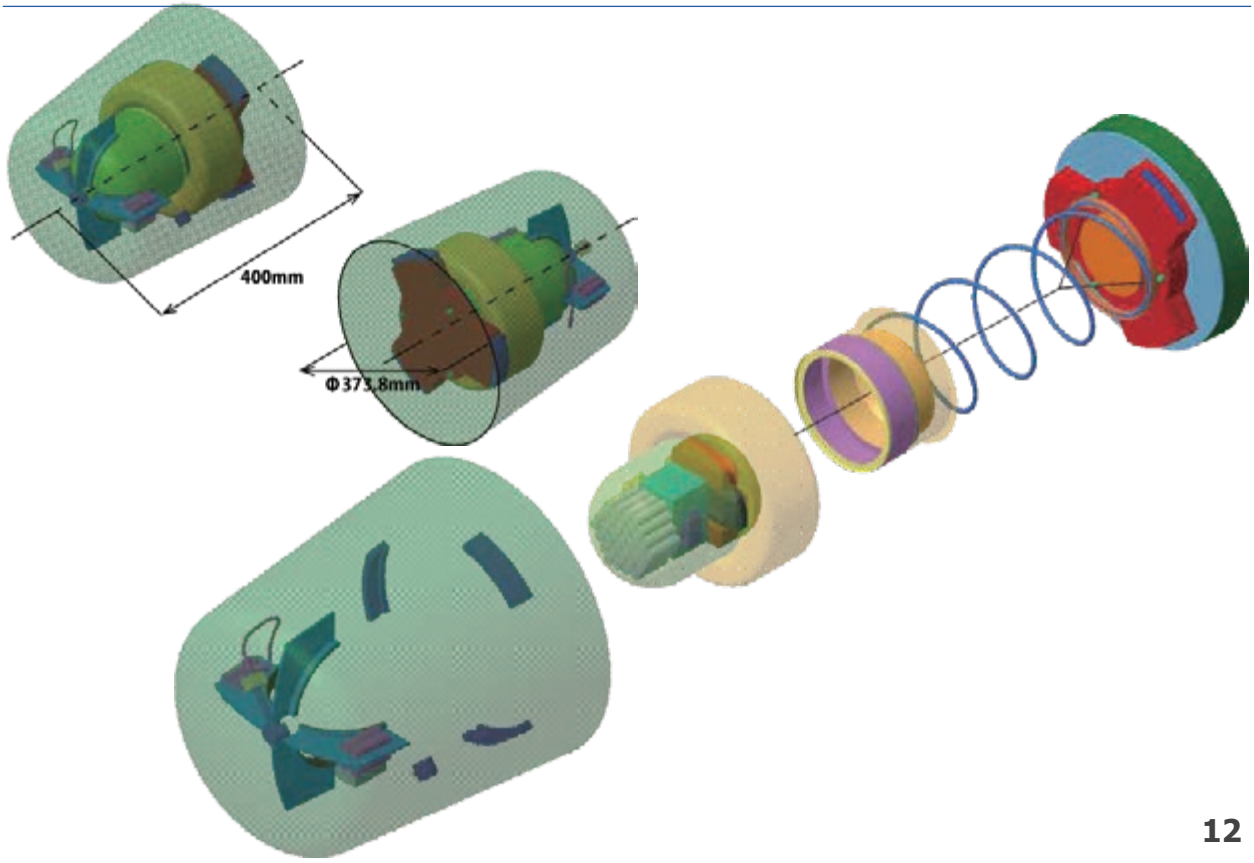
5. ロケット再突入データ取得システムによる解析精度向上の取組み



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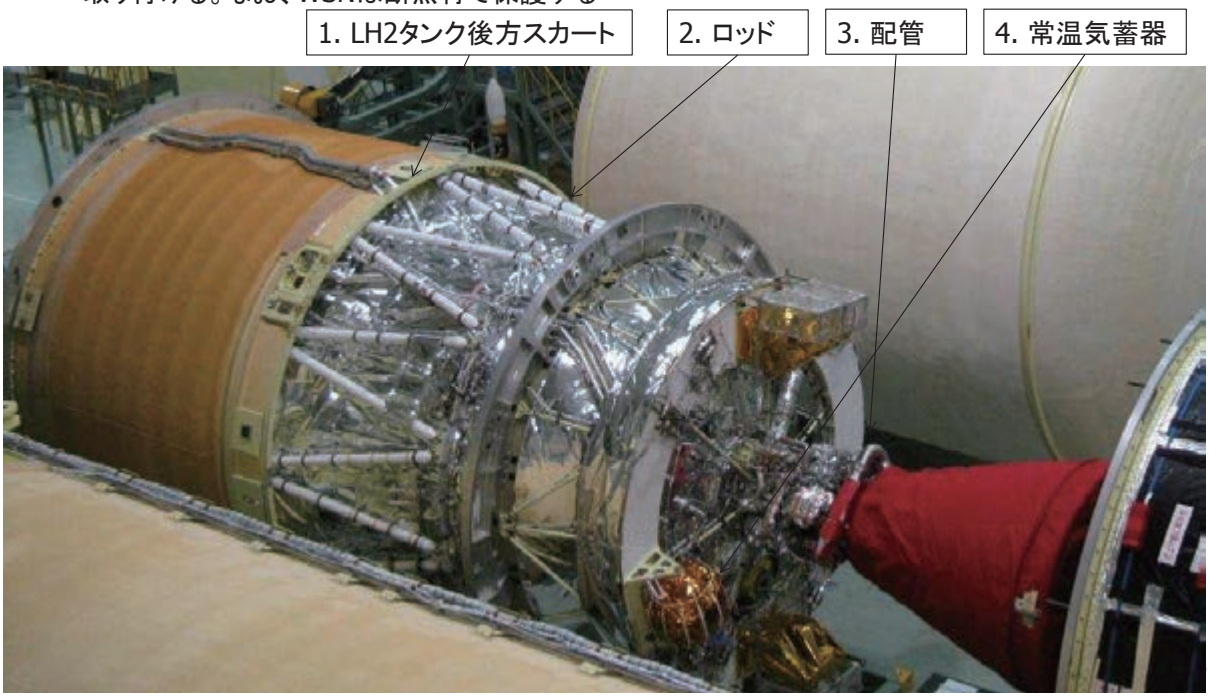
5. ロケット再突入データ取得システムによる解析精度向上の取組み

- 計測仕様案
  - 溶融解析結果と艤装性から、下図の4コンポーネント（溶融コンポ2つ、溶融しないコンポ2つ）
  - 温度センサ（K型熱電対プローブ）とWSN（wireless sensor network）を一体として、各計測箇所に取り付ける。なお、WSNは断熱材で保護する



6. まとめ

- デブリ対策で主にロケットに求められることは
  - A) 運用終了後可能な限り早く保護領域（右上図）から退避
  - B) 再突入の地上リスク低減
- 欧米のベンチマークから、Aは遵守、Bは対応ミッションが増える傾向
- 現状のロケットであるH-IIA/BやイプシロンはH-IIBの制御落下やイプシロンのヨータンブラ削除など、デブリ対策の取組みを行っている
- 将来ロケットに向けては、Aは遵守、Bは主なミッションで対応できる、よう開発する方針

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C2

地球周回近領域デブリの影響評価及び その起源イベントの識別

Evaluation of the impacts of near-Earth-orbit debris removal & track of impactful events' origins

○メリッサ ゼムラ、花田俊也（九州大学）、河本聡美 (JAXA)
○Melissa Zemoura, Toshiya Hanada (Kyushu Univ.), Satomi Kawamoto (JAXA)

本研究は，スペースデブリ除去による地球周回環境への影響を評価することが目的です。4 つのシナリオについて，軌道環境予測モデルによる 200 年間のモンテカルロシミュレーションを100回行った。2009 年の宇宙機初期分布から、ENVISAT 衛星、ADEOS2 衛星、18 個の SL-16 ロケット上段の除去の有無による影響について，全く除去を行わないシナリオと比較することで解析を行った。その結果，ENVISATと ADEOS2 の場合、将来の宇宙環境に影響があまりなく、SL-16 の場合は、物体分布が少し下がることが判明した。本研究から，除去の有効性は、物体の高度と除去する数を評価基準にできることが分かった．さらに，本研究では、将来発生する可能性がある破片に関して，親物体を特定するアルゴリズムの開発を行なって、除去の有効性が高い物体の識別ができた．この手法により、どんな物体を今から除去すべきか分かるようになることが期待されます．

This proposed study aims to evaluate the effects of remediation activities on the future evolution of the space environment around the Earth. 4 scenarios were run over 200 years, through 100 Monte-Carlo simulations. The focus was made on the removal of respectively ENVISAT satellite, ADEOS 2 satellite, and 18 pieces of SL-16 rocket upper stage from the initial population of year 2009, and the results were compared to the Baseline (scenario without removal). The analysis let underline noticeable differences between the scenarios: removing ENVISAT or ADEOS 2 reveals not to have significant impact on the future population; but removing 18 pieces of SL-16 rocket conducts to a decrease of the debris population at same epoch, which demonstrates the importance of the number of objects to be removed in order to strengthen the impact of a remediation activity. The altitude of removed objects also appeared as a significant criterion. In addition, a program has been implemented in order to track the origins at initial year of all fragments present in a given year in order to determine the most impactful objects in terms of debris generation. This process lets expect to better understand the conditions for an effective removal procedure
.

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Thursday Session - Modelling

Evaluation of the impacts of near-Earth-orbit debris removal & track of impactful events' origins

Mélissa ZEMOURA* Toshiya HANADA Satomi KAWAMOTO

Kyushu University, Japan *Kyushu University, Japan* *JAXA, Japan*

Structure of the presentation

- Introduction – Motivation of the study

I. Presentation of evolutionary model / initial conditions

II. a. Study of 3 removal scenarios
   - ADEOS 2
   - ENVISAT
   - SL-16 R/B (18 pieces)

   b. Comparison with baseline scenario
   c. Conclusions / Proposal to interpret results

III. Presentation of debris-origin-tracking function
   a. Implementation
   b. Results on study-cases / application to part. II

- Conclusion

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Introduction – Motivation of the study

- 2 directions :
  → Estimate the future evolution of the population (200 years)
  → Track the generative events in the past
- 1st part :
  → Study the effects of removal of target objects
  → Tentative to understand : Are these targets the good ones ??
- 2nd part :
  → Determine today's objects that generate tomorrow's debris
  → Question : Which objects may be good candidates for removal ?
  → Results on mean of 94 statistical cases

I. Structure of the evolutionary model

- NEODEEM (Kyushu University – JAXA*)
  → Near-Earth Orbit Debris Environment Evolutionary Model

Japan Aerospace Exploration Agency

- Prediction of future environment
  → Existing objects & occurring events at each year
  → Here : from year 2009 to year 2209
- Regions : LEO, MEO & GEO
- Included forces :
  - Sun & Moon gravitation
  - Solar radiation pressure
  - Atmospheric drag (Jacchia-Roberts density model)
  - Non-spherical part of Earth's gravitational attraction

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I. Evolutionary model : Initial conditions

- Initial population as baseline for the simulation
  → all catalogued objects as of May, 1st 2009
  → 20,788 objects / 5 types *(provided by ESA for IADC WG2 AI27.2)*
- Launch traffic frequency = 8-year cycle
  → 2003-2010 recorded launches *(but not used in this study)*
  → 699 recorded objects

Table of the objects' repartition in the input files

Object type	Initial population	Launch traffic records
Space crafts	2 014	320
Rocket upper stages	1 332	256
Mission related objects	851	123
Explosion fragments	16 591	0
Collision fragments	0	0

II. Impact of 3 targeted objects' removal

- Aim : evaluate the effect of presence/suppression for

Target object	Mass (kg)	Size (m)	Inclination (deg.)	Altitude (km)
ADEOS 2 (s/c), Japan	3680	4.05	98	805
ENVISAT (s/c), Europe	8110	8.96	98	775
SL-16 (R/B – 18 pieces), Russia	9000	9.85	71	825

- Comparison with Baseline scenario (all objects present, included targets)
- Period : 2009/05/01 (initial population) – 2209/01/01
- Setting conditions (simulation assumptions) **100 MC simulations**

Event	Status in the simulation
New launches	No
Other objects' removal	No
Future explosions	No
Collisions	Yes
Performed PMD	90% success rate

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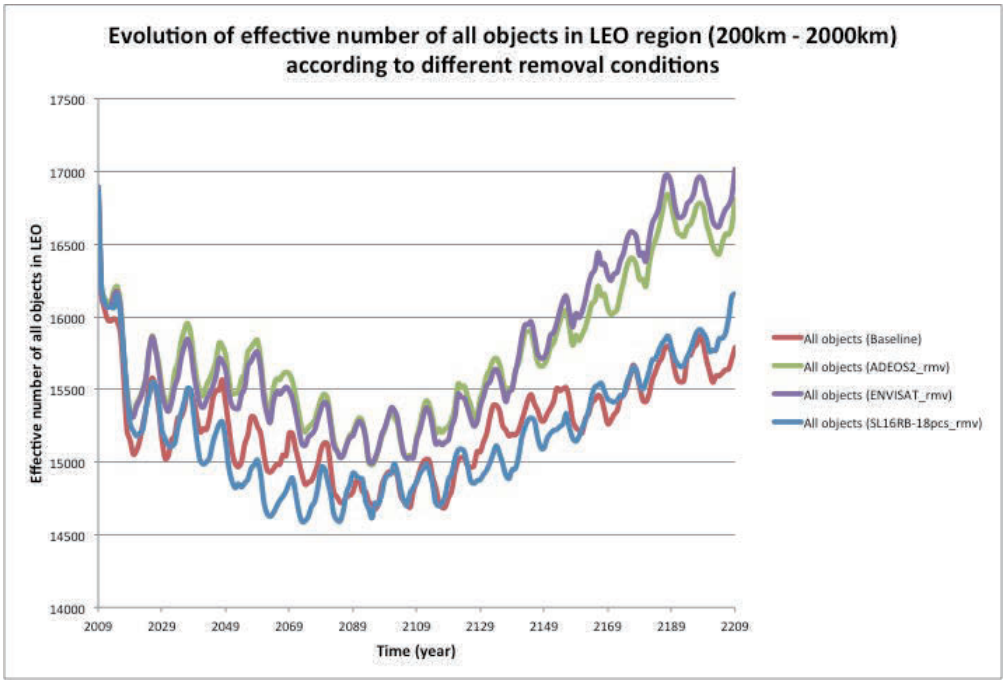
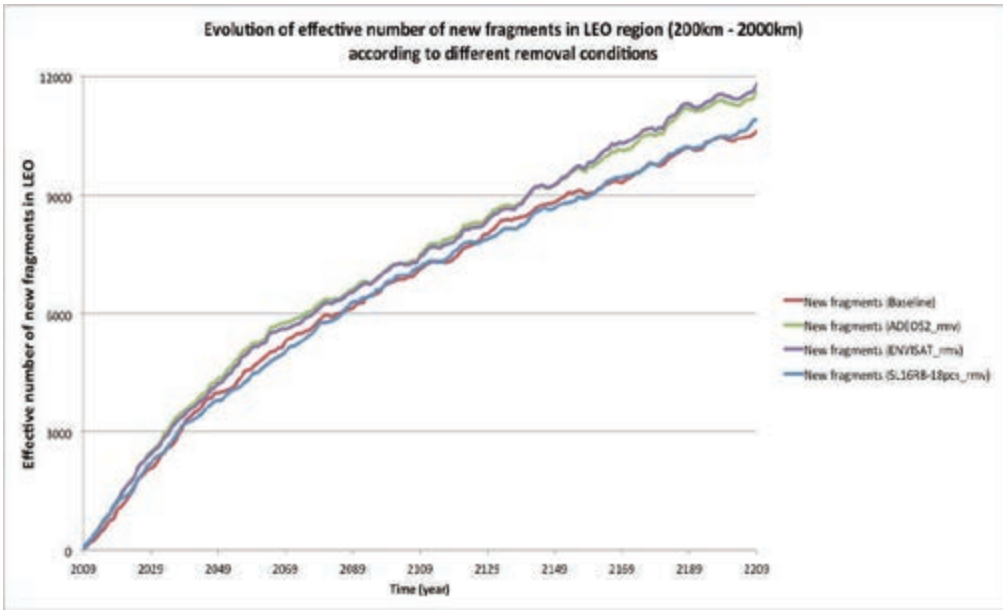
II. Targeted objects' removal - Results



II. Targeted objects' removal - Results



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II. Target objects' removal – Proposal for interpretation

- **SL-16 R/B** case :
  - global trend : similar to Baseline
  - slight decrease of population in 2 periods (from 2035 and from 2120)

- **ADEOS2 & ENVISAT** cases : no positive effects on future population reduction
  - slight increase of population w/r. Baseline
  - tentative to understand → Analyze collisions in **Baseline scenario**

Use of origin-tracking program

Object	Collision year	Collided object (mass)	Number of direct fragments	Number of remaining fragments in 2109
ENVISAT (7 collisions)	2030 (10th MC)	1760 kg (r/b)	4633	1192
	2031	0.607 kg	4	0
	2047	0.0539 kg	0	0
	2060 (66th MC)	717 kg (s/c)	4243	1402
	2110	0.215 kg	4	0
	2125	4.084 kg	19	0
	2068	0.472 kg	3	0
ADEOS 2 (2 collisions)	2050	0.370 kg	0	0
	2068 (84th MC)	1420 kg (r/b)	2839	953

II. Target objects' removal – Conclusions

- 1st conclusion: number of removed objects = key parameter for efficiency

- 2nd conclusion: effects of altitude = reentry of fragments from low-altitude collision with time

- Question / wondering : collision with ADEOS2 or ENVISAT
  → avoidance of more catastrophic collision in scenarios where absents (?)

  Ex. : ENVISAT-removed scenario
  → study of the 1760kg-object that may collide with ENVISAT in Baseline (10th MC)
  → After 2030 :

Scenario	MC recurrence	Collision recurrence	Number of generated fragments	Mean number of fragments on 100 MC
Baseline	7	7	4383	43.83
ENVISAT-removed	7	8	7765	77.65

→ *Collision with ENVISAT may avoid catastrophic collisions in the future* ***(?)***

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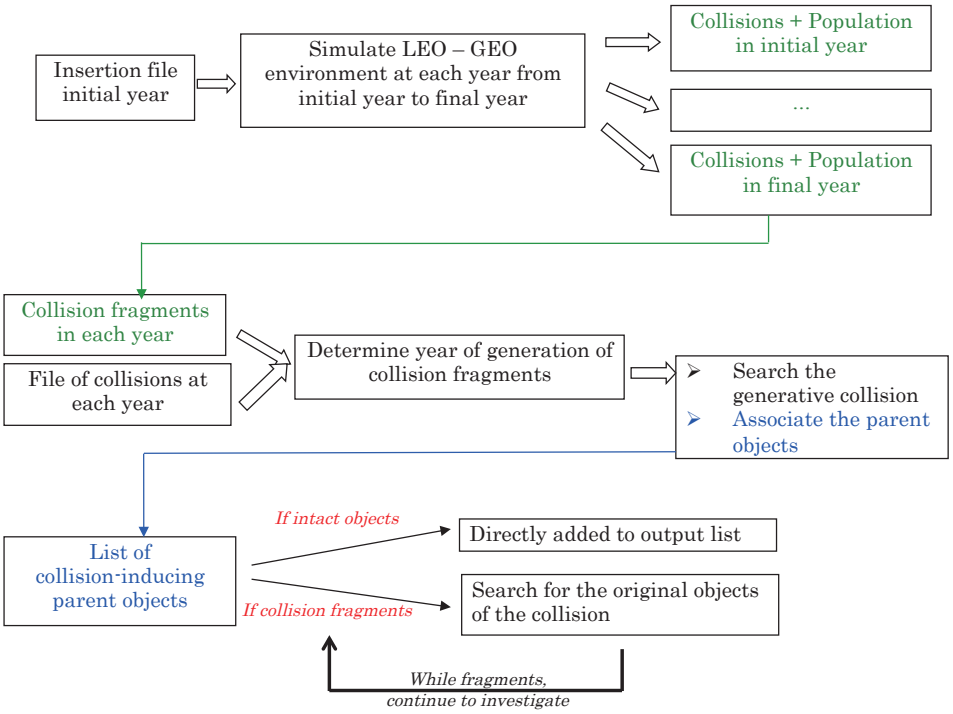
III. Debris-origin-tracking function

- Aim
  ➔ Find out the origin of debris estimated in a final year (future)
  ➔ Track this origin back to past, until current year (present)

- In one simulation :
  * input = list of collisions at each year
    list of all objects at each year
  * output = list of debris-inducing objects in present year

III. Origin tracking function - Implementation



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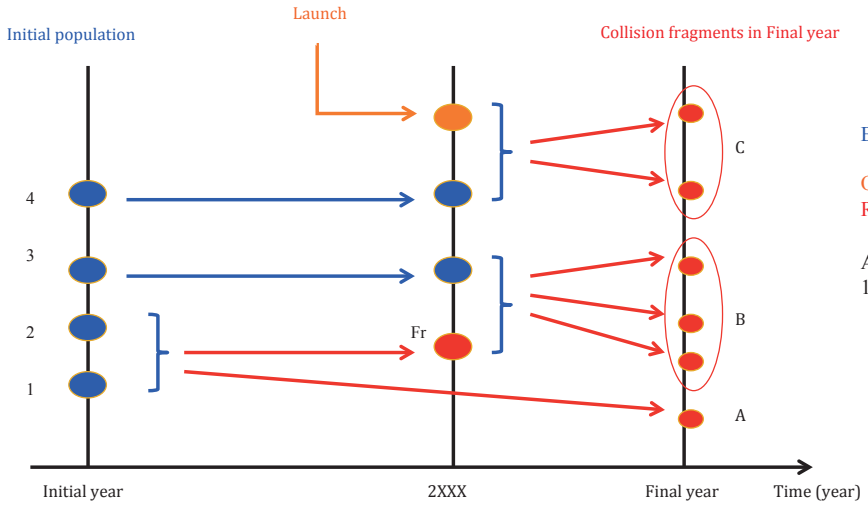
III. Origin tracking function - Implementation



Blue : objects from initial population
Orange : objects from new launch
Red : collision fragments

A, B, C : groups of the fragments
1, 2, 3, 4 : identification number of the objects

Process inside 1 MC simulation – after identifying the collision fragments in Final year

- Groups defined w/r. time-closest generative collision
- In each group : access to mass and size of each fragment
- Ex. : 1,2 → grps A&B / 3 →grp B / 4 → grp C

Data provided in the list of parent objects 1 to 4:
→Number of generated fragments in Final year
→Fragments' group number(s)

III. Origin tracking function – Study-case results (Application to Removal study Part. II)

Object's number	Type	Number of generated fragments	Groups of fragments
878	Spacecraft	1859	1 & 9
1415	Spacecraft	1859	1 & 9
1236	Rocket body	1124	2
2580	Spacecraft	1124	2
1183	Explosion fragment	4	3
11312	Explosion fragment	4	3
1354	Rocket body	856	4
4443	Explosion fragment	856	4
1476	Spacecraft	498	5
1967	Spacecraft	498	5
1629	Rocket body	565	6 & 10
6025	Explosion fragment	565	6 & 10
1352	Rocket body	1119	7 & 8 & 12
2323	Spacecraft	1119	7 & 8 & 12
1400	Spacecraft	2	8
1609	Rocket body	712	9
3466	Mission related object	24	10
825	Spacecraft	1284	11
3097	Spacecraft	1284	11
2477	Explosion fragment	3	12
2185	Spacecraft	1904	13 & 14
2383	Spacecraft	1904	13 & 14
1318	Rocket body	960	14

Application on 1MC

Example of Baseline scenario:
Initial year : 2009
Final year : 2109
2nd MC simulation
PMD 90%
No launch
ADR 0
No explosion

23 objects at the origin of fragments estimated in 2109

→ 14 groups
→ Total number of collision fragments : 9213

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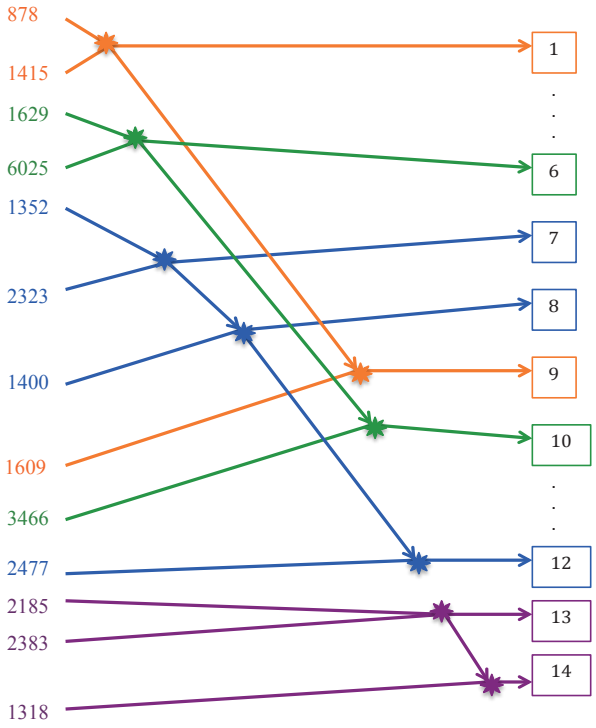
III. Origin tracking function – Study-case results (Application to Removal study Part. II)



Example of Baseline scenario:
2nd MC simulation

Initial year : 2009
Final year : 2109

PMD 90%
No launch
ADR 0
No explosion

Multi-group generating objects

III. Origin tracking function – Results on 94MC mean (Application to Removal study Part. II)

Object's number	Mean number of fragments	Mean number of fragments > mass criterion	Mean number of fragments > size criterion
876 s/c	121.4	4.7	120.5
754 r/b	119.8	7.6	118.8
700 frg	104.5	6.5	104.5
841 r/b	92.9	5.0	92.0
1349 r/b	89.6	3.0	88.6
466 r/b	83.4	5.2	82.4
818 r/b	81.6	4.1	80.6
659 r/b	77.4	3.3	76.4
709 frg	74.5	2.5	73.6
815 r/b	72.3	4.7	71.4
1318 r/b	65.2	2.4	64.3
2309 r/b	64.1	2.1	63.1
1411 r/b	63.7	5.4	62.8
936 r/b	63.4	2.2	62.5
1535 s/c	62.9	2.4	61.9
1607 r/b	60.7	4.3	59.8
795 r/b	60.3	3.4	59.3

List of year-2009 objects generating more than 60 fragments in mean on 94 MC

Example of Baseline scenario:
Mean on 94 MC simulations

Initial year : 2009
Final year : 2109

PMD 90%
No launch
ADR 0
No explosion

Criteria for size & mass :
→ Mass criterion = 10kg
→ Size criterion = 0.1m

s/c : spacecraft
r/b : rocket body
frg : explosion fragment

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III. Origin tracking function – Study-case results (Application to Removal study Part. II)

Which objects are first estimated candidates for removal ?
→ Top 5 *(among 94 MC)*

Type	Mass (kg)	Altitude (km)	Inclination (deg)	Object
Spacecraft	4500	949.8	74.94	COSMOS 952
Rocket body	8230	842.4	71.0	SL-16 R/B (1990-046B)
Explosion fragment	2990	947.4	70.94	?
Rocket body	8230	833.8	71.01	SL-16 R/B (1998-045B)
Rocket body	1420	975.0	82.92	SL-16 R/B (1979-028B)

Study concerning Removal scenarios :
In the 94 MC-mean list, 3 pieces of SL-16 R/B:
→Among top 5 debris-generating objects.

Correlation of results

→If top 10: 6 pieces of SL-16 R/B ; 1 SL-8 R/B ; 1 COSMOS 952; 2 expl. fragments

But : ADEOS2 nor ENVISAT don't appear here

Conclusion

- Study of the effects of targets' removal
  → Surprising results w/r. evolution of population
  → Conclusions: altitude & number of removed objects
  → Assumption: more catastrophic collision avoidance (?)
  → Results strengthened through origin-tracking investigation

- Track of debris origin : completed
  → Could propose **new list of potential targets**
  → Plan: * complete mean on 100 MC
  * rerun simulation without targeted objects
  (for double-check to strengthen the list)

- *Acknowledgements to ESA for providing list of year-2009 initial population*

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C3

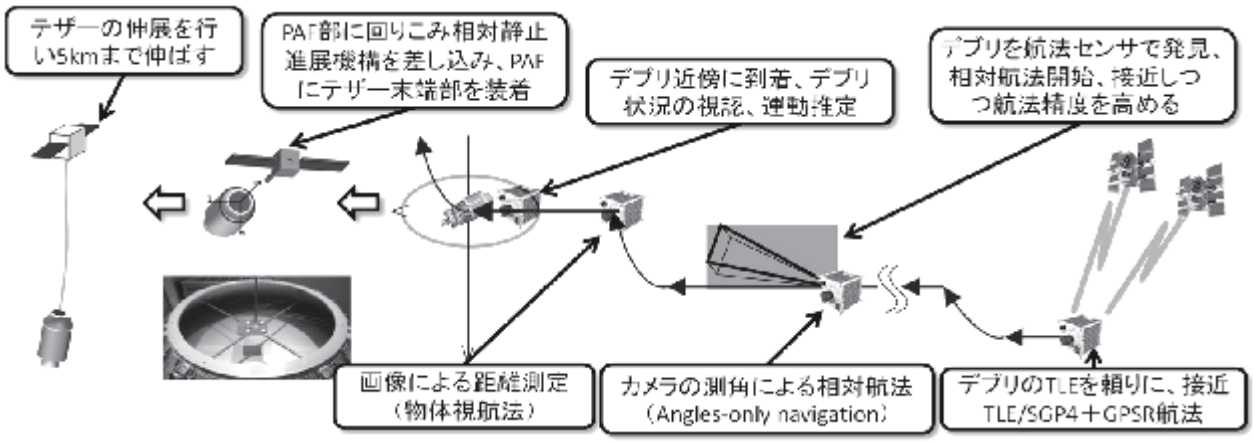
非協力的ターゲットに対する航法誘導制御技術の研究

A research toward guidance, navigation, and control for a Non-Cooperative Target

○中島悠, 山元透, 村上尚美, 山中浩二 (宇宙航空研究開発機構)
○Yu Nakajima, Toru Yamamoto, Naomi Murakami, Koji Yamanaka (JAXA)

デブリの積極的除去にあたり、チェイサ衛星はデブリに接近し推進系を取り付ける必要がある。ISS のような協力的ターゲットと異なり、デブリのような非協力的ターゲットへの接近は、入手できる軌道情報の精度が低い、相対航法の継続性・安定性の確保が困難、といった課題がある。これらの課題を考慮した接近シナリオの検討状況について紹介する。遠方域では TLE/SGP4+GPSR を利用して接近し、搭載カメラでターゲットを認識できる距離まで近づくと Angles-only Navigation による相対航法を開始する。ターゲットの大きさを認識できる距離へ接近後は物体視航法によって接近する。航法センサ候補として可視光・赤外カメラ、LIDAR 等があり、これらの性能を評価するために実物大ロケット PAF モデルを用いた試験を実施した。また、近傍域での接近軌道と接近シミュレーションの結果も示す。デブリ除去の推進系の一例として導電性テザーの進展ダイナミクスの検討も紹介する。最後に、今後の課題と技術開発プランについて述べる。

For the sake of Active Debris Removal (ADR), a chaser satellite is required to attach a propulsion system on the space debris. Unlike cooperative targets such as ISS, Non-cooperative targets like debris are difficult to approach and rendezvous since its trajectory information (TLE) has low precision and relative navigation has less reliability and stability. In order to overcome those technical difficulties, our groups has examined a possible approach scenario. For a far approaching phase, the chaser approaches toward the debris based on TLE/SGP4 and GPSR information. As they get close such that the debris is observed as a tiny dot through navigation camera, the chaser started approach by Angles-Only Navigation (AON) to start relative navigation and get more closer. Lastly, for the near phase such that the size and posture of debris is observable, the chaser starts for precise control and approach. Visible cameras, Infra-Red (IR) cameras, and LIDARs are candidates of the navigation sensor for rendezvous, thus those cameras are evaluated through the experiment using a full-scale H-IIA PAF model. In addition, near phase approaching trajectory plan and its simulation study are introduced. Moreover, ElectroDynamic Tether Tether (EDT), one of the candidate propulsion system to de-orbit the debris, is described and its extending dynamics study is also introduced. Lastly, future works toward the ADR are explained.



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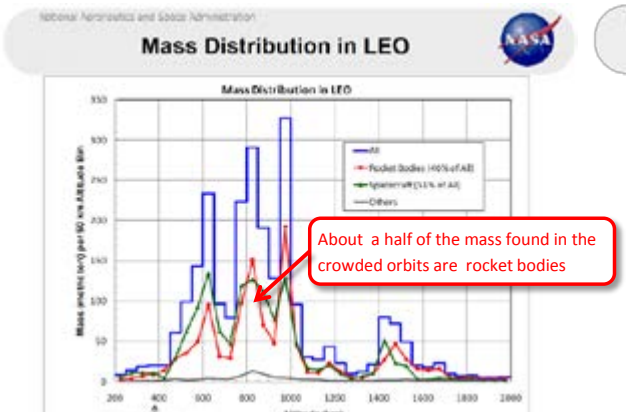
A research toward guidance, navigation, and control for a Non-Cooperative Target

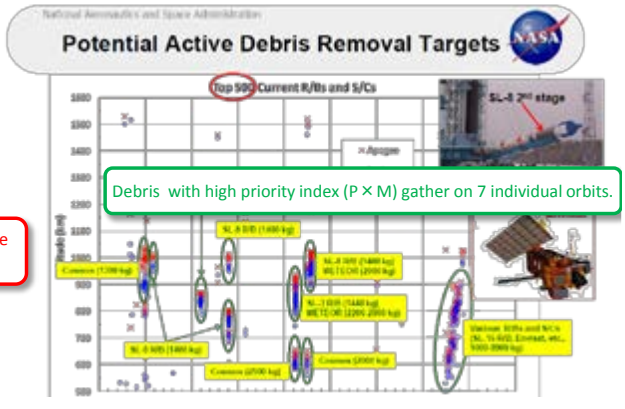
Y. Nakajima, T. Yamamoto, N. Murakami, and K. Yamanaka
Guidance and Control Group
JAXA

1. Background and Motivations

- Target debris to be removed
  - Priority index of target debris is defined as Collision possibility (P) × Mass (M)
  - About half of the mass found on crowded orbits are rocket bodies
  - Most rocket bodies have similar structure, which reduces requirements for navigation and caputre



J.-C. Liou, Orbital Debris and Future Environment Remediation, OCT Technical Seminar NASA HQ, Washington, DC, 2011



J.-C. Liou, The Near-Earth Orbital Debris Problem and the Challenges for Environment Remediation, The 3rd International Space World Conference, Frankfurt, Germany, 2012

Rocket bodies on the crowded orbits are good options for ADR

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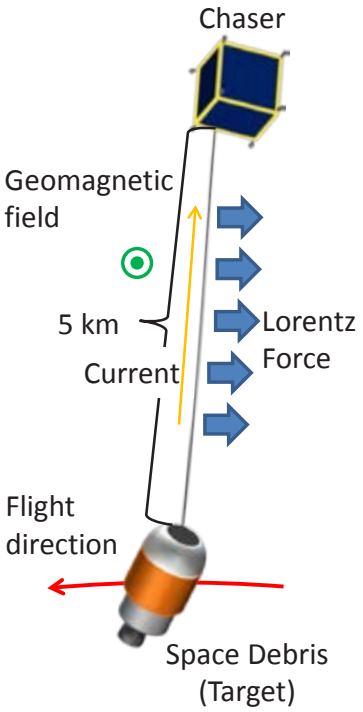
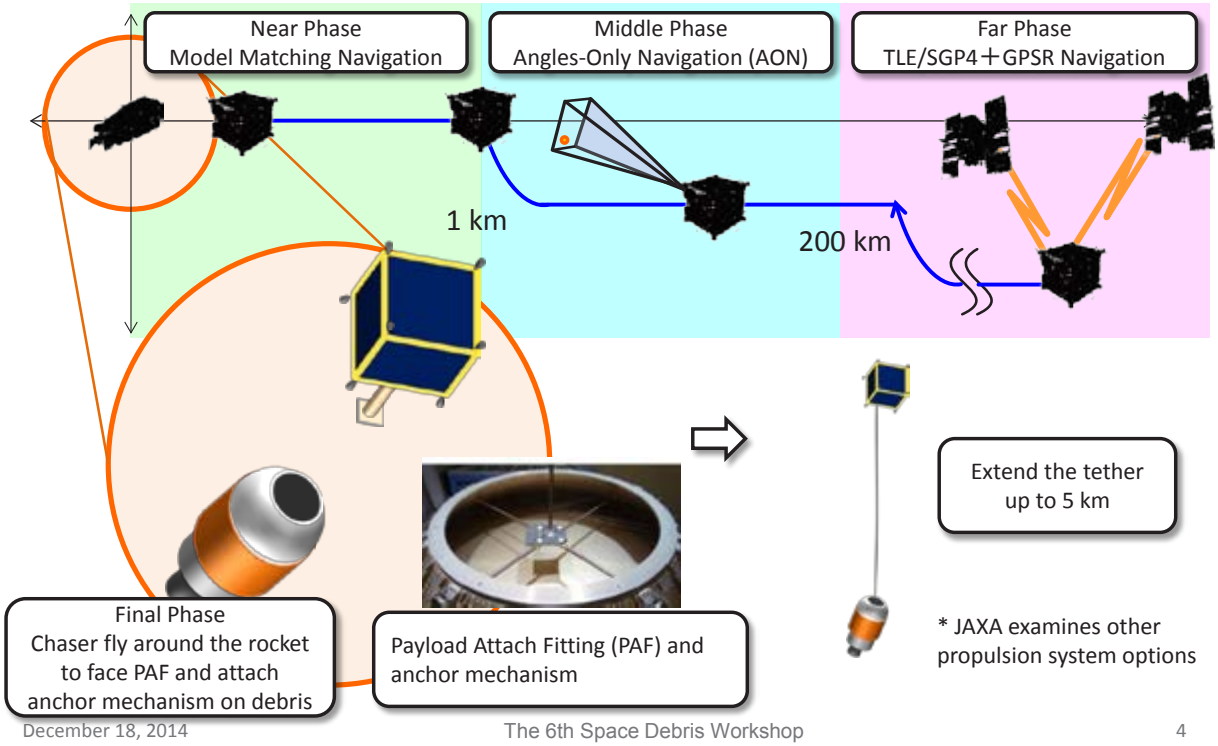
1. Background and Motivations

- JAXA studies the Electro-Dynamic Tether (EDT) system as one of the candidate devices for Active Debris Removal (ADR)
- The ADR mission to apply the EDT system for deorbiting a rocket upper stage is investigated as one of the reference design missions
- Non-cooperative rendezvous is a key technology for the ADR mission
  - Navigation system
  - Safe trajectory
- Extending EDT without entanglement is a major difficulty in case of ADR using EDT



1. Background and Motivations

- ADR plan overview



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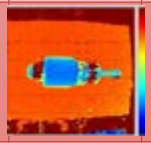
1. Background and Motivations

- Objectives
  - Prototyping the rendesvous system and operation scenario for the ADR mission
    - Overall navigation concept
    - Navigation sensor system
    - Navigation filter
    - Rendezvous trajectory
  - Demonstration of the proposed system and operation scenario by numerical simulations
  - Funadamental experiment to characterize the navigation sensor candidates using real scale rocket model
  - Simulation studies for EDT extension to clarify its difficulties

2.1. Navigation Sensors Concept

- Candidates comparison

			Attitude	Range		LOS Angles	Night	Pros	Cons
				Far	Near				
Visible Camera (VISCAM)			✓	NG	✓	✓	NG	Low cost Avaliable at long distance High resolution	Not available during eclipse Sensitive to lighting conditions Poor range accuracy
Infrared Camera (IRCAM)			✓	NG	✓	✓	✓	Low cost Available during eclipse Robust to lighting conditions	Low resolution Poor range accuracy
Laser Sensor (LIDAR)	LIDAR (Range only)		NG	✓	✓	NG	✓	Available during eclipse Available at long distance High range accuracy	Expensive LOS angles not measured Expensive
	Scanning LIDAR		✓	✓	✓	✓	✓	Available during eclipse Avalialbe at long distance High range accuracy Pose estimation capability	Very Expensive
	Flash LIDAR		✓	NG	✓	✓	✓	Available during eclipse Pose estimation capability	Expensive

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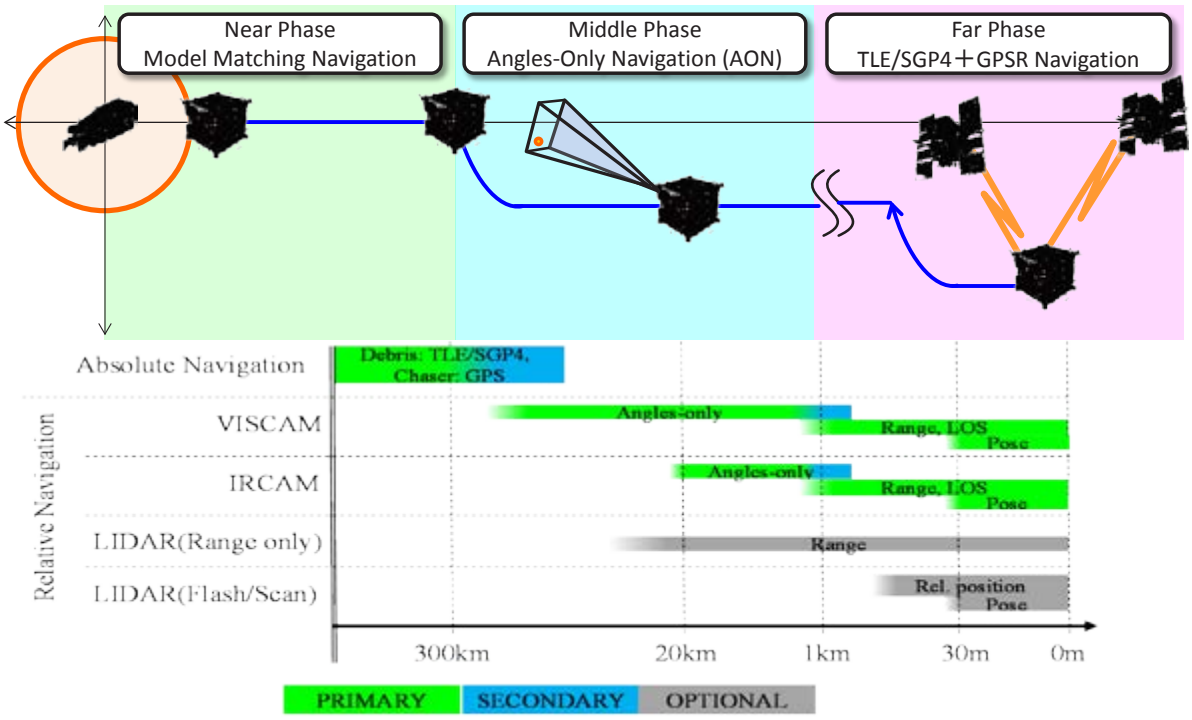
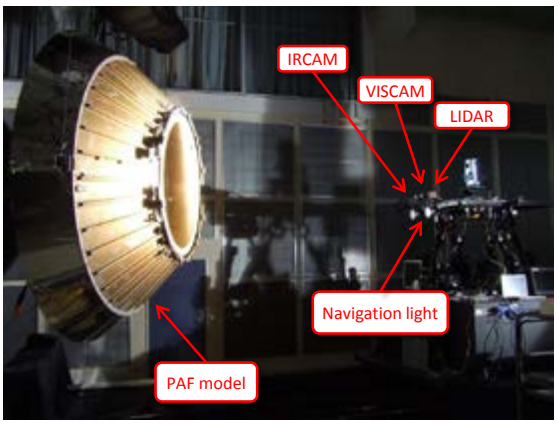
2.2. Overall Navigation Concept

- Navigation Sensor Usage

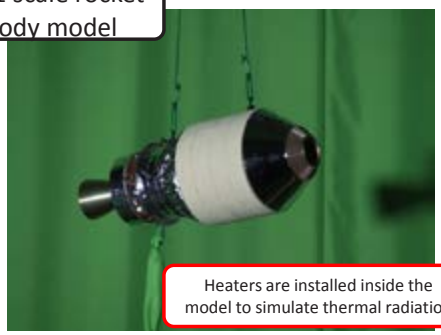


2.3. Navigation Sensors Evaluation

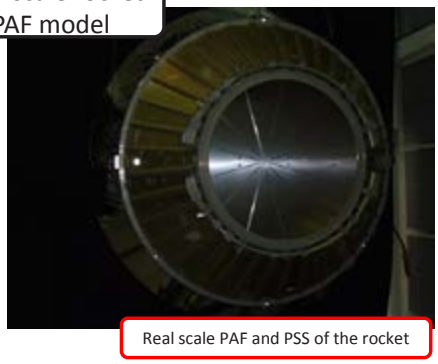
- Experimental verification



20:1 scale rocket body model



Real scale rocket PAF model



- Conditions
  - 3 sensors (IRCAM/VISCAM/LIDAR)
  - 2 models
    - 20:1 rocket body scale model
    - Real scale rocket PAF model
  - Solar light / navigation light
  - Distance (20m～2m)

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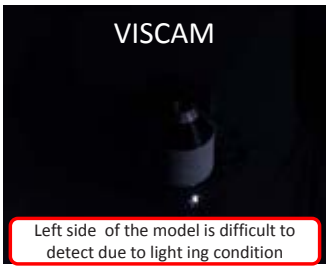
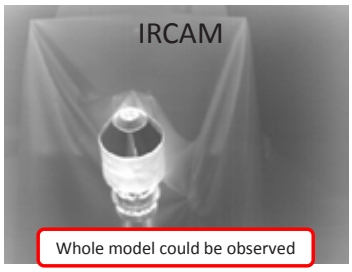
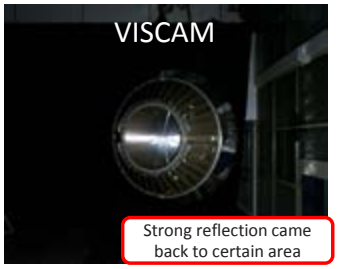
2.3. Navigation Sensors Evaluation

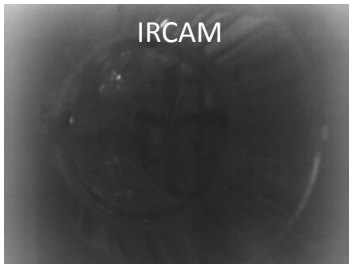
- Scale model images @ 2.5m (corresponding to 50m in real scale)

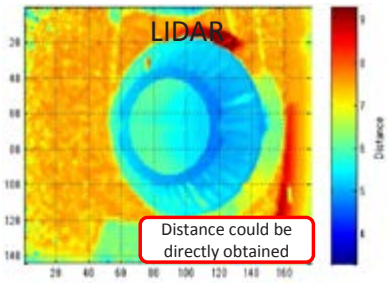




- Real Scale PAF images @ 5m



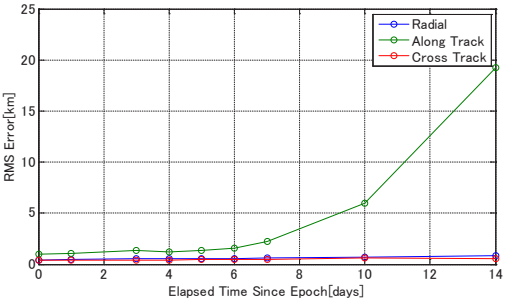




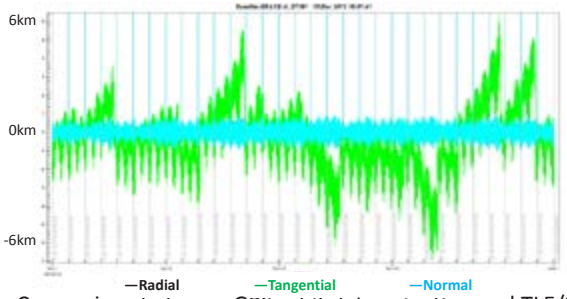
- **Various images are obtained through the experiment**
- **Now we use them to evaluate navigation sensors and design the navigation system**

3.1. Far Phase Navigation (TLE/SGP4)

- Orbit determination accuracy by TLE/SGP4
  - JSpOC (TLE)
    - Various researchers have evaluated orbit prediction error by TLE/SGP4
    - ADEOS-II (800km) data suggested the along-track error after 2 days of propagation is 2 km
    - GRACE-A (500km) data implied the along-track error after 2 days of propagation is 2~7 km
  - Domestic / Oversea Radar site
    - Domestic site: Kamisaibara Spaceguard Center Oversea Site : TIRA(FHR; Germany)
    - The timing of orbit determination can be intentionally chosen, thus suitable for critical operation phase
    - TIRA has the accuracy of 400 m (along-track) after 1 day of propagation [1]



Comparison between GPS orbit determination and TLE/SGP4(ADEOS-II)



Comparison between GPS orbit determination and TLE/SGP4 (GRACE-A) TLE updated every 2 days

[1] Kahle R., Weigel M., Kirschner M., Spiridonova S., Kahr E., Letsch K. : Relative Navigation to Non-Cooperative Targets in LEO: Achievable Accuracy from Radar Tracking Measurements, 5th International Conference on Spacecraft Formation Flying Missions and Technologies, 2011

Holding chaser 20km apart from the target can be achieved by TLE/SGP4

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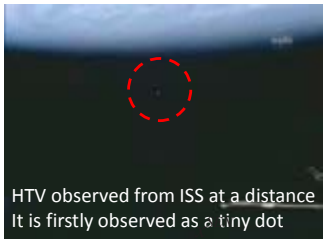
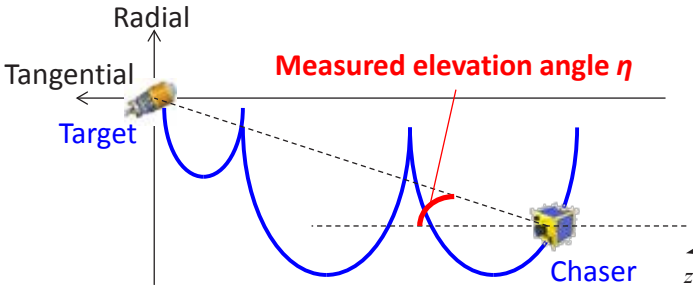
3.2. Middle Phase Navigation (AON)

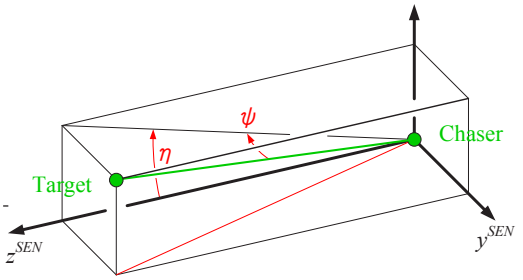
- What is Angles-only navigation (AON)?

  Navigation method to estimate relative position and velocity by only target direction (Azimuth/Elevation) from cameras

- Why angles-only navigation is necessary ?
  - A target is seen as a tiny point from long distance
  - If laser sensors are not available, a chaser must approach to a target using only direction information until target shape can be seen on a camera image
- Features of angles-only navigation
  - No direct 3D position information
  - Trajectory should ensure visibility and observability
  - Proper maneuver execution stimulates observability

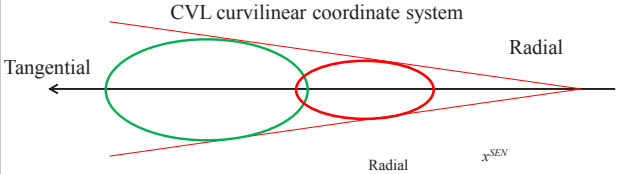


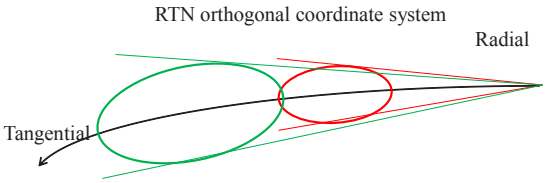


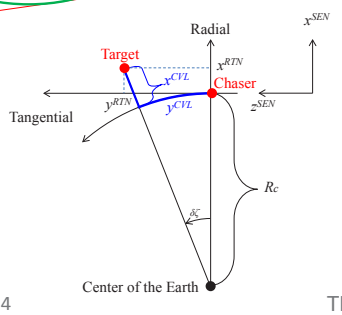


3.2. Middle Phase Navigation (AON)

- Observability of AON
  - Processing LOS angle measurements of natural relative orbit can make the system observable
  - There are infinite similar solutions comprising relative orbits to reproduce the same LOS angle measurement profiles
  - However, the CW equations are actually linearized with respect to the curvilinear CVL coordinate frame, whereas the LOS angles are measured in the orthogonal RTN frame
  - Similar solutions of relative orbits obtained by CW equations in the CVL frame are not similar when mapped into the RTN frame
  - Unique relative orbit can be determined by the LOS angle measurements







$$\boldsymbol{c}_{CVL}^{RTN}(\delta\hat{\boldsymbol{r}}^{CVL}) = \begin{pmatrix} \delta\hat{r}_x^{CVL}\cos(\delta\hat{\xi}) - R_c(1-\cos(\delta\hat{\xi})) \\ (R_c + \delta\hat{r}_x^{CVL})\sin(\delta\hat{\xi}) \\ \delta\hat{r}_z^{CVL} \end{pmatrix}$$

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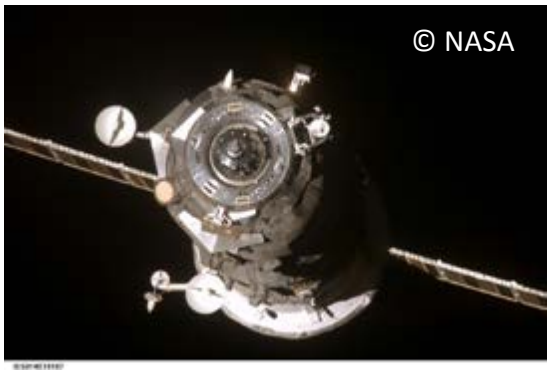
3.3. Near Phase Navigation (MMN)

- Model Matching Navigation
  - The target shape can be recognized from the distance of 1 to 2 km
  - Distance to the target is estimated by comparing the structure model and obtained image
  - Whole target may not be obtained by visible cameras due to its shadow
  - Image obtained by IR cameras will not be interfered by lightning conditions

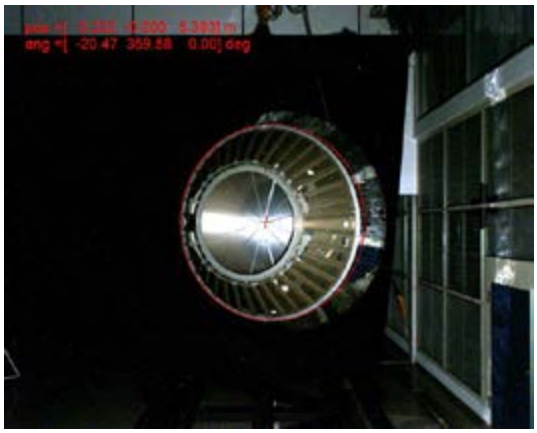


Progress observed from ISS
Shaded part of the Progress is difficult to distinguish from the background

MMN is used from the distance of 1 to 2 km to the target

3.4. Final Phase Navigation (MMN)

- Model Matching Navigation
  - Control requirements are ±10 cm for distance and ±5 deg for attitude
  - A simple model matching algorithm is tested as a preliminary study
    - Circular joint plane of the PAF is detected from the image
    - Distance and orientation of the circular joint plane are estimated from the detected result
  - Further improvement might be achieved by enriching the algorithm, however it would increases the calculation time
  - The trade-off study will be conducted to find out the optimal design



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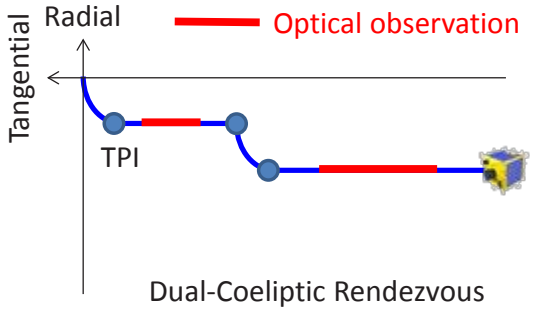
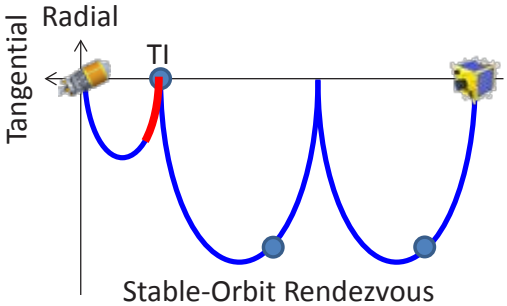
4.1. Far/Middle Phase Trajectory Design

- Candidate Trajectories



Dual-Coeliptic Rendezvous



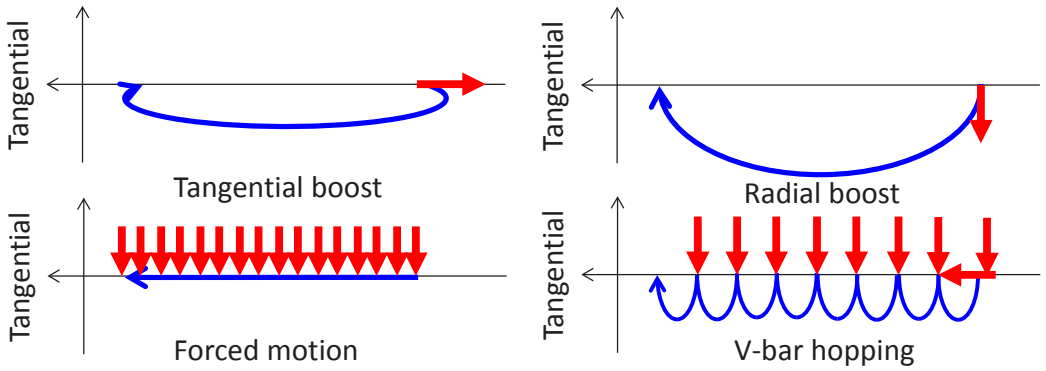
Stable-Orbit Rendezvous

Dual Co-elliptic Rendezvous (DCR)	Stable Orbit Rendezvous (SOR)
Pros: PA is safe	Pros: Chaser can stay at the V-bar hold point and adjust the arrival time arbitrarily
Cons: Restriction to the arrival time adjustment	Cons: Difficulty in ensuring passive abort (PA) safety

DCR is adopted for far phase rendezvous

4.2. Near Phase Trajectory Design

- 4 kinds of possible V-bar approach trajectories are compared



	PA Safety	Guidance Error	ΔV
Tangential boost	×	△	○
Radial boost	△	△	○
Forced motion	○	○	×
V-bar hopping	○	○	△

V-bar hopping trajectory is adopted for near phase approach

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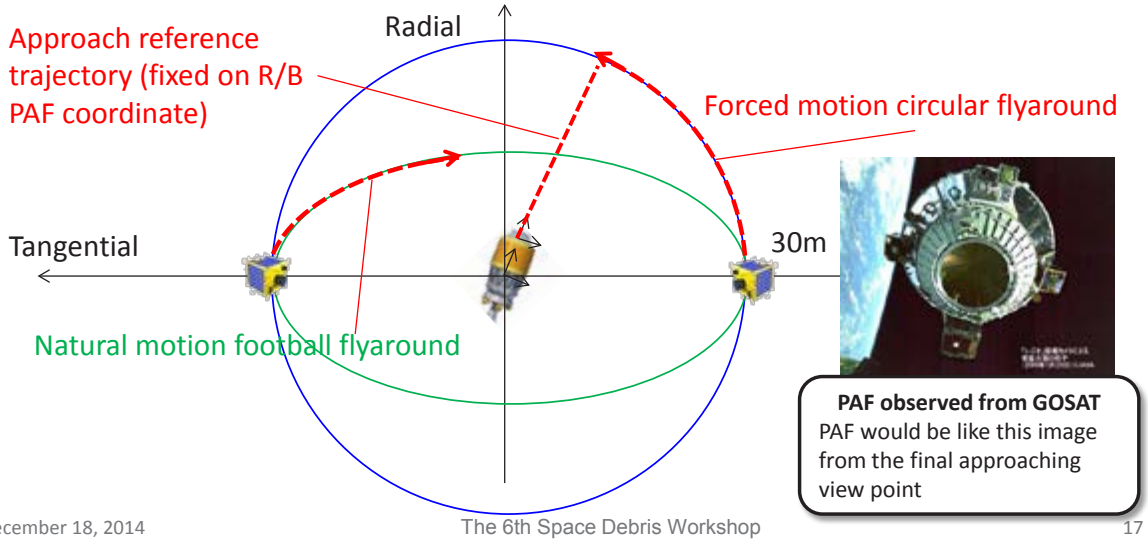
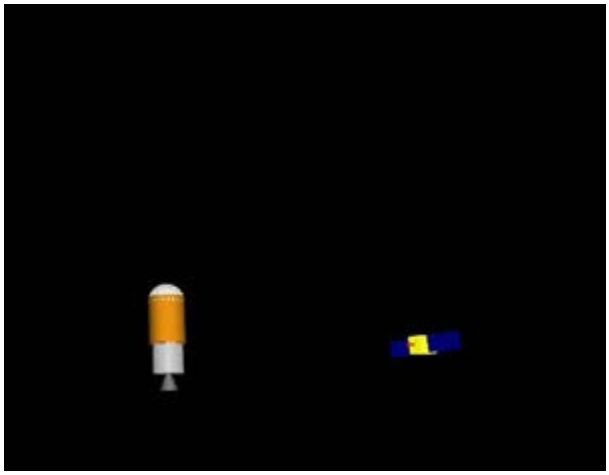
4.3. Final Approach Trajectory

- Since energy has been dissipated by Eddy current effect, the rocket bodies are expected to stand still and slightly swinging by gravity gradient torque
- Gravity center, motion, and rotation of the debris are observed from the 30m point
- Chaser flies tracing the circular trajectory to face PAF and relative navigation start as chaser get in front of PAF
- The anchor mechanism is attached to the PAF after approaching by relative navigation



4. 3. Final Approach Trajectory

- Several initial conditions of the debris rotation were tested
- Estimation error of the image processing was modeled tentatively
- As long as the navigation is successful, the chaser could approach to the debris by relative navigation to attach the anchor mechanism



- **Chaser could attach the anchor mechanism on the debris with slow rotation**
- **Navigation error model must be refreshed reflecting the experimental data**

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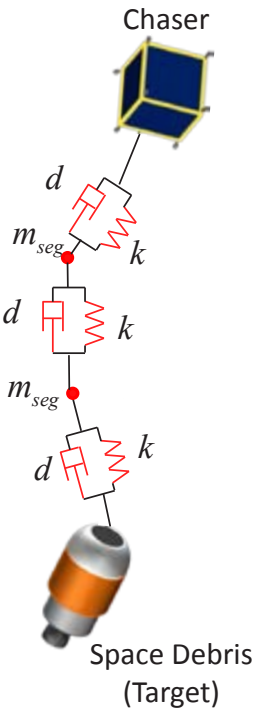
5. EDT Extension

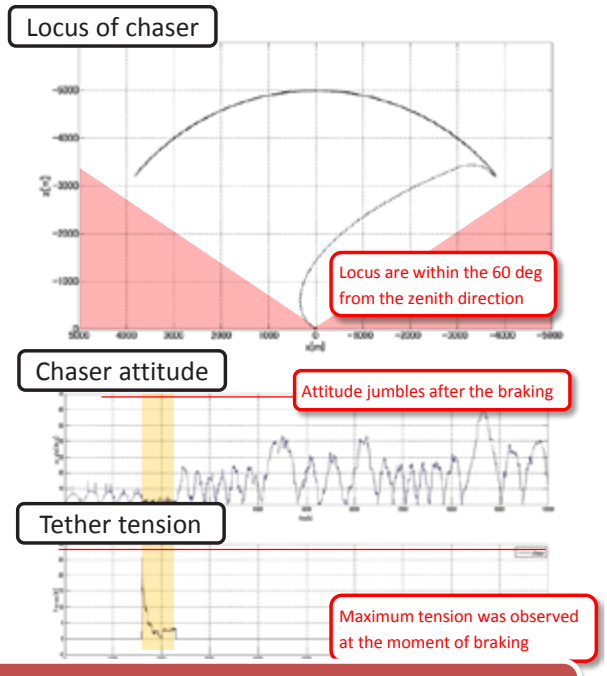
- Objectives
  - It is desirable if EDT could be extended passively
  - De-orbitting efficiency would be the best if EDT is extended to the vertical to the flight direction
  - Tension of the EDT must be kept under 100 N
  - It is desirable if the attitude of chaser and debris are calm



- Simulations
  - Multi-mass model
    - soft tissue of the EDT is modeled as:
      - divided into the segments with mass connected by spring and damper
      - tension will not be generated if the segment length is less than natural length
  - Brakes are implemented to reduce the speed before 5km

5. EDT Extension

- Simulation Results



- **EDT extension can be achieved with only the early phase acceleration**
- **However, EDT swings back and forth with quite a large angle**

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6. Conclusions and Way Forward

- This work addressed the design of the relative navigation and the rendezvous trajectory toward debris.
  - Overall navigation concept for the reference mission is designed
  - Preliminary experimental study of the candidate navigation sensors are introduced
  - The approach trajectory is elected from the viewpoint of passive abort safety considering unreliable relative navigation
  - Numerical simulations are conducted to verify the designed reference trajectory and EDT extension up to 5 km
- Navigation system should be refined, reflecting the results of experimental verifications.
- Simulations with updated parameters based on the experiments should be done to verify the reference scenario more precisely.
- Further discussions are needed to select the propulsion sytem to de-orbit the debris.

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C4

デブリ近傍領域における除去衛星の姿勢軌道制御について

Attitude and orbit control of the active debris removal satellite

○田中啓太、加藤貴昭、桑尾文博（NEC）、
山元透、中島 悠、村上尚美、池内正之（JAXA）
○Keita Tanaka, Takaaki Kato, Fumihiro Kuwao (NEC),
Toru Yamamoto, Yu Nakajima, Naomi Murakami, Masayuki Ikeuchi (JAXA)

本論文はデブリ近傍領域における除去衛星の姿勢軌道制御について議論する。除去衛星はデブリからの距離約 100km の地点から相対航法を開始し、DCR 接近、Vbar 接近、最終接近を経てデブリに到達する。この最終接近フェーズにおいて、はやぶさで用いられたスラスタ ON/OFF 制御を適用し、誘導が可能であることを数値的に示した。また同じ制御則を用いて、デブリに対して相対停止、デブリから離脱できることを確認した。

This paper discusses the attitude and orbit control of the active debris removal satellite in the vicinity of the target. The satellites begins the relative navigation w.r.t. the debris at 100 km from it and approaches it through the DCR and V-bar trajectories. We proposes that the same thruster-control law as the asteroid explorer HAYABUSA can be applied in the very final approaching phase of this mission and confirms its validity through a numerical calculation. The results shows that the proposed navigation successfully guides the satellite in the direction of the debris.

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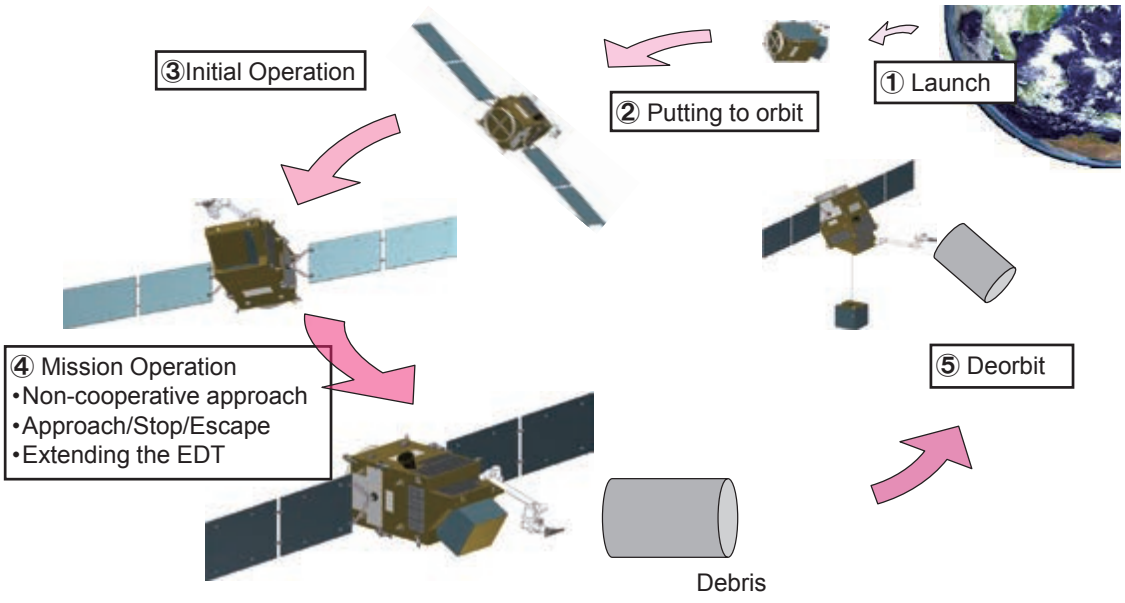
Attitude and Orbit Control of the Active Debris Removal Satellite

Keita Tanaka, Takaaki Kato, Fumihiro Kuwao (NEC)
Toru Yamamoto, Yu Nakajima, Naomi Murakami, Masayuki Ikeuchi (JAXA)

Debris Removal Satellite

A satellite which makes a debris deorbit by attaching a removal device on it.



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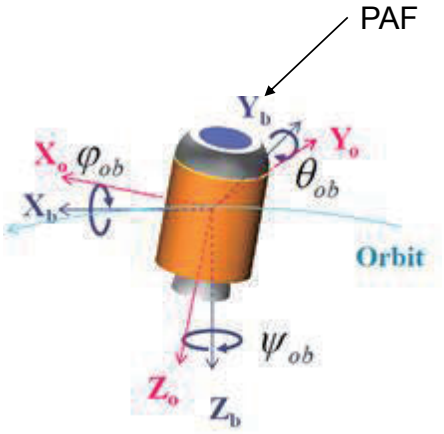
Target

Target

- Upper part of a H2A rocket.
- Attach a debris-removal devices on the PAF.



Debris removal device

- Electrodynamic Tether(EDT）

EDT system
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Objective

Show a feasible operating plan
of the debris-removal mission
from the viewpoint of the attitude/orbital control.

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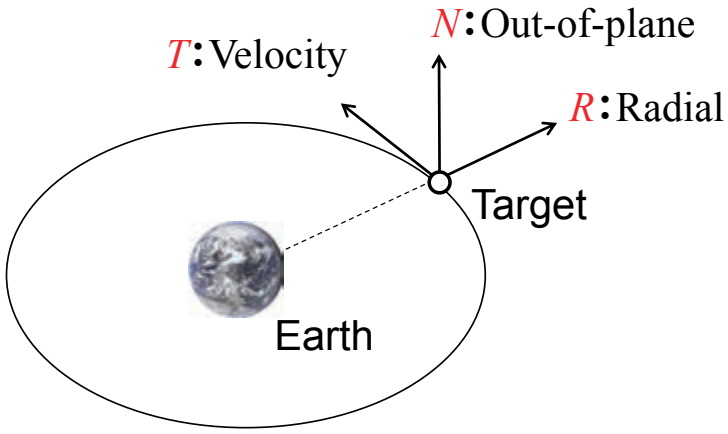
Coordinate

- Target-centered RTN coordinate system
  - Target-fixed orthogonal coordinate system.



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Analysis

- Motion of the satellite in the distant realm from the debris.
  - Orbital motion of the satellite
  - Orbital motion of the debris
- Motion of the satellite in the vicinity of the debris.
  - Orbital / Attitude motion of the satellite
  - Orbital / Attitude motion of the debris

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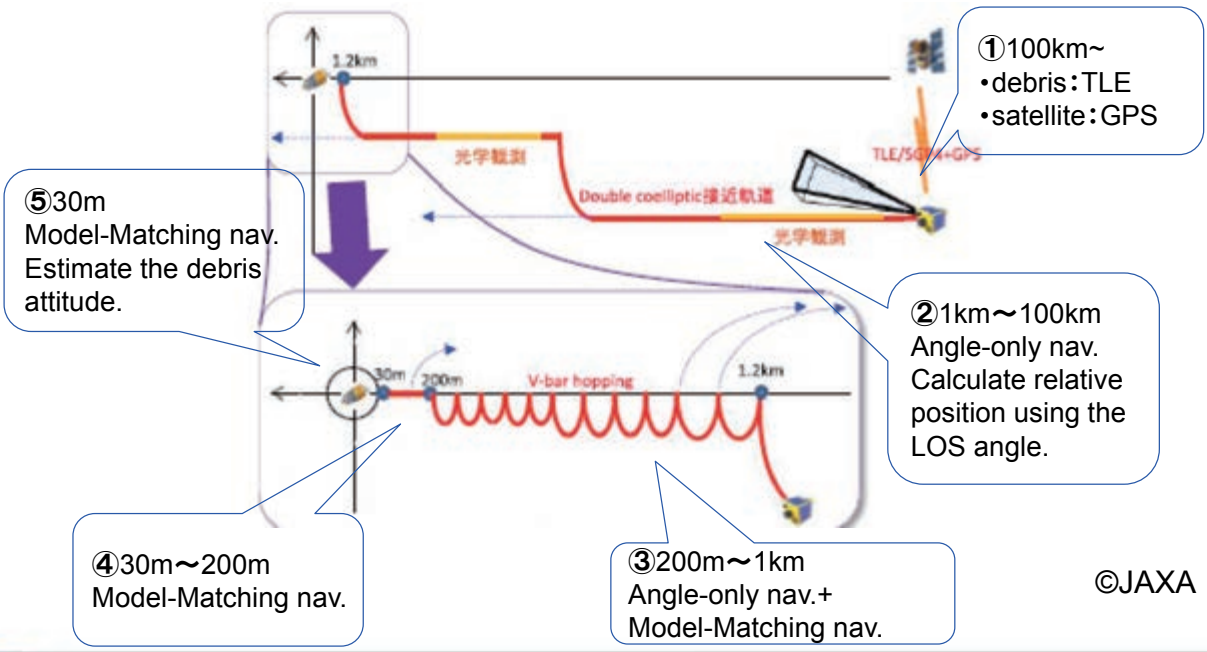
Motion of the satellite in the distant realm from the debris

Analyze the motion of the satellite in the realm of 30m ~ 100km from the debris.



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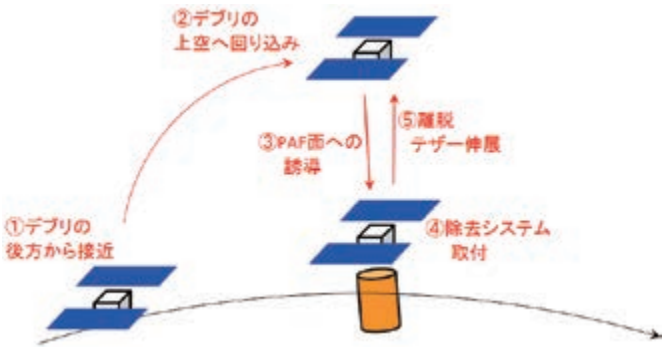
Motion of the satellite in the vicinity of the debris

Analyze the motion of the satellite in the realm of 1m ~ 30m from the debris.

- Estimate the attitude of the debris at 30m from it.
- Plan the approaching trajectory.
- Fly around above the PAF.
- Approach.
- Stop and keep an appropriate distance from the debris.
- Attach the removal device.
- Escape.



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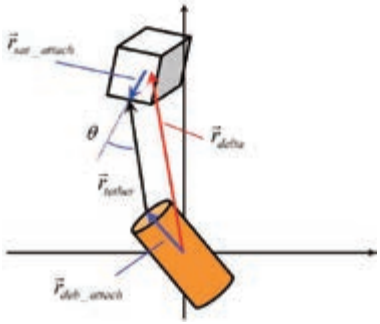
Equation of Motion

Calculate the motion of the satellite and the debris using the following the equations. of motion.

$$
\begin{cases}
\dfrac{d\vec{x}_{deb}}{dt} = \vec{v}_{deb} \\
\dfrac{d\vec{v}_{deb}}{dt} = -\mu \dfrac{\vec{x}_{deb}}{|\vec{x}_{deb}|^3} + \dfrac{\vec{F}_{deb_tether}}{m_{deb}} + (\text{摂動による加速度}) \\
\dfrac{d\vec{\omega}_{deb}}{dt} = \vec{I}_{deb}^{\,-1}\left(\vec{T}rq_{deb_tether} + \vec{T}rq_{deb_gravity} - \vec{\omega}_{deb} \times \vec{I}_{deb}\vec{\omega}_{deb}\right) \\
\dfrac{d\vec{q}_{deb}}{dt} = \dfrac{1}{2} E([q_{deb}])\vec{\omega}_{deb} \\
\dfrac{d\vec{x}_{sat}}{dt} = \vec{v}_{sat} \\
\dfrac{d\vec{v}_{sat}}{dt} = -\mu \dfrac{\vec{x}_{sat}}{|\vec{x}_{sat}|^3} + \dfrac{\vec{F}_{sat_thruster} + \vec{F}_{sat_tether}}{m_{sat}} + (\text{摂動による加速度}) \\
\dfrac{d\vec{\omega}_{sat}}{dt} = \vec{I}_{sat}^{\,-1}\left(\vec{T}rq_{sat_thruster} + \vec{T}rq_{sat_tether} - \vec{\omega}_{sat} \times \vec{I}_{sat}\vec{\omega}_{sat}\right) \\
\dfrac{d\vec{q}_{sat}}{dt} = \dfrac{1}{2} E([q_{sat}])\vec{\omega}_{sat}
\end{cases}
$$



$$
E([q_{sat}]) = \begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{bmatrix}
$$

$F_{thruster}$: Force due to the thruster
F_{tether} : Force due to the tether.
$Trq_{thruster}$: Torque due to the thruster
Trq_{tether} : Torque due to the tether.
$Trq_{gravity}$: gravity gradient torque

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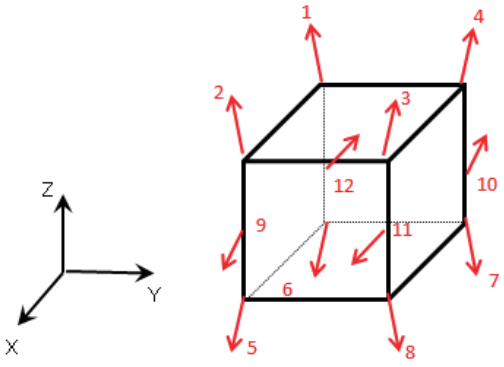
Modeling of the satellite

Model the satellite as a cube.

- Size = 1m*1m*1m
- Mass = 500kg

Set 12 thrusters.

- Force = 4N
- Isp = 220s
- Error = 5%



		使用スラス	並進力 [N] X	並進力 [N] Y	並進力 [N] Z	トルク [Nm] X	トルク [Nm] Y	トルク [Nm] Z
並進	+X	10,12	7.52	0	0	0	0	0
	−X	9,11	−7.52	0	0	0	0	0
	+Y	10,11	0	2.74	0	0	0	0
	−Y	9,12	0	−2.74	0	0	0	0
	+Z	5,6,7,8	0	0	15.76	0	0	0
	−Z	1,2,3,4	0	0	−15.76	0	0	0
回転	+X	1,2,7,8	0	0	0	6.09	0	0
	−X	3,4,5,6	0	0	0	−6.09	0	0
	+Y	2,3,6,7	0	0	0	0	5.75	0
	−Y	1,4,5,8	0	0	0	0	−5.75	0
	+Z	11,12	0	0	0	0	0	5.13
	−Z	9,10	0	0	0	0	0	−5.13

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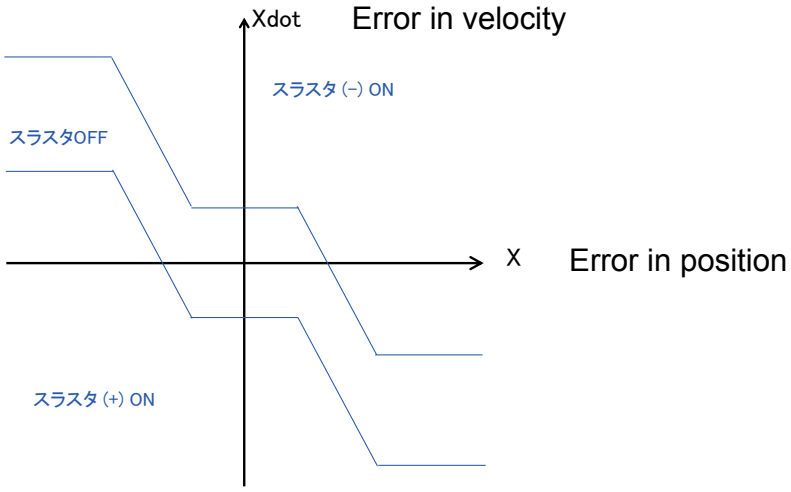
Thruster control in the vicinity of the debris

- Plan a reference trajectory and navigate the satellite to follow it.
- Switch on and off of the thrusters depending on the difference between the actual and planned states.

  ⇒ Control law of HAYABUSA.



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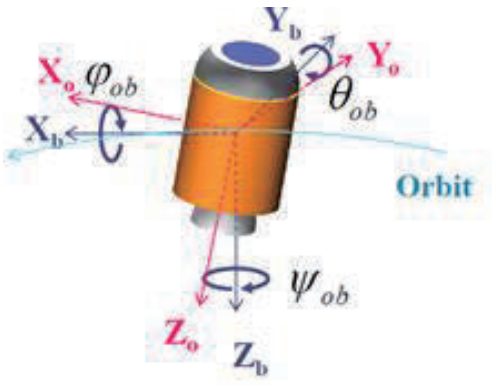
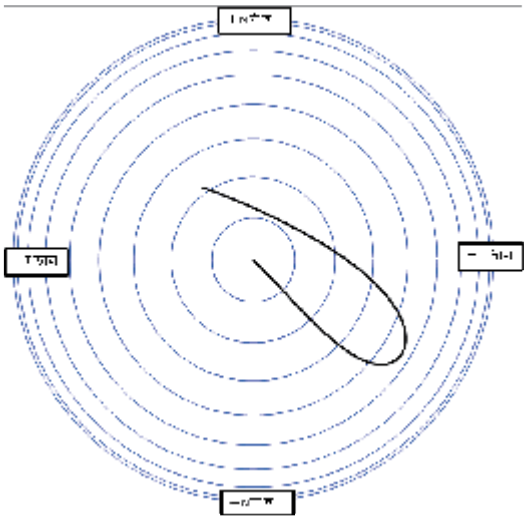
Modeling the debris

- Model the debris as a cylinder stabilized due to the gravity gradient.
  - Nutation





Movement of the central axis

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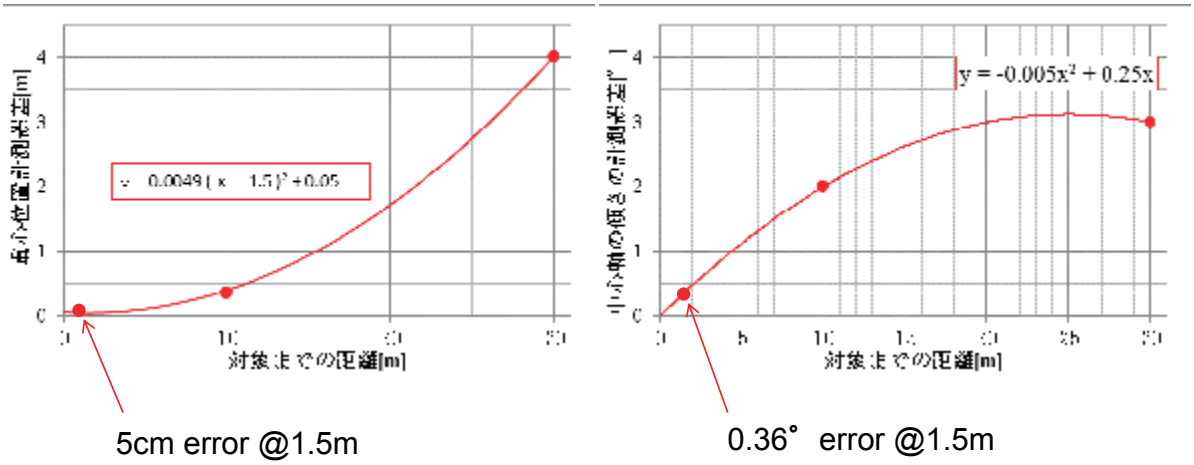
Observation error

- Define observation errors as a function of the distance between the satellite and the debris.

  Error in position [m] = $0.0049 (x - 1.5)^2 + 0.05$

  Error in attitude [°] = $-0.0048x^2 + 0.2433x$



5cm error @1.5m

0.36° error @1.5m

Simulation results

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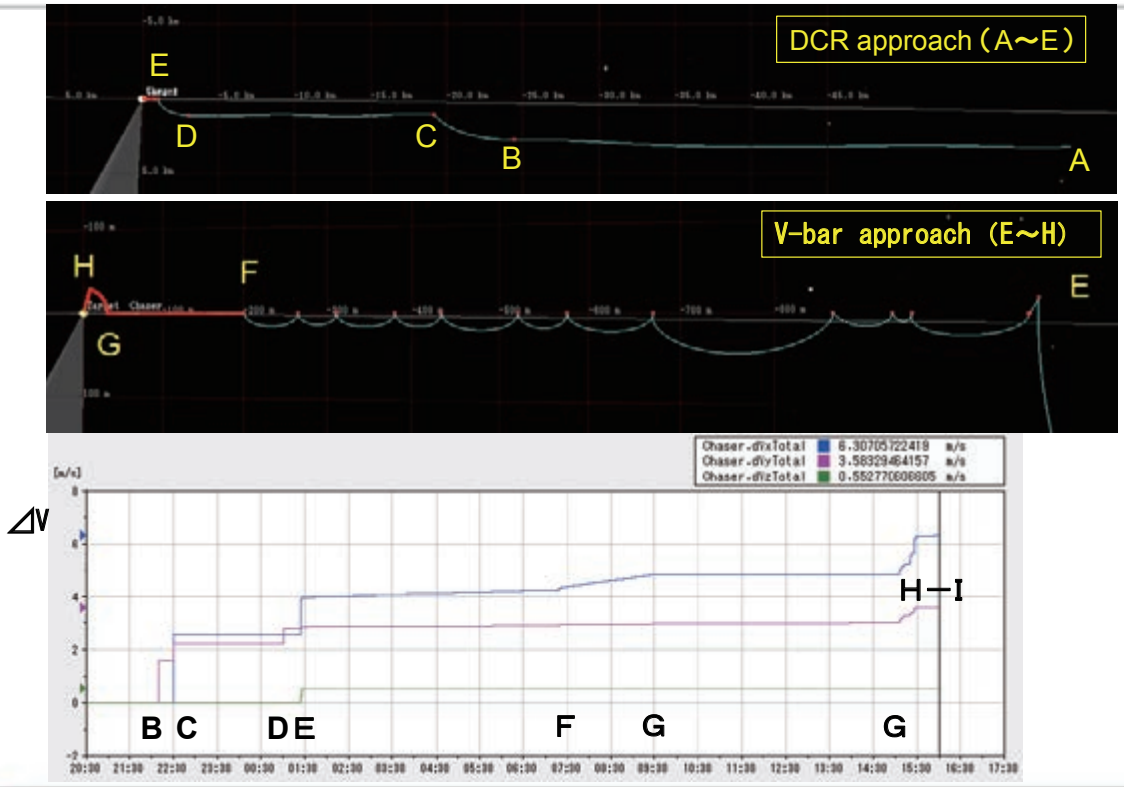
Motion of the satellite in the distant realm from the debris



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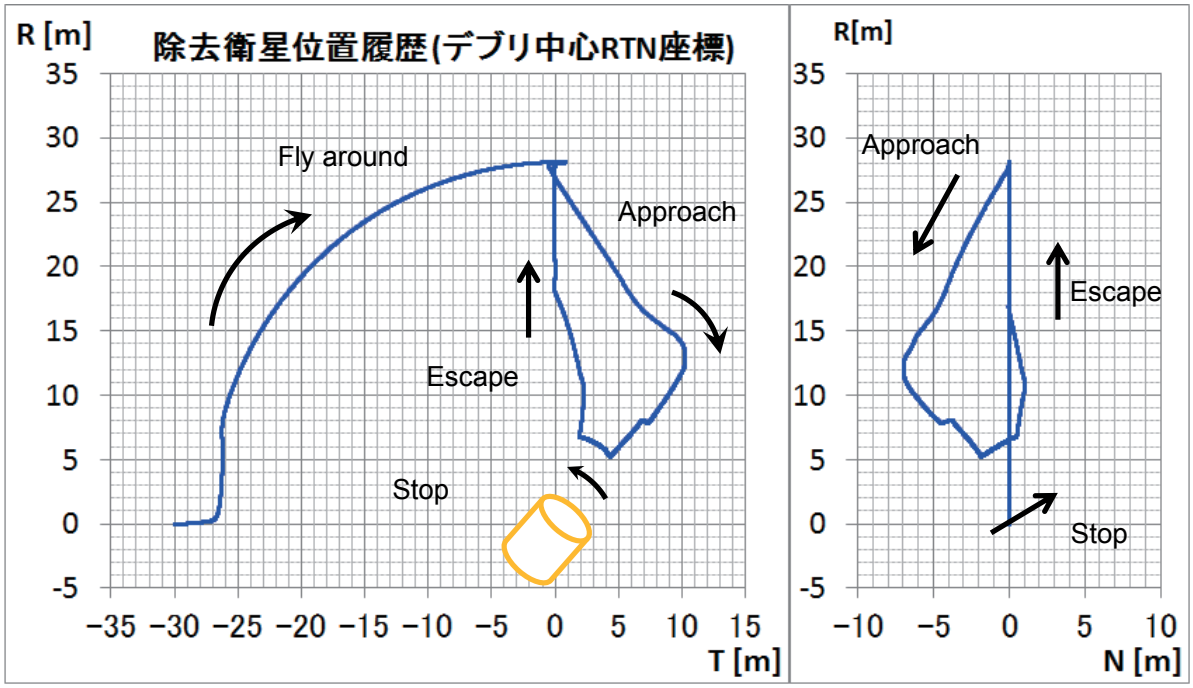
Motion of the satellite in the vicinity of the debris



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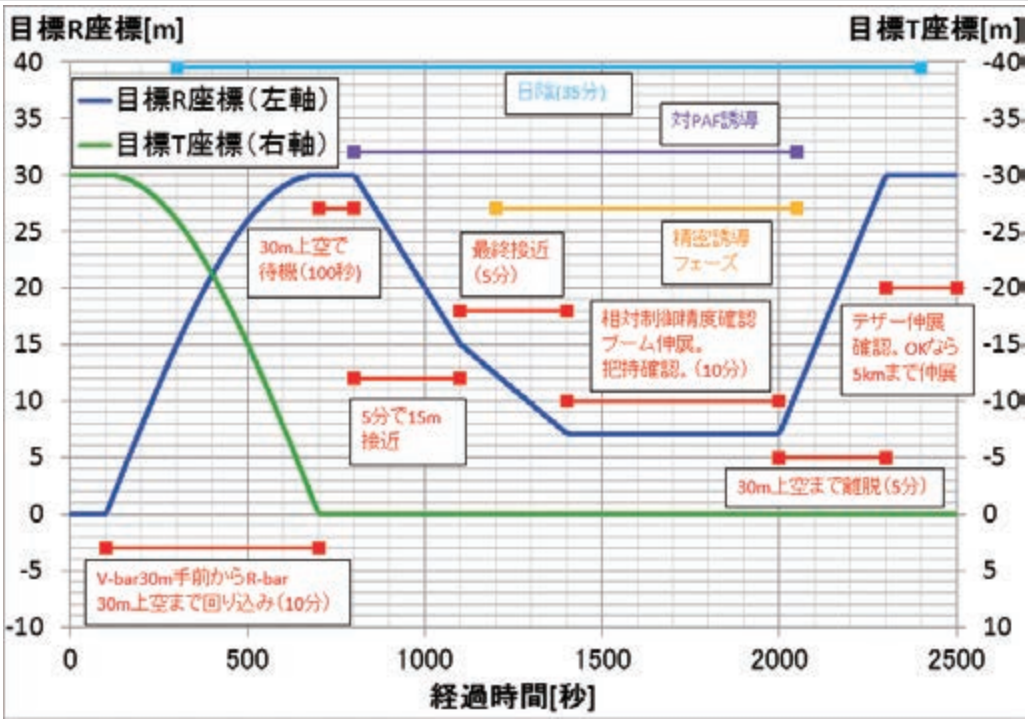
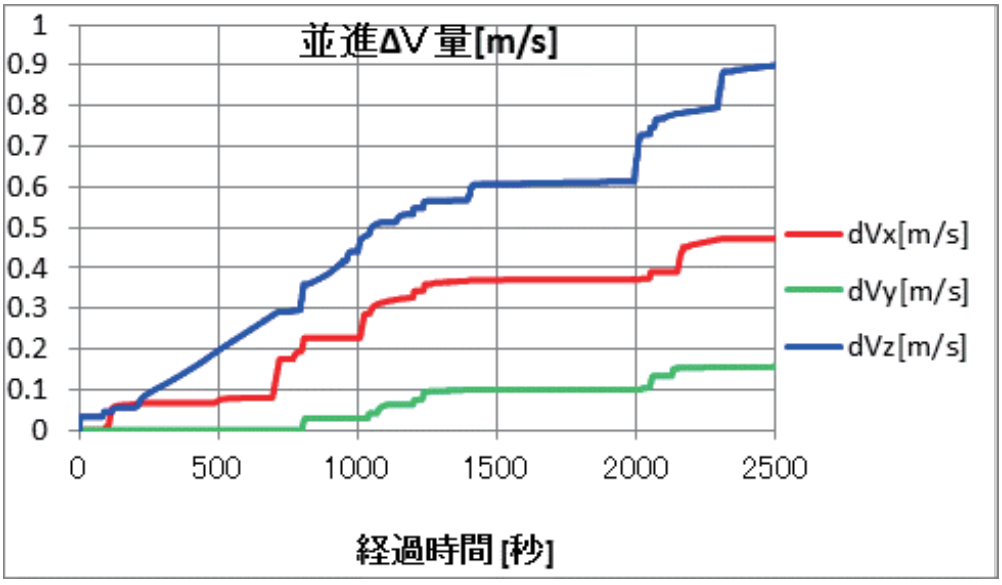
Navigation



ΔV

- ΔV of each axis is less than 1m/s (x=0.45m/s, y=0.15m/s, z=0.9m/s) at the end of the sequence.



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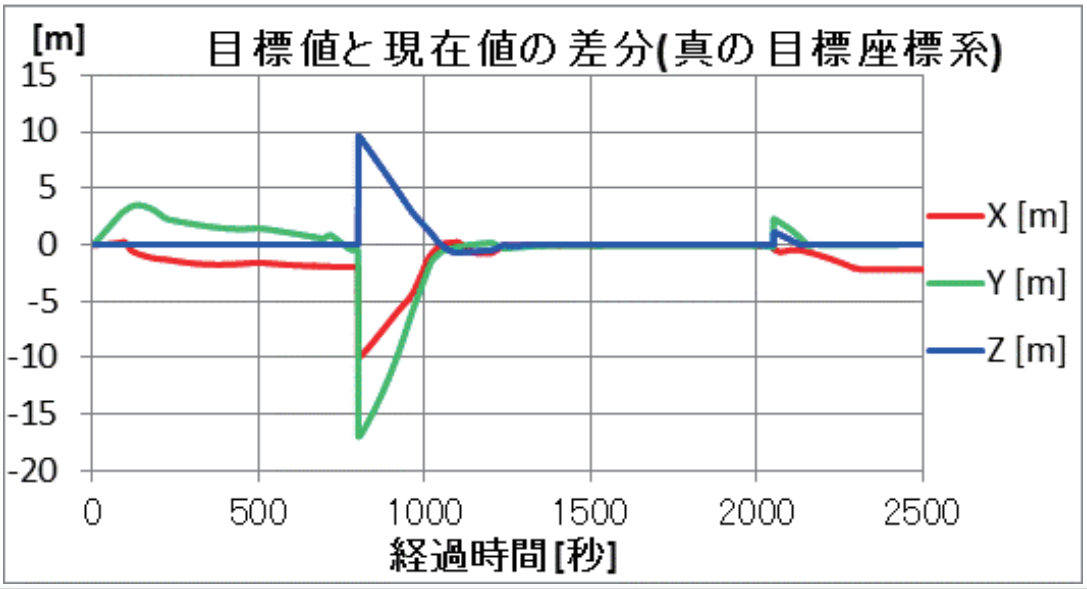
Error in position

- Converge gradually and become nearly-zero at the relative-stop phase.
  - less than ±10cm



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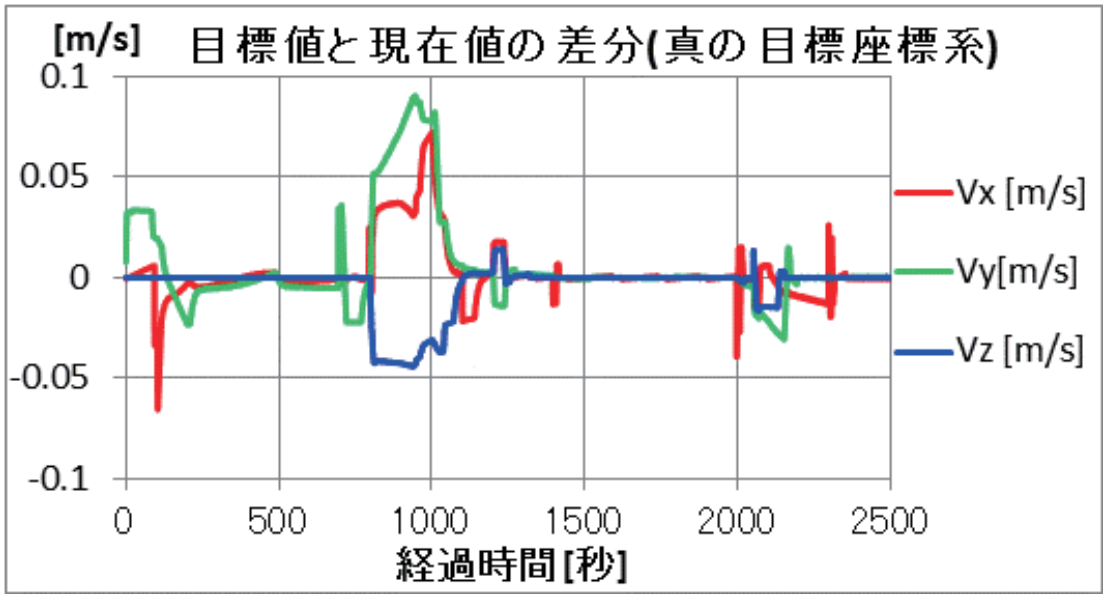
Error in velocity

- Less than ±5cm/s



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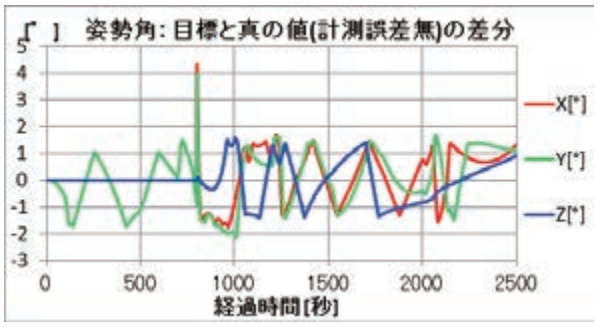
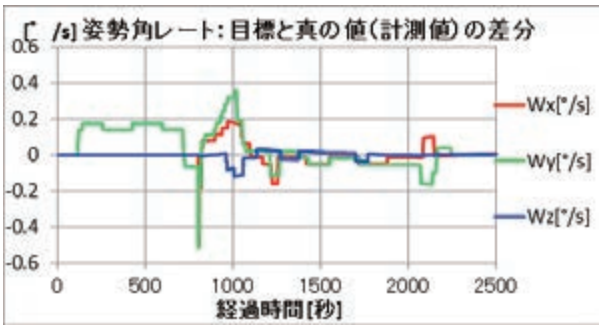
Error in attitude angle / attitude angle rate

- Less than ±5deg in the attitude angle.
- Less than ±1deg/s in the attitude angle rate.





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Summary

- Simulate the orbital / attitude motion of the satellite in the distant and close realms from the debris.
- The result shows that the satellite gets closer the debris through DCR and Vbar approach.
  - 19 hours, ΔV=10.4m/s, stating from 80km point
- It also shows that the satellite successfully approaches, stops and escapes from the debris using the thruster control law of HAYABUSA.
  - ΔV of each axis is less than 1.0m/s
  - Errors in position/velocity are nearly-zero.
- Estimation of the position and attitude of the debris using image processing is now under study.

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C5

デブリ除去における画像計測と運動推定についての現状報告

Current Progress in the Application of Visual-based Perception and Motion Estimation for Space Debris Removal

○片山 保宏, 渡邊 恵佑, 鈴木 悟史(JAXA),
林 正人(有限会社ニック), 河本 聡美(JAXA)
○Yasuhiro Katayama, Keisuke Watanabe, Satoshi Suzuki(JAXA),
Masato Hayashi (Ltd. Nick), Satomi Kawamoto (JAXA)

デブリ衛星の除去を実現するためには、デブリ衛星の計測と運動推定の技術が必要不可欠である。安全で確実にミッションを実施するためには、数十 m 程度の距離からデブリ衛星の外観観測とその運動推定の実施し、その後、デブリ衛星へ数 m 程度の近距離まで接近し、除去装置の取り付け作業が特に重要となる。我々は、システムを小規模で構築でき、遠方から近距離まで広範囲で利用可能な画像を用いた計測手法が有効と考え検討を進めている。ステレオ視による 3 次元形状復元や、モデルマッチングによる対象の位置・姿勢推定などのアルゴリズム検討、そして、計測精度評価や処理速度見積もりを実施している。また、画像を用いる際に問題となる太陽光の映り込みや夜間など多様な照明環境を評価するために、実験室内に光学シミュレータを整備し実験を行っている。本発表では、画像計測と運動推定についての状況についての報告を行う。

Perception and motion estimation of a target are extremely crucial for space debris removal. A safe and secure mission to achieve this involves the following steps: first, checking the appearance and estimating the motion of a target from a distance of few tens of meters; then, approaching it until the distance is reduced to a few meters; and finally, setting a removal equipment for it. A visual-based perception system is found to be useful for these tasks because it can be compactly structured and measure a wide and long range. We studied this system for practical applications such as stereo vision three-dimensional (3-D) reconstruction, model-based matching for pose-position estimation, and so on. We built an optical simulator that can be used for testing various optical situations in an orbit. This paper briefly describes the current progress of our activities.

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the 6th Space Debris Workshop
Dec 19, 2014

Current Progress in the Application of Visual-based Perception and Motion Estimation for Space Debris Removal

○ Yasuhiro Katayama (JAXA), Keisuke Watanabe (JAXA), Satoshi Suzuki(JAXA),
Masato Hayashi (Ltd. Nick), Satomi Kawamoto(JAXA)

デブリ除去における画像計測と運動推定についての現状報告

○片山 保宏（JAXA），渡邊 恵佑（JAXA），鈴木 悟史（JAXA），
林 正人（有限会社ニック），河本 聡美（JAXA）

Abstract

Perception and motion estimation of a target are extremely crucial for space debris removal. A safe and secure mission to achieve this involves the following steps: first, checking the appearance and estimating the motion of a target from a distance of few tens of meters; then, approaching it until the distance is reduced to a few meters; and finally, setting a removal equipment for it. A visual-based perception system is found to be useful for these tasks because it can be compactly structured and measure a wide and long range.

We studied this system for practical applications such as stereo vision three-dimensional (3-D) reconstruction, model-based matching for pose-position / motion estimation, and so on. We built an optical simulator that can be used for testing various optical situations in an orbit. This paper briefly describes the current progress of our activities.

デブリ衛星の除去を実現するためには、デブリ衛星の計測と運動推定の技術が必要不可欠である。安全で確実にミッションを実施するためには、数十m程度の距離からデブリ衛星の外観観測とその運動推定の実施し、その後、デブリ衛星へ数m程度の近距離まで接近し、除去装置の取り付け作業が特に重要となる。

我々は、システムを小規模で構築でき、遠方から近距離まで広範囲で利用可能な画像を用いた計測手法が有効と考え検討を進めている。ステレオ視による3次元形状復元や、モデルマッチングによる対象の位置・姿勢、運動推定などのアルゴリズム検討、そして、計測精度評価などを実施している。また、画像を用いる際に問題となる太陽光の映り込みや夜間など多様な照明環境を評価するために、実験室内に光学シミュレータを整備し実験を行っている。本発表では、画像計測と運動推定についての状況についての報告を行う。

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デブリ除去とその手段について

- 軌道上のスペースデブリは年々増加しており、今後の宇宙開発において大きな問題になると懸念されている。デブリを増やさず減らすことが、継続的な宇宙開発のために必要である。
- このためには、デブリ衛星を軌道上から除くデブリ除去が有効である。上段ロケットなどの大規模の対象を除くことが、多数のより小さなデブリの発生防止に効果的で、また、技術的にも取り組みやすい。
- デブリ除去は、国際的にも重要であることが認識されており、継続的なデブリ除去活動としての産業化の可能性も高い。

- デブリ除去は、デブリ衛星に軌道離脱のための装置を取り付ける必要があり、導電性テザー（EDT: Electrodynamic Tether）や推進装置の取付などが考えられている。
- 何らかの除去装置を取り付けるためには、非協力対象であるデブリ衛星への接近と装置取付作業のための計測・認識技術が重要となる。

EDT装置によるデブリ除去イメージ図

デブリ衛星への接近・作業のために必要な計測・運動推定

- デブリ衛星への接近・除去装置取付作業のためには、デブリ衛星の（現在の）外見形状と運動、デブリ除去衛星との位置姿勢関係を、計測・認識する必要がある。下記の様な計測や運動推定が考えられる。

  方位計測： デブリ衛星の方位を計測する
  距離計測： デブリ衛星までの距離を計測する
  相対位置姿勢推定：デブリ衛星とデブリ除去衛星との
  　相対的な位置姿勢を推定する。
  形状復元： デブリ衛星の形状を復元する（対象が既知の場合は不要）
  運動推定： デブリ衛星の運動を推定する
  作業支援： 除去装置の取付作業を支援する

- 我々は、コスト面で有利で計測レンジの広い画像を用いた計測や運動推定による検討を行っている。本発表では、その現状について報告する。

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画像計測・運動推定について

- デブリ衛星の計測・運動推定を行うために、アクティブ方式であるレンジファインダ等や、パッシブ方式である画像計測等が考えられ、以下の様な特徴がある。

（レンジファインダ）LIDAR、LRF等
  - 正確な距離・形状が計測可能
  - 遠方（数100m以上）からの計測、広範囲の計測に不向き
  - リソース（電力、重量）が大きく、コストが大きい

（画像計測）ステレオ視、モデルマッチング等
  - 遠方からの計測、広範囲の計測に向いている
  - リソース（電力、重量、規模）が小さく、コスト面で優位
  - 計測アルゴリズムや計測精度向上が必要
  - 照明環境に制約を受ける

- 画像計測は、研究開発要素が高い計測技術であるが、計測レンジが広く、搭載性やコスト面で優位性があり、戦略的に獲得すべき技術項目である。レンジファインダとの併用の可能性も考えられる。

画像計測・運動推定の課題と、研究開発の進め方

【画像計測・運動推定の課題】
  - 照明条件によるデブリ衛星の見え方の違い
  - 撮影位置・姿勢の違いによる見え方の違い（地球背景処理）
  - デブリ衛星の運動と、デブリ除去衛星の運動の区別
  - 形状モデルとの差異（詳細部分、経年変形、経年変色）
  - リソース（撮像系、計算処理系）の制限
  - 研究開発段階で、実際の画像を得ることができない。

【研究開発の進め方】

一般的な画像計測センサの研究開発では、実際の画像を用いることができるが、デブリ除去では、実際の画像を得ることが難しい。このため、下のように幅広い手段により研究開発を進める必要がある。

  - コンピュータグラフィクス（CG）や数値解析の利用
  - 縮小模型を用いた実験
  - 実際のデブリ対象（H2A上段ロケット等）の画像
  - 実際の撮影環境での画像の利用（ISS、HTV、HIIA等の取得画像）
  - 実証実験による画像取得

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画像計測・運動推定の検討状況について

我々の実施している画像計測・運動推定の現状として、下記の内容を紹介する。

① HII展示機による実スケール画像計測実験
② 数値解析によるステレオ視の精度見積
③ デブリ除去軌道上光学環境模擬実験設備（光学シミュレータ）
④ 光学シミュレータを用いたモデルマッチングによる運動推定
⑤ KITE（HTV搭載導電性テザー実証実験）での画像取得

① HII展示機による実スケール画像計測実験

- JAXA筑波宇宙センターのHII展示機を撮影対象とし、ステレオ視による画像計測実験を実施。（この実験は、IHI社殿の支援を頂き、本発表ではJAXAの結果のみを紹介）
- HIIA上段ロケットを実スケールのデブリ衛星として、HII展示機に対し、実スケールのステレオカメラシステムにより、距離計測精度や夜間照明の効果を知るために実験を実施。トータルステーションを用い、対象に対する撮影位置を正確に取得

JAXA筑波宇宙センター　HII展示機
（赤枠内の上段ロケット部がデブリ対象）

正面、斜め前・後などの各位置から撮影
（赤点は、およその撮影位置）

JAXA 4眼ステレオ
カメラ（80×80cm）

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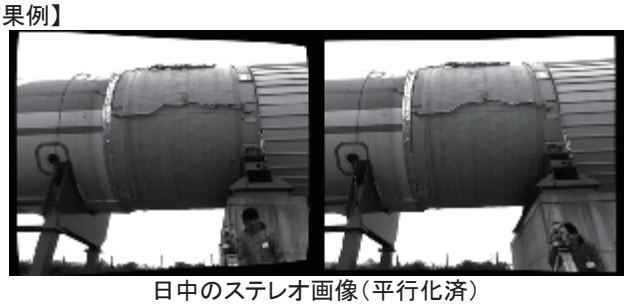
HII展示機の画像計測結果について

- ステレオ視による3次元計測で計測精度の評価を実施した。30m～約2m の位置からの計測が行えることが確認できた。
- 今後、疎な計測点群からのモデル化、性能を向上させるため、再キャリブレーションや多眼（4眼）ステレオへの拡張を行う予定である。
- 夜間に照明によるステレオ画像撮影を行い、計測可能であることが確認できた。照明を用いれば夜間の計測・運動推定の実現が期待できる。

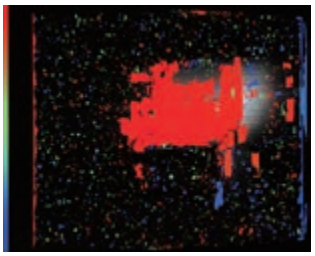
【処理結果例】



日中のステレオ画像（平行化済）

対応点探索結果 （カラー部が計測できた点）

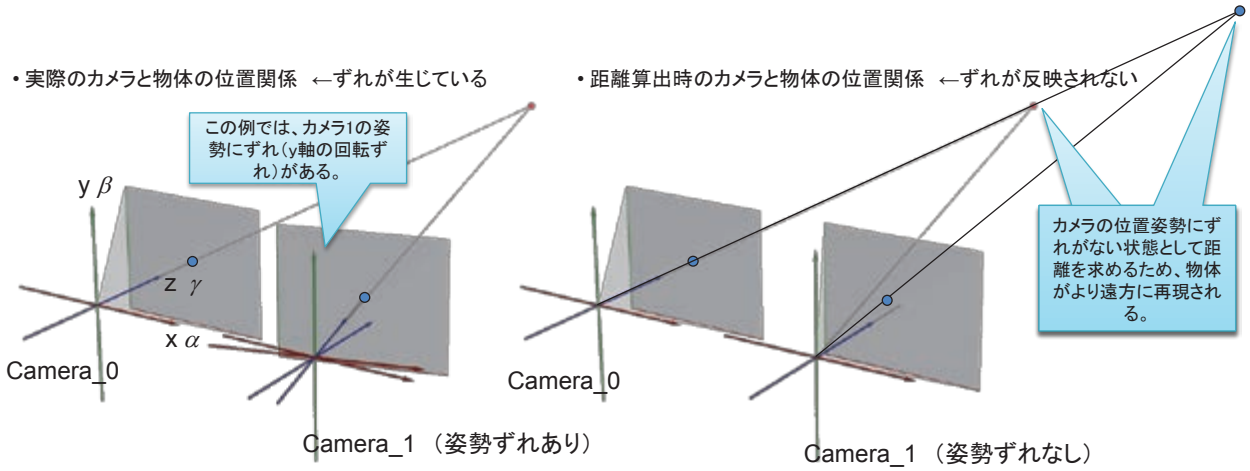
夜間の照明撮影によるステレオ画像（平行化済）



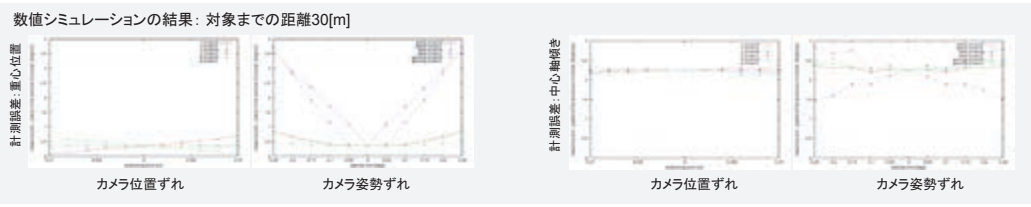
対応点探索結果

② 数値解析によるステレオ視の精度見積

- ステレオ視による3次元計測について、数値解析により計測精度を見積もっている。
- 下記のように、カメラの姿勢にずれがある場合などの影響を評価している。



【処理結果例】



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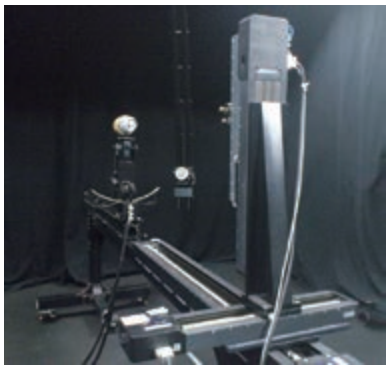
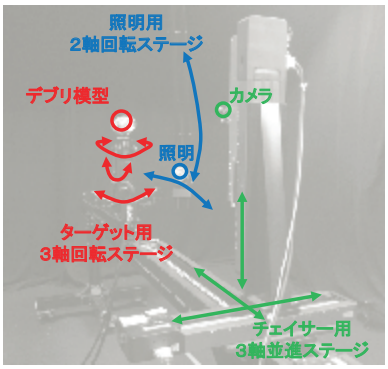
③ デブリ除去軌道上光学環境模擬実験設備（光学シミュレータ）

- JAXA調布航空宇宙センター実験室内に、光学シミュレータを設置し、様々な実験を行っている。
- 軌道上のデブリ除去中の光学条件を再現し、カメラを用いて画像計測・運動推定を行う。
- デブリ衛星軌道、太陽位置、デブリ除去衛星のダイナミクス等を模擬することが可能。

- 光学シミュレータの構成：
  - デブリ用3軸回転ステージ
  - チェイサー用3軸並進ステージ
  - 照明用2軸回転ステージ
  - 動的地球背景投影装置（今年度製作中）
  - 統合シミュレータ（上記のソフトウェア）
  - 平行模擬太陽光源（固定式）
  - HIIA上段ロケット模型（1/30）
  - 多眼ステレオカメラや汎用計測装置の搭載

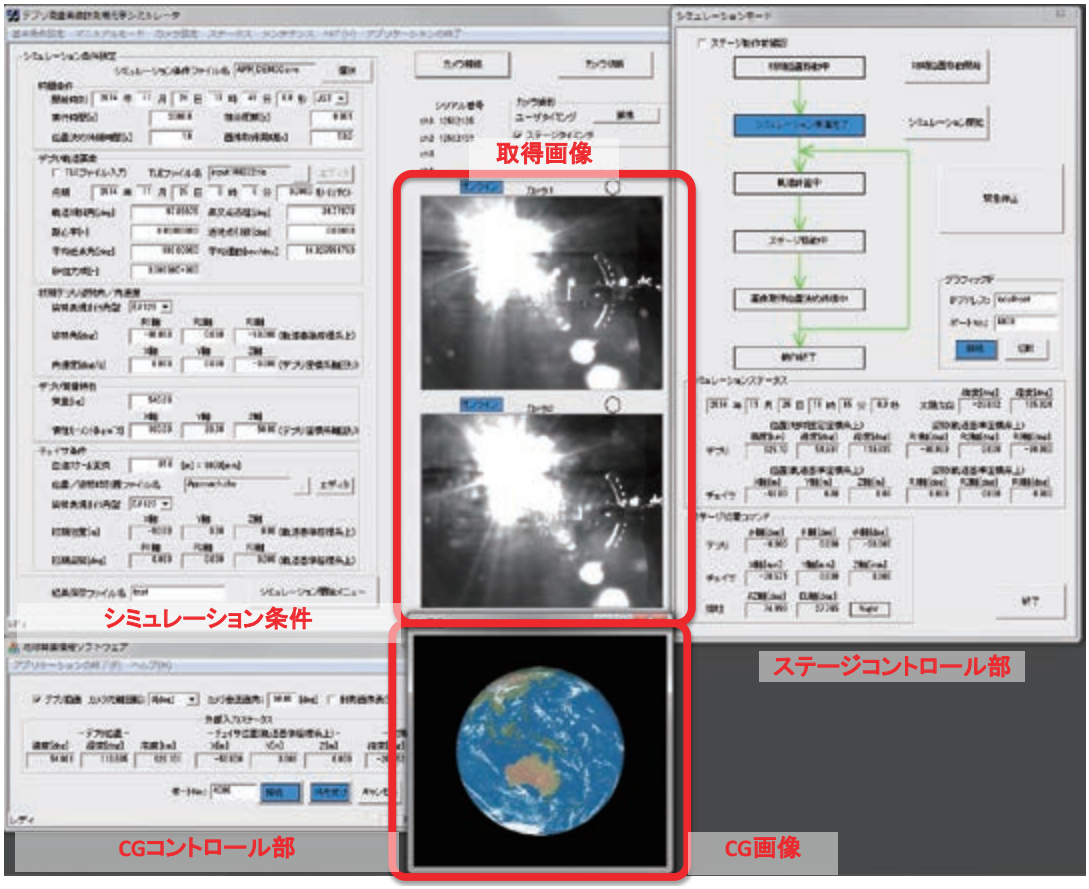
- 今後の検討課題
  - 画像計測結果による自動接近機能（今年度製作中）
  - 照明やステージの影、背景面への照明の映り込みの解消





光学シミュレータの外観

光学シミュレータのコントロール画面例



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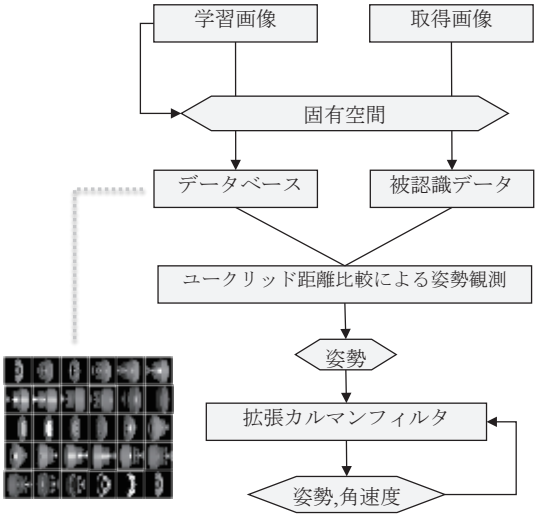
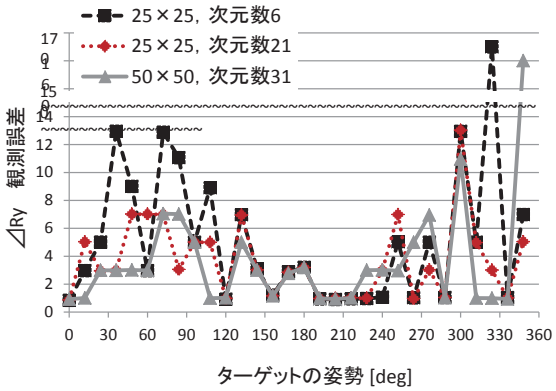
④ モデルマッチング（固有空間法）による位置姿勢推定

- 連携大学院 電気通信大学、菊池直彦 H25年度修士論文：固有空間法によるスペースデブリの単眼視運動推定 より
- 単眼視によるモデルマッチングによる姿勢推定、及び運動推定の研究を実施している。
- 固有空間の比較により得られた姿勢情報（時系列情報）に対して、拡張カルマンフィルタを用いた運動推定（回転運動）を実施する。

→ 固有空間法で大まかに運動を観測すれば、その連続時間計測と拡張カルマンフィルタで良好に運動計測が可能であることを運動計測実験で確認できた。

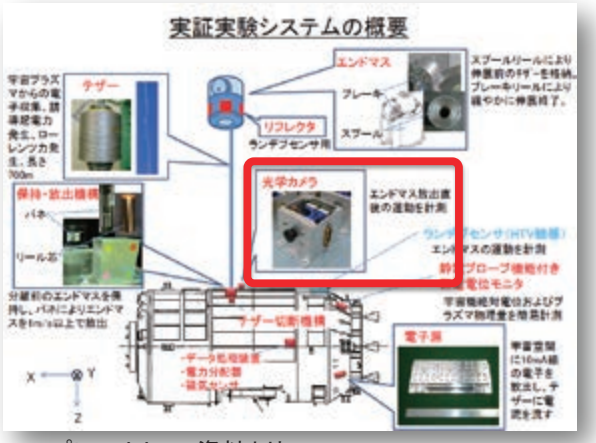




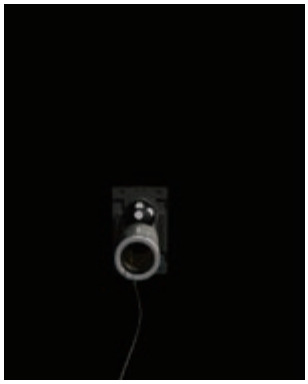
（全条件）固有空間法による観測誤差

⑤ KITE（HTV搭載導電性テザー実証実験）での画像取得

- KITE（HTV搭載導電性テザー実証実験）に搭載されたカメラにより画像を取得する。
- 実際の軌道上での画像を取得することができ、光学条件などのデータ収集を目指す。
- 画像による計測システムの実運用に関わる技術・ノウハウを修練する。



JAXA プレスリリース資料より



KITE エンドマス外観と、エンドマス放出予想図
※検討値等から推定したCGモデルなので、実際とは異なる。

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おわりに

- デブリ除去では除去装置の取付が有効であり、その計測システムとして、画像による計測・運動推定の検討を実施している。

- 画像計測・運動推定の研究開発の進め方を示し、現在の検討状況を紹介した。
  - HII展示機による実スケール画像計測実験
  - 数値解析によるステレオ視の精度見積
  - デブリ除去軌道上光学環境模擬実験設備（光学シミュレータ）
  - 光学シミュレータを用いたモデルマッチングによる運動推定
  - KITE（HTV搭載導電性テザー実証実験）での画像取得

- 引き続き上記の検討を進めるとともに、処理時間や専用処理装置、他のセンサとの融合についての検討を進める。

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C6

デブリ軌道変換用の推進系取付技術について

Mounting Technology of the Propulsion System for De-orbiting Debris

○青山順一、河本聡美、大川恭志、奥村哲平、壹岐賢太郎、
片山保宏、山元 透、村上 尚美、中島 悠 (JAXA)
○JunIchi Aoyama, Satomi Kawamoto, Yasushi Ohkawa, Teppei Okumura, Kentaro Iki,
Yasuhiro Katayama, Toru yamamoto, Naomi Murakami, Yu Nakajima (JAXA)

人類が将来に亘り宇宙開発・利用を持続させていくためにデブリ除去は不可欠なテーマと考えられている。その実施に不可欠な要素技術の一つにデブリをデオービットするための推進系をデブリに取付ける推進系取付け技術が挙げられる。推進系の取付については、各種の方式が検討されているが、デブリのタイプとデオービットの方式により適否が決まるので、これらの条件を定めて、方式を選定する必要がある。ここでは、持続的な宇宙開発・利用に効果的に寄与することを想定して、一回の衝突で多数のデブリを発生させる低軌道周回軌道上のロケット上段部等の大型デブリを、低コストで除去できる方式として、導電性テザー方式を想定して検討している。この方式に対する推進系取付け技術として、ブーム伸展方式、パンチャ打ち込み方式などが候補として挙げられるので、その実現性に向けた課題などの検討を進めている。本プレゼンテーションでは、これらのトレードオフを要約すると共に、その実現性に向けた仕様・課題などにつき講演する。

The removal of the debris is considered to be the inevitable item for the sustainable space development and utilization activities of the mankind. To realize this item, the technology for mounting the propulsion system on the debris to deorbit it is thought indispensable. Various kind of concept on the mounting method are studied today and the selection from them must be made based upon the type of the debris and the method to de-orbit. We are thinking that the most effective targets to be decayed are the large scale debris, such as upper stage of the launching vehicle which had been used to putting the payload satellites on to the orbit, because they may create huge number of small debris at the single collision with other space flying object. We are now studying the Electrodynamics Tether(EDT) method for the deorbit of the above described large scale debris taking into account its feature of low cost and the simpleness. So we are now picking up the various mounting technologies to suit to EDT, such as the boom expanding method and puncher injecting method to study the trade-off and feasibility ,items subject to be solved and so on. In this presentation, current status of the above study and subject to be solved are to be summarized.

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Mounting Technology of the Propulsion System for De-orbiting Debris

○ JunIchi Aoyama , Satomi Kawamoto, Yasushi Ohkawa , Teppei Okumura, Kentaro Iki[1)]

Yasuhiro Katayama [2)]

Toru yamamoto , Naomi Murakami , Yu Nakajima[3)]

Japan Aerospace Exploration Agency

1) Innovative Technology Research Center Space Debris Unit

2) Robotics Research Group Innovative Technology Research Center

3) Guidance and Control Group

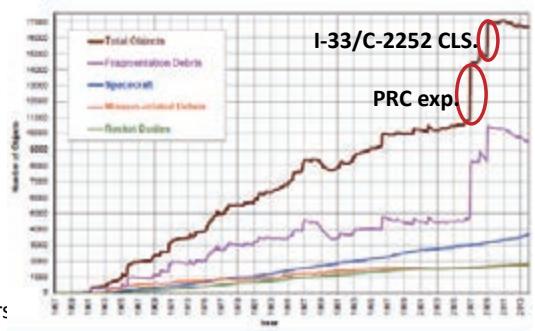
Introduction

- The mounting technology of the propulsion system on the debris is one of the indispensable item for the debris removal.
- The selection of the mounting technology depends strongly on the type of the debris and the method to deorbit.
- Debris of many small size may be the candidates to damage operating satellites, it's **not cost effective** to deorbit them, because there are so many of small debris.

On the hand, **large debris**, such as upper stage of launch vehicle or non-operating large satellites, are candidate to generate a lot of small debris at a single collision.

⇒It is **cost effective** to de-orbit the **large debris** to suppress the increase of debris, especially **upper stage**, and also to progress the standardization of the debris removal because many rockets used PAF.

（e.g. H-ⅡA、Ariane、Delta、Atlas,Soyuz,Proton and others



NASA The Orbital Debris Quarterly News 18-1 (2014, Jan)

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Requirements on Mounting of the Propulsion System

- Mount the propulsion system on debris with :
  - approach to the **non-cooperative** debris,
  - existence of the **uncertainty** of the **attitude** and **position** of the debris
  - possibly **tumbling** at the rate of about few degree per second.

  } **Robustness** is needed.
- Transfer large total momentum to debris:
  - with the **uncertainty of position of CG.**
  - △V : a few of 100m/sec to the several tons of debris
- **Cost effective** & **simple** debris removal is needed

⇒**Robustness** with **cost-effective** and **simple method** is strongly desired.

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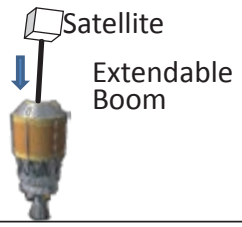
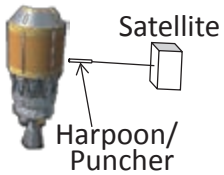
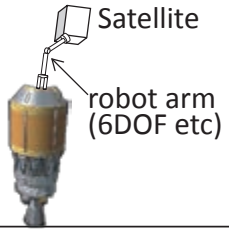
Mounting Technology of Propulsion System(1/2)

Items \ Method	Extendable Boom Hooking	Harpoon/Puncher Penetrating	Robotics Arm Grasping
Concept to Capture			
Method	Boom are extended into PAF of debris to hook it.	Harpoon/Puncher is lodged in the body of debris to capture it	Robotics arm on satellite grasps debris.
Merit	Easy to test. Need not precise position and attitude information.	Easy to test. Need not precise position and attitude information.	Flight exp. of robot. Perform. test :easy. Retry possible.
De-merit	Appligable only to PAF.	Risk of generation of small paticles.	Precise estimation of motion needed. High cost ,heavy
Remark	Upper stage of many rocket using PAF.	Reduction of reaction force at fire of hapoon/puncher is needed.	Several mechanism at side of PAF may obstruct the roperation.

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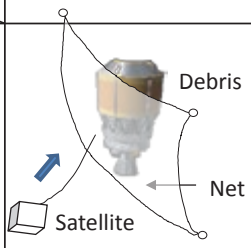
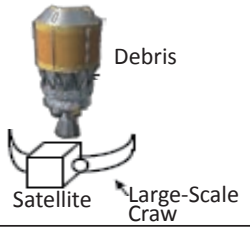
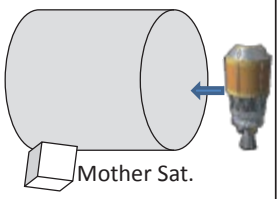
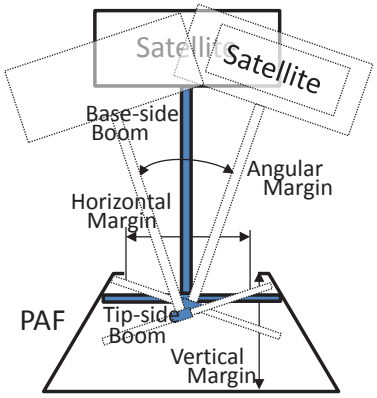
Mounting Technology of Propulsion System(2/2)

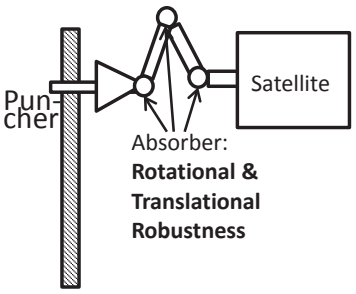
Item \ Method	Net Wrapping	Large-Scale Craw Grasping	Mother sat. pulling in
Concept to Capture			
Method	Net thrown to debris wrapping the debris.	Large-scale craw mounted on satellite grasps the debris to capture	Mother sat. pulling in debris thru the mouth
Merit	Adaptable for tumbling and nutating small debris.	Effective for small debris	Small debris may be easy to be pulled in.
De-merit	Not easy to analyze and test performance	Needs large craw mechanism	Large debris cannot be pulled in.
Remark	Not easy to capture large debris(upper stage of rocket or large sat.)	Not easy to capture large debris(upper stage of rocket or large sat.)	Not easy to capture large debris(upper stage of rocket or large sat.)

Robustness of Propulsion Mounting System

Ⅰ. Extendable Boom

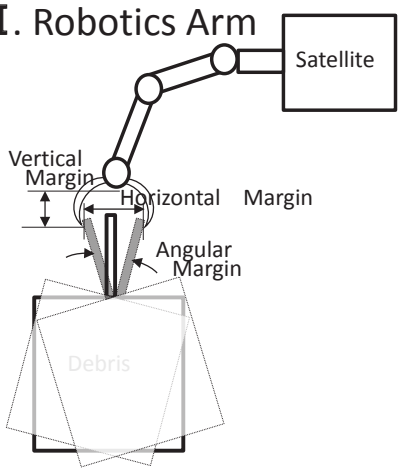


Ⅱ. Puncher



Outer Wall of Debris

Ⅲ. Robotics Arm



Robustness \ Type	Ⅰ. Extendable Boom	Ⅱ. Puncher	Ⅲ. Robotics Arm
Transverse Robustness	Horizontal & Vertical Margin	Transverse Adjustable Range	Horizontal & Vertical Margin
Rotational Robustness	Angular Margin	Rotational Adjustable Range	Angular Margin

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Extendable Boom Capturing(1/2) Debris Capturing Concept

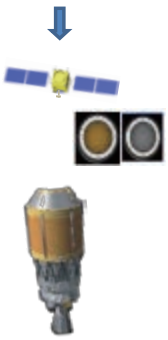
① Estimate the relative attitude and position of debris analyzing the pictures of PAF.

②-1 Extend the base-side extendable boom to the center of PAF at the position of 1.5m away from PAF.

-2 Extend the 4 tip-side extendable booms radially toward circle of PAF.

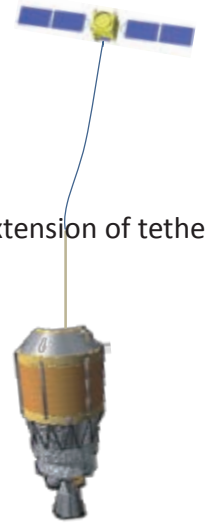
③ Making sure of the completion of extension of booms to be fixed at hem of PAF, the satellite escape extending the tether.

Concept of Extendable Boom on Satellite



①Estimation of attitude and position of debris

② Extension of booms



③ Extension of tether

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Extendable Boom Capturing(2/2) Capturing Feasibility

- Preliminary feasibility of extendable boom capturing of debris was evaluated as follows by the conceptual study :
  - ✓ Alignment requirement of position : ±100 mm along X-axis(long axis of debris)
    : ±200 mm across X-axis
    attitude : no limitation around X-axis
    : ±5 deg. around Y & Z-axis
  - ✓ Approaching velocity of debris: 0 ~ 100 mm/sec. along X-axis
  - ✓ Angular velocity of debris ;±1 deg./sec. around all-axis
- Preproduction sample of boom and extension mechanism was manufactured and evaluated to be :
  - ✓ Basic feasibility of the extendable boom for debris capturing was evaluated.
  - ✓ Some characteristics of boom were find to be improved:
    - ➢ review the extension method of tip side boom to reduce the stress on base-side boom
    - ➢ review the manufacturing process to improve the quality
    - ➢ Increase the stiffness of boom for future mission

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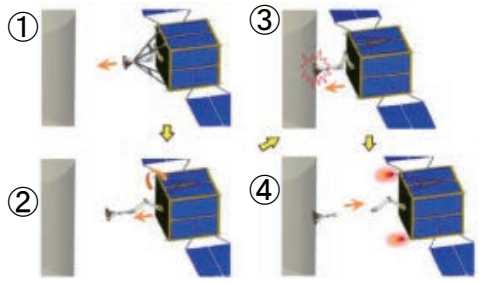
Harpoon/Puncher Penetrating(1/2) Debris Capturing Concept

Ⅰ. Concept of debris capturing (Arm + Puncher Method)



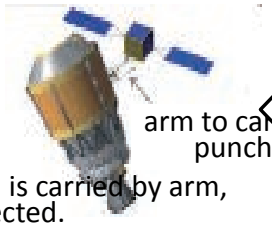
①: Identification of debris motion

②: Puncher arming

③: Capture and penetration of the debris wall

④: Make sure of fixed and then escape

Ⅱ. Reduction of reaction force on satellite at fire



arm to carry puncher

Puncher is carried by arm, then injected.
(Firing by booster is not needed.)
The reaction force is reduced by absorber in arm
(Arm + Puncher method)

Reduction of reaction Force is necessary.

<Candidate>
- Arm+Puncher
- Soft release + Puncher
- Improved Harpoon

Reaction force caused at Harpoon firing may damage satellite mechanical part.

⇒It must be reduced

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Harpoon/Puncher Penetrating(2/2)

Affirmation of the Penetration thru. the Debris Wall

The penetration of the Harpoon/Puncher through the debris wall was evaluated preliminarily :

◆ Collision model study

Possibility of penetration at collision of harpoon/puncher to debris wall was studied to be evaluated in order-level validity.

◆ Preliminary experimental feasibility study

Feasibility was studied by preliminary experiment to be evaluated the penetration of harpoon/puncher to be able. to penetrate the outer wall of debris.

◆ Further studies are to be carried out to evaluate more precise modeling to make sure of the penetration.

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Further to be Studied

Following task are going to be carried out :

<Extendable boom>

Characteristics of boom are to be improved:

- to improve the quality of extension and holding.
- to increase the stiffness for future mission.

<Harpoon/Puncher>

Further studies and tests to evaluate more precise model of penetration to make sure of penetration.

<Debris Removal System >

Further studies are to be carried out on:

- countermeasure for the electric discharge at the contact of satellite with debris of different charge level.
- ensure of communication link at flyaround and capturing .
  electlic power
  thermal balance
  and other system budget

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D1

PAF を対象としたデブリ捕獲用把持システムの概念検討

Conceptual Study of Mechanical and Sensing System for Debris Capturing for PAF

○柴﨑浩一, 久保田伸幸, 榎本雅幸(川崎重工業株式会社),
河本聡美, 大川恭志, 青山順一, 片山保宏
(宇宙航空研究開発機構)
○Kouichi Shibasaki, Nobuyuki Kubota, Masayuki Enomoto (KHI),
Satomi Kawamoto, Yasushi Ohkawa, Junichi Aoyama, Yasuhiro Katayama (JAXA)

近年急増しているスペースデブリは、人工衛星や宇宙ステーション等に対する脅威となりつつある。デブリの影響を低減するには、これから打ち上げる宇宙機のデブリ発生抑止対策だけでは不十分で、現存するデブリを能動的に軌道から除去する仕組みが必須である。ここではデブリとして数が多いロケットの上段部をターゲットとして、デブリ除去衛星が接近するための画像センサ、及びデブリを捕獲するシステムについて概念検討を行った結果を報告する。

The amount of space debris has been increasing, and that is becoming a threat to the currently operated satellites and ISS. The provision to prevent future spacecraft from being debris is not enough to decrease the risk of debris, an active debris removal(ADR) will be needed. The upper stages of expendable launch vehicle have been remaining in the orbit as space debris, and the number of it is so large. This paper reports the results of conceptual study of mechanical and sensing system for capturing the upper stages of expendable launch vehicle.

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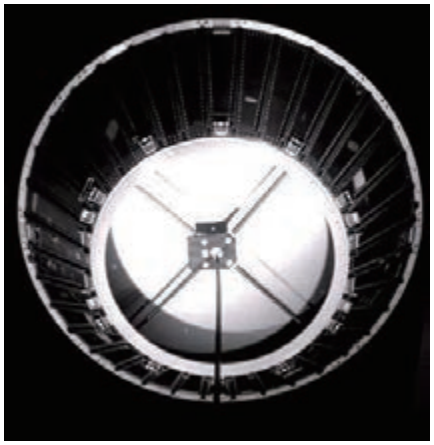
The 6th Space Debris Workshop

Conceptual Study of Mechanical and Sensing System for Debris Capturing for PAF

2014/12/18



○Kouichi Shibasaki, Nobuyuki Kubota, Masayuki Enomoto (Kawasaki Heavy Industries, Ltd.),
Satomi Kawamoto, Yasushi Ohkawa, Junichi Aoyama, Yasuhiro Katayama (Japan Aerospace Exploration Agency)

1

Contents

1. Capture target
2. Capture mechanism
3. Image sensing
4. Conclusion

2

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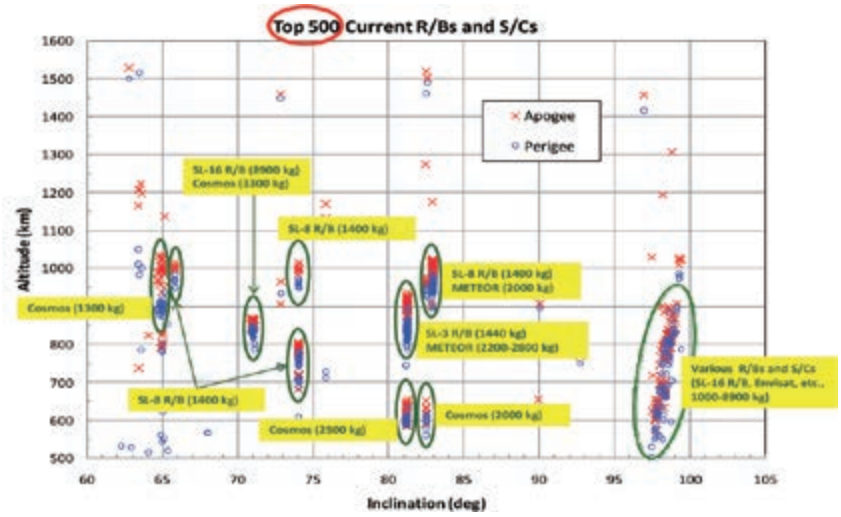
1. Capture target

- There are particular crowded orbit. >1 satellite may be approach to several of debris.
- Debris in sun-synchronous orbit or sun-synchronous sub-recurrent orbit are target.



Ref. J.-C. Liou, An active debris removal parametric study for LEO environment remediation, Advances in Space Research Volume 47, Issue 11, 1 June 2011, pp.1865-1876.

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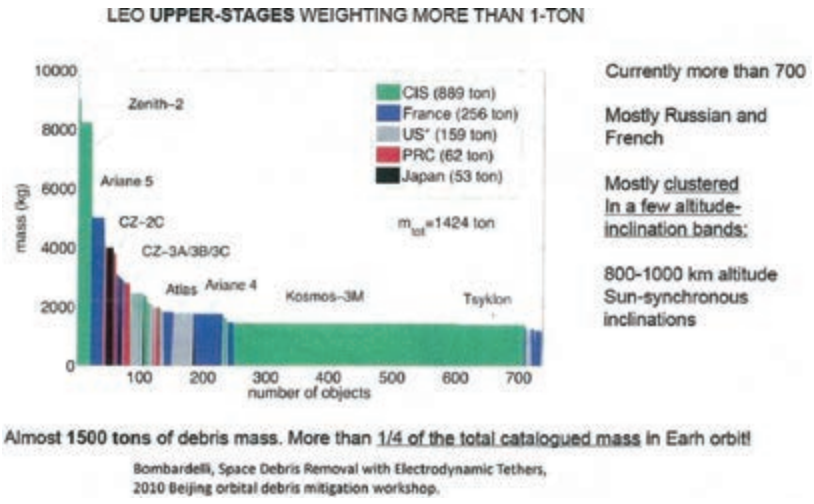
1. Capture target

- Upper stage of several of rocket remains in the sun-synchronous orbit.
- Since the upper stage of the rocket have large volume and large mass, it is estimated that the effect due to the collision is large.
- Since a shape is constant for each rocket, it is suitable as an target of recognition and capture.



Upper stage of the rocket has been selected as the capture target.

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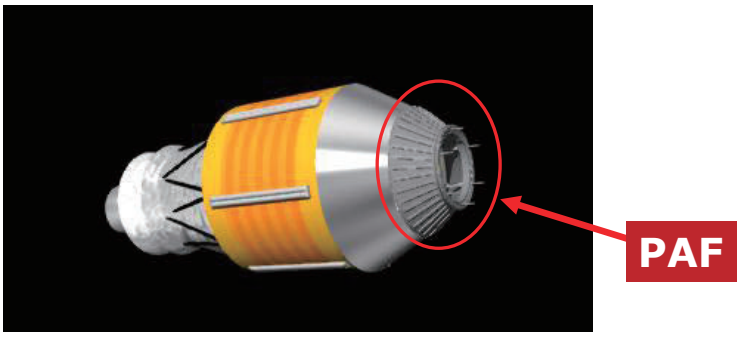
1. Capture target

- Many upper stages of rocket have PAF (Payload Attach Fitting).
- The diameter of the satellite attachment are similar size such as 937,1194,1666.



H-2A Rocket 2nd stage image

- PAF is a structure for fixing the satellite, strength and stiffness are secured, shapes are clear.
- PAF is a circular structure. So, it is suitable for image processing at approach.

PAF (Payload Attach Fitting) has been selected as the target, which is applied to a upper-stage of many rocket.

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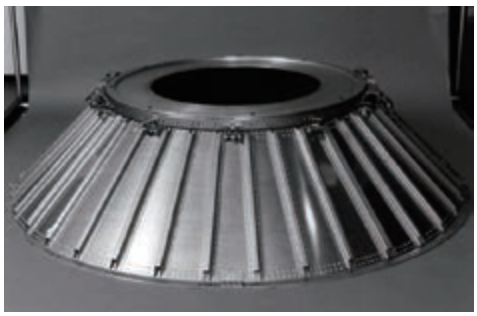
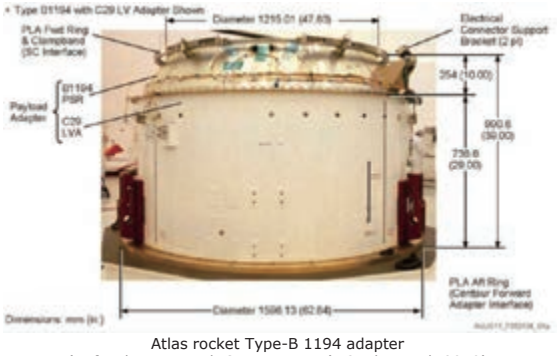
1. Capture target

PAF of various rocket



H-2A rocket PAF1194
(Ref. H-2A rocket users manual)

Ariane rocket PAF1194V5
(Ref. Ariane-5 User's Manual Issue 4 Revision 0)



Atlas rocket Type-B 1194 adapter
(Ref. Atlas V Launch Services User's Guide March 2010)

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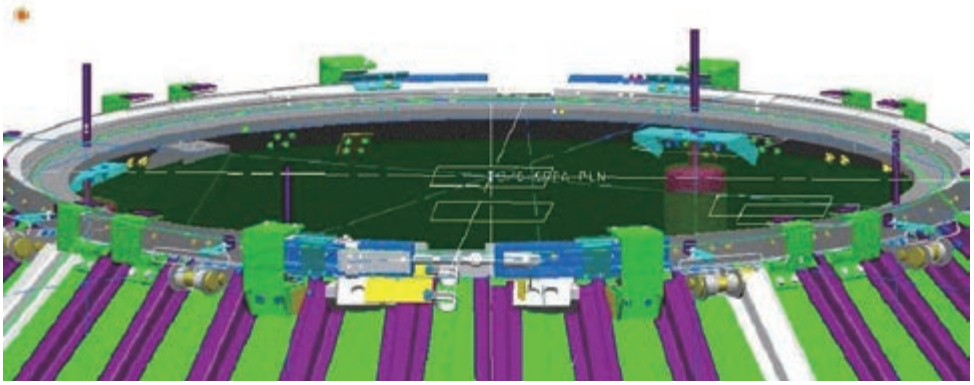
1. Capture target

- When grasping the end face of the PAF as an attachment position of the debris removal device, a plurality of different shapes parts around the ring structure is mounted, the shape of the grasping subject is different depending on the position.
- Since collar portion of the ring structure is narrow, it may not be sufficiently clamped.
- Some push-rods to push satellite are obstacles in the debris rotating state.



H-2A rocket PAF1194, Detail of satellite interface

To grip the PAF end surface was estimated to be difficult.

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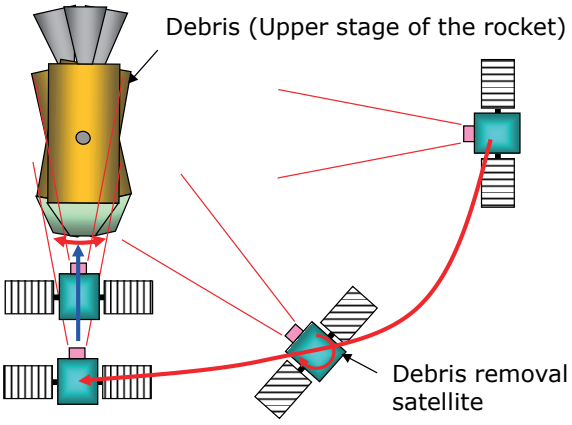
2. Capture mechanism

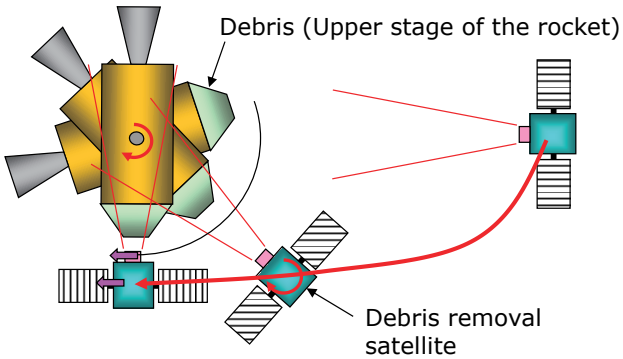
The upper stage is estimated to be either of the following two states.

- Swinging toward the long axis to the earth by gravity gradient stabilization
- Rotating in orbit

It is necessary to consider the grasp method suitable for each of the two states.
Then, it is necessary to devise a capturing method that can be applied to both states.



In swing state, approaching after wrapping around the longitudinal direction



In rotating state, to approach to match the speed of PAF after approaching tangentially

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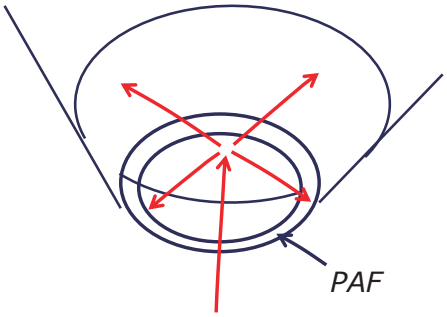
2. Capture mechanism

As a method for grasping that are suitable for approaching method, instead of gripping the end faces of the PAF, grasping method by inserting the extendable booms inside the PAF can be considered.



The advantage of this method is as follows.

- Accuracy of estimating the motion of the PAF, are likely to need to be rough as compared with the case of grasping the end face of the PAF. Because, for inserting the deployment devise into the opening of the PAF having a diameter of about 1m.
- Since there is no obstacle within the opening, the pattern matching for extracting a location for gripping is not required. Estimation accuracy by image processing may be rough.
- In order to aim the center of the opening, projections from the end face of such as a push rod is less likely to obstacles.

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2. Capture mechanism

- For inserting the expandable devise to the inside of the PAF
- For fixing the grasping mechanism to the inside of the PAF

} It was considered also to apply the extendable boom for both functions

Extension (extension speed: about 1m/sec)

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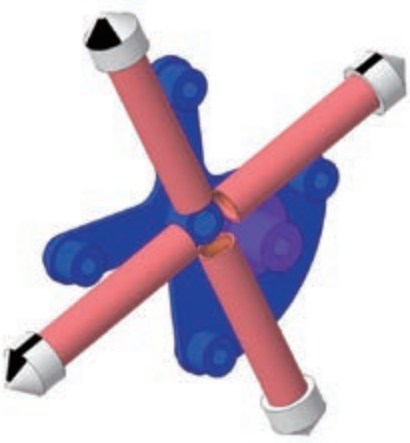
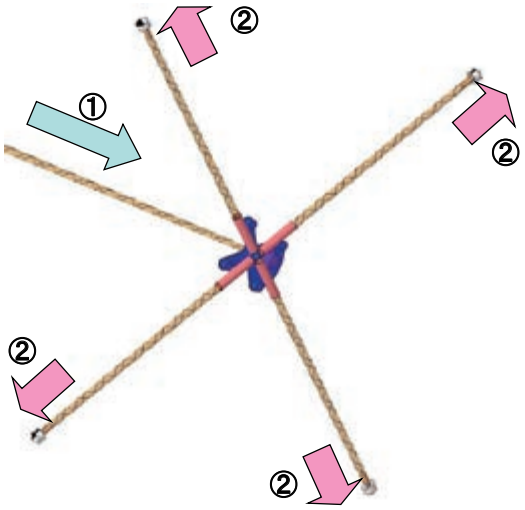
2. Capture mechanism

1. By one of the extendable boom, the expandable devise is inserted into the PAF.
2. By four extendable booms extending in the PAF, the grasping mechanism is fixed.



Assembly of four extendable booms
(Stored)



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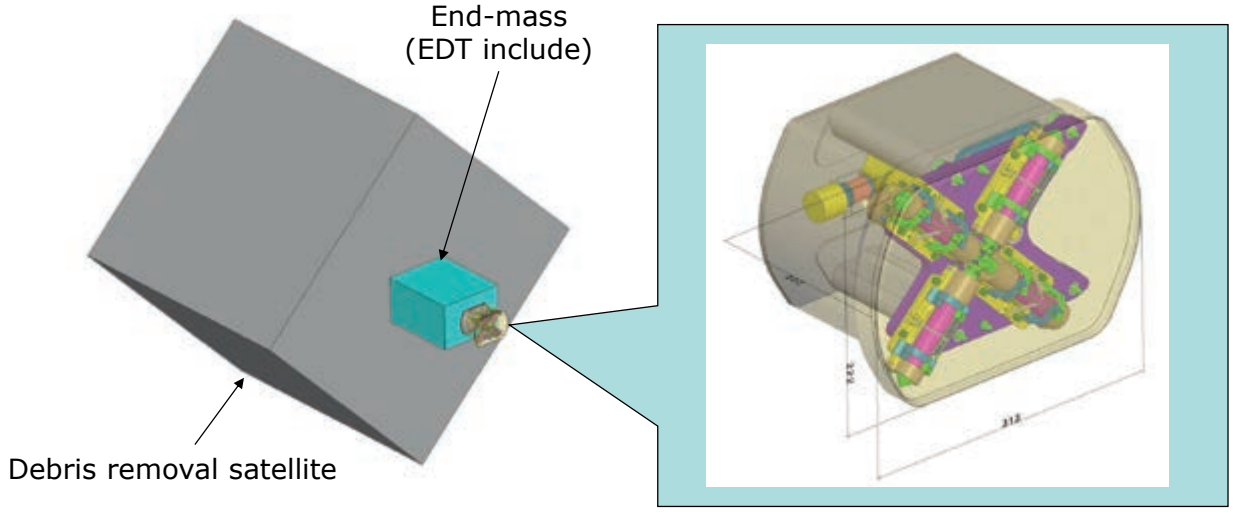
2. Capture mechanism

Design examples of the grasping mechanism using extendable boom



Device equipped example
of the satellite structure

Design examples of the grasping mechanism

12

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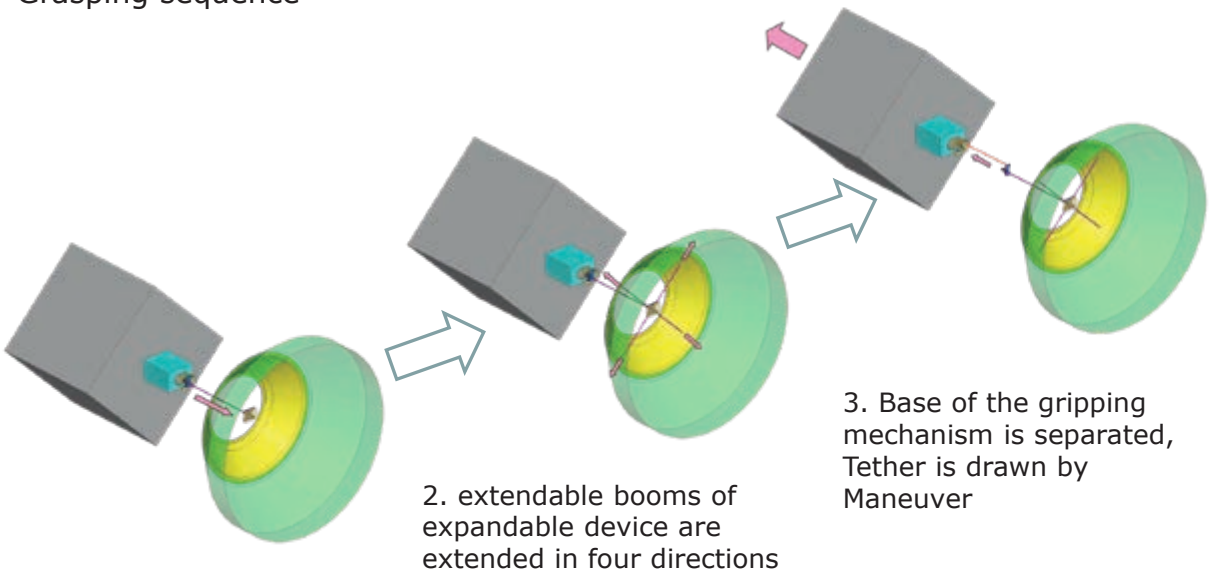
2. Capture mechanism

Grasping sequence



1. By extendable boom, expandable device is inserted into the PAF

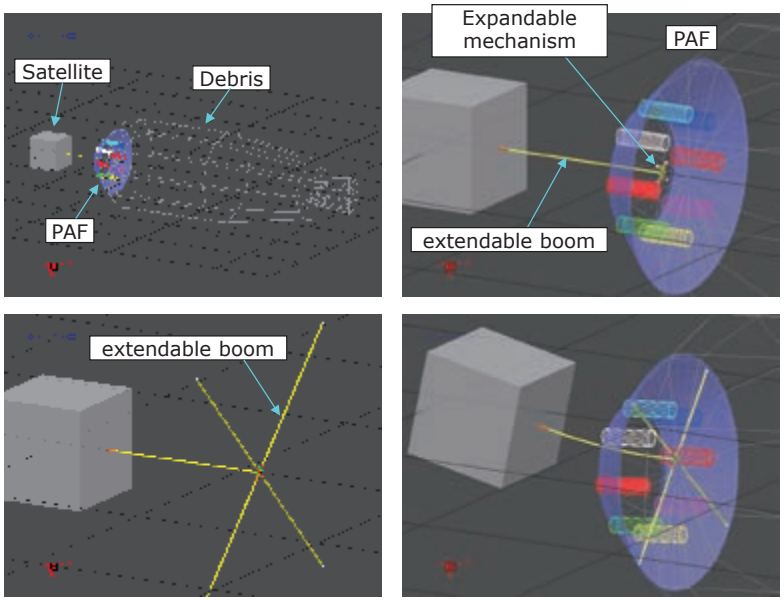
2. extendable booms of expandable device are extended in four directions

3. Base of the gripping mechanism is separated, Tether is drawn by Maneuver

13

2. Capture mechanism

Dynamics analysis of grasping



Analysis model for DADS

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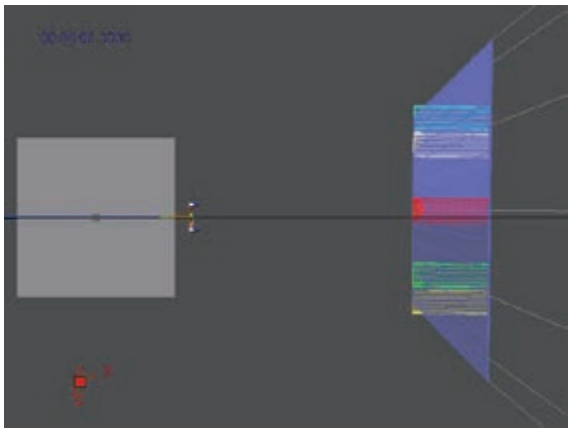
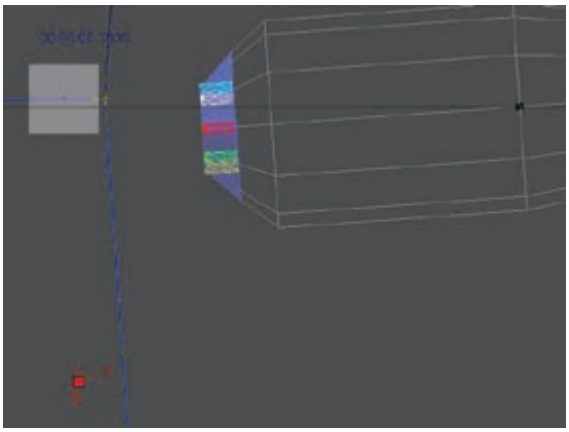
2. Capture mechanism

Result of dynamics analysis of grasping (example)





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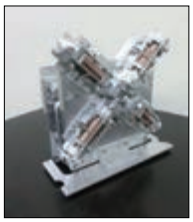
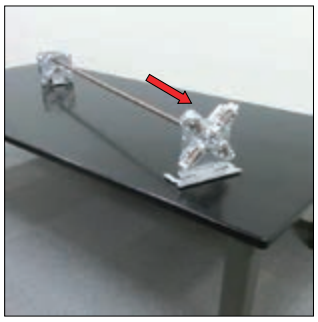
2. Capture mechanism

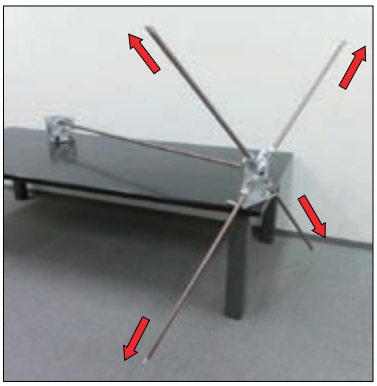
Functional check of the grasping sequence by the functional verification prototype of grasping mechanism



1. Stored



2. By extendable boom, expandable devise is extend



3. extendable booms of expandable devise are extended in four directions

4. Base of the grasping device is separated

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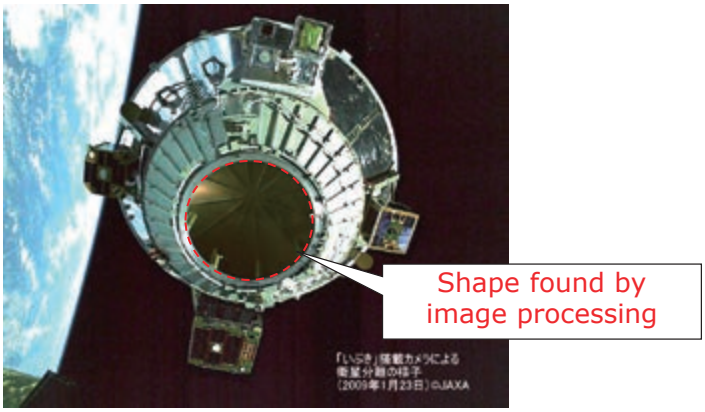
3. Image sensing

PAF is suitable in the following points as a subject for image recognition.

1. Shape is circular and simple, it is possible to robust recognition with high accuracy.
2. Diameter of PAF is as large as 1m, it is possible to stable visible even from a distance.
3. Material is stable, less possibility of deformation and alteration, it is possible to estimate the reflection characteristics.
4. Internal PAF is void, it is easy to obtain a clear contrast, is suitable for feature extraction.



PAF of H-2A 2nd-stage

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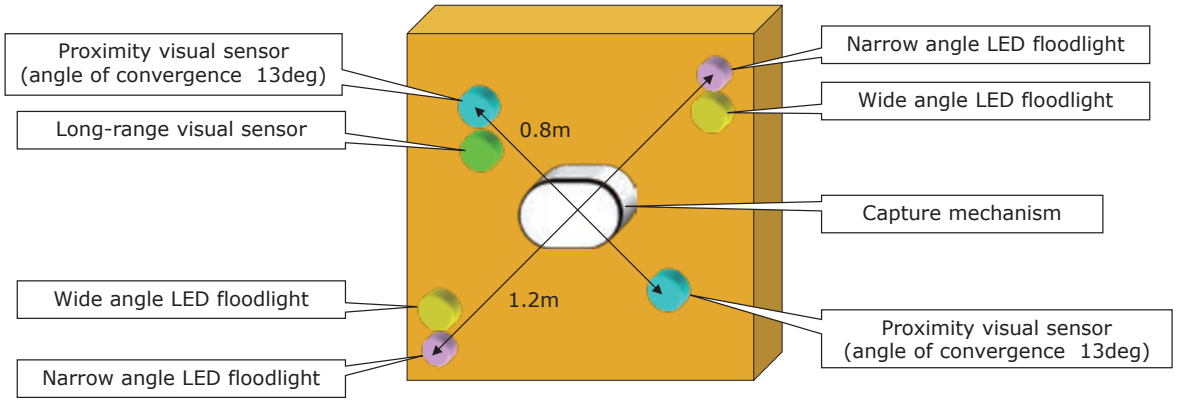
3. Image sensing

Sensor system configuration (optical system)

Proximity visual sensor (PVS)	View angle 53deg / 26deg
Long-range visual sensor (LVS)	View angle 6deg
Wide angle LED floodlight	Irradiation angle 53deg
Narrow angle LED floodlight	Irradiation angle 10deg



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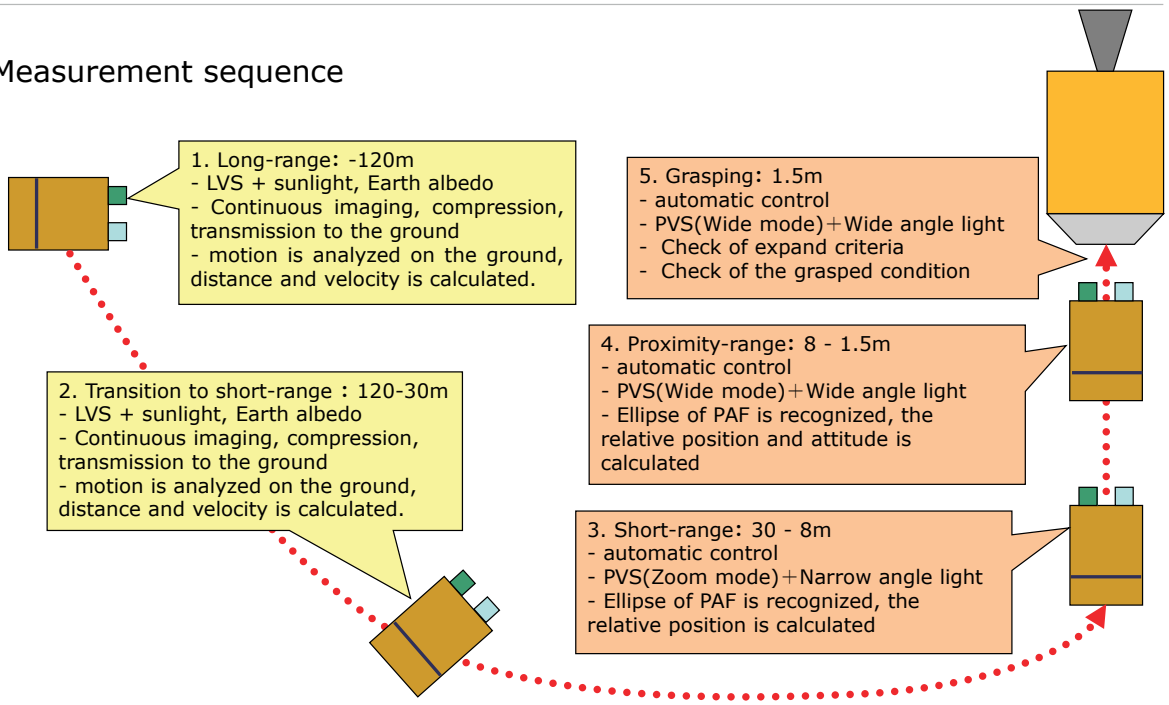
3. Image sensing

Measurement sequence



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3. Image sensing

Long range(- 30m)
Imaging by LVS(Long-range visual sensor)
ground control

Short range (30m - 1.5m)
Imaging by PVS(Proximity visual sensor)
Onboard processing

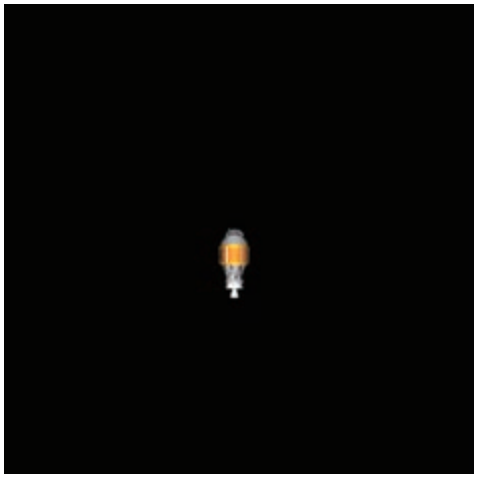

Image sample (300m)

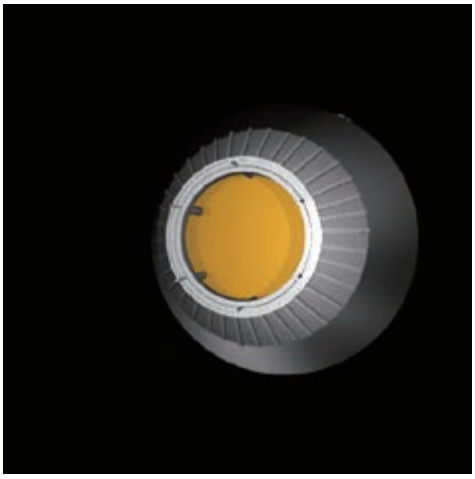

Image sample (4m)

20

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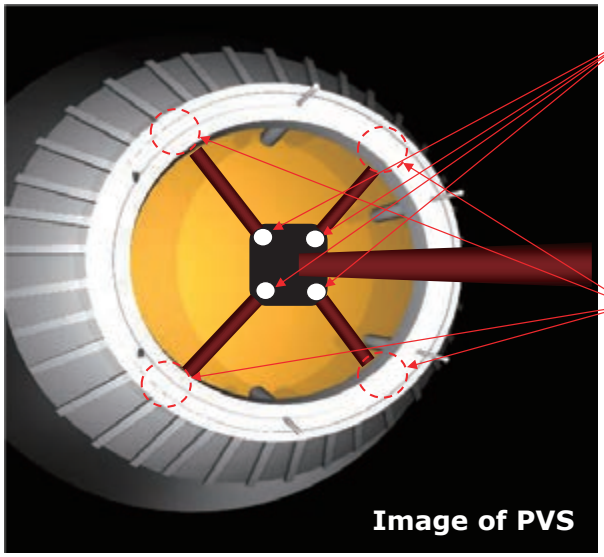
3. Image sensing

Image recognition method for Grasping



1. Depth is calculated from the spacing of the markers are measured. The expandable device behind the flange that has entered is verified.

2. From the image, it is detected that the tip of the extendable booms are not in front of the flange.

For grasping mechanism is a cooperative target, assignment for measurements such as reliability and accuracy are little.

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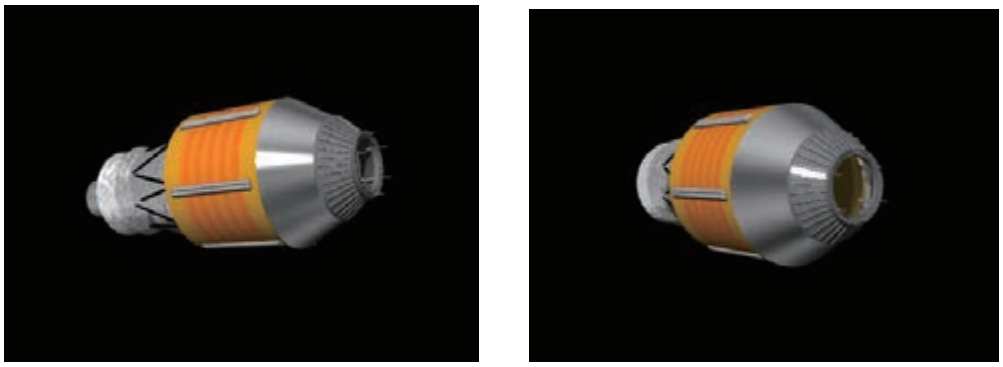
3. Image sensing

Study by CG

Create a 3D-CG model H2A second stage, generates a CG image by the rendering to examine the applicability of image processing techniques



H2-A second stage rendering image

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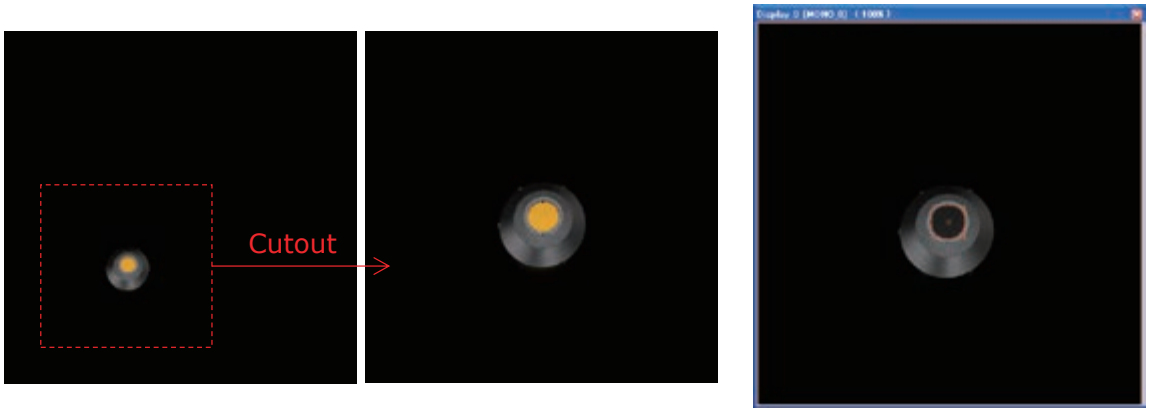
3. Image sensing

Examples of study results by CG

Conditions: Distance 30m, Relative attitude 10 °



CG image (Wide mode) | CG image (Zoom mode) | Processing result

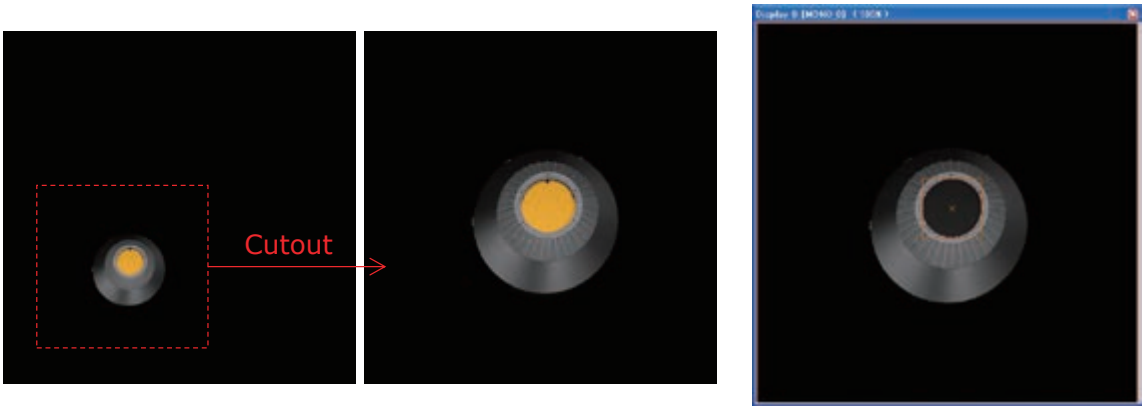
Recognizable

23

3. Image sensing

Examples of study results by CG

Conditions: Distance 16m, Relative attitude 10 °



CG image (Wide mode) | CG image (Zoom mode) | Processing result

Recognizable

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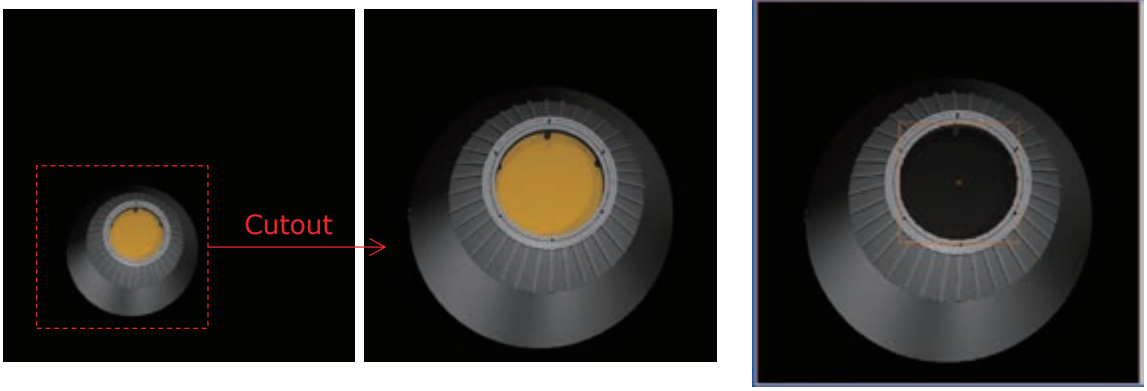
3. Image sensing

Examples of study results by CG

Conditions: Distance 8m, Relative attitude 10 °



CG image (Wide mode)

CG image (Zoom mode)

Processing result

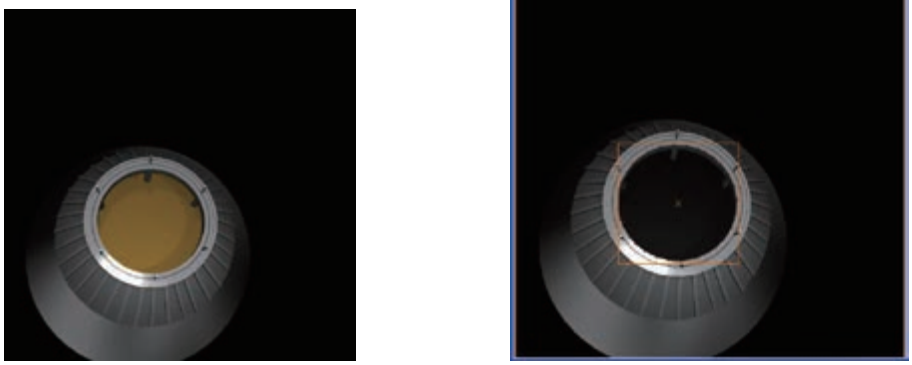
Recognizable

25

3. Image sensing

Examples of study results by CG

Conditions: Distance 4m, Relative attitude 10 °



CG image (Wide mode)

Processing result

Recognizable

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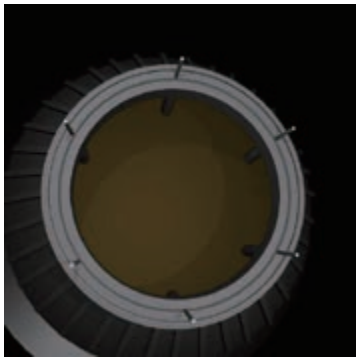
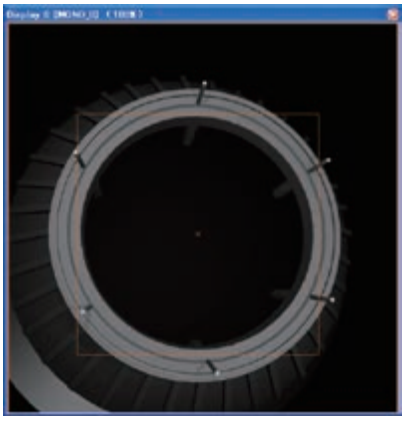
3. Image sensing

Examples of study results by CG

Conditions: Distance 2m, Relative attitude 0 °



CG image
(Wide mode)



Processing result

Recognizable

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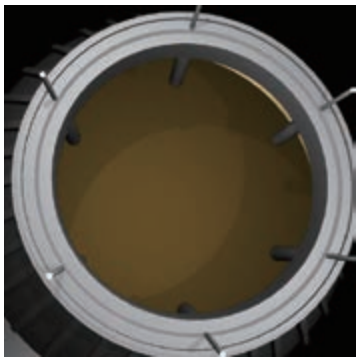
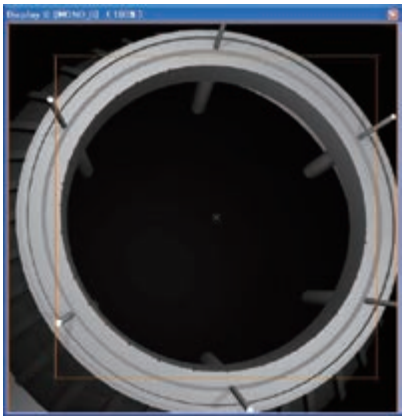
3. Image sensing

Examples of study results by CG

Conditions: Distance 1.5m, Relative attitude 0 °



CG image
(Wide mode)



Processing result

Recognizable

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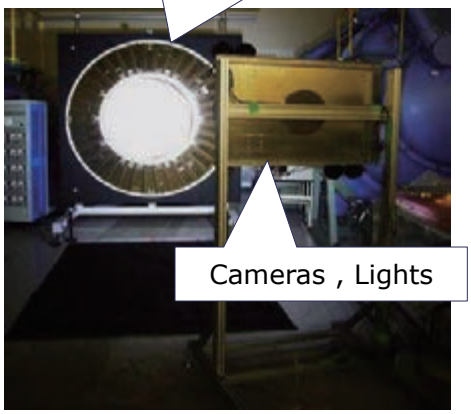
3. Image sensing

Image acquisition of PAF

For the trial image processing algorithms, images of PAF were acquired.

- In a dark room to the indoor, the real PAF as the imaging target, in the light of the LED projector, and images were acquired with two cameras.
- This test was executed in the distance range of 16m ~ 1.5m.
- These distances correspond to the short range area.



Test situation

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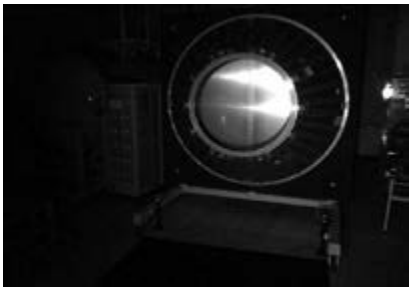
3. Image sensing

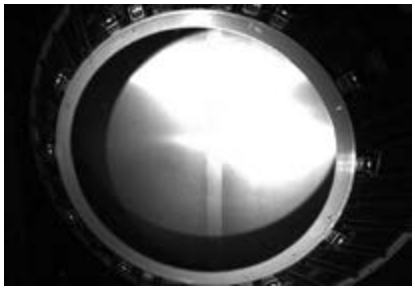
Examples of examination results

Distance 16m, Relative attitude 10 °

Distance 8m, Relative attitude 10 °



Distance 4m, Relative attitude 10 °



Distance 1.5m, Relative attitude 0 °

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4. Conclusion

1. Capture target
   Upper stage of the rocket has been selected as the target. PAF has been selected as a target of the grasp and image processing.

2. Capture mechanism
   Method for capturing debris by gripping the PAF was examined. As a simple and reliable method, a device using an extendable boom was invented.
   Dynamics of the grasping has been analyzed. Feasibility of the grasping methods have been confirmed.
   In addition, a prototype for the functional verification has been made. Technical Issues are being extracted for function and performance.

3. Image sensing
   Imaging target is selected according to the length range. The configuration of Camera and lighting for image processing has been selected.
   The image processing algorithm using the CG was confirmed, it was confirmed that there is enough image processing.
   Additionally, image acquisition examination for real PAF was performed.
   Investigation and trial for image processing algorithm has been developed.

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D2

デブリ除去のための導電性テザー技術の検討

Study of Electrodynamic Tether technology for Active Debris Removal

○壹岐賢太郎、河本聡美、大川恭志、
奥村哲平、青山順一（JAXA）
○Kentaro Iki, Satomi Kawamoto, Yasushi Ohkawa,
Teppei Okumura, JunIchi Aoyama (JAXA)

JAXA では，低軌道上のデブリ除去技術の有力な候補として導電性テザー（EDT）の研究を進めている．EDT はテザーに流れる電流と地球磁場との干渉を利用するため，推進剤を必要とせずに軌道変換のための推力を得られる高効率な推進系である．EDT システムを搭載したデブリ除去衛星を設計するためには，数 km 級テザーシステムの重量・体積，電力や電位，衛星への外乱トルクを確認する必要がある．そこで，デブリ除去衛星ミッションのデオービットフェーズにおける EDT 伸展および伸展終了後の EDT システムの挙動に関する数値解析を実施してきた．本発表ではデブリ除去衛星での EDT システムの概要を紹介する．

The Japan Aerospace Exploration Agency (JAXA) has been investigating electrodynamic tether (EDT) as a very promising candidate for Active Debris Removal (ADR) technology in the lower earth orbits. The EDT is an advanced propulsion system which can generate sufficient thrust for orbital transfers without the need for propellant by utilizing interactions between Earth’s magnetic field and currents through the tether. In order to design the debris removal satellite installing the EDT system, the mass and volume of several kilometers tether system, required electrical power, electrical potential, and disturbance torque to the satellite should be confirmed. Consequently, the numerical simulations for EDT system dynamics during and after tether deployment in the phase of deorbiting in the removal satellite’s mission have been conducted. This presentation introduces the overview of EDT system for the removal satellite.

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Study of Electrodynamic Tether Technology for Active Debris Removal

デブリ除去のための導電性テザー技術の検討

○壹岐賢太郎，河本聡美，大川恭志，奥村哲平，青山順一
JAXA 研究開発本部
○Kentaro Iki, Satomi Kawamoto, Yasushi Ohkawa,
Teppei Okumura, JunIchi Aoyama
Japan Aerospace Exploration Agency
Aerospace Research and Development Directorate

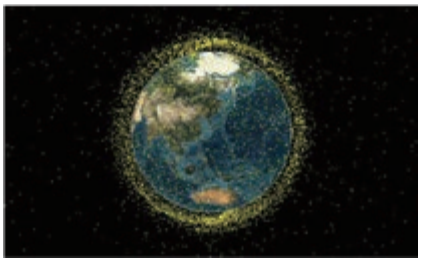
6th Space Debris Workshop @ Chofu Aerospace Center
December 18, 2014

Introduction

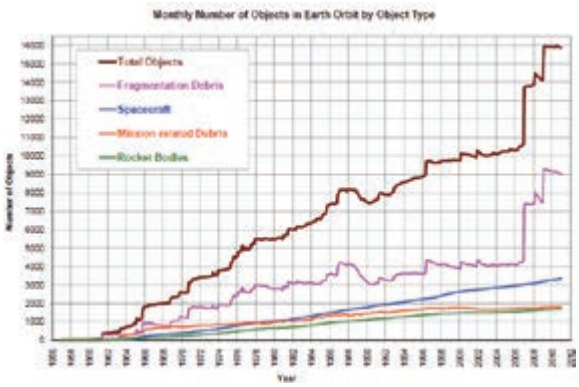
It is predicted that

- Catastrophic collisions will occur every five to ten years
  mainly in the crowded orbits due to rapid increase of space debris
- The number of debris objects will increase even with no new launches

➡ The active debris removal (ADR) from the crowded orbits must begin as soon as possible



Space debris in LEO



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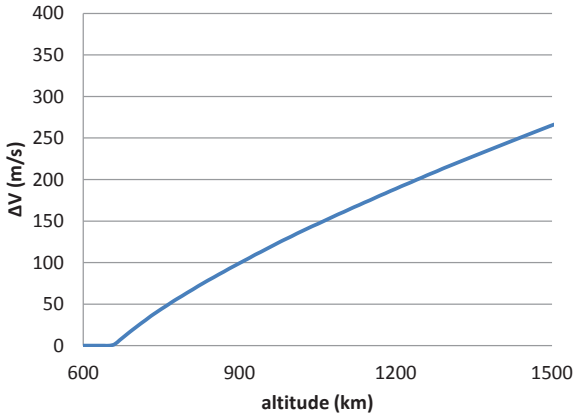
Active Debris Removal

- ΔV :~100 m/s is needed for deorbit of several tons of mass from altitude between 800km and1000km to orbit whose lifetime is 25 years (650 km)
- More propellant (ΔV) is needed for
  - deorbit to lower altitude
  - deorbit with controlled re-entry



ΔV needed for deorbit to orbit whose lifetime is 25 years(650 km)

3

Electrodynamic tether

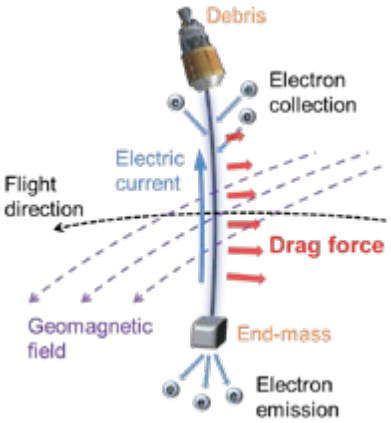
- Electrodynamic Tether (EDT) is “Propellant-free propulsion”

- Fundamentals
  - Attitude stabilization by gravity gradient
  - Electromotive Force (EMF) by orbital motion :

$$V_{EMF} = (\mathbf{v_{orb}} \times \boldsymbol{B}) \cdot \boldsymbol{L}$$

  - Electron collection and emission
  - Electric current through tether
  - Lorentz Force :

$$F_{lorentz} = (\boldsymbol{I} \times \boldsymbol{B}) \cdot \boldsymbol{L}$$



Principle of EDT System

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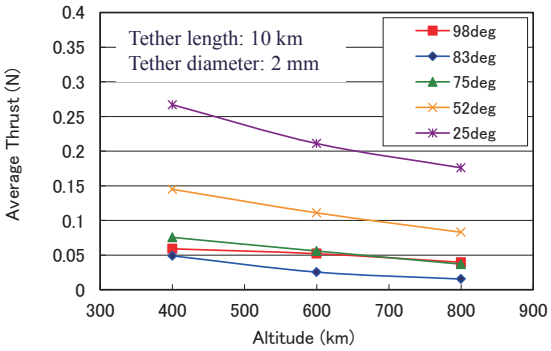
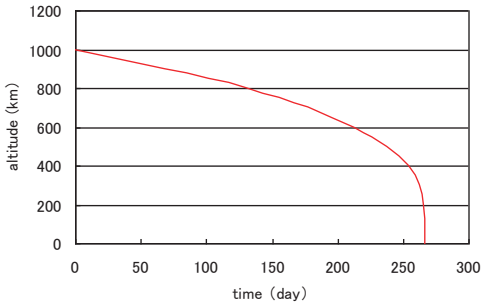
Electrodynamic tether

- EDT thrust becomes smaller in higher inclination orbits, but is still great enough to transfer debris from SSO
- EDT with a length of 10km can transfer 1.4 ton debris in orbit altitude 1000 km, inclination 83deg to atmosphere within one year
- EDT of 5~10km is needed to generate sufficient thrust



Average thrust of EDT in altitude of each inclination



Change in altitude of debris in orbit altitude 1000 km, inclination 83 deg (1400kg) with EDT of 10 km.

5

Advantages of EDT for ADR

- **High efficient propulsion**
  - "Propellant-free propulsion"
  - Utilizing interactions between Earth's magnetic field and currents through the tether
- **Simple system**
  - Propellant tank, valves and pipes are not required
  - System can be simple, light weight and compact
- **Easy attachment to debris**
  - Not requiring firm attachment because of small thrust of EDT
  - Not requiring alignment between thrust axis and debris' C.G because small thrust is distributed along tether
- **No need of thrust vectoring control**
  - EDT thrust is automatically directed towards lowering altitude
  - In general propulsion, thrust direction must be controlled by active attitude control for deorbit

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Deorbit Propulsion System for ADR

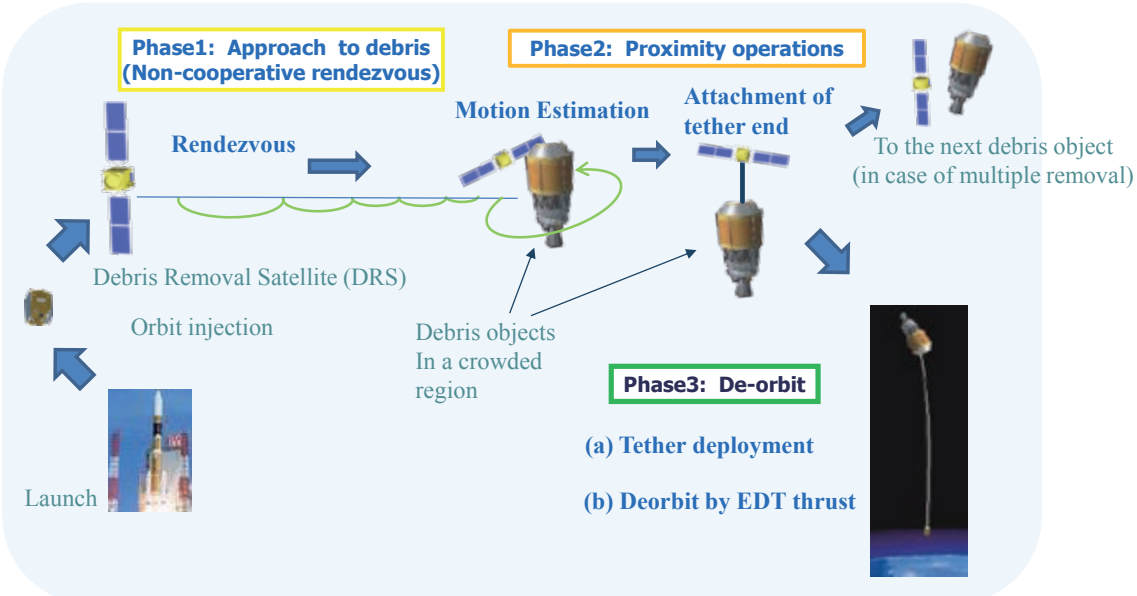
Method	Fuel	Electric power	Attachment to debris	Thrust vector control	Applicable orbit	Applicable debris
Electro-dynamic tether(EDT)	◎ 0 kg	○	○ only tether end	◎ not necessary gravity gradient stability	○ LEO	Intact debris in LEO that does not require controlled reentry
Chemical (Liquid/ Solid)	△ > 100 kg	◎	△ strong force considering thrust axis	△ necessary	◎	Intact debris in LEO that requires controlled reentry
Ion beam irradiation	○ high efficiency	△ high	◎	△ necessary	◎	GEO debris
Drag augment-ation	◎ 0 kg	◎	○	◎ not necessary	△ lower LEO	Small satellite in lower LEO

7

Operation Scenario for Active Debris Removal

- JAXA's roadmap for realizing ADR with EDT

①Key technology demonstration (target:2016)
②System demonstration :single debris removal (target:2020)
③Practical ADR :multiple debris removal (target:2020s middle)



Operation scenario of practical ADR

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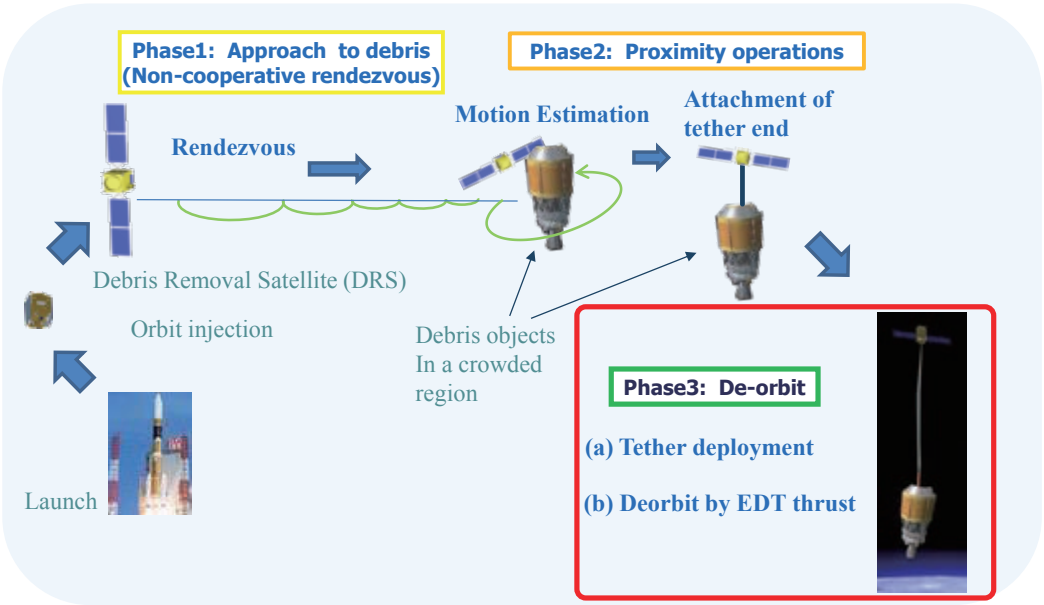
Operation Scenario for Active Debris Removal

②System demonstration (target：2020)

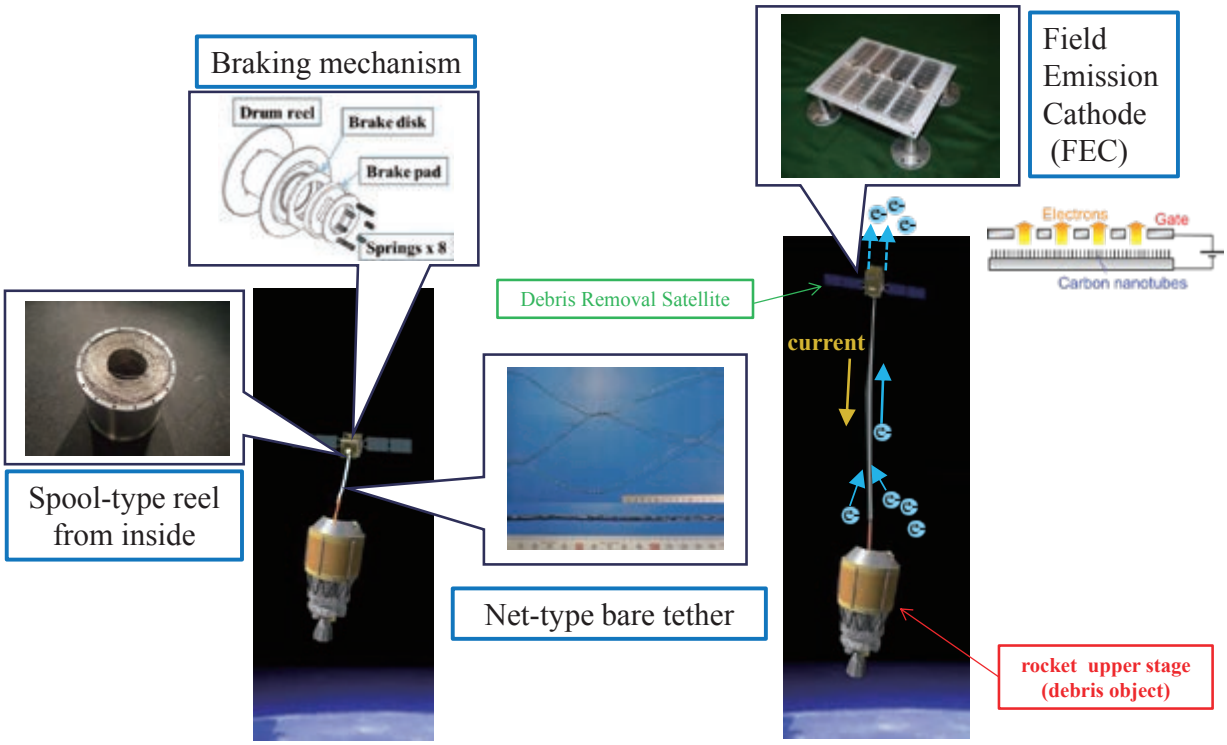
- target debris object : H-IIA rocket upper stage (altitude: 620km, inclination: 98deg)
- Single debris removal



Operation scenario of System demonstration

9

Key components of EDT system



(a) Tether deployment (b) Deorbit by EDT thrust

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EDT System

In order to generate enough thrust for deorbiting large debris objects from crowded orbits

- Tether length : 5~10 kilometers
  - ➢ Gravity gradient is increasing
    →Tether should be made of hi-specific strength material
  - ➢ Deployment velocity and tether libration during deployment are increasing
    → Braking mechanism for deceleration is needed
    Tether libration suppression by thruster is needed
- Electrical current: Several Amperes

Mission of System demonstration

- target debris object : H-IIA rocket upper stage debris
  (altitude: 620km, inclination: 98deg)
- Single debris removal
  - tether deployment dynamics
  - EMF, Current, thrust during deorbit

} Numerical simulation

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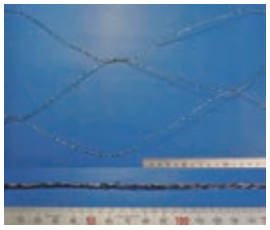
Tether

Tether : net-type bare tether

Tether	Al-SUS tether	Al-Aramid tether
Development step	Key technology demonstration (~2 km)	System demonstration / Practical ADR (5~10 km)
diameter	1.01 mm	2.08 mm
line density	0.96 g/m	1.69 g/m
material	Aluminum wires + Stainless steel wires • Al : Conductive • SUS: tensile strength	Aluminum wires + conductive aramid filaments • Al : Conductive • conductive aramid: high-specific strength, preventing discharge
Withstand tension force	55 N	140 N



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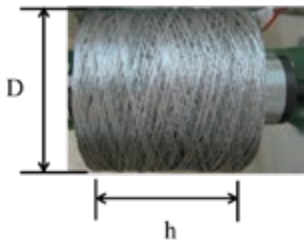
Mass and Volume of tether spool

Tether	Al-SUS tether	Al-Aramid tether	
length	2 km	5 km	10 km
mass	1.92 kg	8.45 kg	16.9 kg
volume	2.48×10^6 mm^3	2.47×10^7 mm^3	4.86×10^7 mm^3
Height	150 mm	300 mm	300 mm
Diameter of tether spool	170 mm	**330 mm**	**460 mm**

Estimated value

Tether spool（2 km Al-SUS tether）
h:150mm



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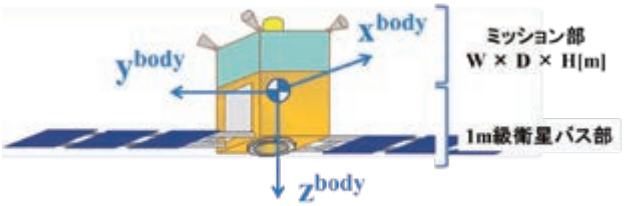
Debris Removal Satellite

			Size W×D×H	Mass
Debris Removal Satellite			**1.0 × 1.0 × 1.5 [m]** **	**360 kg**
	Bus		1.0 × 1.0 × 1.0 [m]	—
	Mission		1.0 × 1.0 × 0.5 [m]	—
		Tether spool	・10 km: φ0.46 × 0.3 [m] ・5 km ：φ0.33 × 0.3 [m]	—
H-IIA rocket upper stage debris (620km, 98deg)			**φ4.0 × 10 [m]**	**3000 kg**

** SAP is neglected



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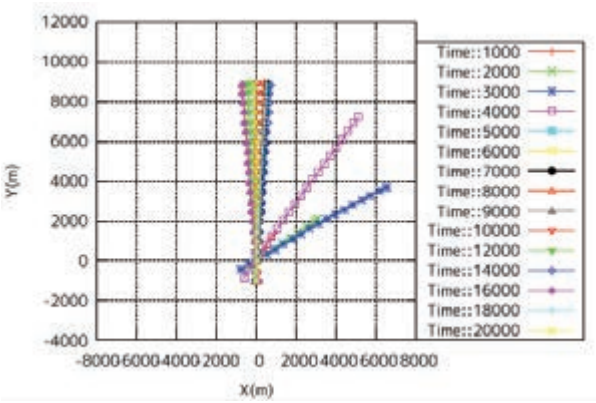
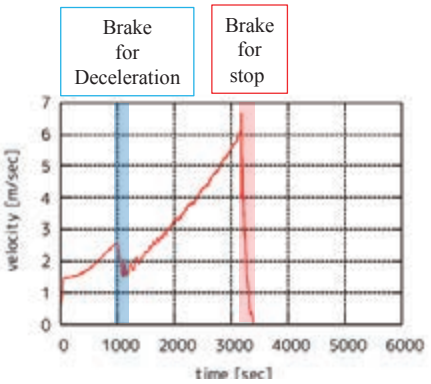
Tether Deployment

- In order to deploy the whole tether length (10km),
  - Deceleration braking is activated at in-plane libration angle 45 deg (100 sec)
  - Thruster is activated for tether libration suppression (9.2N, 600 sec)
- Braking for deceleration has been studied
  - Deployment friction
  - Passive braking mechanism



Change in form of tether (Hill's frame)



history of deployment velocity (~6000 sec)

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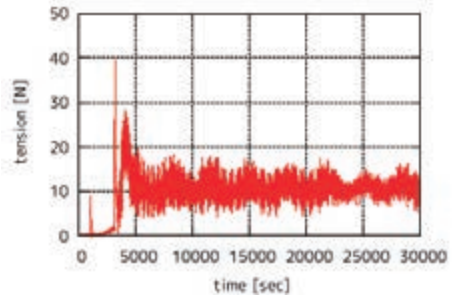
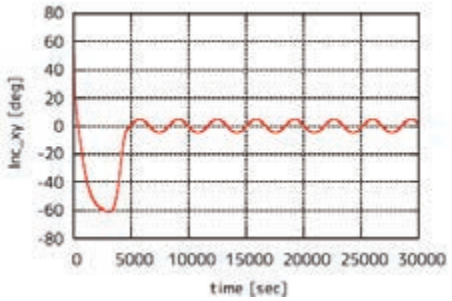
Tether Deployment

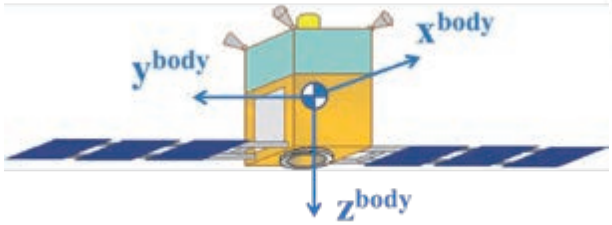
- Max tension : 40 N < withstand tension force of tether : 140 N
- In-plane libration angle after deployment : ±5 deg
- Disturbance torque : ±1 Nm

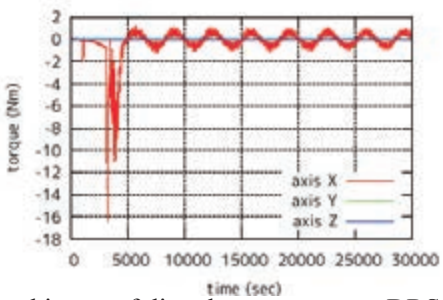


history of tension



history of in-plane libration angle





history of disturbance torque to DRS

* axis y, z : 0

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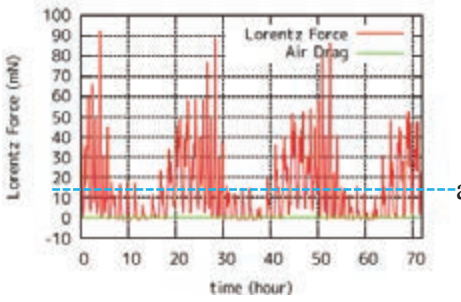
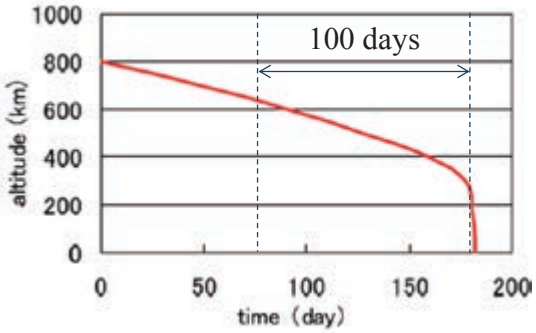
Deorbit by EDT thrust

- Lorentz force : 13 mN (average)
- The term of deorbit by thrust of EDT of 10km : about 100 days
  - In the mission of system demonstration, the deorbit phase is supposed to be stopped in 1 month



history of lorentz force



Change in altitude of debris in SSO (3400kg) with EDT of 10 km.

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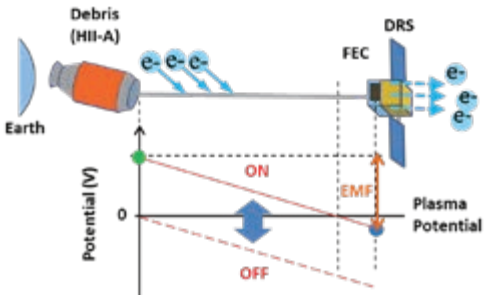
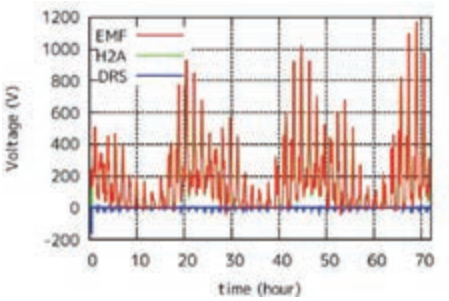
Deorbit by EDT thrust

- electrical potential
  - Debris side >> plasma (0V) > DRS
  - Electromotive Force V_{EMF} : 1000V (max)

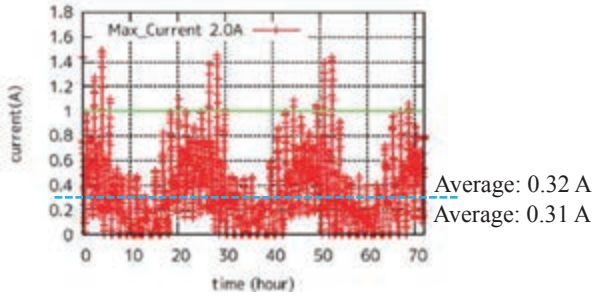


- Current
  - Current max value: 1.5A
  - High limit value 1.0A: 0.31A(average)
  - High limit value 2.0A: 0.32A(average)

not much different



history of electrical potential



history of current

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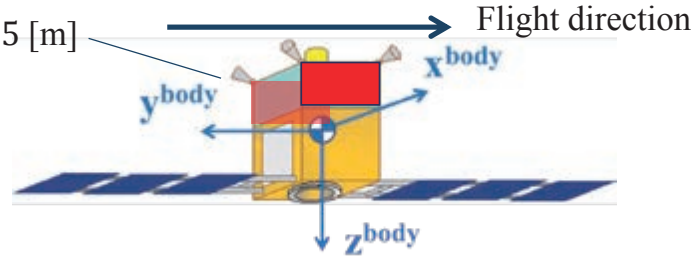
FEC on satellite

- Field Emission Cathode (FEC) should be attached on 2 parallel faces
  - Ram face: CNT is deteriorated by AO
  - Wake face: decrease of plasma density
  - Area: 1.0 × 0.5 [m^2] × 2 [face] = **1.0 m^2 (max)**

1.0 × 1.0 × 0.5 [m]



Expected performance of FEC

High limit value	Required area	Electrical power	
		Average	max
1.0 A	0.43 m^2	40 W	130W
2.0 A	0.87 m^3	40W	260 W

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Conclusion

- EDT is a very promising candidate for ADR propulsion because of
  - high efficiency
  - Simple system
  - easy attachment to debris
  - no need of thrust vectoring control
- JAXA has a roadmap for realizing Active Debris Removal with EDT
  - Key technology demonstration
  - System demonstration
  - Practice ADR
- Deorbit by EDT thrust using debris removal satellite has been studied
  - Tether deployment dynamics
  - EMF, current, thrust during deorbit

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D3

HTV 搭載導電性テザー実証実験（KITE）について

Current Development Status of Electrodynamic Tether Experiment on HTV

○大川恭志、河本聡美、奥村哲平、壹岐賢太郎、堀川雄太、川島一能、三浦尚幸、
高井元、鷲谷正史、川崎治、辻田大輔、葛西徹、植松洋彦、井上浩一（JAXA）
○Yasushi Ohkawa, Satomi Kawamoto, Teppei Okumura, Kentaro Iki, Yuuta Horikawa,
Kazutaka Kawashima, Yoshiyuki Miura, Moto Takai, Masahito Washiya, Osamu Kawasaki,
Daisuke Tsujita, Toru Kasai, Hirohiko Uematsu, and Koichi Inoue (JAXA)

HTV6 号機への搭載を目指して、JAXA では導電性テザー（EDT）実証実験「KITE」の開発を進めている。EDT は、導電性のワイヤー（テザー）に流れる電流と地磁気との干渉によって生じる電磁気力を利用する推進剤不要の推進系であり、システムの小型軽量化が可能な点に加え、マヌーバ中の推力方向制御が不要であることやデブリへの固定の容易性などの点で、低軌道デブリのデオービット用推進系として有力である。KITE では 700m 級のテザーによる EDT 技術の実証を予定しており、EDT を使用したデブリ除去システム構築のための最初のステップとなる。

An on-orbit demonstration of electrodynamic tether (EDT) on H-II Transfer Vehicle (HTV) is planned in JAXA. This plan is called KITE, Konotori Integrated Tether Experiment. The KITE is the first step to develop active space-debris removal systems using EDT. EDT is a promising as the de-orbit propulsion of the debris removal systems on low-earth orbits because of its various advantages, such as no consumable and low electric power required, no thrust vectoring needed during the maneuver, and easy attachment to debris. The primary objective of the KITE is to demonstrate the key technologies of EDT for debris removal.

This document is provided by JAXA.

6th Space Debris Workshop
JAXA Chofu, December 18, 2014.

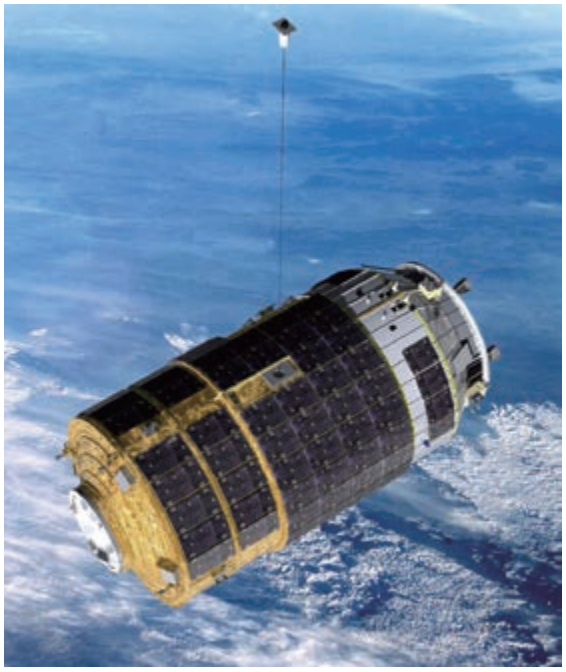
Current Development Status of Electrodynamic Tether Experiment on HTV

by KITE Team
Y. Ohkawa, S. Kawamoto, T. Okumura, K. Iki, Y. Horikawa, K. Kawashima, Y. Miura, M. Takai, M. Washiya, O. Kawasaki, D. Tsujita, T. Kasai, H. Uematsu, and K. Inoue
(Japan Aerospace Exploration Agency)

1

Presentation Outline

- *Introduction*
- *Overview & Objectives of KITE*
- *Mission Time Line*
- *Major Components*
- *Functions of Major Components*
- *Development Status*
- *Summary*



2

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Introduction

- Demonstration plan of electrodynamic tether (EDT) propulsion on H-II Transfer Vehicle 6 (HTV-6) is on-going
- The project is called *KITE*, Konotori Integrated Tether Experiment
- KITE-EDT mainly consists of bare-wire-tether for electron collection and field-emission-cathode for electron emission. This pair provides completely propellant-less propulsion system
- KITE is also equipped with other own components such as end-mass releasing mechanism, camera, magnetic sensor, electric potential monitor with plasma current probe, and data handling unit

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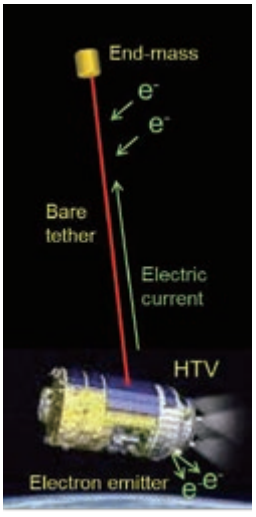
Overview of KITE



KITE Image on Orbit

KITE Specifications

Platform	H-II Transfer Vehicle (HTV)
Mission duration	7 days (planned)
Orbit	20 km (or more) below ISS orbit Altitude: 300 – 400 km Inclination: 52 deg.
Tether length	700 m (approx.)
Tether current	10 mA (approx.)
Electron collector	Bare tether
Electron emitter	Field emission cathode

Completely Propellant-less Combination

※EDT Thrust: ～0.1 mN (max.)

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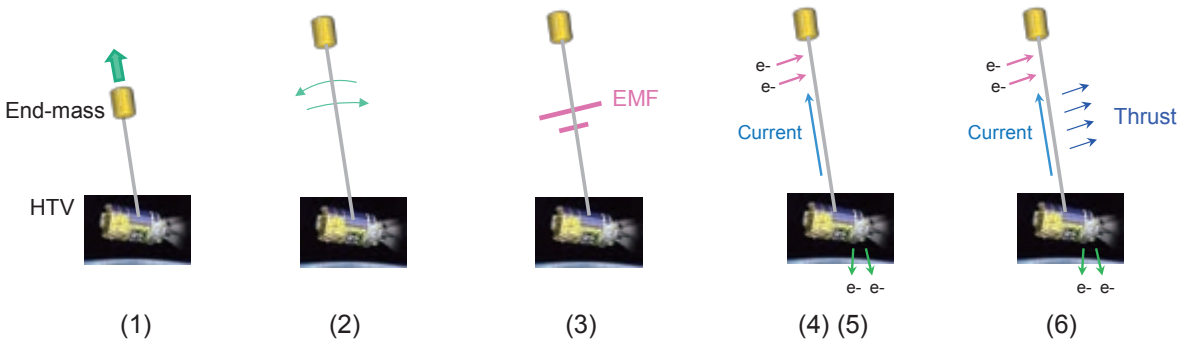
Objectives of KITE

- Primary objective of KITE is “To demonstrate key technologies of EDT preparing for future debris-removal application”
  - (1) Deployment of bare tether
  - (2) Motion monitoring of tether and end-mass
  - (3) Electric potential generation by electromotive force
  - (4) Electron collection by bare tether
  - (5) Electron emission by field emission cathode
  - (6) Thrust measurement



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Mission Time Line (1)

Day	Event	Image
Day 1	①Checkout of KITE Components	② Deployment ③ =3
	②End-mass Ejection (Tether Deployment)	
	③Tether Motion Stabilization by HTV Maneuver	
Day 2	④Observation of Tether Dynamics & ⑤Measurement of Electromotive Force	④ Vibration ⑤ EMF
Day 3	⑥Checkout & Characteristics Measurement of Field Emission Cathode	⑥⑦ Electron emission e-e-
	⑦Measurement of HTV Electric Potential with and w/o Electron Emission	

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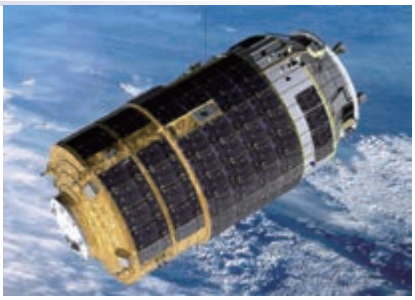
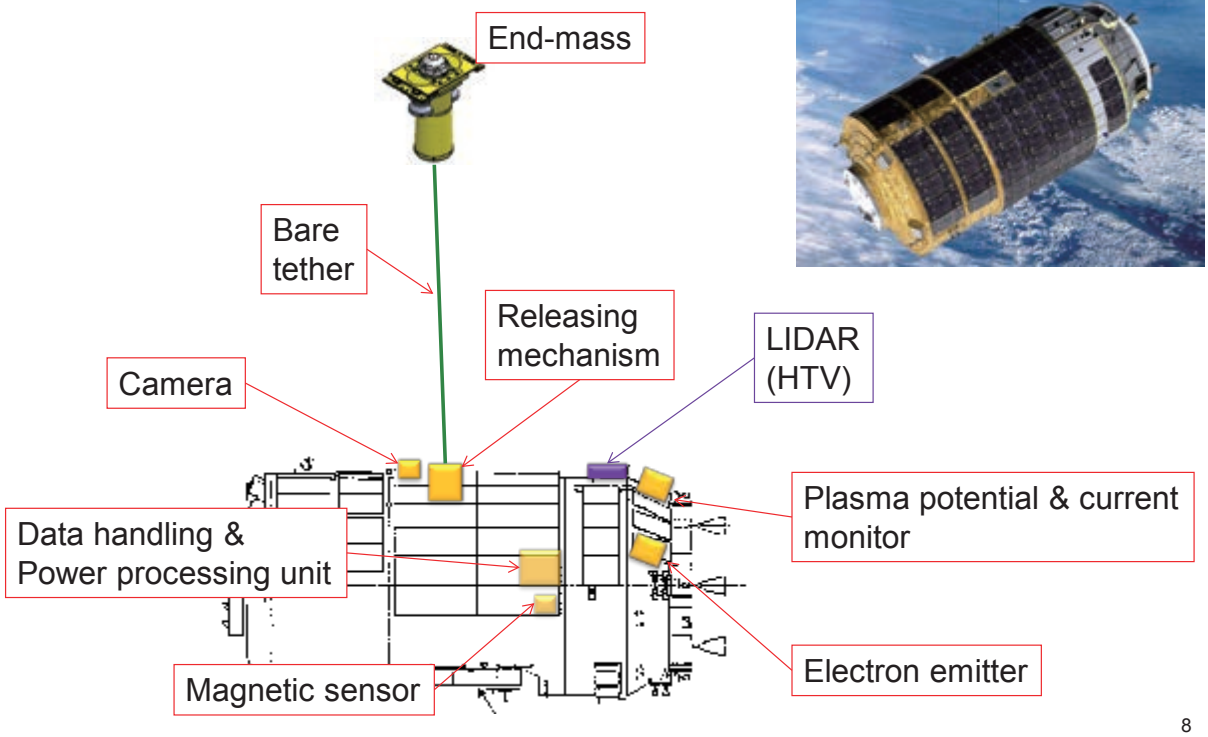
Mission Time Line (2)

Day	Event	Image
Day 4	⑧Repetitive Measurement of Tether Electric Potential & Current for EDT Fundamentals	⑧ Electron collection, Current, Electron emission
Day 5	⑨Tether Motion Stabilization by HTV Maneuver (If required) ⑩Autonomous EDT Operation at Several Settings	⑩ Electron collection, Current, Electron emission
Day 6	⑪Autonomous EDT Operation at Maximum Electron Emission for EDT Thrust Measurement by Tether Vibration Monitoring	⑪ Observation of end-mass motion
Day 7	⑫Extra Time for Additional Tests ⑬Cutting of Tether from HTV	⑬ Cutting

7

Major Components





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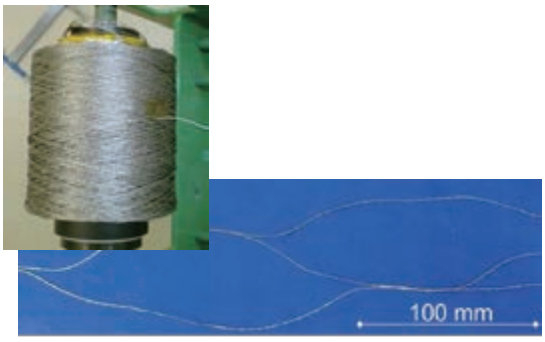
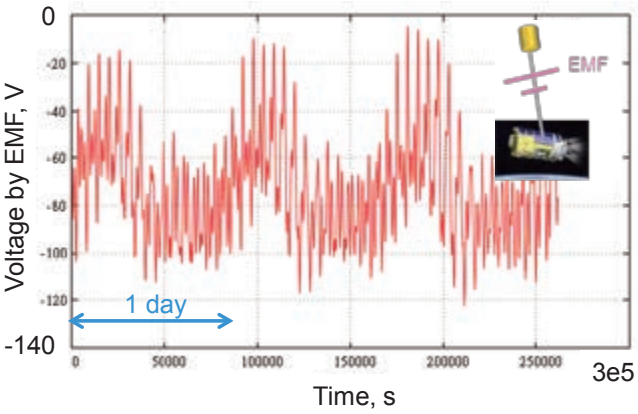
Bare Tether

- Functions
  - Electron collection from ambient space plasma
  - Voltage generation between tether ends by Electromotive force
  - Thrust generation by interaction between current and geomagnetic field



- Tether Length of 700 m
- Having "net" shape for tolerance to small debris impact and efficient electron collection

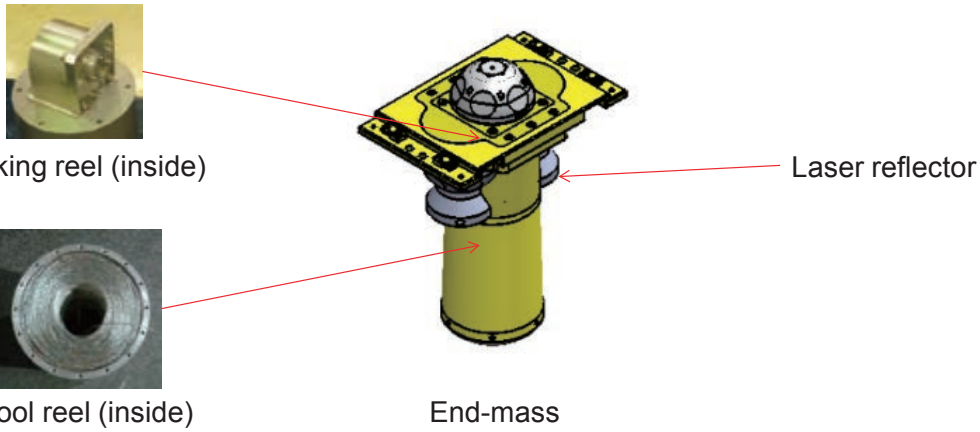


Estimated EMF variation on orbit

9

End-mass

- Functions
  - Mass for tether motion stabilization
  - Storing bare tether before deployment ⇒ Spool reel
  - Smooth termination of tether deployment ⇒ Braking reel
  - Target of HTV LIDAR ⇒ Laser reflector



10

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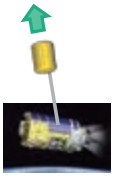
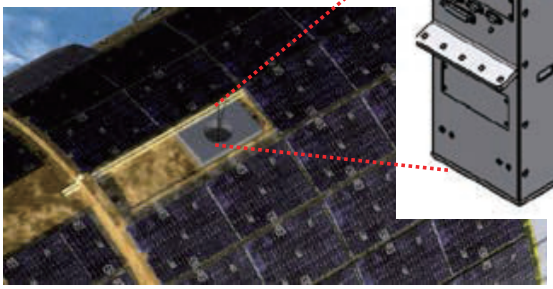
End-mass Releasing Mechanism

- Functions
  - Holding end-mass until KITE mission start ⇒ Actuators
  - Releasing end-mass with initial velocity ⇒ Spring





End-mass

Non-explosive actuators for holding and releasing end-mass (inside)

Spring for giving initial velocity to end-mass (inside)

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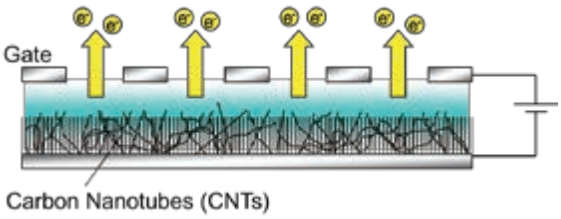
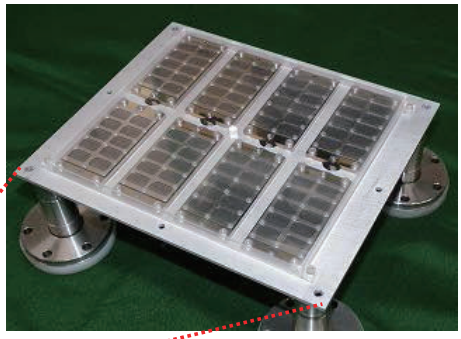
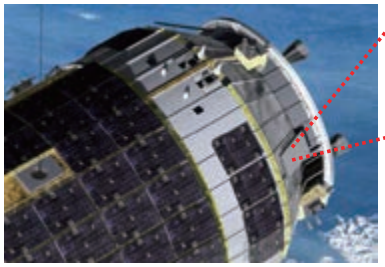
Electron Emitter

- Functions
  - Emitting electrons from HTV to ambient space plasma for tether current driving ⇒ Field Emission Cathode (FEC)



Conceptual image of FEC





FEC Head for KITE

Electron emission current of 10 mA (max.)

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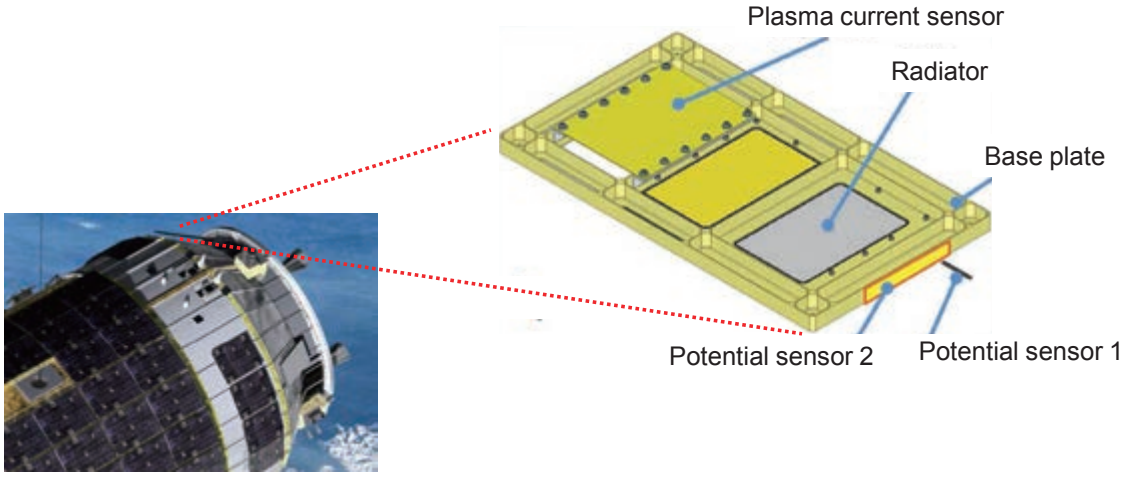
Plasma Potential & Current Monitor

- Functions
  - Monitoring HTV potential with reference to space plasma
  - Monitoring ambient plasma current



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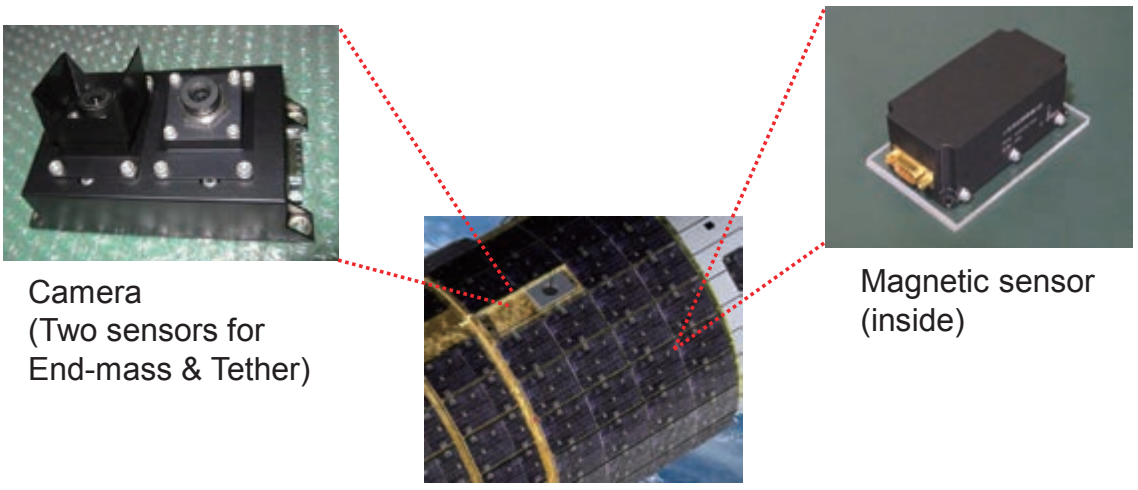
Camera & Magnetic Sensor

- Functions of Camera
  - Monitoring End-mass & Tether motion (Back-up of HTV LIDAR)
- Functions of Geomagnetic Sensor
  - Monitoring geomagnetic field



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Development Status & Summary

- Test phase of engineering model was almost completed and flight unit development of some components was started in this fall

Major milestones of KITE

Event	Date
Mission Definition & System Requirement Review	October, 2012
System Definition Review	February, 2013
Critical Design Review	September, 2014
Flight Unit Manufacturing	Start on October, 2014
Post Development Review	July, 2015 (planned)
HTV-6 Flight	Late 2016 (planned)

- Development is on-going for the flight on HTV-6 !!

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D4

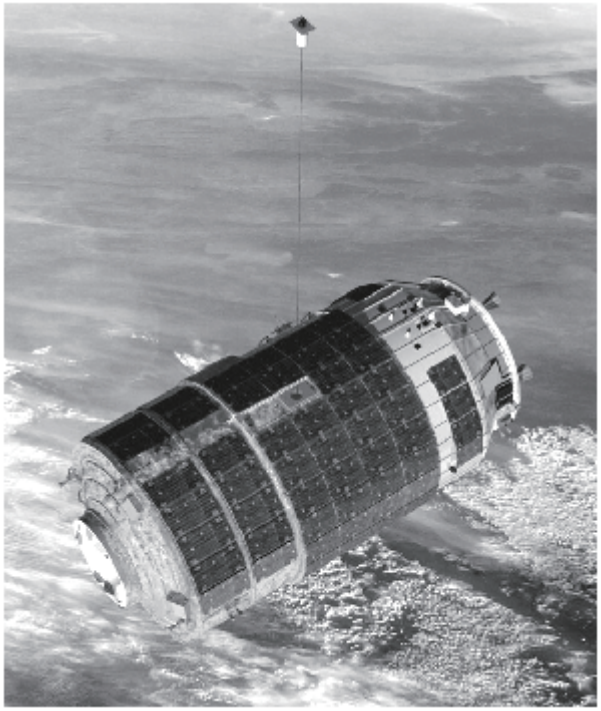
導電性テザー実証実験に向けた HTV 開発状況

HTV Development Status for ElectroDynamic Tether Experiments

○辻田大輔、葛西徹、中野英一郎、植松洋彦、河本聡美、大川恭志、井上浩一（JAXA）
○Daisuke Tsujita, Toru Kasai, Eiichiro Nakano, Hirohiko Uematsu, Satomi Kawamoto, Yasushi Ohkawa and Koichi Inoue (JAXA)

HTV(こうのとり)は, ISS へ物資を補給する宇宙機であり、2009 年から 2013 年にかけて HTV1~4 号機の 4 機連続ミッション成功を実現している実績を持つ。本実績に基づき、HTV4 号機より軌道上プラットフォームを整備して、機器開発ユーザーに軌道上実証機会を提供している。HTV6 号機では、デブリ除去技術の有力な候補である導電性テザー技術の実証実験を行う計画であるが、実験構成機器は 10 個に及ぶ為、軌道上プラットフォームの拡張が必須である。本発表では、実験に向けた軌道上プラットフォームの整備状況、及び、実験構成機器の搭載に向けた各種インタフェース試験状況を報告する。

The H-II Transfer Vehicle (HTV) is Japan's unmanned cargo transfer spacecraft that delivers cargo/supplies, and HTV1 through HTV4 completed the mission successfully. Based on the flight experiences, a on-orbit platform function is developed to provide the demonstration chance to users from HTV4. Currently, ElectroDynamic Tether (EDT) technique is planned to be demonstrated in HTV6, which is a promising candidate of debris removal device. The number of its instruments is as many as ten, and then the platform function has to be extended. The presentation shows its developement status, including the interface test plan and a part of results with experimental instruments.



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導電性テザー実証実験に向けたHTV開発状況

HTV Development Status for ElectroDynamic Tether Experiments

○辻田大輔、葛西徹、中野英一郎、植松洋彦、
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第6回スペースデブリワークショップ
2014.12.17～19
@JAXA調布

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1. Purpose

- The H-II Transfer Vehicle (HTV) is Japan's unmanned cargo transfer spacecraft that delivers cargo/supplies, and HTV1 through HTV4 completed the mission successfully.
- Based on the flight experiences, a on-orbit platform function is developed to provide the demonstration chance to users from HTV4.
- Currently, ElectroDynamic Tether (EDT) technique is planned to be demonstrated in HTV6, which is a promising candidate of debris removal device. The number of its instruments is as many as ten, and then the platform function has to be extended.
- The presentation shows its development status, including the interface test plan and a part of results with experimental instruments.

2

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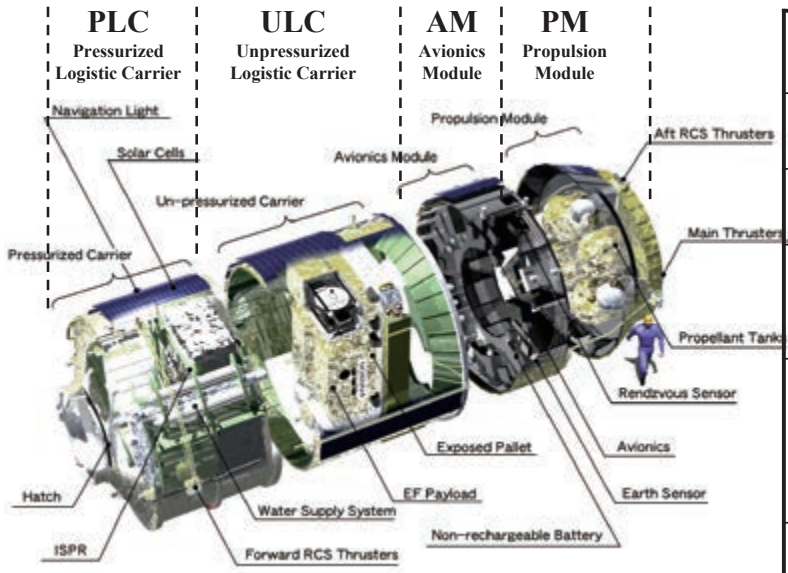
What's HTV?

- Logistic Supply and Waste Disposal Vehicle for the ISS
- Mission Summary of HTV
  - HTV-1: Sep. 11 to Nov. 2, 2009 (Demonstration Flight)
  - HTV-2: Jan. 22 to Mar. 30, 2011 (1st Operational Flight)
  - HTV-3: July. 21 to Sep. 14, 2012
  - HTV-4: Aug. 4, 2013 to Sep. 7, 2013
  - HTV-5 to -7: Planed in 2015 to 2017
- Almost yearly launch can be expected … Good mother spacecraft for demo mission!

Picture (C)NASA

2. HTV Overview –Configuration–



HTV Characteristics

Dimensions	Length: 9.2 m Diameter : 4.4 m
Total mass full loaded	16.5 ton
Launch Vehicle	H-IIB launch Vehicle
Target orbit	Altitude: 350km~460km Inclination: 51.6deg
Cargo capability	6 ton in total
Press.	Up to 5.2 ton
Un-press.	Up to 1.5 ton
Propulsion system	Four 500N main engine Twenty eight 120N RCS thrusters

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2. HTV Overview –Operation–

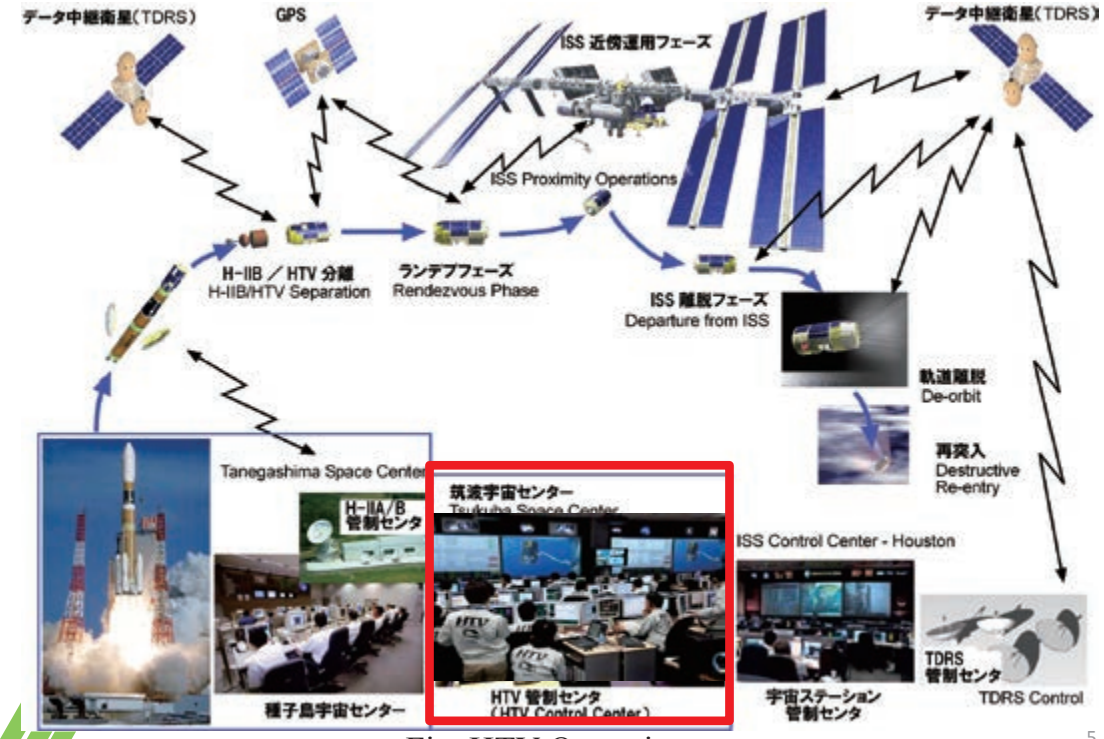
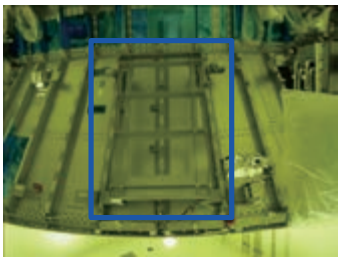


Fig. HTV Operation

3. On-orbit platform

HTV has prepared a new platform from HTV4, where some existing spare electrical and communication channels are provided, and a special seat is developed to provide mounting position for some instruments.



Special Seat

Fig. Platform position

Table. Platform Interface

Item	Content
Electrical IF	50V power supply, On/Off commands, some analog telemetries
Mechanical IF	Mounting on the special seat
Thermal IF	Isolated thermally from the HTV structure
Mass	Less than approx. 5kg
Comm with Ground	Communication with HTV Operation Control System via HTV.

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3. On-orbit platform

- An electrometer was installed on the platform in HTV4. It has the functionality of measuring the potential of HTV against space plasma in the range from -200V to +200V.
- The platform will be used by a similar instrument in HTV5.

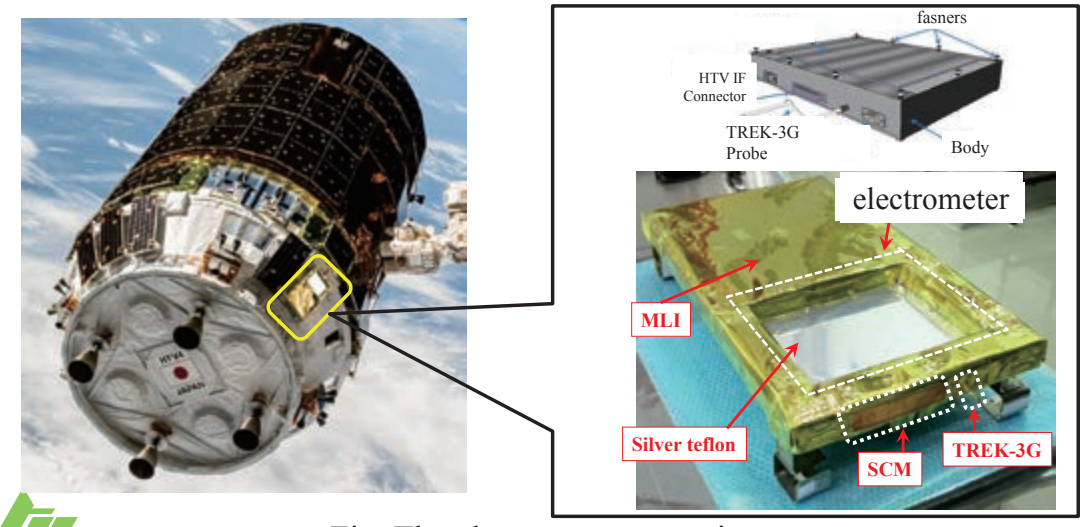

Fig. The electrometer overview

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4. ElectroDynamic Tether (EDT) experiments plan

[Candidate for HTV6]
As larger scale experiments, EDT experiments, are planned in the extended platform on HTV6.

[What is EDT]
An electrodynamic tether is a promising candidate of deorbit propulsion for future active debris removal systems because of its simplicity, high efficiency, easy attachment to debris, and no need of thrust vectoring. Since the electrodynamic tether utilizes Lorenz force by interaction between current on tether and the geomagnetic field to generate deorbiting force, the propulsion system needs neither propellant nor high electrical power in principle

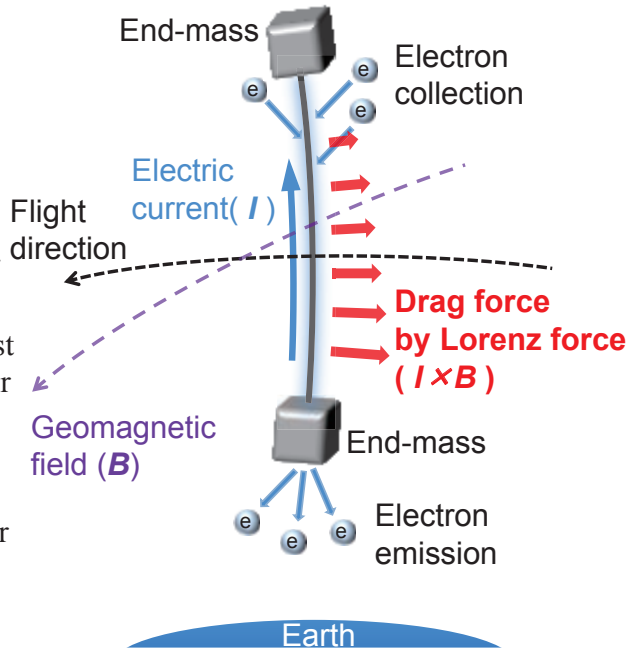

Fig. The EDT Principle

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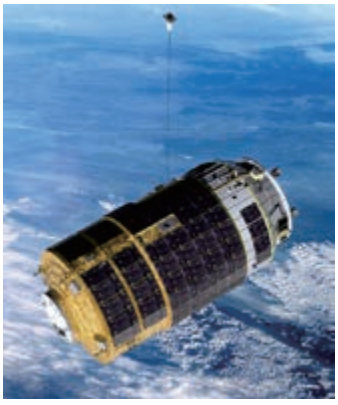
4. ElectroDynamic Tether (EDT) experiments plan

[Configuration]

The endmass is ejected from the HTV to deploy the tether whose length is approximately 700m. Tether current is driven 10mA at the maximum by using electron emitter on the HTV and the direction from nadir to zenith, so that Lorenz force applies on the opposite flight direction.



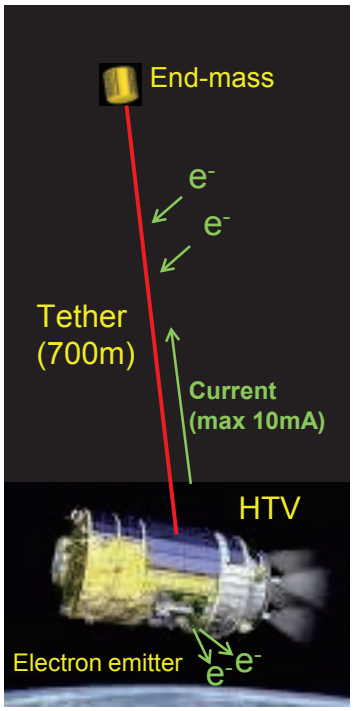


Fig. The Experiments configuration

4. ElectroDynamic Tether (EDT) experiments plan

[System block diagram]

The special characteristic of EDT on the HTV is that the endmass motion is monitored by HTV Rendezvous Sensor (RVS), which is used in approaching International Space Station (ISS). First concept said that GPS monitors the endmass position and transponder transmits the data to the HTV. In that case, the endmass needs batteries / solar array panels / power control unit for the GPS and transponder, at least, which indicates very complex system. However, HTV RVS solves the problem. Only the reflector is needed on the endmass, so that it greatly contributes to simplifying the system.

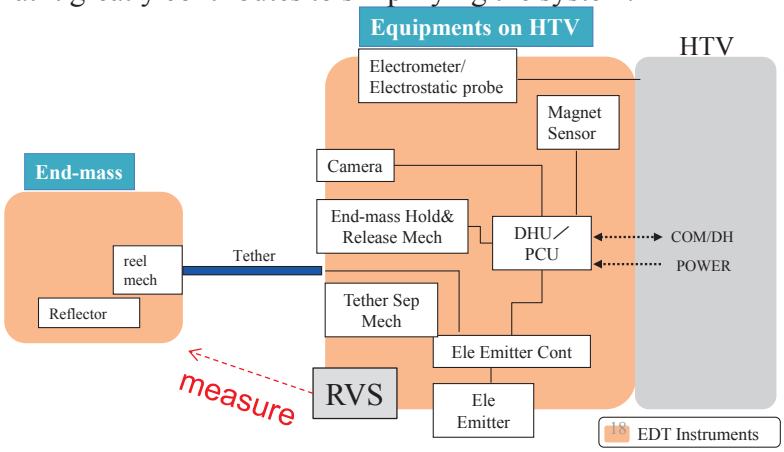


Fig. System block diagram

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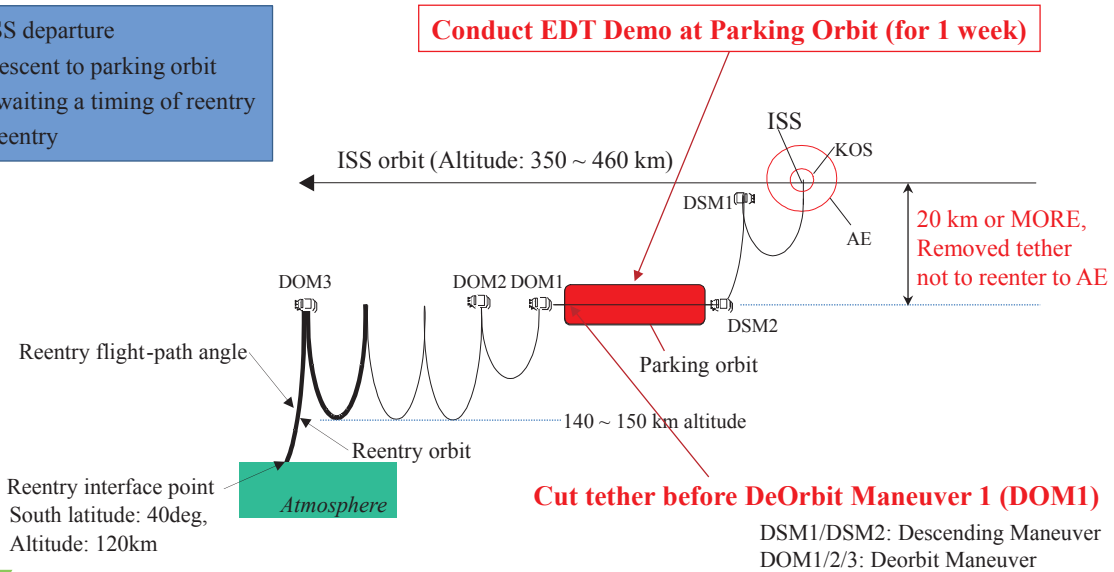
4. ElectroDynamic Tether (EDT) experiments plan

[Mission Profile]

The mission timing is planned for approximately 7 days from the end of integrated operation until re-entry, by prioritizing the HTV mission objective.

1. ISS departure
2. Descent to parking orbit
3. Awaiting a timing of reentry
4. Reentry



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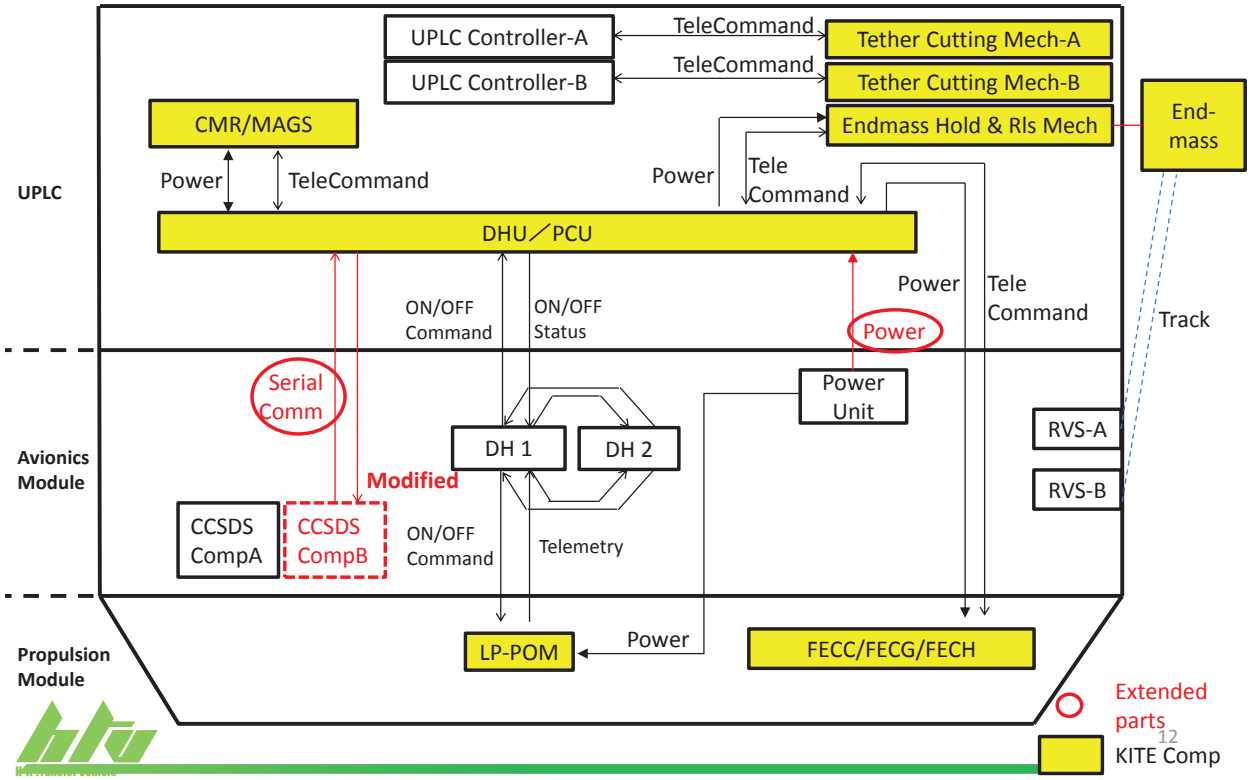
5. HTV development plan for the experiments



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5. HTV development plan for the experiments

UPLC provides the new installation area as the extended platform.

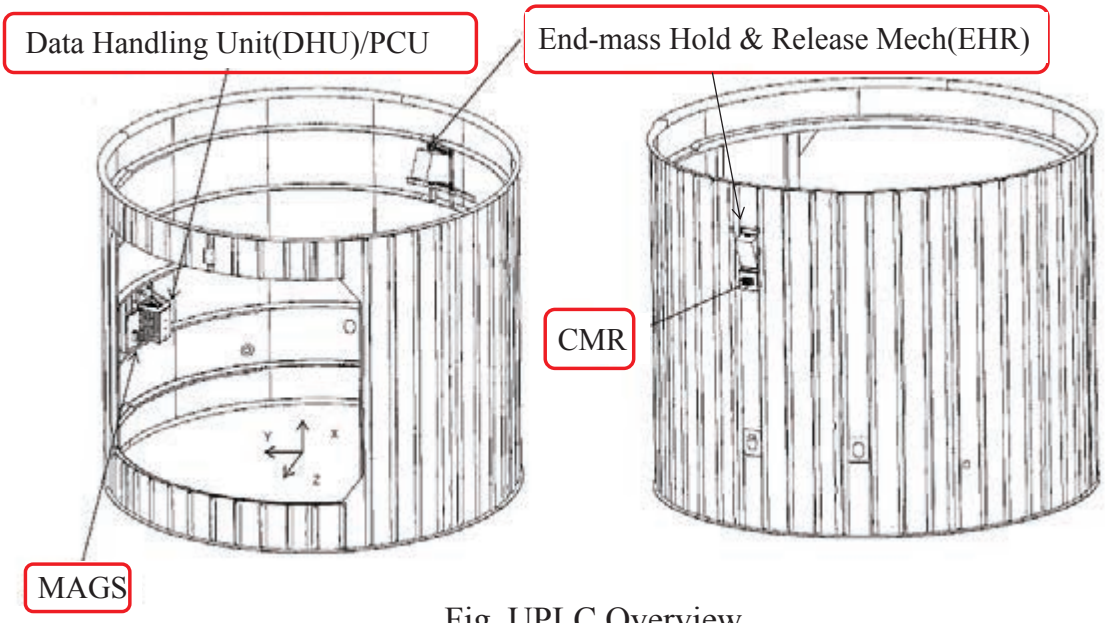

Fig. UPLC Overview

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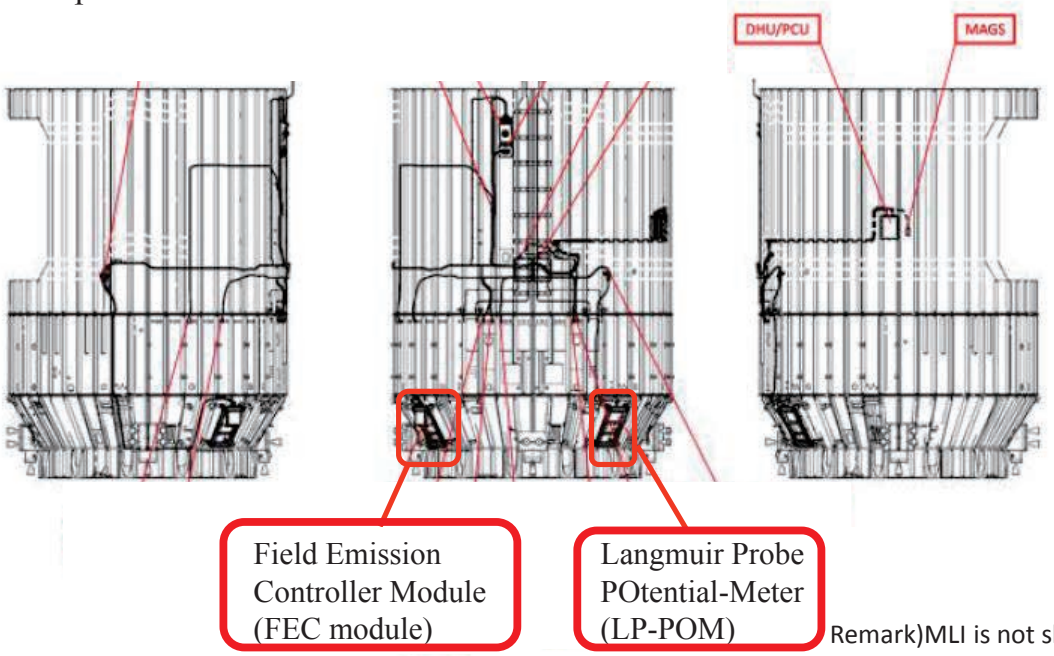
5. HTV development plan for the experiments

PM provides a additional installation area as the extended platform, such as FEC module position.



Remark)MLI is not shown

Fig. HTV development plan overview

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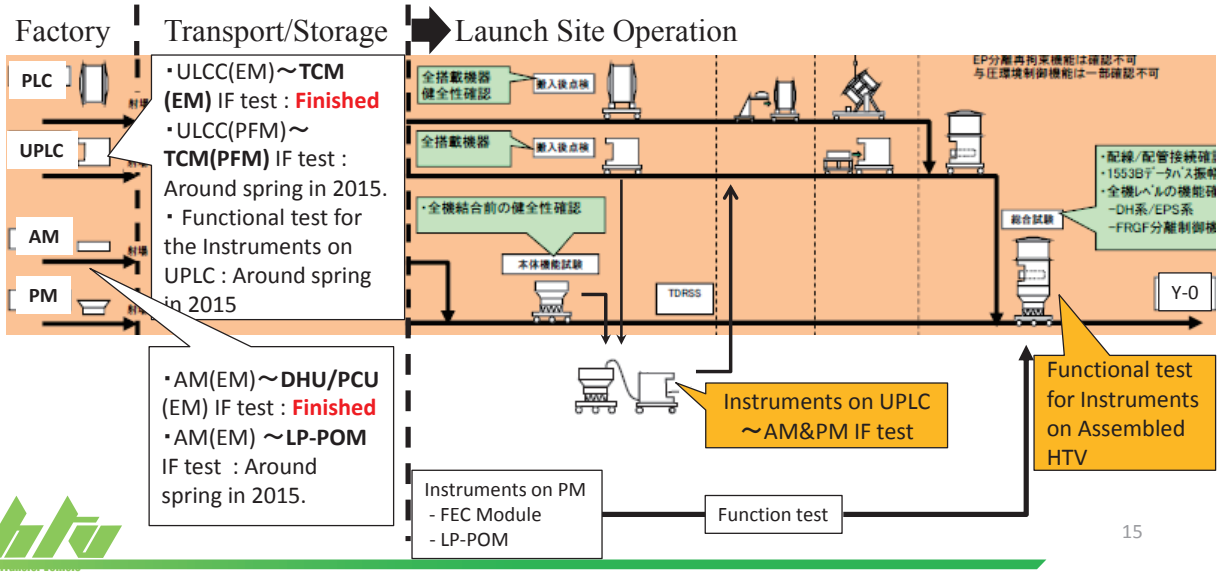
5. HTV development plan for the experiments

・Basically, End to End tests are planned between EDT experiments instruments and HTV until the launch.
・The below figure shows the HTV test plan for installing the instruments.
・The instruments interfaced directly to HTV are planned to have IF test before shipping to the launch site.



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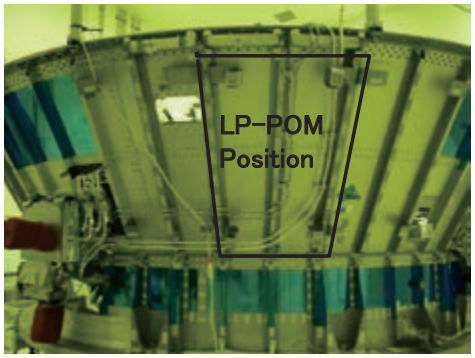
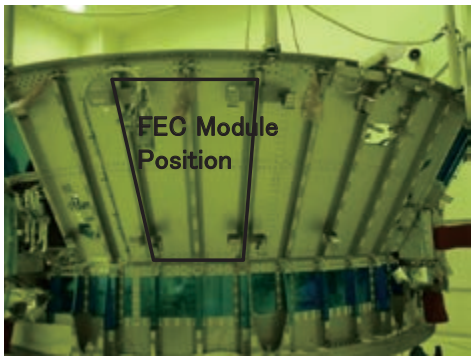
5. HTV development plan for the experiments

HTV6 UPLC picture





HTV6 PM pictures

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6. Summary

- The presentation shows HTV development status for ElectroDynamic Tether Experiments.
  - The extended platform on HTV is being manufactured for EDT experiments.
  - Some interface tests has been done and are planned.
- We would like to execute the plan steadily and provide the flight chance and, finally contribute solving the space debris problem.

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D5

デブリ除去衛星システムサイジング検討〈その 2〉

Debris removal satellite system sizing examination #2

○廣田 賢治, 渡辺 順一郎(TECS), 桑尾 文博, 大塚 聡子(NEC),
河本聡美, 池内 正之(JAXA)
○Kenji Hirota, Junichiro Watanabe(TECS), Fumihiro Kuwao, Akiko Otsuka(NEC),
Satomi Kawamoto, Masayuki Ikeuchi(JAXA)

デブリ除去衛星の開発においては軌道上実証を行い、実用化衛星の開発を目指すというロードマップが立てられている。実証を目指す上で、衛星システムはシンプルかつミニマムな設計を検討した。本報告では、軌道上実証衛星のシステム設計結果を報告するとともに、実用化に向けた課題を検討する。

In the roadmap for developing the active debris removed (ADR) satellite, the demonstration satellite will be launched before the ADR satellite. As the verification is a top priority, the demonstration satellite is minimum designed. The system of the demonstration satellite will be reported and issues to develop the ADR satellite will be discussed.

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D5. The active debris removal (ADR) satellite system sizing study

19 Dec. 2014

○Kenji Hirota, Junichiro Watanabe (TECS), Fumihiro Kuwao,
Akiko Otsuka (NEC), Satomi Kawamoto, Masayuki Ikeuchi (JAXA)

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3. Demo Sat. System design
デブリ除去 『実証』 衛星 システム設計結果
4. Issues for developing ADR Sat.
デブリ除去 『実用』 衛星 に向けた課題
5. Concluding remarks
おわりに

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1. ADR Sat. Outline and Roadmap

Space Debris is dangerous to spacecraft on the orbit. ADR satellite system is being studied.

＜ADR Sat. precondition＞

①The key technologies will be verified using Demo Sat.
Then ADR Sat. will be developed.

②The concept of Demo Sat. design is minimum.

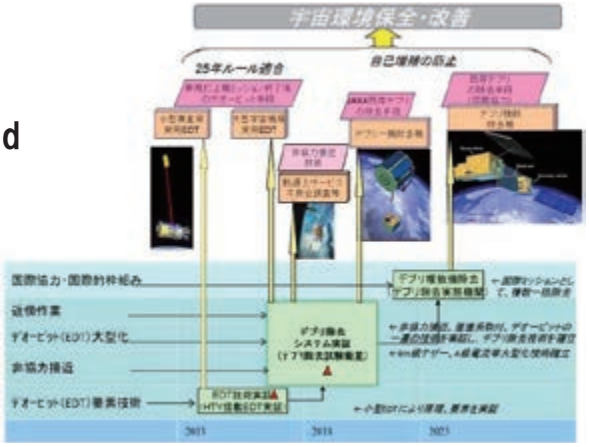

Fig.1 Debris removed Sat. Roadmap

2. ADR Sat. and Demo Sat. Requirement

●ADR Sat. Policy

・デブリ除去を目的とし、継続してミッションを実施できること。

・対象となるデブリの曖昧さ※に柔軟に対応できること。

※曖昧さ:デブリの形状，大きさ，破損状態，軌道/高度の違い，回転エネルギーの有無等

●Demo Sat. Policy

・特定のデブリに対象を絞って、要求を明確かつシンプルに定義する。

・要素技術の確認を目的とする。

・対象デブリを形状や大きさ、状態がわかっているロケット上段とする。

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2. ADR Sat. and Demo Sat. Requirement

Table 1. ADR Sat. and Demo Sat. Requirement (1/2)

Requirement	ADR Sat.	Demo Sat.
System	(1)様々な種類のデブリを除去できること。 (2)複数のデブリを除去できること。 (3)自身がデブリとならないこと。	(1)対象デブリ:非協力対象のロケット上段とする。 (2)ロケット上段は重力傾斜安定していること。 (3)ロケット上段に対して相対停止可能なこと。 (4)デブリ実証衛星一機にてデブリ単体をデオービットできること。
Navigation	非協力対象であるデブリを視認して、接近できること。	カメラ画像を用いて、デブリを視認し接近できること。(光学航法) (1)ロケット上段の運動推定が可能なこと。 (2)画像処理可能なこと。

2. ADR Sat. and Demo Sat. Requirement

Table 1. ADR Sat. and Demo Sat. Requirement (2/2)

Requirement	ADR Sat.	Demo Sat.
Debris Capture	デブリ除去機器の設置ができること。また、回転エネルギーを低減できること。	ロケット上段へデブリ除去機器を取り付けられること。
Debris Removal	デブリに対して軌道変更に必要な力を加え、目的の場所まで移動できること。	デブリ除去に用いる機器は、導電性テザー(以後、EDT:Electro Dynamic Tetherと呼ぶ)を考えている。この導電性テザーを用いて、デブリをデオービットできること。 (1)長さ:5km (2)電流:1A (3)EDT伸展方向:地球 → 天頂

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3. Demo Sat. System design

3.1 Demo Sat. System design

Demo Sat.の要求を満たすシステム設計を行った。構成品及び質量を表2に示す。

Fig.2，3に外観図および寸法を示す。

Table 2. Demo Sat. Component and Mass

デブリ除去衛星　バスシステム機器構成	略号	デブリ除去衛星 質量[kg] 合計
バスシステム		280.89
衛星マネージメント系	SMS	15.43
通信系	TTC	4.87
太陽電池パドル系	SPS	35.00
電源系	EPS	40.38
姿勢軌道制御系	AOCS	54.21
推進系	RCS	25.30
熱制御系	TCS	9.50
構体系	STR	51.30
計装系	INT	24.90
マージン		20.00
ミッション		115.2
EDT-M	EDT-M	11.50
EDT-E	EDT-E	15.50
ミッションコントロール系・画像処理系		41.80
推進系取付機器		8.00
マージン		38.40
衛星合計(ドライ質量)		396.1
推薬		45.0
衛星合計		441.1

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3. Demo Sat. System design

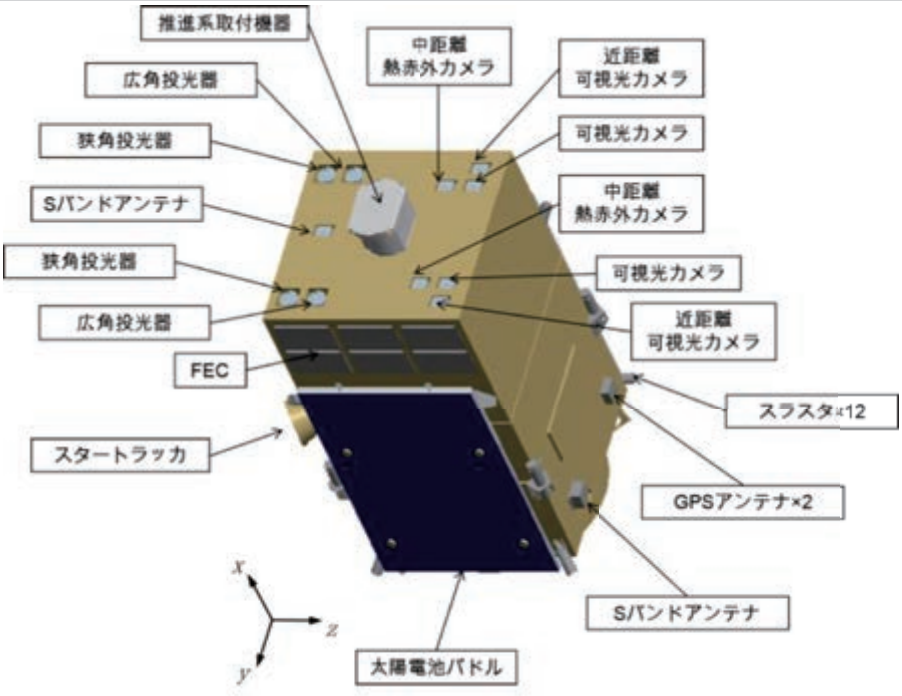

Fig.2 Demo Sat.

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3. Demo Sat. System design

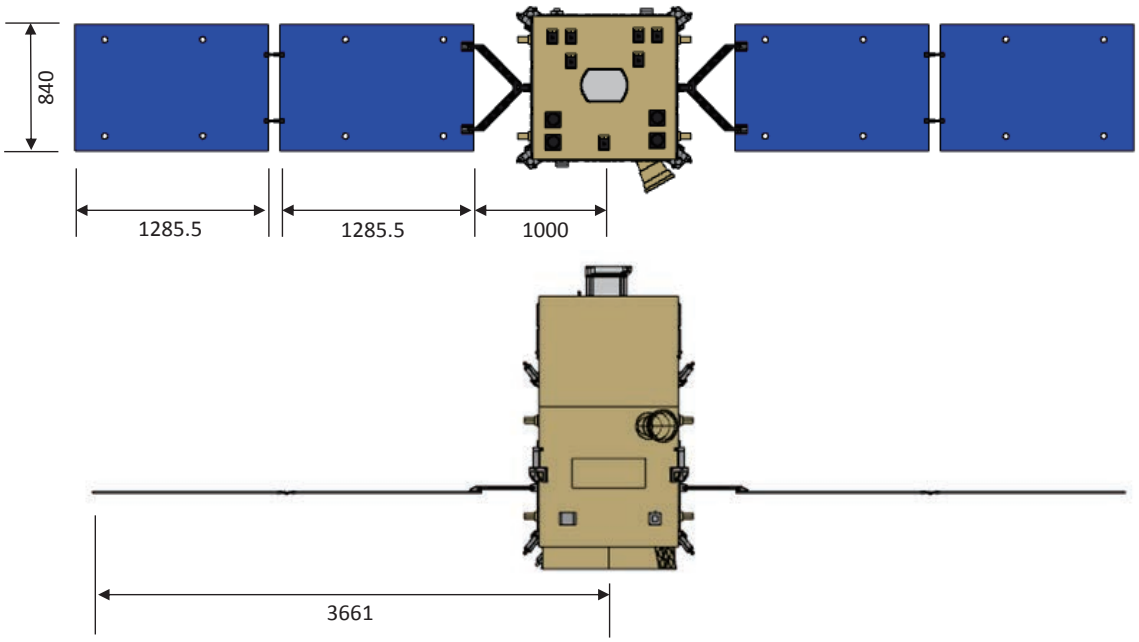

Fig.3 Demo Sat. size

3. Demo Sat. System design

3.2 Non-cooperative approach and nominal scenario

(1) Angles-Only Navigation (AON)

Demo Sat.を実現させるミッション軌道目標 (Fig.4) の成立性を確認した。

ミッション軌道は⊿Vプロファイルの検討を行い衛星軌道を求めた。

デブリは非協力な対象であるため、衛星側に用意されたカメラを用いて光学航法を行う。

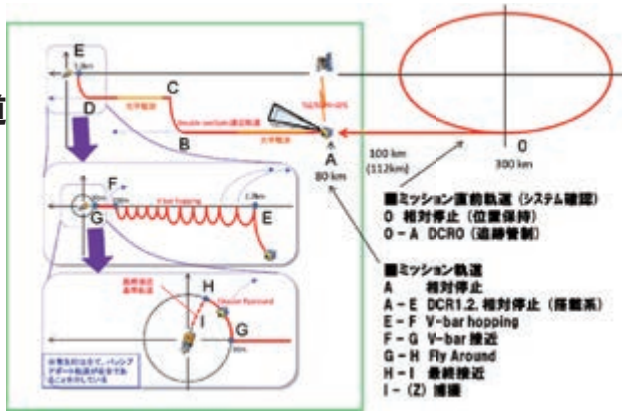

Fig.4 Mission Orbit and Milestone A~I

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3. Demo Sat. System design

3.2 Non-cooperative approach and nominal scenario

(2) Motion of the satellite in the vicinity of the debris

Fig.5にデブリ近傍作業の概要を示す。

Fig.4に示すミッション軌道を目標として、はやぶさの姿勢制御（6自由度制御）をコンセプトとしたシミュレーションを行い、必要な精度で誘導制御が行えることを確認した。

確認結果をFig.7,8,9に示す。

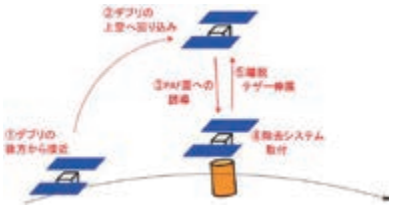

Fig.5 The vicinity of the debris

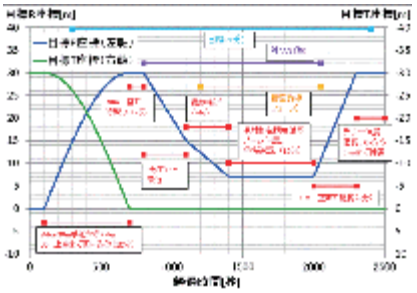

Fig.6 Navigation

3. Demo Sat. System design

3.2 Non-cooperative approach and nominal scenario

Less than ±10cm (1400〜2000sec)

Less than ±3deg (1400〜2000sec)

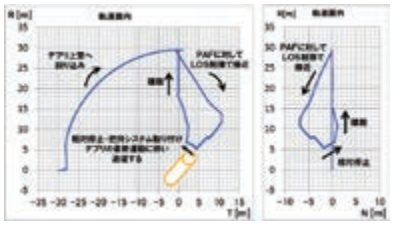

Fig.7 Motion of the satellite in the vicinity of the debris

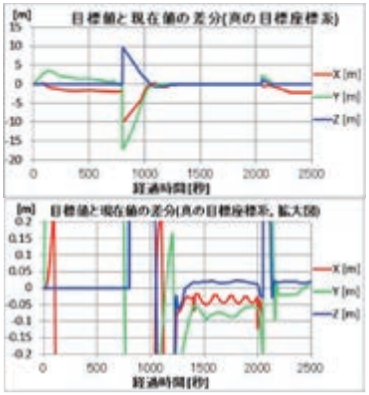

Fig.8 Error in position

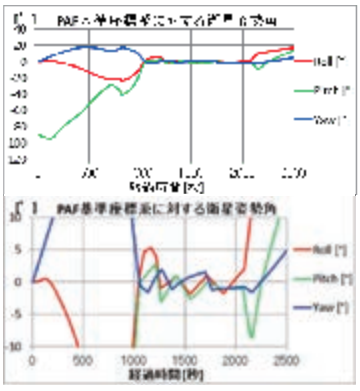

Fig.9 Error in attitude angle

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3. Demo Sat. System design

3.3 Capture Mechanism

(1) Capture Mechanism trade-off

Table 3. Capture Mechanism trade-off

トレードオフ 代表項目	①銛	②伸展ブーム	③多関節アーム
把持動作に伴うリスク ・デブリ，衛星本体の破壊リスク ・新規デブリの発生リスク	銛がデブリへ刺さった際に、デブリが破損する恐れがある。	PAF部への接触のみであり、リスクは小さい。	PAF部への接触のみであり、リスクは小さい。
形状、取付I/Fの明確さ	銛射出時の反動が大きく、今後取り付け方法に軽減策が必要となる。	明確である。	明確である。
把持 開始／完了時 成否判定の容易さ	把持開始判定条件が厳しく、完了後の成否判定が難しい。	把持開始/完了の成否判定が明確である。	把持開始判定条件が明確でない。把持完了後の成否判定は明確である。
既存技術で開発可能かつ開発リスクの少なさ	地上では試験が実施できない。	既存技術で対応可能。	既存技術で対応可能。

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3. Demo Sat. System design

3.3 Capture Mechanism

(2) Capture Mechanism Configuration

PAF is held by a Capture Mechanism.

After Capture of PAF, EDT is extended.

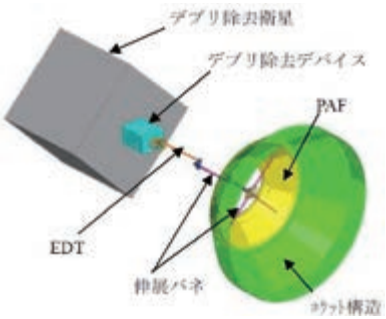

Fig.10 PAF Capture

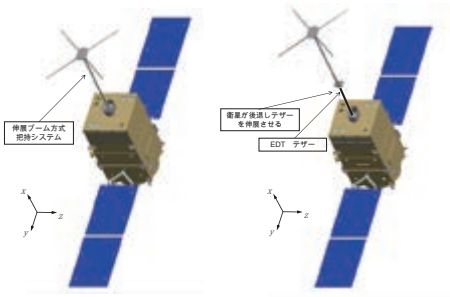

Fig.11 Capture Mechanism Configuration

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3. Demo Sat. System design

3.4 Electro Dynamic Tether (EDT) Configuration

Fig.12にEDT取り付け配置検討結果を示す。

衛星やデブリに対して、余分な回転や振動を与えないために、テザーは衛星重心を通る位置に設置する。また、カメラ画像により伸展状態を確認するため、衛星＋X面に配置する。

EDTシステムは電界放出型電子源 (FEC) から電子を放出する。このFECから放出した電子をテザーで取り込んでしまわないように、衛星の進行方向とはならない、±Y面に配置する。

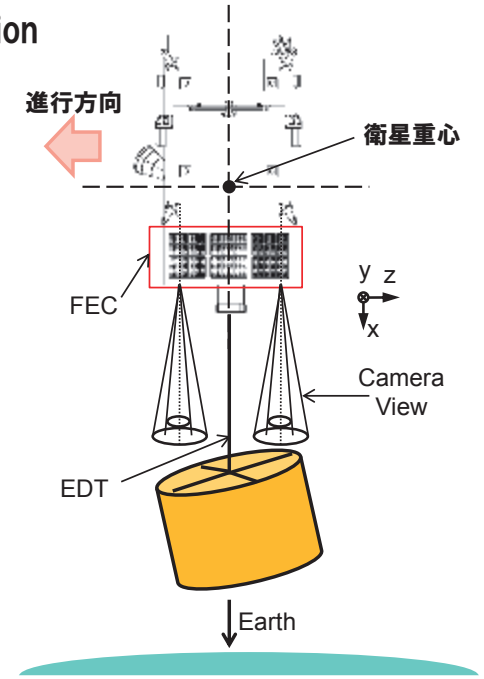

Fig.12 EDT Configuration

3. Demo Sat. System design

3.5 Demo Sat. System Issues and Solutions

(1)【Issue】S-Band ANT View interference

2 SANTs are installed in +X panel and +Z panel.

Fig.13 にS-Band アンテナの視野妨害を示す。

Sバンドアンテナ (SANT) を通して、地上局との通信を行う際に、デブリに接近するほどアンテナ視野が妨害される可能性があることが分かった。

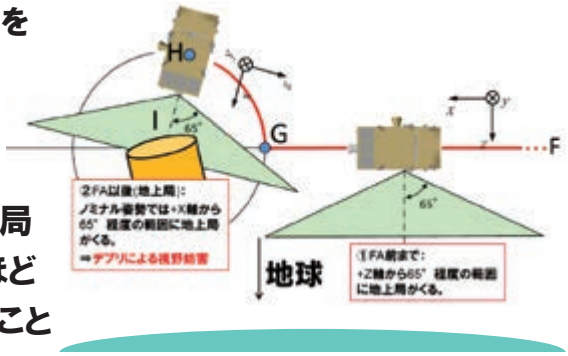

Fig.13 S-Band ANT View interference

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3. Demo Sat. System design

3.5 Demo Sat. System Issues and Solutions

(2)【Solution】

①案:SANT2基の搭載位置，個数を変更せず、また、通信のために中継衛星を使用しない。視野妨害中には自律運用を基本とする。

②案:SANT2基の搭載位置，個数を変更せず、一部運用期間に中継衛星を使用する。(Fig.14)

③案:SANTを4基搭載し、常時中継を使用する。

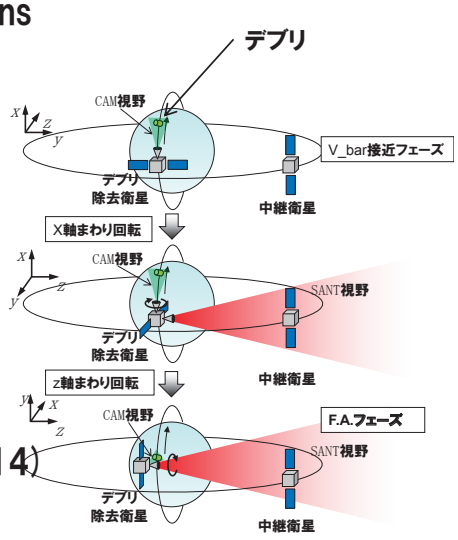

Fig.14 Catch of Relay Satellite

3. Demo Sat. System design

3.5 Demo Sat. System Issues and Solutions

(3)【Solutions trade-off】

コストを低く抑えることができること、非可視中の自律運用は不可能ではないこと(はやぶさの実績を想定)を考慮して、①案を第一候補とする。

①案
SANTを2基搭載し、中継衛星を使用しない。視野妨害中には自律運用を基本とする。

Table 4. Solutions of S-Band ANT View interference trade-off

番号	衛星コンフィギュレーション		中継衛星の利用	可視性	運用	コスト	実証・運用
	SANT配置位置	重量					
①	+X面と+Z面(2つ)	–	なし	・可視機会は限定される。 ・デブリ極近傍まで接近した際、デブリによって遮蔽される可能性有り。	・オンボードによる自律運用が基本。	–	・実用向け ・低コストで実現可。
②	+X面と+Z面(2つ)	–	一部期間であり	・地上局から非可視のとき、一時的に姿勢変更を行い、中継衛星を利用して通信を行う。	・オンボードによる自律運用が基本。 ・運用状態を地上でモニタし、必要に応じてマニュアル運用を行う。	・中継衛星の利用によるコスト増	・実証向け ・確実性を重視
③	各面に3～4つ配置。ほぼ全方向のSANT視野を確保	+5 kg	あり	・地上局から非可視のとき、中継衛星を利用して、継続的な通信を行う。		・アンテナ・トラポン・スイッチ等の追加によるコスト増 ・中継衛星の利用によるコスト増	
				①～③は同等の自律性を持つとする。		①を基準	

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4. Issues for developing ADR Sat.

- Demo Sat.のコンセプトのままでは、高（静止）軌道のデブリを除去対象とできない。
- 軌道傾斜角i<90° or i>90° により、衛星の運用方法，機器配置が変更となるため、汎用的なADR Sat.を用意できない。
- Demo Sat.ではロケット上段PAF部を把持対象としているため、他形状のデブリは把持できない。
- 回転エネルギーを持ったデブリの除去手法が明確でない。
- 複数デブリの除去手法が明確でない。
- 通信遮断時間や遅れを考慮した、自律化，自動化について明確でない。
  （オフノミナル判断および対処も含む。）

7. Concluding remarks

Demo Sat.に向けた検討を進めてきたことにより、対処すべき具体的な課題が挙がり、シナリオの実現性も見えてきた。

しかし、Demo Sat.のデブリ除去手法のみでは、ADR Sat.に向けた様々な環境条件にあるデブリすべてに対応することは難しい。

今後もDemo Sat.に向けた検討を行うが、常にADR Sat.に向けた目をもってデブリ除去衛星のシステム検討を進めて行く必要がある。

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E1

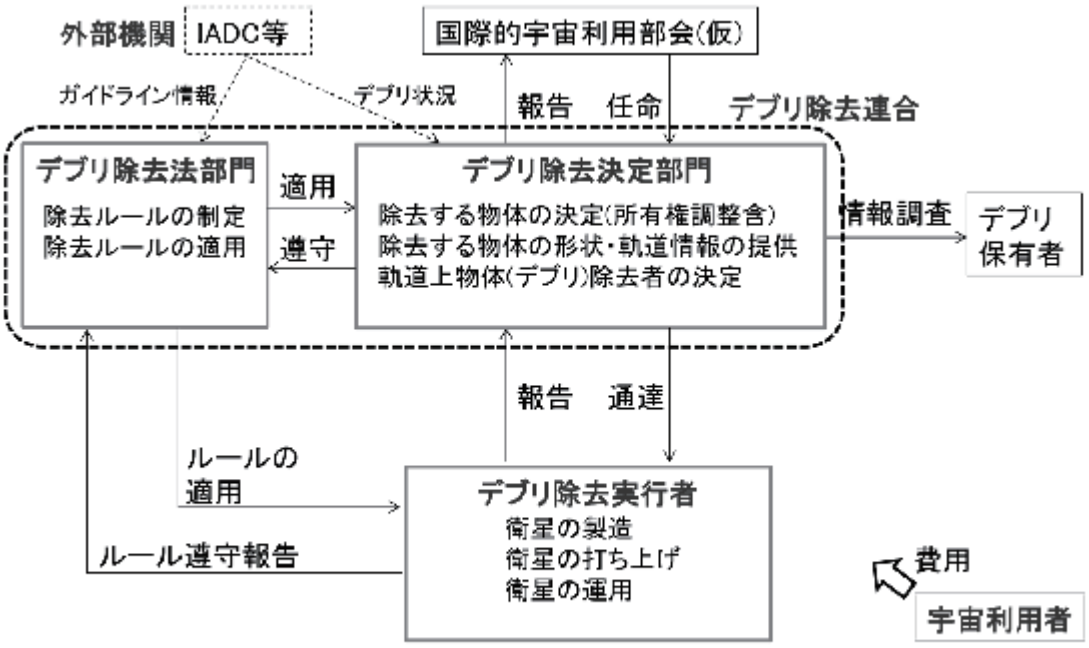
デブリ除去のための国際枠組みの検討

Study of International Framework on space debris removal

○後藤大亮、辻田大輔、河本聡美（宇宙航空研究開発機構）、
大塚聡子、神武直彦、狼嘉彰（慶應義塾大学大学院 SDM 研究科）
○Daisuke Goto, Daisuke Tsujita, Satomi Kawamoto (JAXA),
Akiko Otsuka, Naohiko Kotake, Yoshihiko Ohkami (Graduate School of SDM, Keio University)

近年、各国のデブリ対策、および除去に向けた研究開発へ投入されるリソースは拡大しつつあり，宇宙環境保全のためのデブリ除去は必須であると世界各国が捉え始めている。我々は、人類の共通活動領域である宇宙の環境保全は国際協力の下に実施すべき課題であると捉え，最大の除去効果を定常的に得られるように導くことが可能となるような枠組みを検討した。本検討では，枠組みをシステムとして捉え、システムエンジニアリングの設計手法を活用し，要求分析・機能分析・機能配分・統合を行った。現行の国際的枠組みである温暖化ガスや INTELSAT 等をリファレンスモデルとして，枠組み構築過程，及び，枠組みの運用も考慮した。これらをまとめ、実現性の高いデブリ除去枠組み案を構築した。

Recently, many countries begin to invest much resource for developping the debris removal technologies. This indicates these countries acknowledge it is important to realize clean space environment by removing debris for future space utilization. However, currently, each is only carrying out engineering developments respectively. Since space should be shared by the entire human race, we consider the debris problem as a worldwide problem, not a country's one. Based on the awareness of the issue, we study establishing the international framework for space debris removal.



国際デブリ除去枠組み（組織）案

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デブリ除去のための国際枠組みの検討

Study of International Framework on Space Debris Removal

後藤大亮、辻田大輔、河本聡美(JAXA)
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Akiko Otsuka Naohiko Kohtake Yoshihiko Ohkami Keio Univ. SDM

第6回スペースデブリワークショップ
6th Space Debris Workshop in Japan
2014.12.17～19

1

<注意事項>

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2

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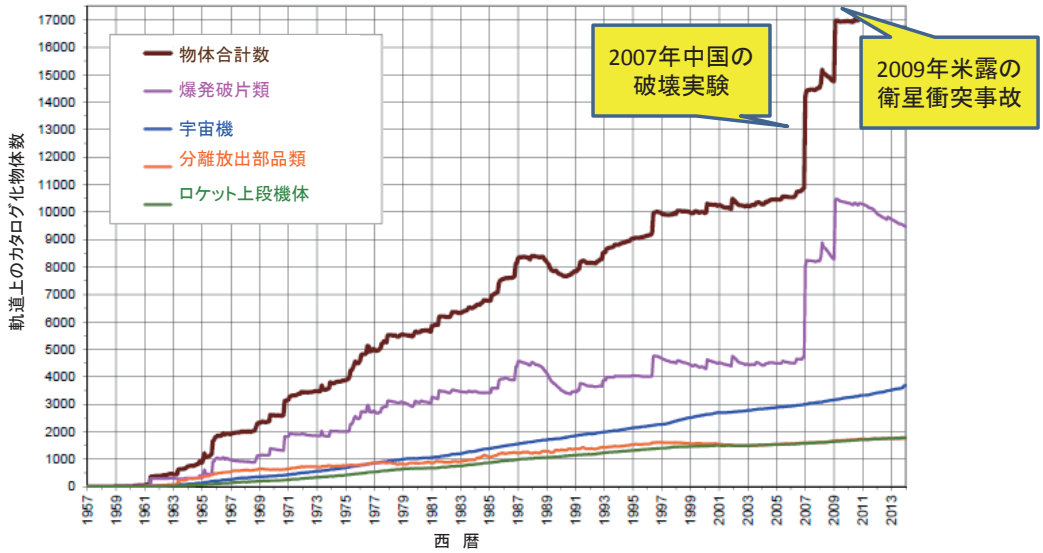
1.導入 Debris number Increasing

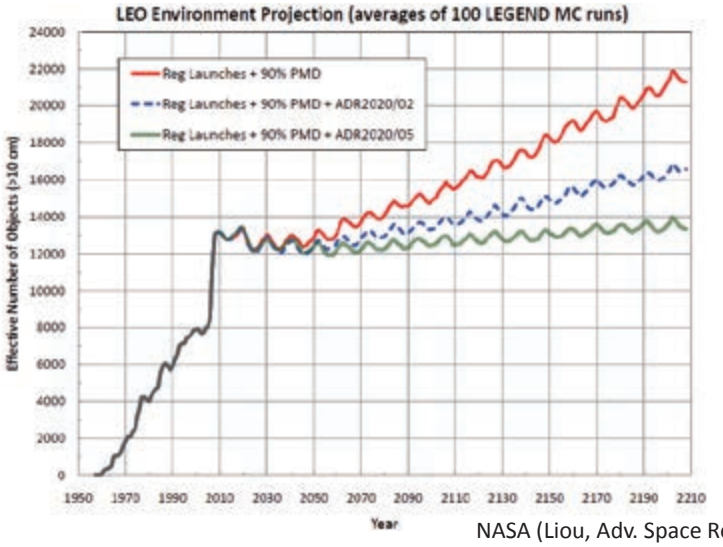


軌道上デブリ数は年々増加の一途を辿っており、IADCによるデブリ除去低減ガイドラインの提示、及び、デブリ除去ガイドライン作成着手、それに呼応して進む各国のデブリ除去研究開発へのリソース投入状況から、デブリ除去による宇宙環境保全は必須と世界各国が捉え始めている。 Ralizing the Sustainable Space Environement

本発表では、現状を踏まえ、**「持続的な宇宙環境保全を実現する」**ことを要求として、システムエンジニアリングのシステム設計に基づく、デブリ除去枠組み構築検討結果を示す[3]

2.1 要求分析 What is necessary for Realizing Sustaibale Space Environment (Debris) ?

環境保全、即ち、軌道上デブリ数の低減の為にできることは、**「デブリを発生させない」**、及び、**「デブリを除去する」**の2点である。この2点を実行した場合の解析結果を示す。



NASA (Liou, Adv. Space Res, 2011)

①デブリ低減ガイドラインを遵守してPMD(Post Mission Disposal)を90%以上の軌道上物体が満足して衛星爆発もゼロの場合、②ADRを年間5機以上、③持続的に実施すれば、軌道上デブリ数増加を防ぐことが出来る。[4]

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2.1 要求分析 Requirements to the framework

①デブリ低減ガイドラインを遵守(PMD 90%以上、爆発防止、等)

Requirement 1: Debris mitigation guideline have to be obeyed. ex. PMD

⇒[分析]

運用終了後の衛星／ロケット等は、宇宙先進国を中心にIADCの制定したデブリ低減ガイドラインに従って軌道遷移を行う傾向が進んでいる。現状、数10%程度の実施率であり、継続して当該ガイドラインの遵守を推奨し続ける必要あり。

②ADRを年間5機以上

Requirement 2: More than 5 debris to be removed per year.

⇒[分析]

ADRは各国が個々にデブリ除去技術開発を進めているが、その達成目標数値は各国別であり、共有されていない。また、宇宙は人類の活動領域であり、その環境保全の実施は、世界各国協調の下で実施することが望ましい。

③持続的

Requirement 3 : Sustainable ADR activities by every major space actors.

⇒[分析]

各国独自で実施している限り、各国の経済状況等によって、除去が実施されない事態が起こりえる。除去活動を各国が補間し合えるようにする為にも世界各国が協調して活動できる枠組みがあることが望ましい。

【分析まとめ】

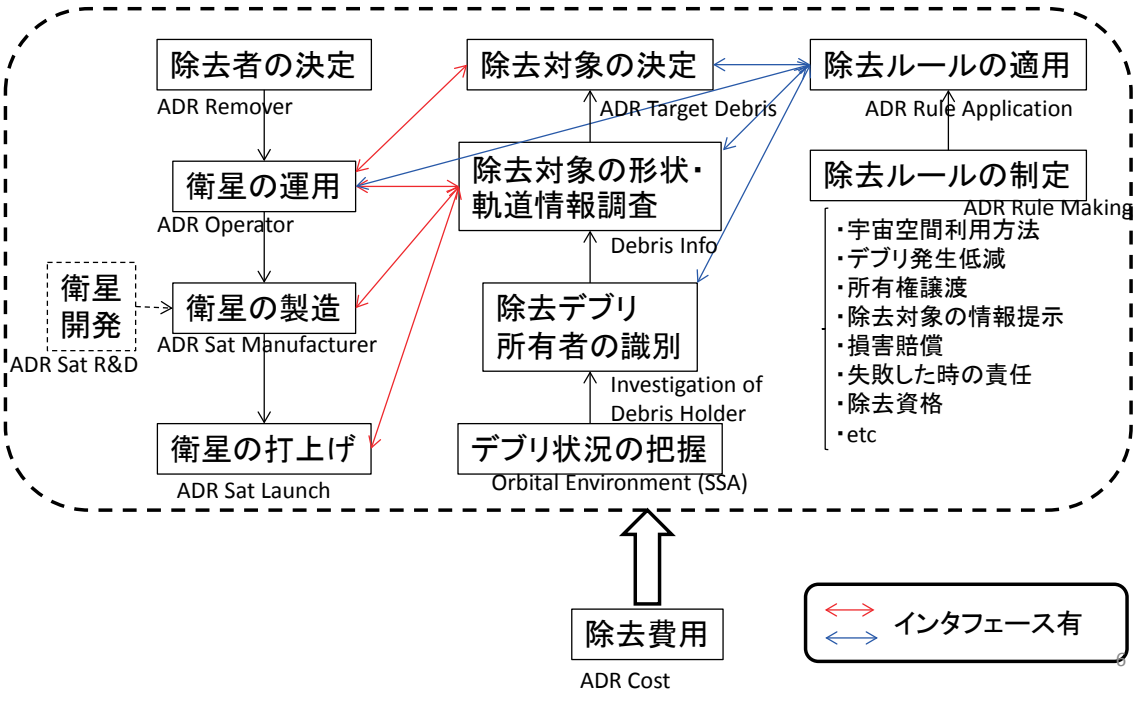
軌道上デブリ除去を推進する世界的な枠組みの構築が必要。本枠組みは、世界各国のリソース状況に応じて、相互協力の下、最大の除去効果を定常的に得られるように導くものである。

International Framework is inevitable for sustaibale ADR.

5

2.2 要求機能分析 Analysis of Requirement and function distribution

デブリ除去を行う上で必要なプロセスに基づき、枠組みへの要求機能を分析。



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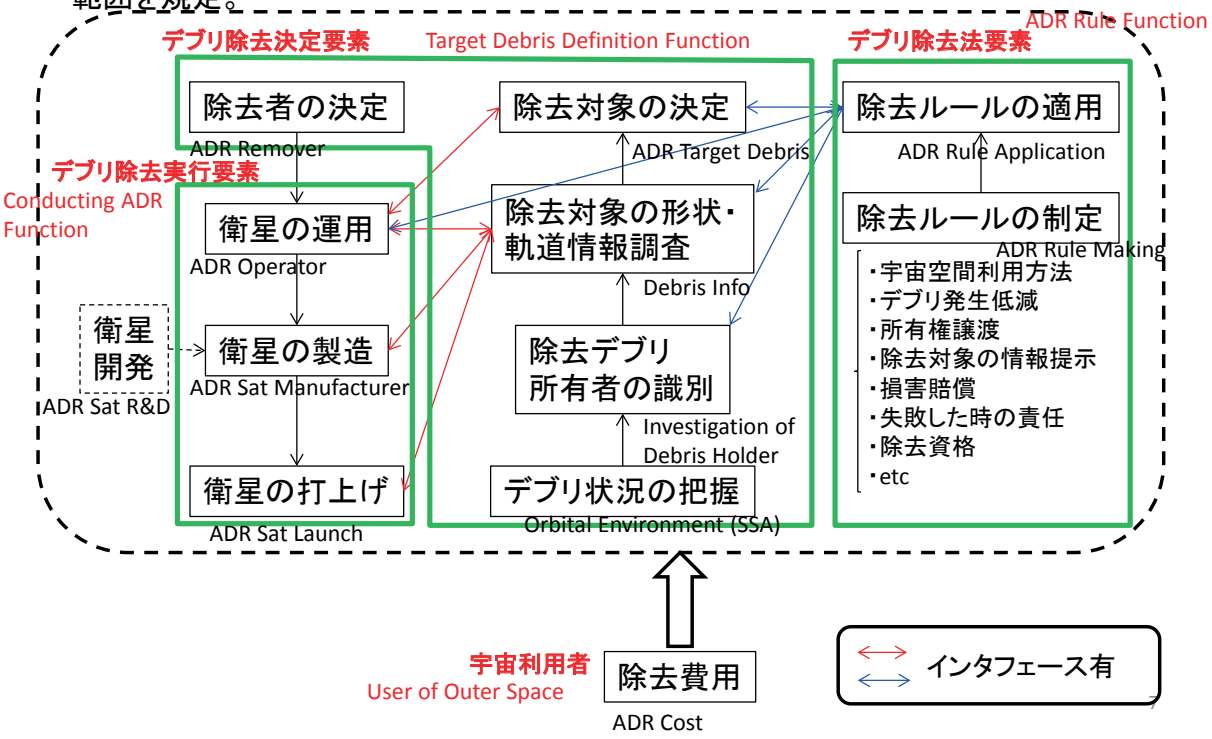
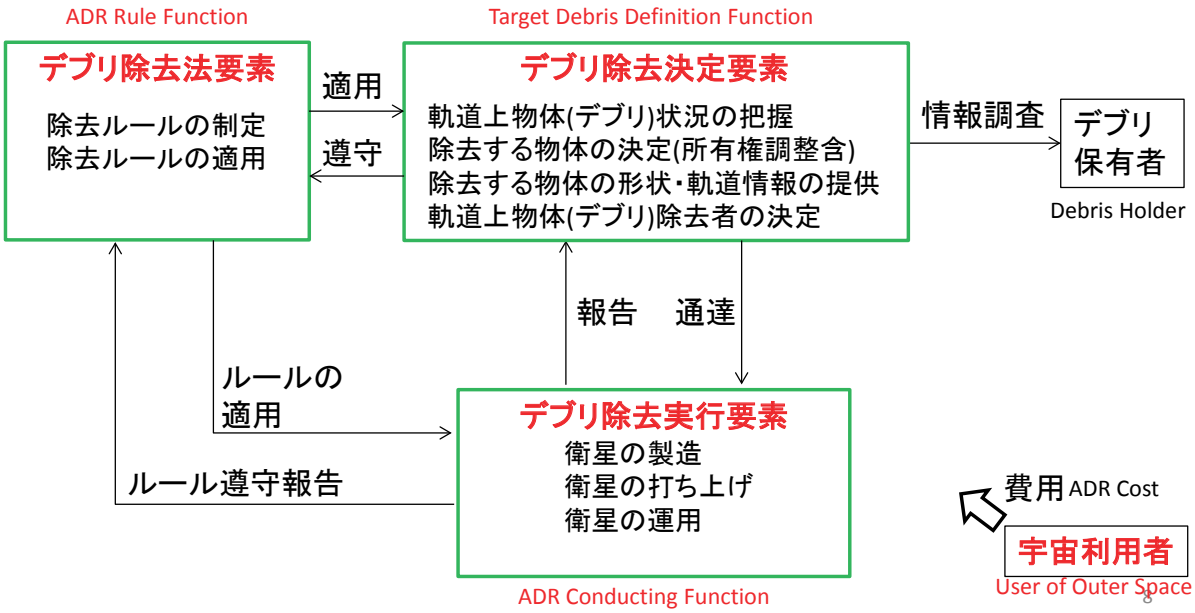
2.3 要求機能配分 Results of function distribution

インタフェース数が最小になり、実行要素と法要素は独立となるように機能配分の範囲を規定。



2.4 統合 Unity of function distribution

デブリ除去機能分析・配分検討結果から、世界的なデブリ除去枠組みの骨格として、以下の統合結果を得た。



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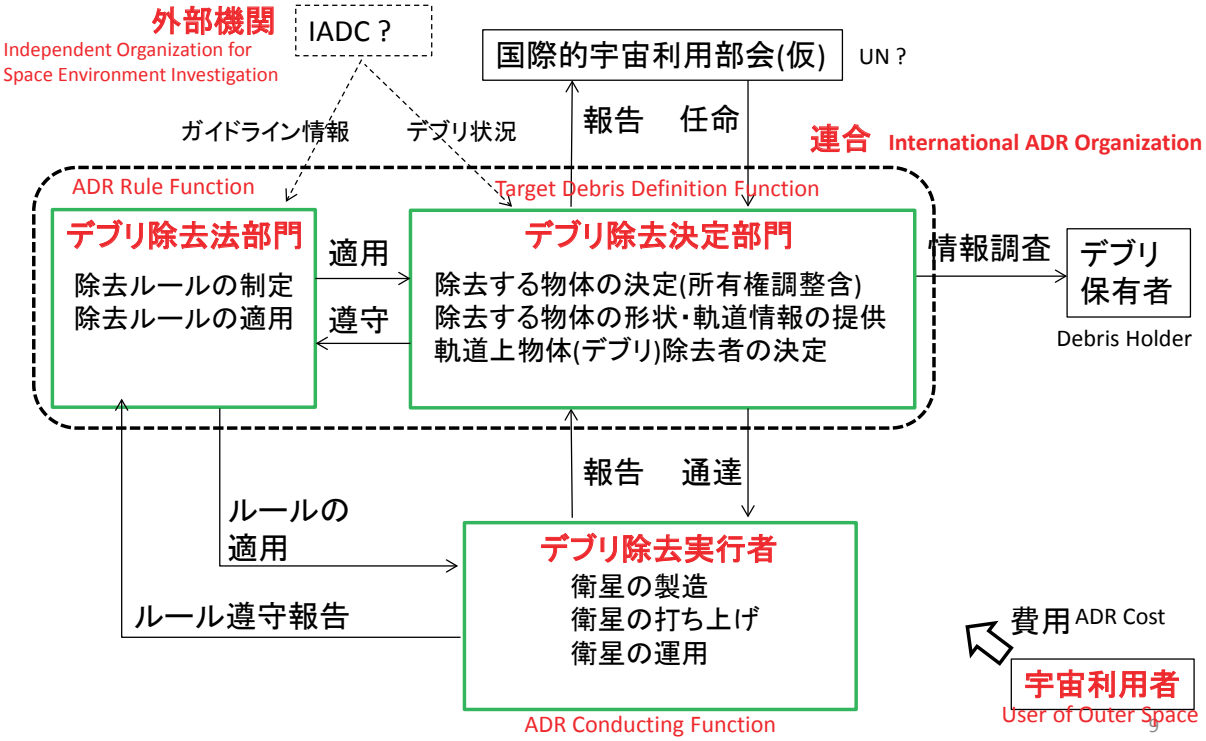
2.5 統合結果の現実解 An example of function distribution

要求分析に基づく、要求機能分析／配分／統合検討したデブリ除去国際的枠組みの構成。



2.5 統合結果の現実解(補足1) Notes 1

統合で得られた骨格をベースに、リファレンスモデルとして温暖化ガス、INTELSAT、家庭ごみ等の仕組みやその構築過程を参照しつつ、現実運用シナリオを検討した。以下に、主要なポイントについて列記する。

①枠組みの構成

除去技術・除去対象デブリは軍事技術等の各国の機微に関わる内容になり得る為，新規に国際機関を立ち上げることは各国間の利害衝突が発生する可能性が高い。従って，現行の組織である，世界各国が参加していて，且つ，各国間の問題調整能力を有している**国連の傘下に，「デブリ除去決定部門(=要素)」と「デブリ除去法部門(=要素)」を持つ「デブリ除去連合」機関を設立する。**

It is considered to be better that an International ADR Organization will be constructed under UN.

②外部機関の利用

枠組み構築の観点からは、デブリ観測による状況把握は重要な機能であるが、既に宇宙状況監視(SSA)活動は国際協力調整フェーズに入っており、SSAまで含めた枠組みにすることは複雑化を招き、枠組み実現そのものが難しくなる可能性があると評価した。連合としては、除去対象デブリ選定における**透明性**を確保する為に、現行の科学者主体の調整会議である**IADCの提供するデブリ状況情報に基づいて活動する**ものとする。

SSA Activity is not contained in this framework. IADC is independent from an ADR organization and report the orbital environemt information,

③低減活動

IADCの制定するデブリ低減ガイドラインを、連合の除去ルールの一部として制定して、連合参加国の遵守を直接的に促す。現行ガイドラインを適用することで、参加国の遵守に対するハードルは低いと評価。

Debris mitigation guideline is unitied with the ADR rules.

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2.5 統合結果の現実解(補足2) Notes 1

④資金調達 (ADR Cost)

・民需ベースの可能性評価

(Is it possible to construct complete private cost bearing ? – Probably No.)

低コストデブリ除去技術の発展には，民間ベースでの競争が有効であるが，完全民需ベースの枠組みでデブリ除去費用を捻出することは現状困難と評価。

<理由> 例えば，現行の仕組みである軌道上衛星に対する保険に対して，デブリ損害保険の加入を義務付けて，その保険料をデブリ除去費用に割り当てることが考えられる。しかし，現時点では，軌道上衛星のデブリ衝突に伴う損害発生の事例が少ない為，デブリ損害保険設定額は廉価にならざるを得なく，デブリ除去費用の原資になり得ない。同様に，打上げ費用にデブリ除去費用分をかさ上げする等のいくつかの手段があり得るが，いずれも適切に費用設定することは困難と考える。

(It might be necessary that the ADR Demand is provided by each country's governments.)

以上から、国を主体とし，国がデブリ除去の需要を作り出すことで，民間ベースでの競争を促進する枠組みが有効であると評価する。この観点から，**デブリ除去実施者は各国政府レベルとする。**但し，政府が委託した機関や民間企業も可とする。これにより，デブリ除去技術が軍事技術に極めて近いことにまつわる問題である，各国による国内産業育成・保護のための除去技術の国外流出や公開の歯止め等に関して，連合は何ら関与せずに実効的なデブリ除去を推進することが可能となる。

・デブリ除去資金の調達方法

(The two cases of ADR cost payment, Case 1: Payed by the organization, Case 2 : Payed by the each governments)

「ケース1：連合が参加国から資金収集して，除去指示した国へ必要資金を供与」と「ケース2：除去指示された国の自国負担」の2ケースを比較評価。

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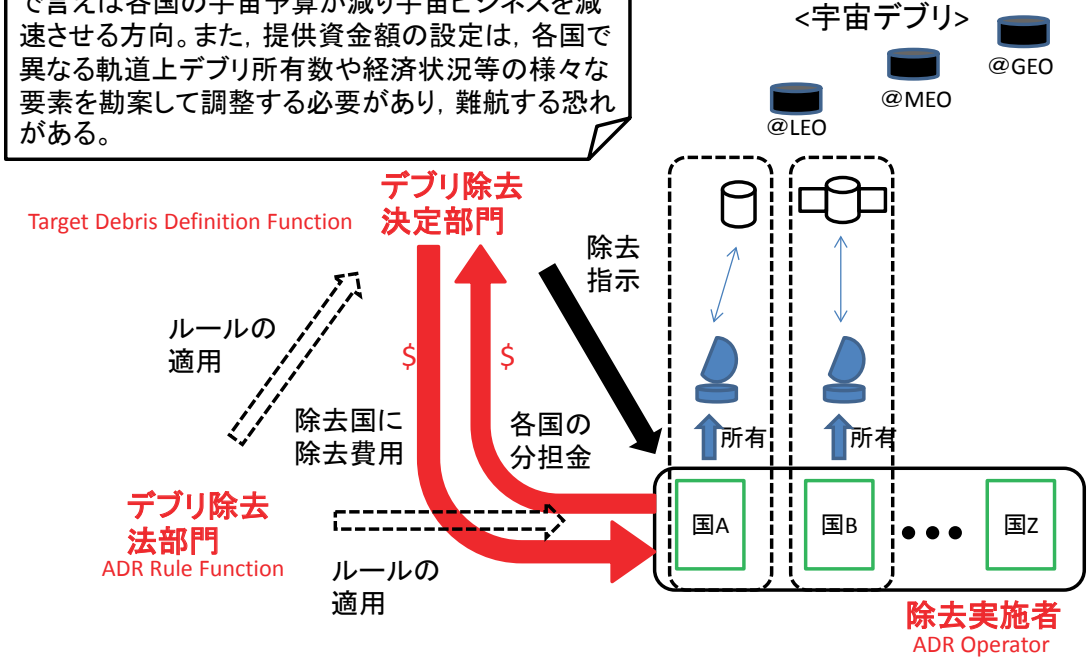
2.6 資金調達方式 ADR Cost Payment Case:1

<ケース1:資金集中型> Payed by the organization

評価：× (Negative)
各国に資金提供を強制的に求める為，予算面のみで言えば各国の宇宙予算が減り宇宙ビジネスを減速させる方向。また，提供資金額の設定は，各国で異なる軌道上デブリ所有数や経済状況等の様々な要素を勘案して調整する必要があり，難航する恐れがある。

<宇宙空間>
平和的無差別利用対象



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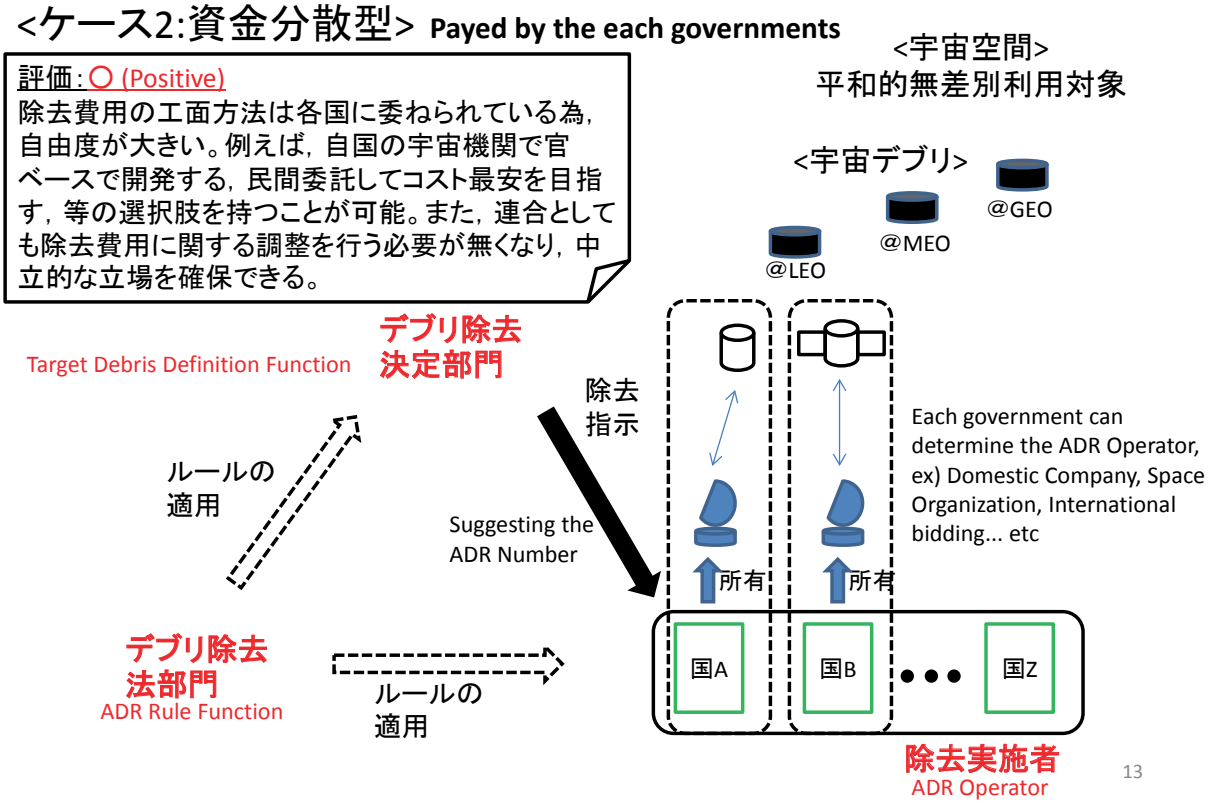
2.6 資金調達方式 ADR Cost Payment Case:2



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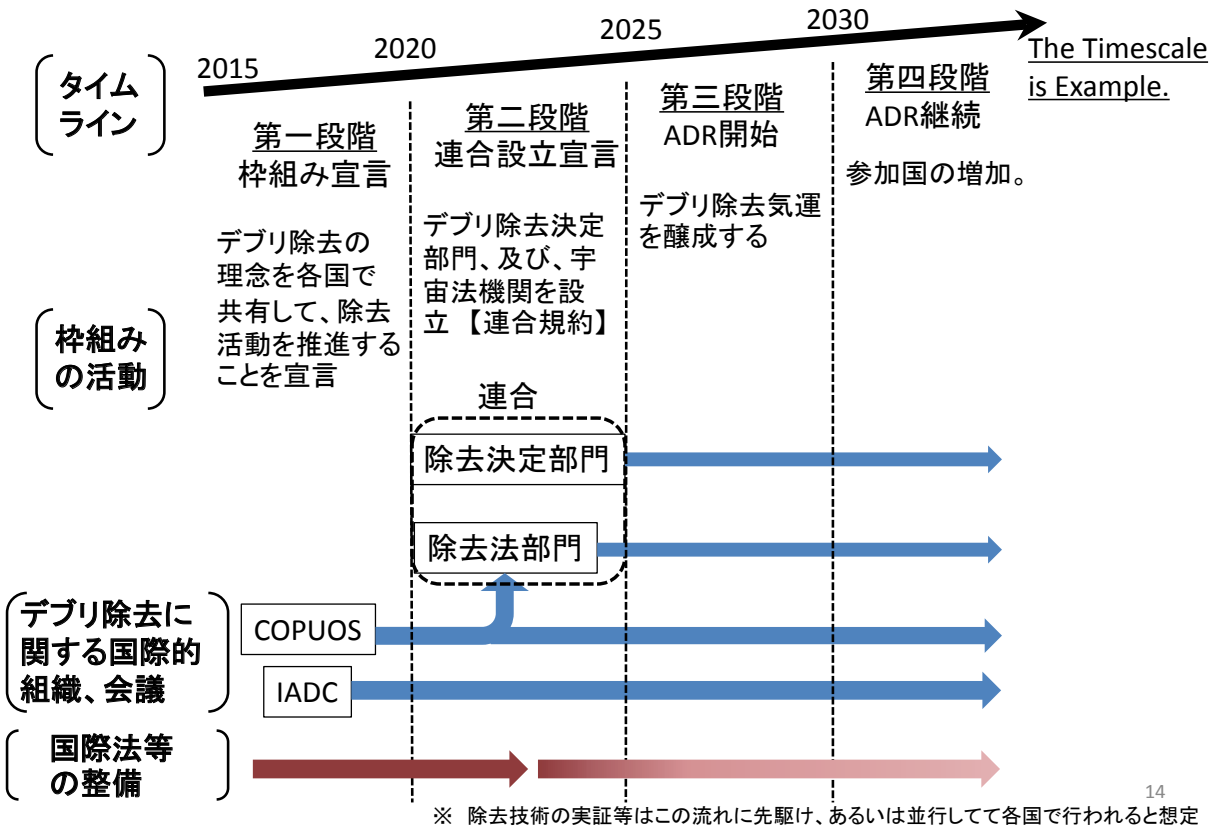
3. 段階的枠組み構築の考え方 Phased Approach of Framework Construction



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※ 除去技術の実証等はこの流れに先駆け、あるいは並行してて各国で行われると想定

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4 デブリ除去連合の責任範囲 Responsibility of International ADR Organization

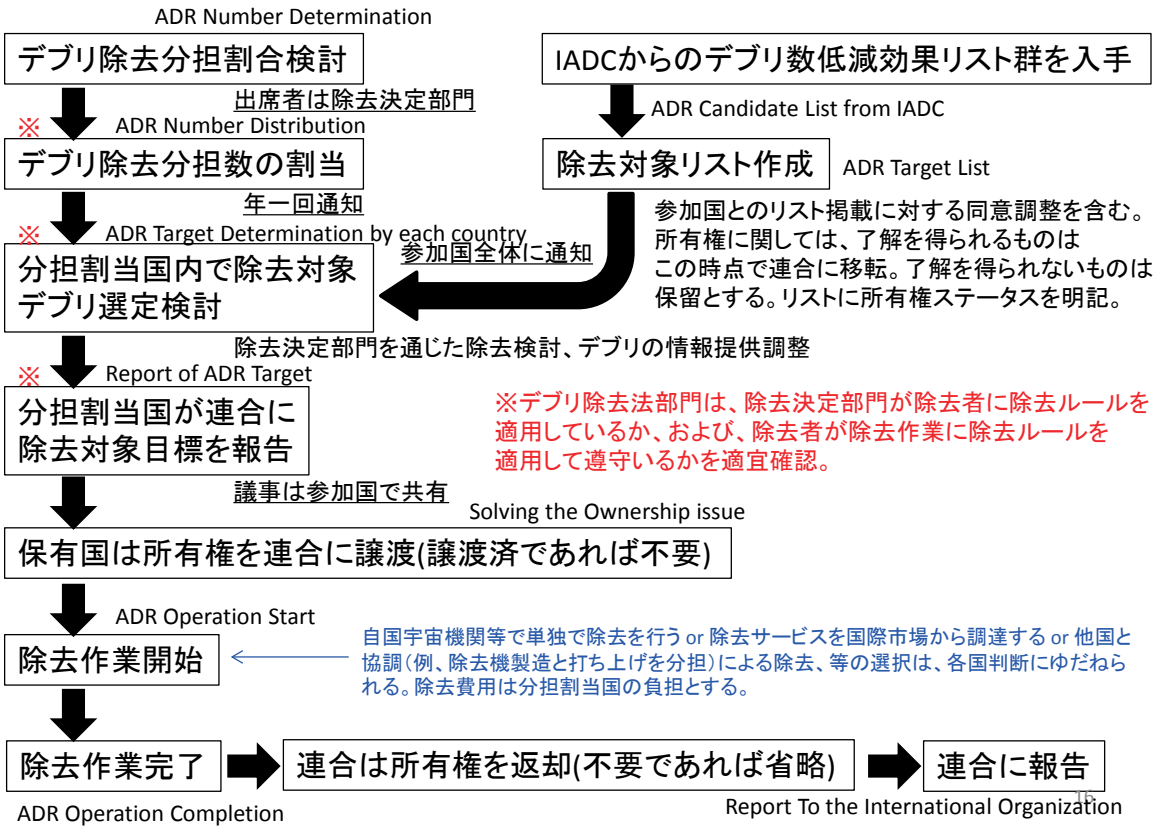
デブリ除去作業に伴う避けられない問題として，除去作業の失敗リスク，除去デブリの衛星衝突や地上落下等の潜在的リスク，除去対象デブリの所有権問題がある。各国個別に負うリスクとしては無視しがたく，また，所有権に関しては，一国では解決が困難なケースもあり，自国の所有デブリを除去するという選択肢に陥りがちになる恐れがある。そこで，世界機関である連合は，以下を規則とする。

(1) 除去責任 (Responsibility to the Space Environment)
「持続的なデブリ除去活動を行い，宇宙環境保全を確保する。」
本規則により，参加国は連合の下，除去責任を負う，即ち，各国で除去責任を分担することになる。

(2)除去作業責任 (Resoponsibility to the ADR failure)
「除去対象デブリの除去作業に関して，失敗も含めて，デブリ除去連合がその全ての責任を負う。責任履行は国際宇宙法の規定に従う。」
本規則により，連合がデブリ除去作業の責任を全て負うことで，除去作業に伴うリスクを各国で分散できる

(3)所有権 (Ownership)
「連合の参加国は，除去に同意したデブリが除去対象に識別された場合は，その所有権を連合に無償譲渡しなければならない。所有権の譲渡に伴い，管轄権は連合に移転する。」
所有権保有者にとっては，譲渡すれば，当該デブリに関する責任は，連合に一切移管することが出来る。

5. 連合によるデブリ除去プロセス Overall Process of ADR



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6. コンプライアンスマトリクス

連合のデブリ除去要求に対するコンプライアンスマトリクスを示す。

No	要求	設計結果	評価
1	PMDを90%以上の軌道上物体が満足すること	左記要求を記載しているデブリ低減ガイドラインを、デブリ除去法部門にて、連合内の除去ルールとして制定することで、参加国の遵守を実現できる。 尚、枠組み構築の第一段階の「枠組み宣言」に、参加国はデブリ低減ガイドラインの遵守しなければならない、旨を明記することで、早期実現を目指す。	○
2	ADRを年間5機以上	・各国への除去分担割合を定める機能を除去決定部門が有することで、ADR5の設定を可能とする。 ・設定を実現する為には、宇宙先進国の連合への参加が必須である為、除去責任を連合が負うことで各国で責任分散ができる、特に既存デブリ保有者の宇宙先進国に有利な仕組みとした。	○
3	持続性	・デブリ除去責任を連合が負う仕組みにすることで、連合に各国が参加し続ける意義を設けた。 ・除去決定部門は除去指示をするだけで、除去方法等は各国に委ねることで、自由度を大きくして、受け入れやすい仕組みとした。 ・除去決定部門が除去指示に関して一括取り纏めすることで、各国の除去実施状況に応じて、適切に配分を決定し、除去負荷を分散可能にした。これにより、除去指示に対応が困難な状況に陥った国の脱退を防止する。	○

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枠組み検討にあたり重視したポイント

- 各国が参加する意義を見出せる枠組み作り

⇨ （例1）連合がデブリ除去に関する全責任を負うことで、除去リスクの分散を可能とする。
（例2）連合に軌道上物体所有権を譲渡した時点から、連合が当該物体の責任を負う。

- リファレンスとなる他分野の枠組を参考

⇨ （例1）IADCをデブリ除去決定部門から敢えてはずした立ち位置とする。
※気候変動問題のIPCCと同様の考え方
（例2）枠組み宣言→連合設立という段階的設立方式
※気候変動問題のCOPから京都議定書へとつながる流れ。 等

- 他分野の枠組の教訓を反映

⇨ （例）各国政府／議会の反発を防ぐため、デブリ除去手段の選択について、中央集権的なやり方は避け、各国の努力にある程度委ねる枠組みとする。（リファレンスモデルである温暖化ガスにおいて、米国が京都議定書を批准しなかったことにより、COPでのCO_2削減量が実効的意味をなさなかったことの教訓）

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まとめ

- 宇宙の環境問題（デブリ問題）のため、継続的なデブリ除去活動は必須でああある。そのためには，幅広い分野の技術的情報をベースとして，技術外の分野（社会，経済，国際関係等）を見据える必要がある。
  In order to realize sustainable space environment (Debris Issue), the technical information as well as non-technical approach (social, economical and international affiars) is inevitable.
- システムエンジニアリングによってデブリ除去の国際的枠組みの検討を行い、現存する世界の機関，仕組みを最大限活用して，近未来のあり得べき現実的な解に落とし込む作業を行った結果を示した。
  With the systems-engineering-process, the idea of an international framework for ADR is studied.
- 本枠組み検討結果を現実のものとするべく，関係者一同検討を深めていく所存である。
  Further discussions, investigations and activities are necessary for realizing the ADR framework.

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E2

宇宙法研究所におけるデブリ研究会検討状況の報告

Status report of Debris Study Group in the Institute of Space Law

青木節子（慶應義塾大学），小塚荘一郎(学習院大学),
内冨素子，岸人弘幸，○川島興介（JAXA）
Setsuko Aoki (Keio Univ.), Kozuka Souichirou (Gakushuin Univ.),
Motoko Uchitomi, Kishindo Hiroyuki, ○Kosuke Kawashima(JAXA)

民間主導による宇宙活動が活発化する時代が間近に迫ってきている一方、安定的な宇宙活動を行う上でスペースデブリが大きな問題となっており、国際的な議論が行われている。今後はデブリ発生の低減だけでなく除去の必要性が叫ばれるようになっていることを踏まえ、日本においても慶應宇宙法研究所と JAXA 法務・コンプライアンス課が行っている共同研究の一環であるデブリ研究会において、デブリ除去に関する法的研究が開始されている。本研究会ではスペースデブリ除去の事業化を題材に、まずデブリの国際法上の位置付けについて検討を始め、その後事業化を安定的に継続して行う上で障壁となる課題を洗い出し、その課題を解決するためにどのような制度を創設する必要があるかについて、国際環境法の視点も踏まえながら検討を行っている。今回は本研究会の検討状況について紹介する。

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Status report of Debri Study Group in the Institute of Space Law

Kosuke Kawashima
Legal and Compliance Division General Affairs Department, JAXA

Proceedings of the 6th Space Debris Workshop 18th December 2014

Contents

1. Cooperation between Keio universities and JAXA
2. Activities of joint research project on active debris remediation
3. Conclusion

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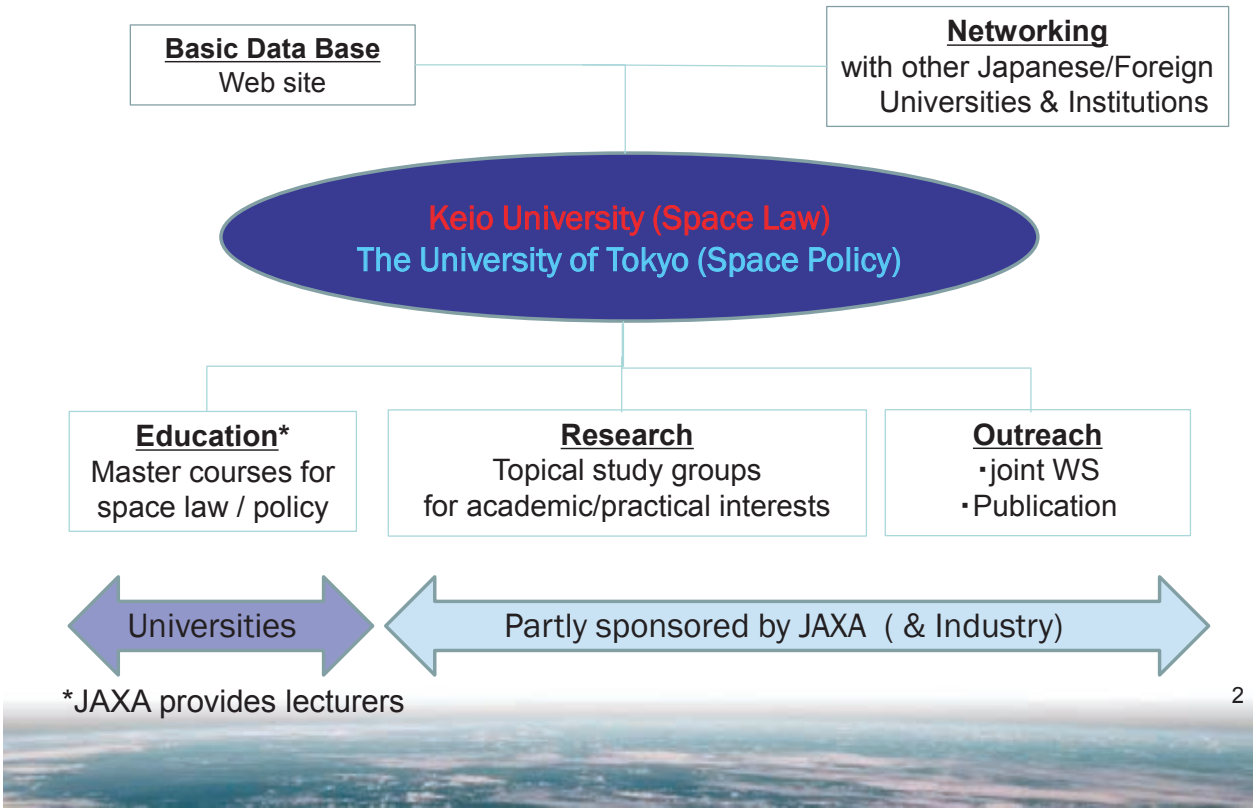
Basic framework of capacity-building through cooperation between 2 leading universities and JAXA



2

Space Law Research in Keio Advanced Research Center for Space Law

"Institute of Space law" established in Jan. 2012

Consideration for the space activities from legal viewpoint

Capacity building in Japan's space law research

Nurturing practitioners and researchers

Capacity building in Asian countries

3

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Joint Research Programs

The 2013-2014 programs:

(1) Space commercialization: possibilities and challenges
(2) Legal Issues relating to Global Navigation Satellite Systems (GNSS)
(3) Space law database (provided in Japanese)
(4) Aerospace governmental procurement programs and the WTO
(5) Space debris removal: Legal Issues
(6) Suborbital Flights

4

The International Regime for Space Debris Remediation in Light of Commercialized Space Activities

Souichirou Kozuka
(Gakushuin University)

Read by Kosuke Kawashima
(JAXA)

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Disclaimer

- The views expressed in this presentation are the authors' personal views and do not reflect the positions of any organization that the authors are or may be affiliated.
- The research was conducted by the Space Law Center of Keio University.
- The original paper was co-authored with Ms. Motoko Uchitomi and Mr. Hiroyuki Kishindo (both JAXA)

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The Environmental problem in Space

- More than 16,000 pieces of space debris are catalogued.
- Space debris is becoming a threat to safe and open space activities.
- Proposal of active debris remediation has been made.
- Technology for debris remediation is being developed.

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Elements to be considered.

- International regime is yet to be established ("tragedy of commons").
- To establish a workable regime:
  - The private law aspects of debris needs be dealt with.
  - The international environmental law must be the basis for the regime.
  - The possibility of conducting remediation as commercial service has to be considered.

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Private law aspect: ownership

- Comparison with the removal of wreck on the sea (Nairobi Convention of IMO).
  - Duty of the registered owner to remove the wreck
  - Or, the government removes the wreck and the owner pays for the cost.
- Consent of the owner of the debris is necessary.
- Government's authority to remove the debris and collect the cost: to be dealt with in national space legislation.

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Approval of the state

- Difference from the wrecks on the sea: approval of the state having jurisdiction over the debris is needed.
  - Responsibility of the state over the space activities
- Which state?
  - State of registry, if the debris is registered or derived from a registered space object.
  - State of the owner of debris in other cases – general international law

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Incentives of for removing the debris

- Little benefit in recovering the debris (as opposed to the salvage on the sea)
- Commercial benefit may be found in securing the safe use of orbit.
  - Benefit of other operators, rather than the benefit of the owner/operator of the debris
- If the debris removal becomes feasible, the responsibility of the state not to leave dangerous debris can be affirmed (preventive principle).

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Liability for damage caused by debris?

- It will not be easy to establish liability even where the debris collides into another space object:
  - Because proving the fault is difficult, as the result may not be foreseeable in many cases.
- Product liability of manufacturer of the debris is more likely to arise, because “defect” does not require foreseeability of the occurrence of damages.

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National legislation to address the debris issue

- If a state can be responsible for leaving the space debris on orbit but the owner/operator cannot be held liable in many cases, what can a state do? – National space legislation.
  - Requirement to arrange for active remediation once the space object becomes debris.
  - Strict liability for damages caused by the debris. (polluter pays principle)

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How to share the cost?

- Who pays? – “polluter pays” or the beneficiary pays?
  - It does not affect the efficiency of the regime (Coase theorem)
- However, the sharing of cost will determine the attractiveness of the regime.
- International fund based on contributions from both the polluter and beneficiary.

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Proposal for a contribution scheme

- Practical solution: combined approach.
- Beneficiary makes contribution and records “Request for remediation.”
- “Polluter” also makes contribution and makes a record in “list of remediation subject.”
  - Polluter gets release from any possible liability by making a contribution.
- Matching of “Request” and “List” is made (“Marketplace”).

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Conclusion

- Active debris remediation is necessary for securing safe and open access to the space.
- International regime for debris remediation must:
- Reflect the reality of commercialized space activities – private law aspect must be deal with.
- International environment law needs to be considered.
- The regime to enable remediation as the commercial service must be established.

Thank you very much for your kind attention.

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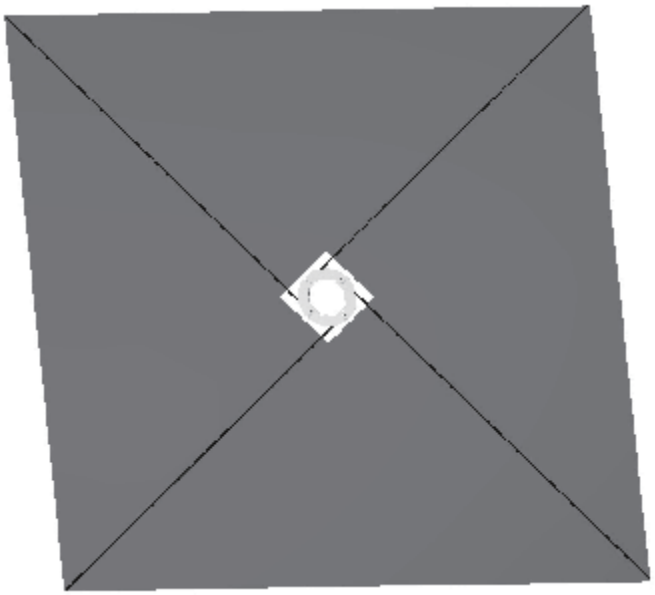
E3

デオービット用膜面展開機構の開発

Development of Membran Deployment mechanism for Deorbiting

○高井 元(宇宙航空研究開発機構), 古谷 寛, 坂本 啓(東京工業大学),
奥泉 信克, 宮崎 英治, 井上 浩一(宇宙航空研究開発機構)
○Moto Takai(JAXA), Hiroshi Furuya, Hiraku Sakamoto(Tokyo Institute of Technology),
Nobukatsu Okuizumi, Eiji Miyazaki, Koichi Inoue(JAXA)

近年、世界的に 50〜100kg もしくはそれ以下のサイズの超小型衛星の開発が積極的に進められており, 短期開発及び低コストであることから今後とも数が増加していくことが予想される. 一方で大多数の超小型衛星は非常にリソースが小さいことから推進系を持ち合わせておらず、軌道高度によってはスペースデブリと化してしまう恐れがある。軌道上離脱手段としては、アクチュエータを動作するだけの手軽さから膜面展開による大気抵抗を用いた手段が有力視されている。本発表では JAXA が開発している軌道上離脱用膜面展開機構のコンセプトと開発状況について紹介する。



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Development of Membrane Deployment Mechanism for De-orbiting

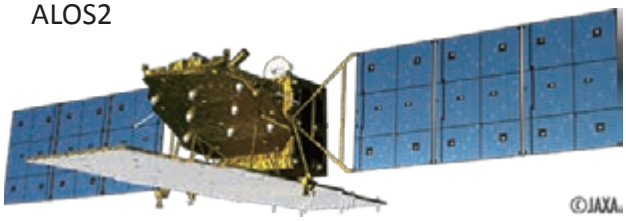
Moto Takai[1], Hiroshi Furuya[2], Hiraku Sakamoto[2],
Nobukatsu Okuizumi[1],Eiji Miyazaki[1],Koichi Inoue[1]
[1]JAXA, [2]Tokyo Institute of Technology

Small Satellite

Development of small-sat is growing in the world

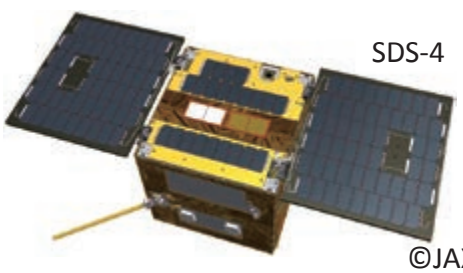
- Small Satellite
  - Low cost(hundreds of million yen)
    - piggy-back payload(low launch cost)
  - Light weight(1～100kg)
  - Small(10～100cm order)
  - Short life(2～3 years)

ALOS2



- Large Satellite
  - High cost(multibillion yen)
    - Main Satellite(High launch cost)
  - Heavy weight(several tons)
  - Large scale(1～10m order)
  - Long life(5～10 years)

SDS-4



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Rapildy increasing of small-sat by satellite constellation

- Planet labs:3U CubeSat constellation consists of 131 sat
  - creates a daily photo mosaic of most of Earth
- Skybox Imaging:100kg class sat constellation consists of 24 sat
  - offers customers timely access to high-resolution satellite imagery, video and data
- Axel Space:80kg class Remote sensing constellation consists of 60 sat
  - provides low-cost and high readiness Remote-sensing images

25 Year Rule

- IADC Space debris Mitigation Guidelines require that spacecraft or orbital stages passing through LEO region should be maneuvered to reduce their orbital lifetime 25 years or relocated if they cause interference with highly utilized orbit regions.
- JAXA Space Debris Mitigation Standard also requires that space systems after mission should be reduced the orbital lifetime within 25years or sent as far away from the useful orbital region as possible.

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De-orbiting of Small Satellites

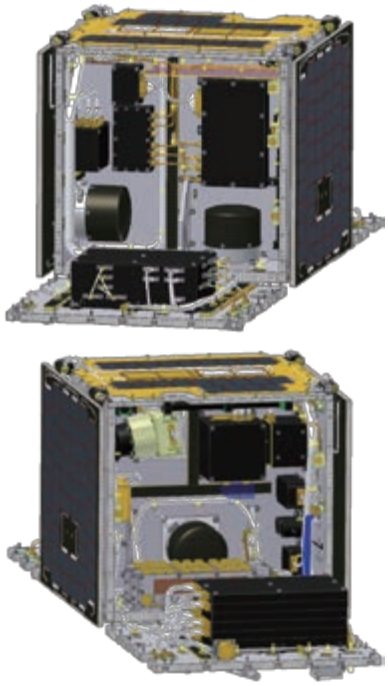
- Small Size and Light Weight
  - constraint of Size,Mass and Power.

  →no resource to mount extra components.

- Piggy-back launch
  - strict constraint not to have impact on main satellite

  →difficult to mount propulsion system

We must design the component that don't effect satellite system as possible.



Component Configuration of SDS-4

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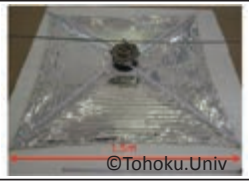
Deorbiting Device Options

	Electric Propulsion Systems	Chemical Propulsion Systems	Atmospheric Drag-based Devices	Electrodynamic Tether
Active / Passive	Active	Active	Passive	Passive
Method	The acceleration of charged ions	The combustion and the expansion of chemical propellants	The exploitation of the natural atmospheric drag effect	The electrodynamic interaction of the tether rapidly moving within Earth's magnetic field
Consideration	・Requires high total impulse	・Requires high total impulse	・Altitude-limited ・susceptible to MMOD degradation	・Large characteristic dimension ・Deployment complexity
Picture				

※The 4S Symposium 2012 – P. Pergola, A. Ruggiero, C. Finocchietti, M.Andrenucci .

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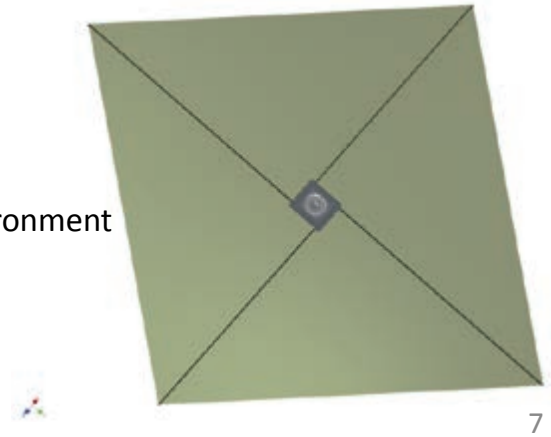
Membrane Deployment Mechanism

- Method
  - chaneges orbit due to atomosperic drag by using membrane
- Advantage
  - No Active Control (attitude, power)
  - No Pressurized Gas
  - Using only their own stored mechanical Energy
  - Simple mechanism
- Disadvantage
  - Only low altitude
  - susceptible to MMOD
  - Long duration against for space environment



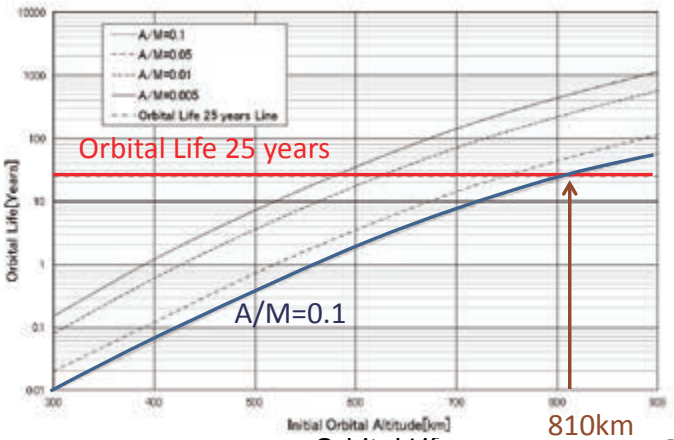
7

Orbit Life Calculation

- A/M=0.1:De-orbiting within 25 years from altitude 810km

$$A = \frac{100(Mass) \times 4(Tumbling)}{2} \div 0.1 = 20m^2$$

- Need 20m^2 as a membrane area.
  - Boom length 3m
  - membrane width 4.5m



Orbital Life

8

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Requirement Specifications

- De-orbiting Capability
  - 100kg class microsat deorbits within 25 years from altitude 810km

  →mounted 3m deployment boom and attached membrane.
- Size
  - 50kg microsat envelope

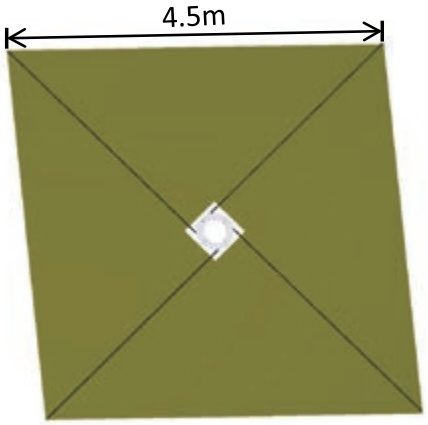
  →mounted in “dead space” to minimize impact for satellite system
- Design
  - Low cost and compatible to JAXA Safety Requirement
  - guarantee environmental resistant(Radiation,Ultoraviolet and Atomic oxygen) in misson and deorbiting term.

  →use AO-resistant Polyimide “BSF-30” and qualify mechanical property after exposing to Ultraviolet and Radiation

Membrane Deployment Mechanism Concepts

- Small satellite makers and Universities are able to conduct satellite development without regard for 25 years Rule.
  - Design the component that don’t effect satellite system as possible.
    - Use “dead space”
    - “Thin” deployment mechanism by the wrapping stowage of the booms and the membrane together on the same hub.
    - Adjust mechanical interface to PAF239M.

stowed configuration



deployment configuration

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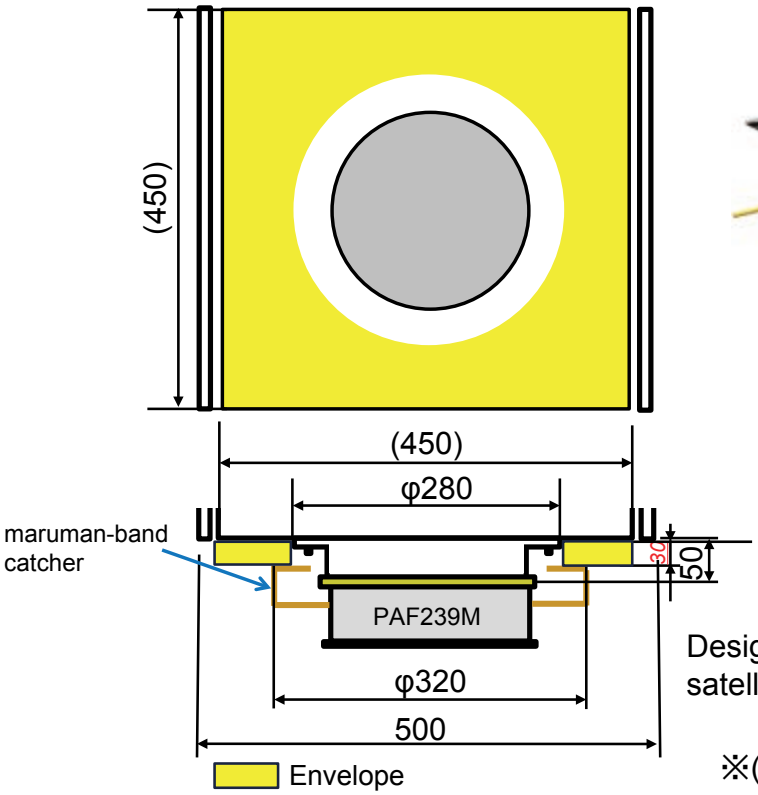
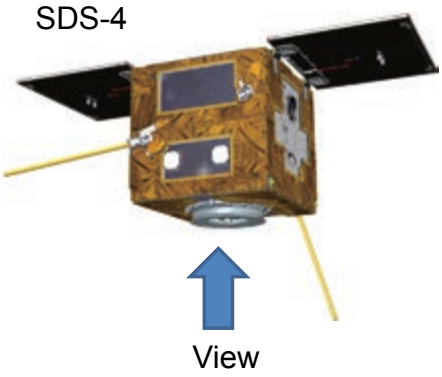
Envelope





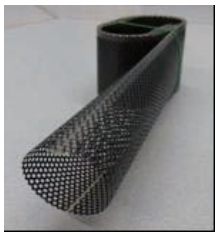
Design the component that don't effect satellite system as possible.

※():Referenceof SDS-4

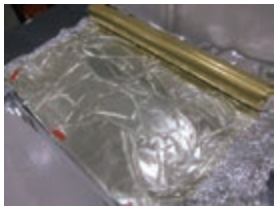
11

Technology of Membrane Deployment Mechanisim

- Tri-axis CFRP deployable boom
  - Good formability and specific rigidity
- Membrane holding mechanism
  - Spiral folding where the membrane thickness is considered
- AO-resistant Polyimide 「BSF-30」
  - self-repairability against Atomic Oxygen


Deployable boom

Folding Pattern


BSF-30

12

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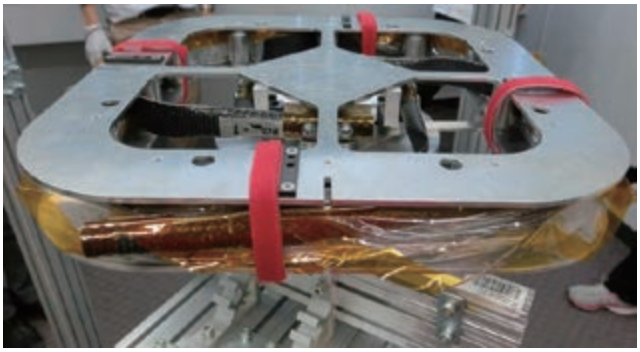
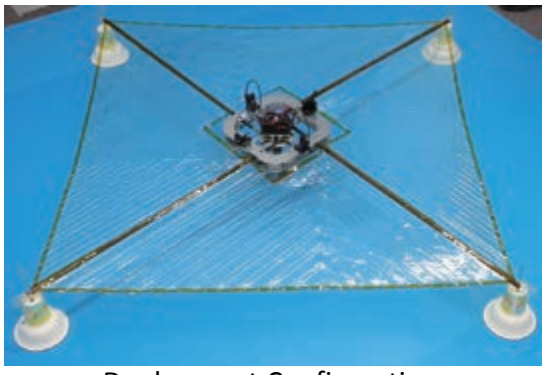
Membrane-Boom Wrapped Structure

- Basic Concept
  - The wrapping stowage of the booms and the membrane together on the same hub.
    - The deployment of the booms and the membrane can be synchronous.
    - Simple mechanism. when a hold mechanism for booms is released, the booms and the membrane automatically deploy together.



Stowed Configuration



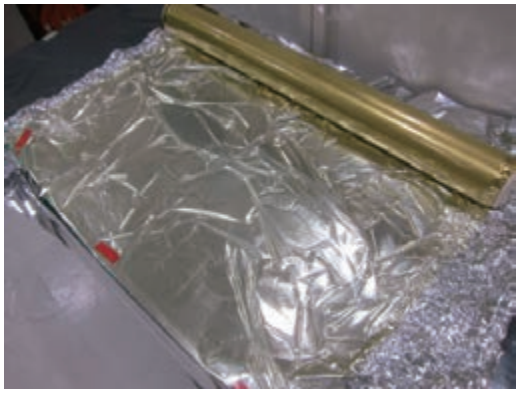
Deployment Configuration

※This study have conducted by Furuya Lab. supported by Solar Sail WG

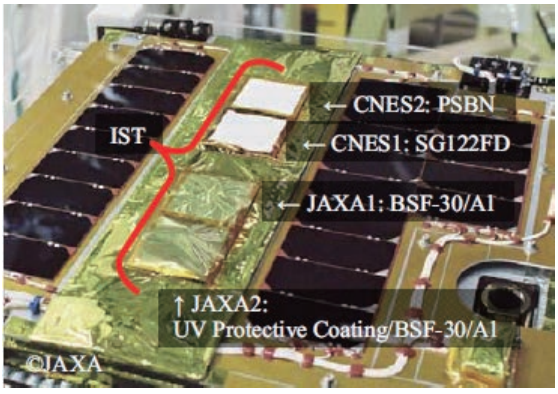
13

BSF-30

- Siloxane-modified polyimides
  - react to Atomic oxygen by add Si to polyimides and self-organize resistant coating of SiO_2 .
    - have self-repairability against Atomic Oxygen
  - In-orbit demonstraion:JEM/MPAC & SEED and SDS-4/THERME



BSF-30



SDS-4/THERME

14

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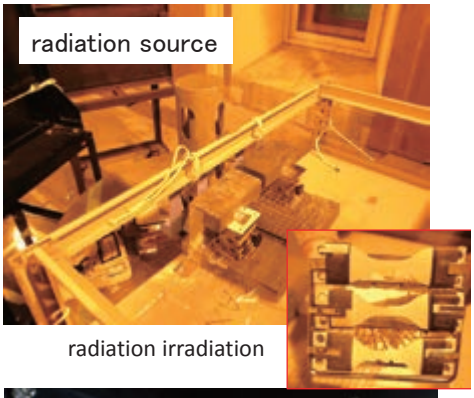
BSF-30 Environmental Testing

- Irradiates with made crease

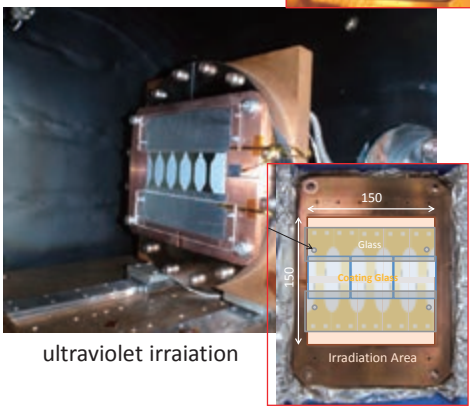
→To confirm ability to deploy membrane when mission terminated.

  - Radiation irradiation test
    - Radiation total dose：15,30,45Mrad
      - 7.8Mrad is radiation total dose in 3 years mission term.
      - Line type: Proton
    - Mechanical properties testing
      - maintain strength after radiation.

  - Ultraviolet irradiation test
    - Radiation dose：50ESD
      - mission term:3 years
    - Mechanical properties testing



radiation irradiation



ultraviolet irraiation

Summary

- Introduce development status of JAXA's Membrane Deployment Mechanism for De-orbiting
  - Numbers of satellites can increase by expanding use of small satellite. Launched all small satellites have to observes 25 years rules.
  - As a de-orbiting method, membrane deployment using atomospheric drag is suitable for small sats.

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E4

Conventional safety consideration for controlled reentry and measures for improvement

吉原 徹（JAXA 安全・信頼性推進部）
YOSHIHARA, Toru (JAXA Safety and Mission Assurance Department)

運用を終了した宇宙機がそのまま軌道上に放置された場合、それ自体がスペースデブリとなるだけでなく他の物体との衝突等によってデブリ環境の悪化に寄与する恐れがある。また、特に低軌道で運用を終えた宇宙機においては、その後無制御で大気圏に再突入した際に溶け残った破片が地上に到達し、人命や財産等に危害を及ぼすリスクとなる。これらのリスクを総合的に低減する方策として、コントロールドリエントリは非常に好ましい運用終了処置と言える。一方で、そのために衛星の運用終了時期を早めなければならない可能性や、リエントリ制御が失敗した場合の社会的なリスク等、運用者から見ると明らかに不利益の方が多いため、促進には規制が必要と考えられる。ここでは、実際にコントロールドリエントリを行う際に考慮しなければならない事項や手続き等について紹介するとともに、規制化を検討する場合に特に議論が必要と認識される事項について整理する。

A spacecraft could be a space debris and its source while it stays on orbit after the mission. Moreover, a natural reentry of a spacecraft to the ground could be a potential risk to the people and assets because certain amount of the fragments may survive and reach to the ground. A controlled reentry would be quite preferable way to minimize both risks besides it gives less incentive to the mission provider because of no or less profit attempting to do so. Therefore, a regulation is one of the practical solution to promote controlled reentry. The conventional safety methodology and consideration for controlled reentry are introduced and some issues are addressed toward the future institutionalization.

This document is provided by JAXA.

Conventional safety consideration for controlled reentry and measures for improvement

December 17th -19th , 2014
6th Space Debris Workshop

Toru Yoshihara
Safety and Mission Assurance (S&MA) department
Japan Aerospace Exploration Agency (JAXA)

“If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property.”

- Section 5.3.2, IADC Space Debris Mitigation Guidelines -

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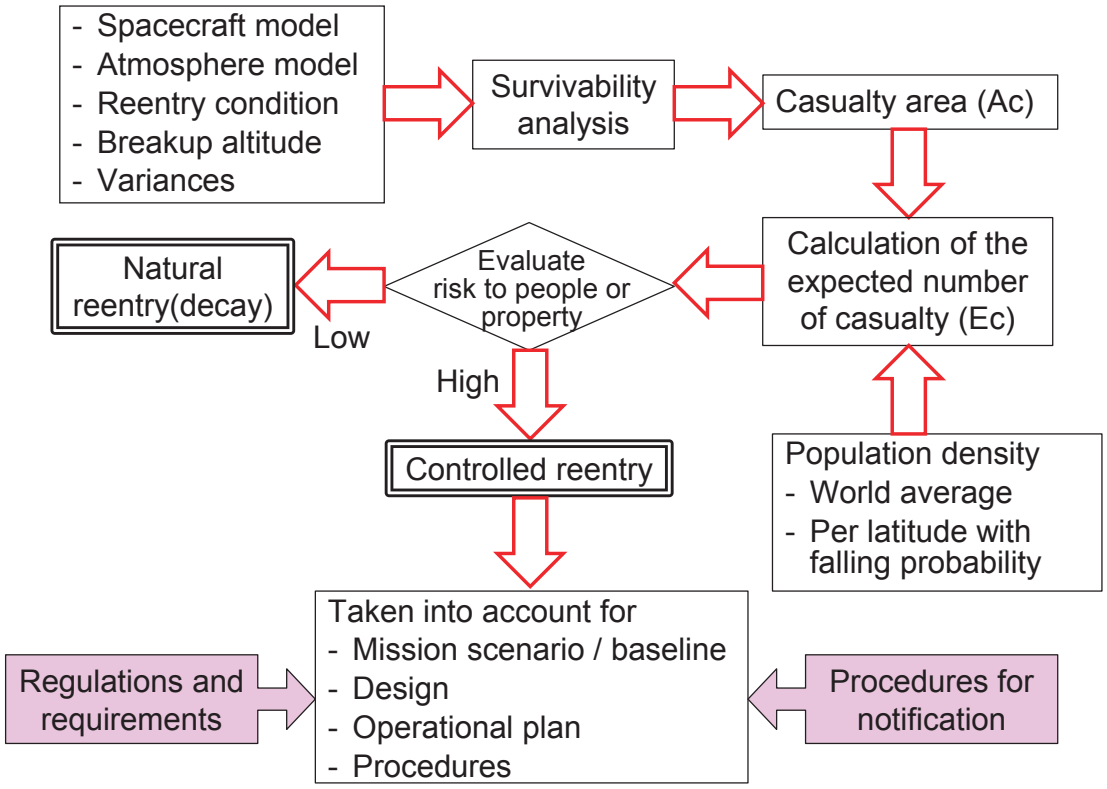
Typical evaluation process



2

Regulations and requirements related to controlled reentry

JAPAN

Regulation of GOJ
- Standard for safety evaluation on launching satellites.

Regulation of JAXA
- Safety standard for controlled reentry.[JERG-0-047] (Applied to HTV)

Europe

- European Code of Conduct for Space Debris Mitigation, 28/06/2004

Regulation of ESA
- Space Debris Mitigation Policy for Agency Projects [ESA/ADMIN/IPOL(2014)2]
- Space Debris Mitigation for Agency Projects Annex1 [ESA/ADMIN/IPOL(2008)2]

Regulation of the other countries.
e.g.
- Flight safety code (Australia) (Applied to Hayabusa)

Requirements for controlled reentry are enrolled or tied with space debris mitigation requirements.

United States

- U.S. Government Orbital Debris Mitigation Standard Practices, December 2000.
- United States Space Command Policy Directive 10-39, “Satellite Disposal Procedures”, 1 May 2001.
- United States Space Command Policy Directive 13-4, Minimization and Mitigation of Space Debris”, 1 February 2001.

Regulation of NASA
- NASA Procedural Requirements for Limiting Orbital Debris [NPR8715.6]
- Process for Limiting Orbital Debris [NASA-STD-8719.14]
- Range Flight Safety Program [NPR8715.5]

Regulation of USAF
- (the United States Air Force’s) Space and Missile System Center (SMC) Orbital/Sub-orbital Debris Mitigation User’s Handbook, Version 1.0, July 2002.

Regulation of FAA
- Reentry of a reentry vehicle other than a reusable launch vehicle, CFR Title14, Vol.4 chapter III Part 435 (2008.5), U.S.A.

3

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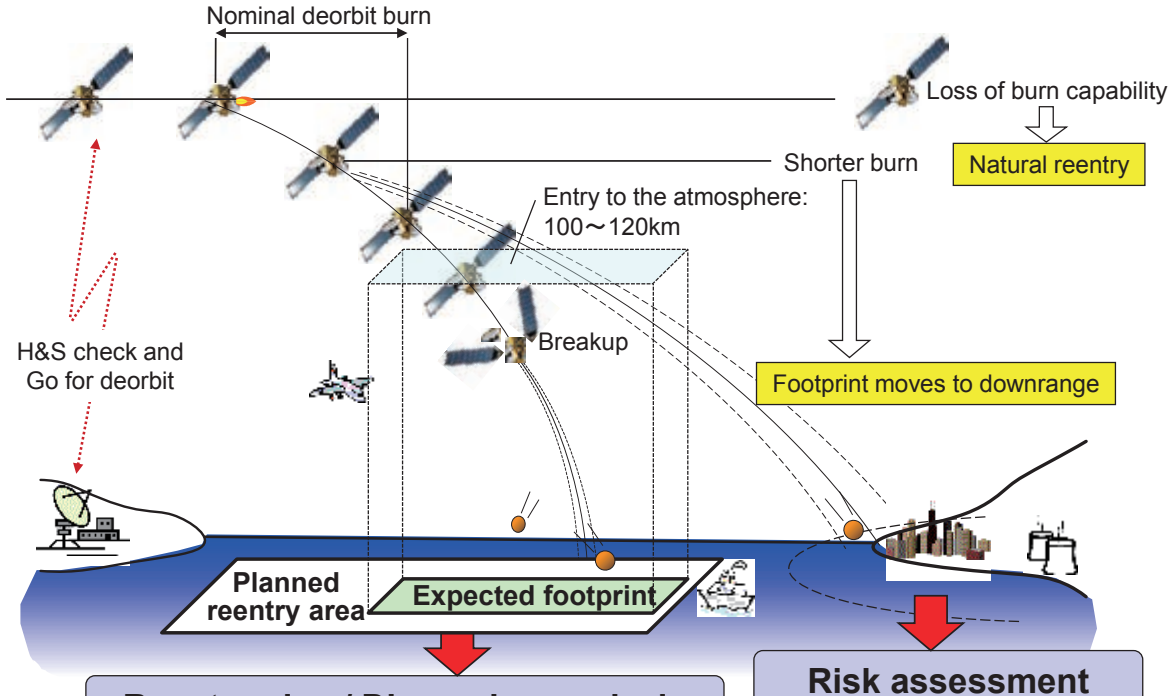
Typical event flow during controlled reentry

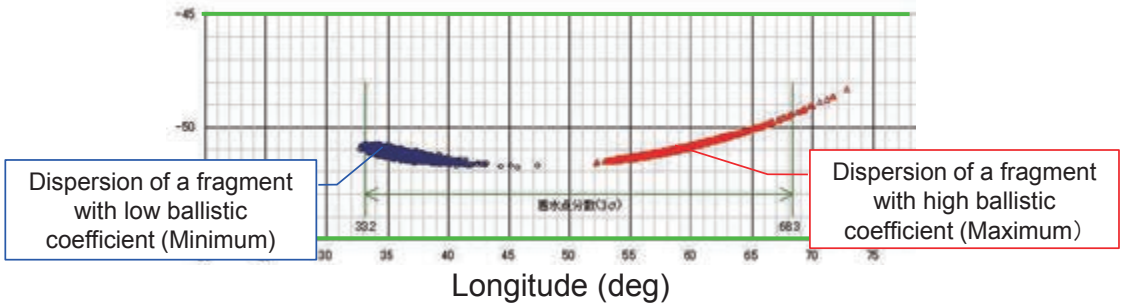


4

Evaluation of the footprint

Expected footprint

- Dispersion analysis is implemented to evaluate the design of the footprint.
- Survivability of the actual flight hardware may or may not be considered for dispersion analysis. It basically depends on program or mission owner.
- The following example is a kind of “worst case” evaluation. That includes the following assumption, errors and uncertainties into account.
  - ✓ Sample fragments are assumed to envelope logically maximum ballistic coefficient regardless actual survivability of the system.
  - ✓ Error of the initial condition such as velocity and trajectory of the vehicle at the reentry interface point.
  - ✓ Dispersion of the atmospheric concentration.
  - ✓ Dispersion of each sample fragment is calculated by Monte-carlo simulation.



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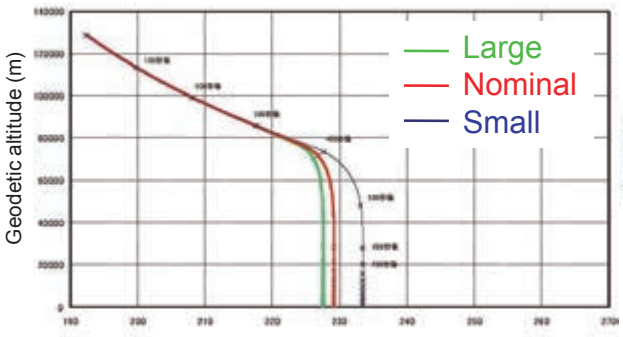
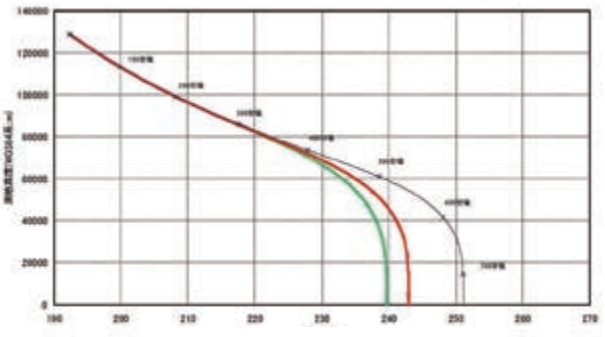
Evaluation of the footprint



Altitude profile for a fragment with low ballistic coefficient



Altitude profile for a fragment with high ballistic coefficient

The effect of the atmospheric concentration

It is also evaluated that,
- the effect by the wind can be considered negligible to this result.
- the acceleration by the typical explosion could only create a negligible effect comparing to the other factors.

6

Procedures for notification upon controlled reentry

Convention on International Civil Aviation.
ICAO - Annex15
- **Aeronautical Information Services**

Aeronautical Information Publication (AIP)

Notice to Airmen (NOTAM)

Plan of the controlled reentry
(Definition of the restricted area, effective date and time.)

AIP publication in every 28days (per AIRAC procedure)

NIL notification

At least seven days advance notice

At least 24 hours advance notice

Execution of the controlled reentry

7

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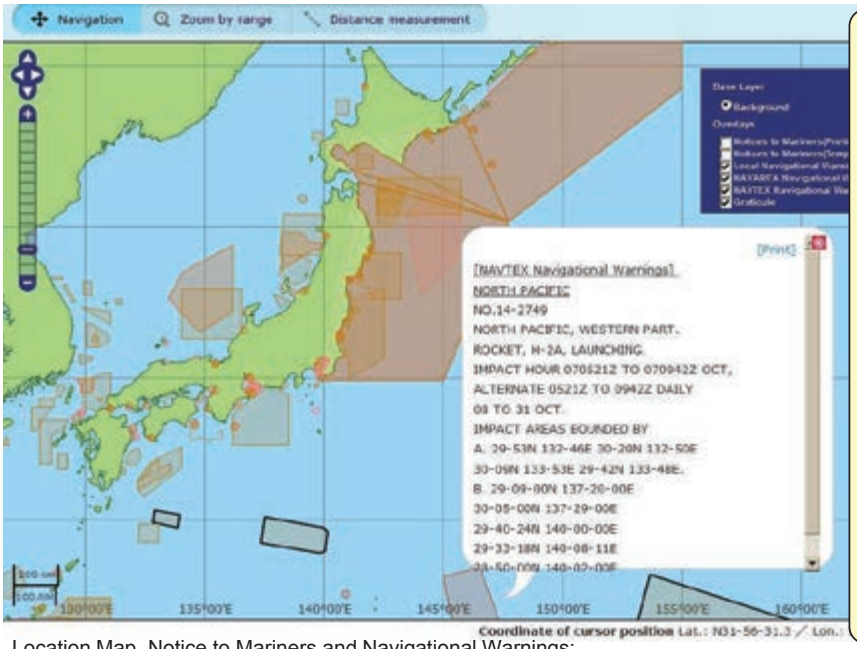
Procedures for notification upon controlled reentry



Location Map, Notice to Mariners and Navigational Warnings:
http://www1.kaiho.mlit.go.jp/TUHO/vpage/visualpage_en.html

Navigational Warnings

NAVAREA warnings
- Warnings that are provided via satellite, inmalsat is used for NAVAREA XI, by the responsible government on each NAVAREA.

NAVTEX warnings
- Warnings that are provided via Medium Frequency from each NAVTEX station on the coast. 518kHz is commonly used in the world.

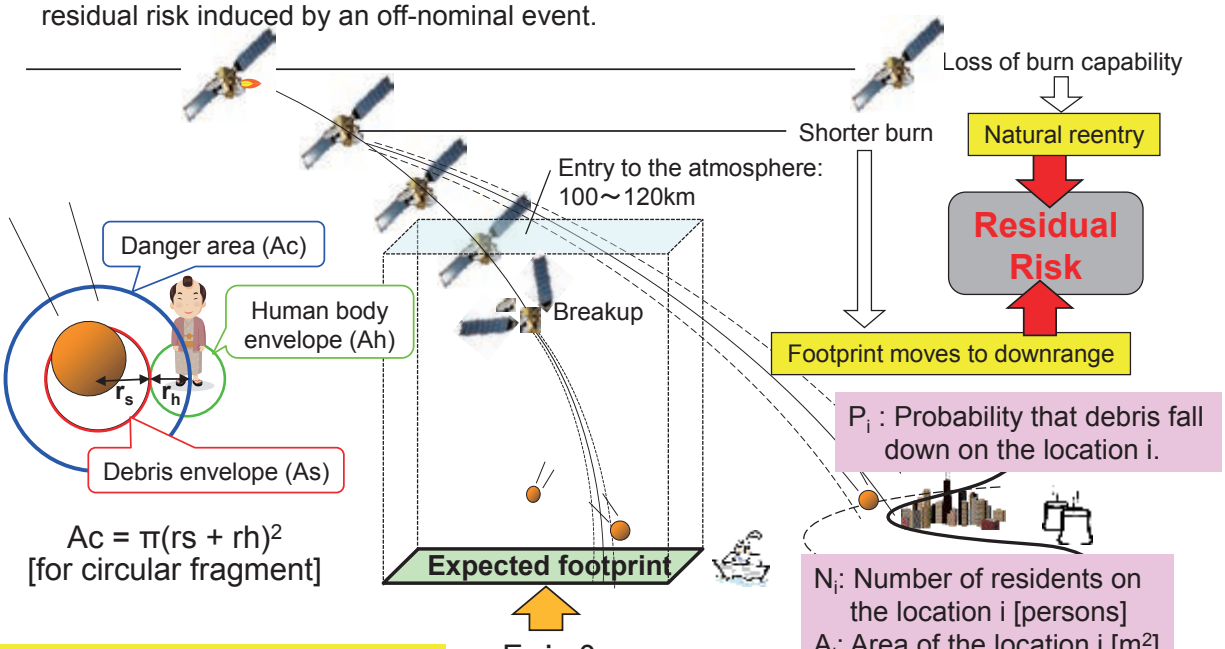
Local navigational warnings
- Additional warnings are locally given by a related government officials.

Notices to Mariners
- Information via publication and internet for updating the latest status on any events affecting a ship route. Updated in weekly basis.

8

Expected number of casualty (Ec)

- Ec is the value to express the casualty risk associated with reentry.
- It is widely utilized for both natural and controlled reentry.
- Because nominal controlled reentry is arranged not to create casualty, Ec basically express residual risk induced by an off-nominal event.



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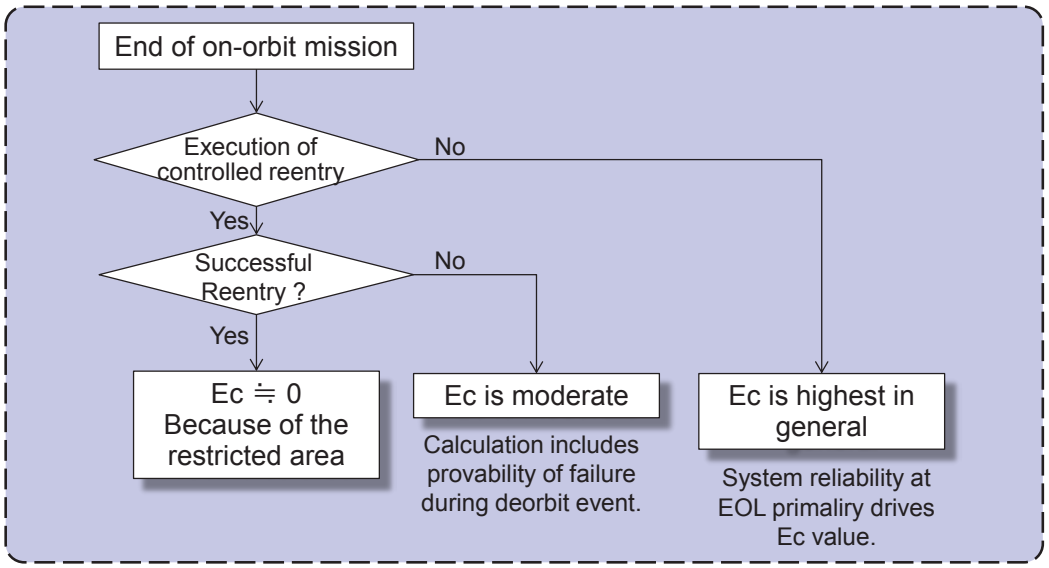
Expected number of casualty (Ec)



- The following population data are applied to the calculation of Ec, as an example in JAXA .
  - ✓ Global average --- The case fragments fall down on the sea.
  - ✓ National average --- The case fragments fall down on the land.
  - ✓ City average --- The case fragments fall down on the congested city.
  - ✓ Average on each latitude --- Natural (Uncontrolled) reentry.

10

Benefits vs. Disadvantages of the controlled reentry

- Controlled reentry is quite preferable deorbit method for both orbiter debris mitigation and public safety.
  - ✓ Unnecessary object such as a satellite at EOL is immediately removed from orbit.
  - ✓ Public risk induced by fallen space object is minimized.
- Besides, spacecraft owners are not motivated to plan controlled reentry because of,
  - ✓ No profit.
  - ✓ Risk of mishap due to unsuccessful reentry.
  - ✓ Additional works to do.
  - ✓ Potential early retirement of a satellite to support reentry.

11

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Suggestions for future

- Controlled reentry is the best option for deorbiting satellite at EOL, if feasible. However a satellite owner would not be motivated to take this option because of disadvantages rather than their profit.
- Regulation may be a practical solution to promote controlled reentry however there must be fair rules and guidelines as a common scale.
- It is also necessary to simplify and standardize risk evaluation techniques and related analysis to support fire judge, while scientists continue searching for real phenomena.

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E5

スペースデブリの超高速衝突解析のモデル化法の諸問題について

Some Problems of Modeling Method on Hypervelocity Impact Analysis of Space Debris

○片山 雅英、竹場 敦史 (伊藤忠テクノソリューションズ株式会社(CTC))
○Masahide KATAYAMA, Atsushi TAKEBA (ITOCHU Techno-Solutions Corporation (CTC))

現在、スペースデブリの超高速衝突問題に適用されている数値解析法に関し、それらの長所と短所について概観した後、特に、サブミリ・オーダの飛翔体(スペースデブリ)が宇宙機の各構成要素に衝突する問題に適用するに際し、問題となる点を指摘・整理する。また、有人ミッションの大型構造物で標準的に用いられる Whipple バンパー・シールド・システムを比較対象として、無人機における防護システムの特殊性という観点から、破砕・衝撃気化といった現象のメカニズムを考慮した物理モデルの問題点と、それらの現象を模擬するための数値解析手法である、数値的エロージョンを含む Lagrange の方法、Euler の方法、SPH(Smoothed Particle Hydrodynamics)法など、各数値解析手法の適用の仕方の是非について再検討を行い、今後の方向性について考える。

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スペースデブリの超高速衝突解析のモデル化法の諸問題について

Some Problems of Modeling Method on Hypervelocity Impact Analysis of Space Debris

○片山 雅英 竹場 敦史
○Masahide KATAYAMA Atsushi TAKEBA

伊藤忠テクノソリューションズ株式会社
ITOCHU Techno-Solutions Corporation
科学システム事業部 科学・工学技術部
Science & Engineering Systems Division
Science & Engineering Analysis Department

The 6th Workshop on Space Debris
at ARD / JAXA
17–19 December, 2014

1

Formulation on the basis of 'Continuum Mechanics'

Mixed system of three physical phases of material in a single problem

Governing Equations

1. Eq. of Continuity (Mass conservation)
2. Eq. of Motion (Momentum conservation)
3. Eq. of Energy (Energy conservation)

- ✓ Eq. of State (EOS)
- ✓ Constitutive Eq. (CE)
- ✓ Failure Criteria

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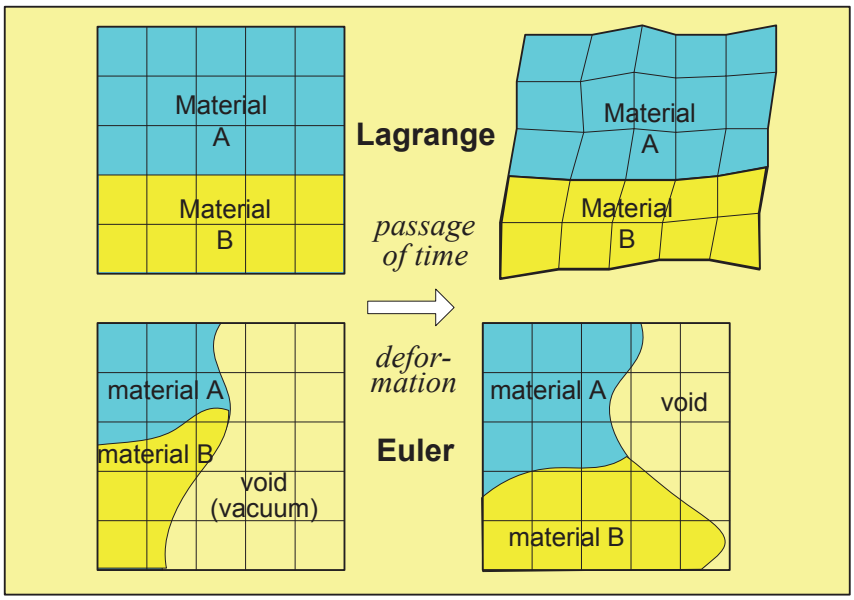
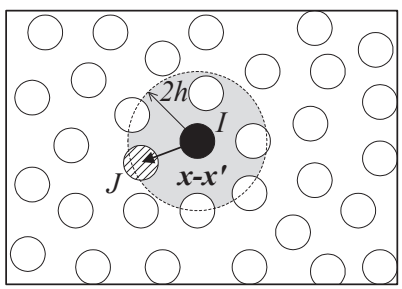
Lagrangian versus Eulerian Method



SPH (Smoothed Particle Hydrodynamics) Method



$$f(x) \approx \int f(x')W(x-x',h)dx'$$

$$\nabla \cdot f(x) \approx \int \nabla \cdot f(x')W(x-x',h)dx'$$

W: Weight Function (Kernel B-spline)

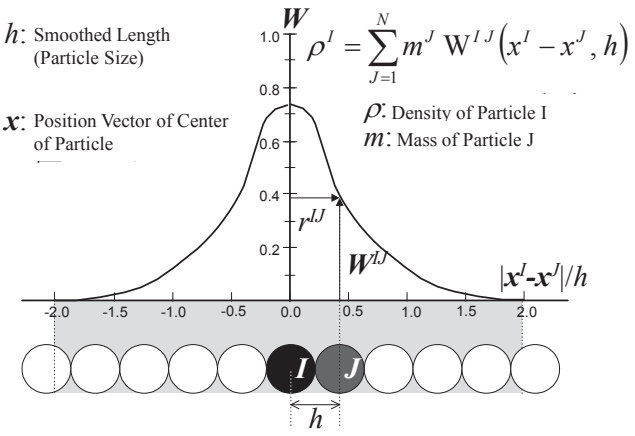
h: Smoothed Length (Particle Size)

x: Position Vector of Center of Particle

$$\rho^I = \sum_{J=1}^{N} m^J \, W^{IJ}\left(x^I - x^J, h\right)$$

ρ: Density of Particle I

m: Mass of Particle J



Schematics of SPH Method

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Origin of Whipple Bumper Shield

No. 1161 1947 THE ASTRONOMICAL JOURNAL 131

Whipple, F. L. Meteorites and space travel.

Meteorites represent a potential hazard to a pressurized space vessel. Of fundamental interest is the value of the probability that the skin of the vessel will be punctured by a meteorite. In case this probability is appreciable the problem of protection from meteorites becomes important.

We shall assume: (a) That the space vessel travels in a part of the solar system where the meteoritic frequencies and velocities approximate those at the earth.

(b) That 4.5×10^5 fifth-magnitude meteors strike the earth daily and that the number increases by a factor of 2.51 per magnitude fainter (Watson).

(c) That (with Opik) the total kinetic energy of a telescopic meteor is 1/0.0006 the energy observed in the wave length region from 4500 to 5700 angstroms.

(d) That the penetrating distance of a meteorite into a solid is equal to (extreme assumption) the length of a right circular cone of 60° total apex angle the volume of which in the solid can be heated and melted by the total kinetic energy of the meteorite.

It follows that a spherical space vessel of 12 feet diameter covered with a ¼-inch steel skin will be penetrated by a meteorite corresponding to an eighth magnitude or brighter meteor at a rate of once in 50 years. Such a meteorite weighs approximately a milligram. For thinner coverings the probability increases rapidly.

Although the probability of meteor penetration is small, a simple protection can be provided other than by the avoidance of known meteor streams. Considerations of the conservation of momentum and energy show that when a meteorite collides with a sheet of thickness comparable to the meteorite's diameter the result is an explosion in which both the meteorite and the corresponding material of the sheet are vaporized and ionized at very high temperatures. Hence a "meteor bumper" consisting perhaps of a millimeter-thick sheet of metal surrounding the ¼-inch skin of the space vessel at a distance of an inch would dissipate the penetrating power of meteorites several times larger than one corresponding to an eighth-magnitude meteor.

Harvard College Observatory, Cambridge, Mass.

Ballistic Limit Equation (Curve)

After Apollo Program:

Modified Cour-Palais Equation → **New Cour-Palais Equation (Christiansen Equation)**

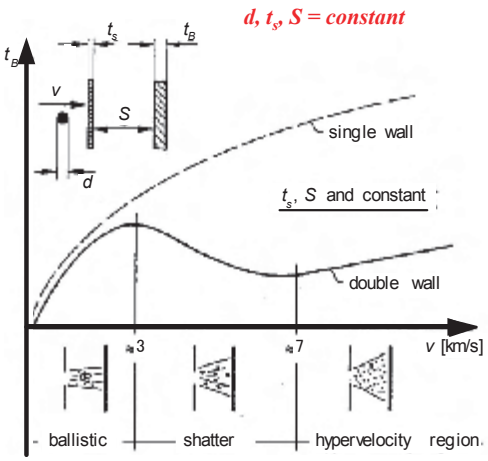

Fig. 3 Behaviour of the bumper protection concept. (H.-G. Reimerdes et al., *Proc. 1st European Conf. on Space Debris*, ESA SD-01, Darmstadt pp.433-439, 1993.)

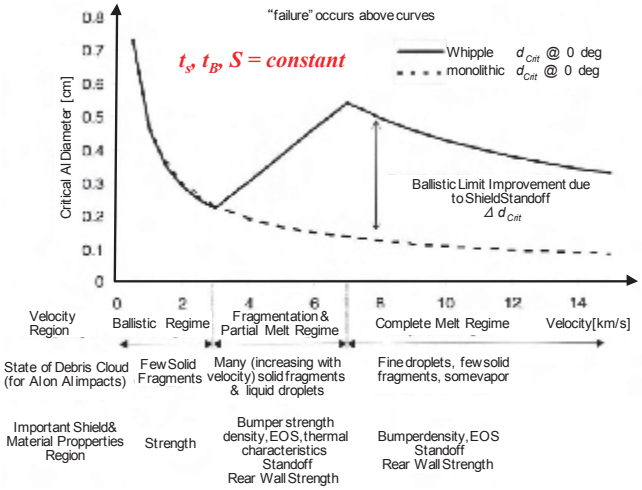

Fig.8 Ballistic limits for equal mass monolithic target and Whipple shield. (E. L. Christiansen, "Meteoroid/Debris Shielding," TP-2003-210788, NASA, 2003.)

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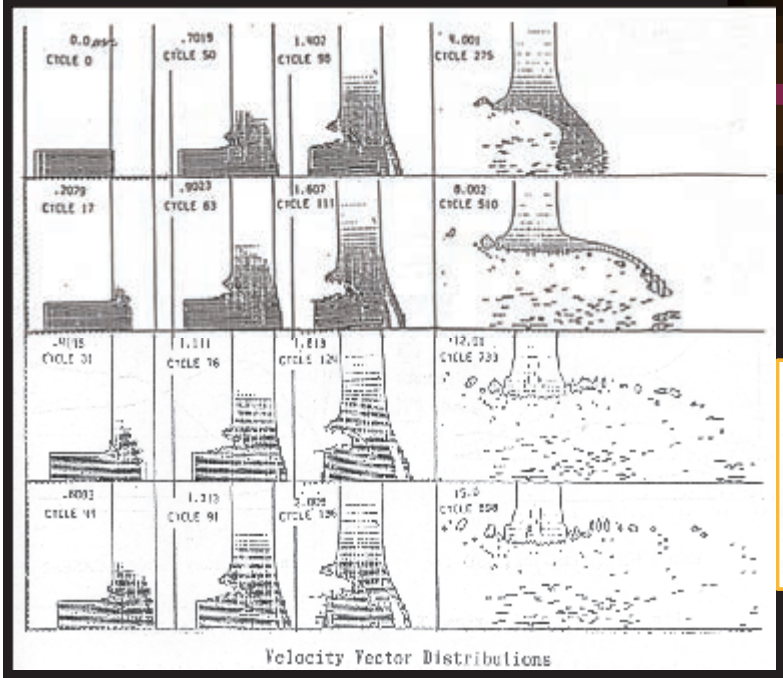
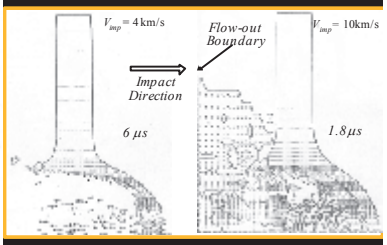
Presented at Hypervelocity Impact Symposium in San Antonio TX, Dec.,1989



NB: Calculations were performed by using multiple-material Eulerian method of PISCES-2DELK in 1986.



Int. J. Impact Engng Vol. 10, pp. 525-534, 1990
Printed in Great Britain
0734-743X/90 $3.00 + 0.00
Pergamon Press plc

MICROMETEROID AND DEBRIS IMPACT TEST ON SPACE STATION BUMPER

Yasuki Adachi

National Space Development Agency of Japan
2-4-1 Hamamatsu-cho, Minatoku, Tokyo Japan

Hideshige Ohtaki, Fumio Suehiro, and Yujiro Shiral

Mitsubishi Heavy Industries, Ltd.
10 Oye-cho, Minatoku, Nagoya Japan

Abstract

To design the micrometeroid and debris protection bumper of the outboard structure space station module, we made a two-stage helium light gas gun and carried out hypervelocity impact tests which simulated micrometeroid and debris impacts on space station. Fundamental characteristics of hypervelocity impact phenomena was investigated, for a projectile mass 0.45gr to 1.5gr, impact velocity about 4km/sec and aluminum-alloy bumpers. When the bumper is of double-sheet type, there exists an optimal front sheet thickness that causes melting of the front sheet. However, for too thin front sheets, penetration occurs, and for thick front sheets, spall fracture occurs. In addition to the impact tests, the computational simulation of the typical test result was carried out using the PISCES code with the Tillotson constitutive equation of aluminum-alloy. The computational simulation result had a good agreement with the test result.

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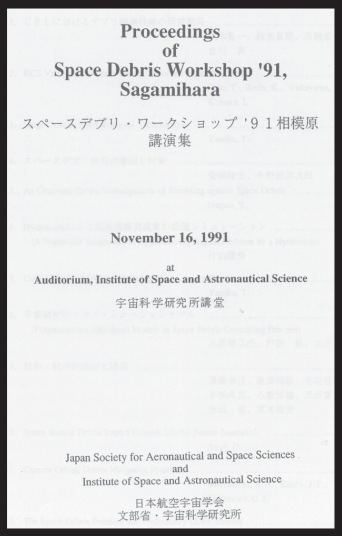
Numerical Simulation of Shock-Induced Vaporization Process



Proceedings
of
Space Debris Workshop '91,
Sagamihara

スペースデブリ・ワークショップ '９１相模原
講演集

November 16, 1991

at
Auditorium, Institute of Space and Astronautical Science
宇宙科学研究所講堂

Japan Society for Aeronautical and Space Sciences
and
Institute of Space and Astronautical Science
日本航空宇宙学会
文部省・宇宙科学研究所

Hydrocodeによる超高速衝突現象の数値シミュレーション
A Numerical Simulation of Hypervelocity Impact Problem by A Hydrocode

CRC総合研究所 片山 雅英
CRC Research Inst. Masahide KATAYAMA

ABSTRACT
This paper presents an overview on the technical methods used in the conventional hydrocodes to cope with the protection problem in the space debris impacts to the structures on the space station. In order to understand the hypervelocity impact phenomena, a physical modeling and two numerical simulations for it are made by using a hydrocode: AUTODYN-2D. The calculated results are investigated and discussed from the viewpoint of the effectiveness of this approach.

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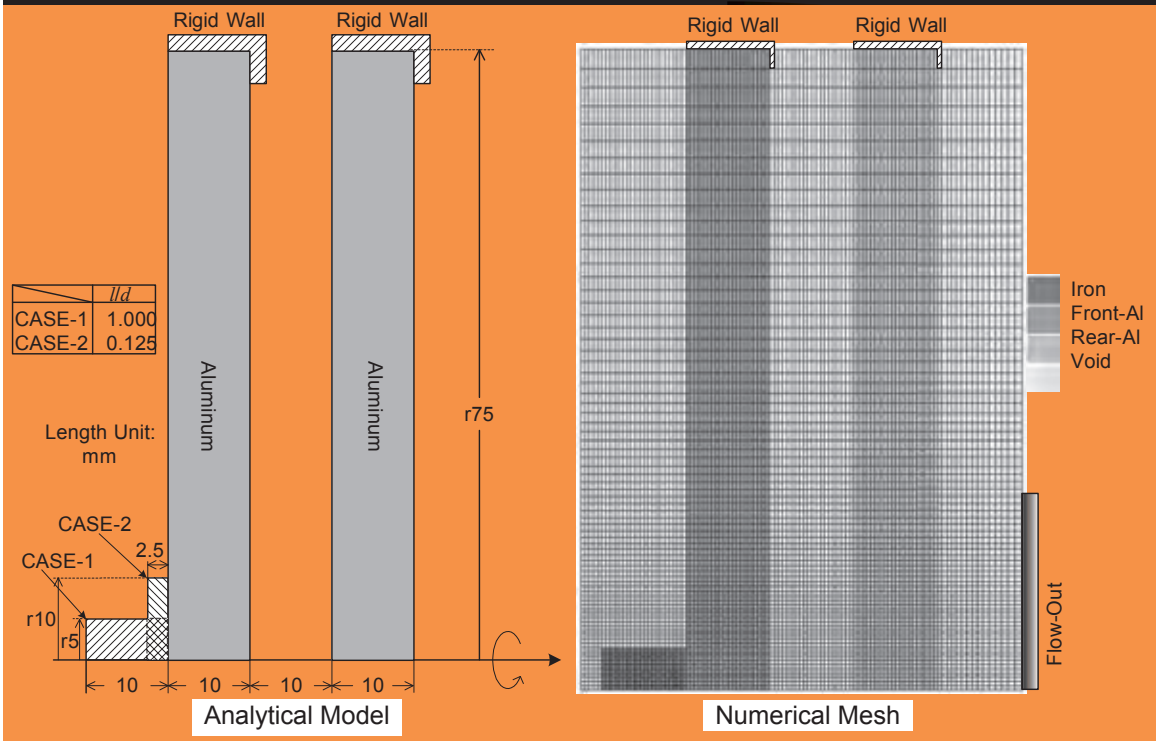
Space Debris Workshop '91 in Sagamihra (ISAS)

by using Multiple-material Eulerian Method of AUTODYN



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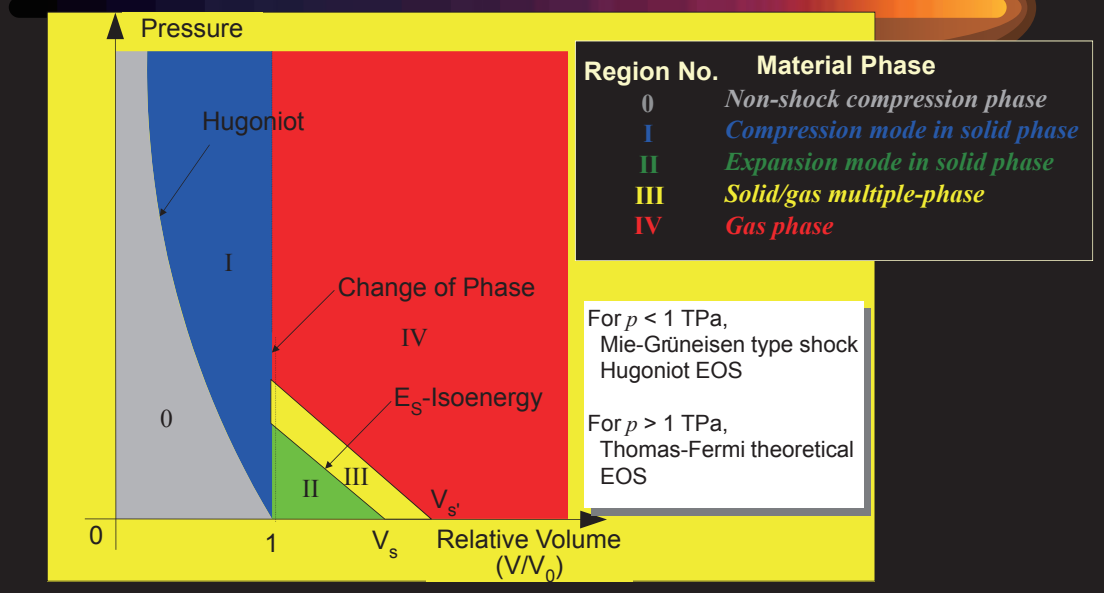
Tillotson's EOS to Model Shock-Induced Vaporization



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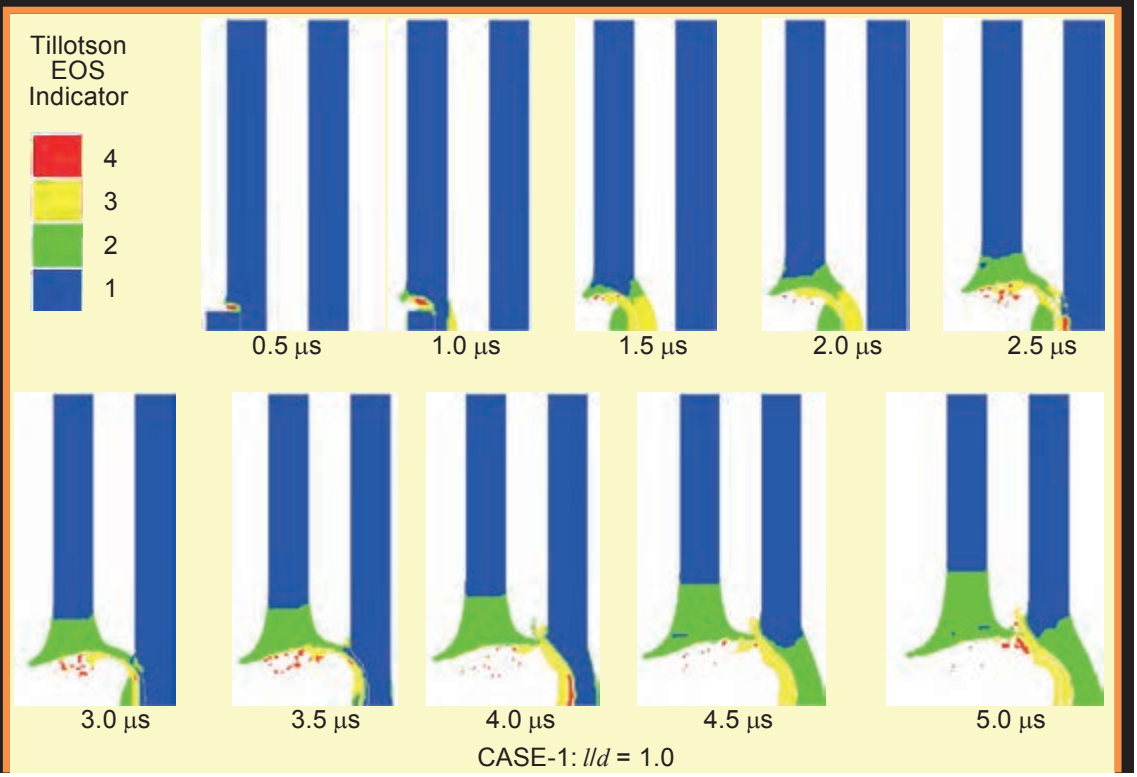
Physical Phase Map for CASE-1



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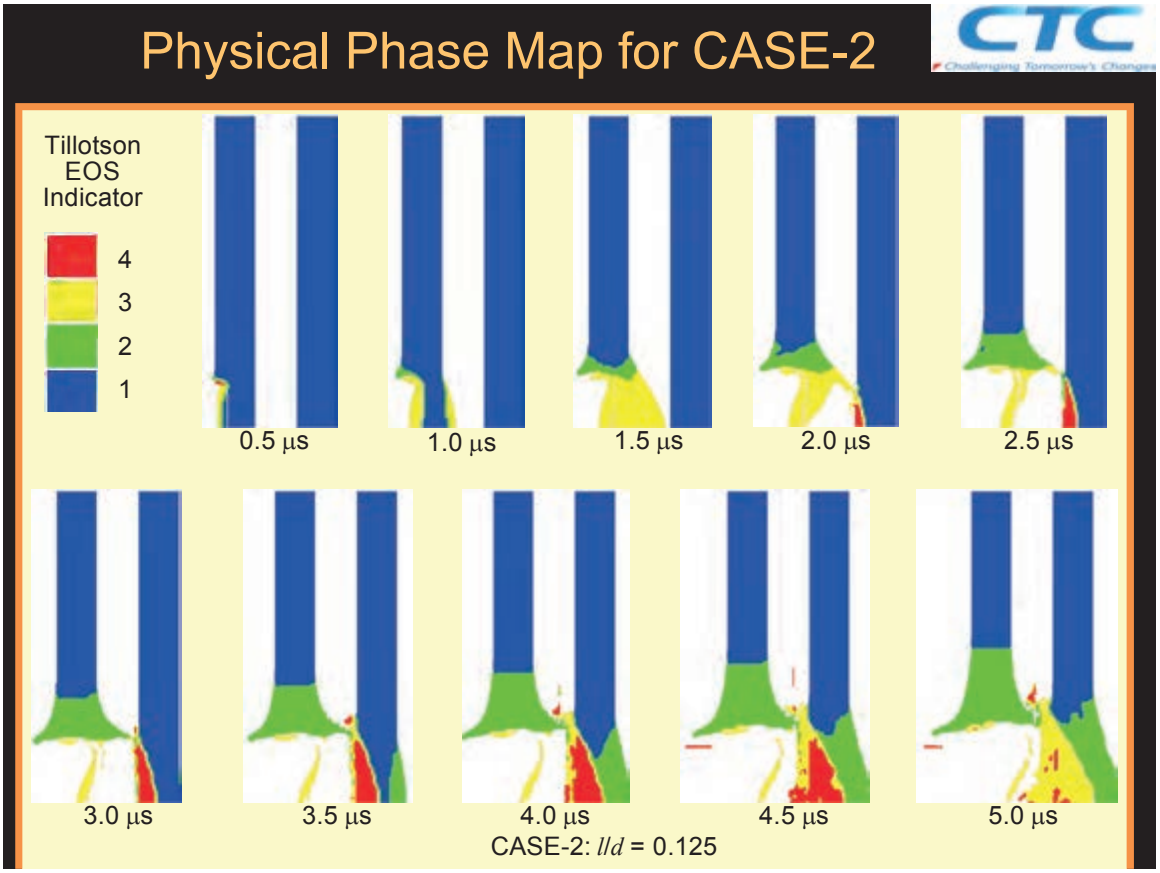

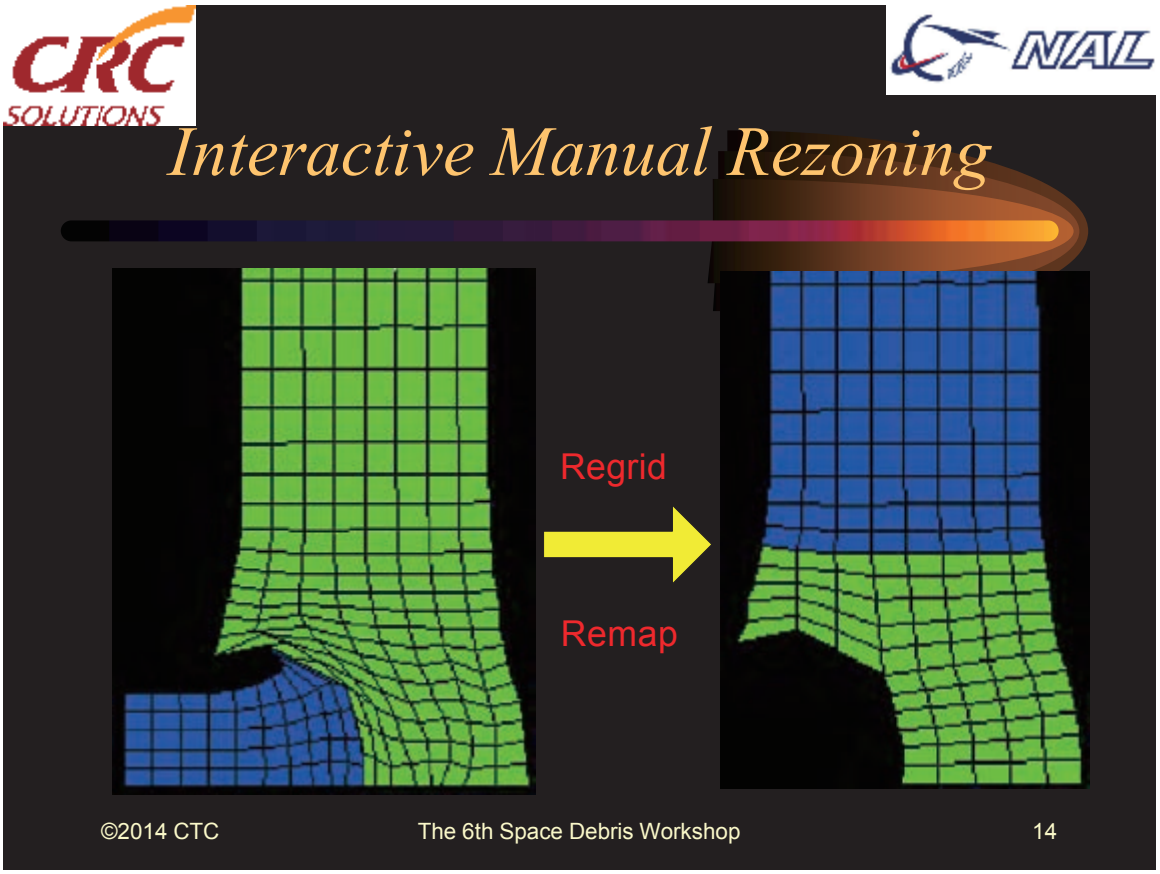

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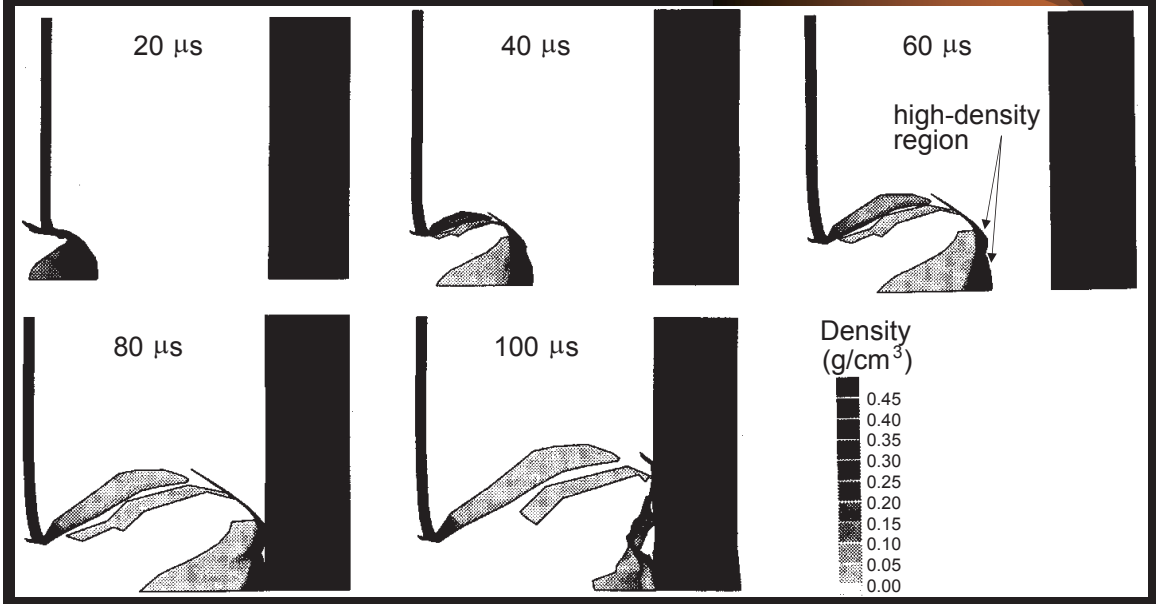
Lagrange/Rezoning Method in AUTODYN Applied to Whipple Bumper Shield in 1992



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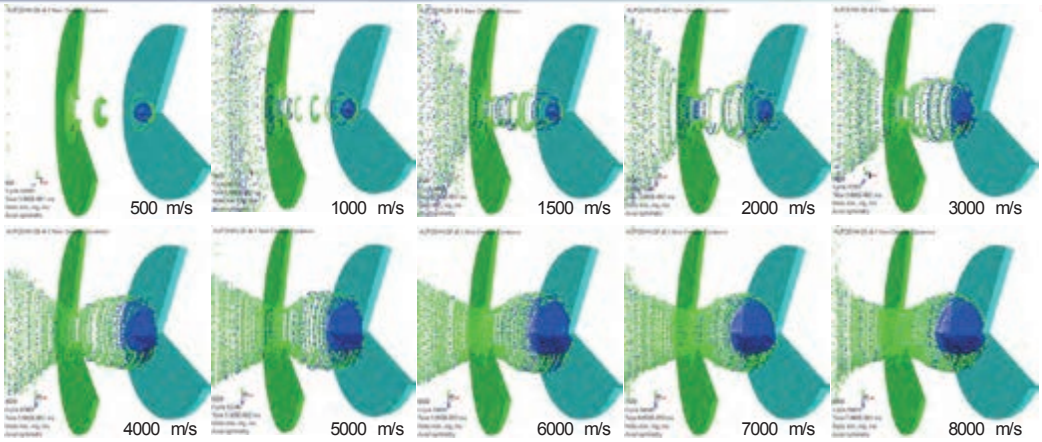
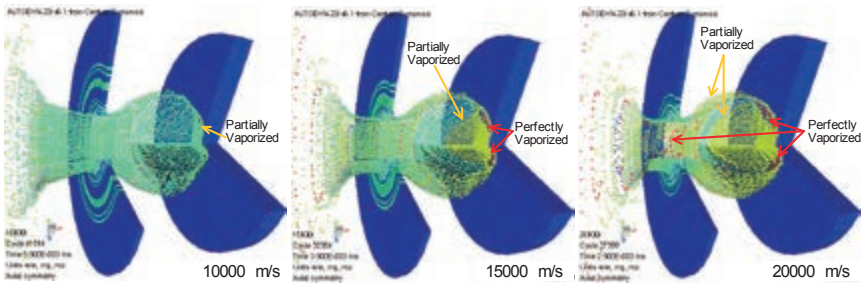
Debris Cloud Formation: 500 to 20,000 m/s



Projectile: 2024-T4,
Shield: 6061-T6,
Back Wall: 7075-T6;
d = 10 mm,
t_s = 2 mm,
t_B = 5 mm,
S = 50 mm,



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IAC-04-IAA.5.12.2.05

Assessment of Numerical Simulations for Hypervelocity Impacts of Space Debris

○Takeshi Kamiya*, Kuniaki Shiraki*, Masahide Katayama** and Atsushi Takeba**
*Japan Aerospace Exploration Agency (JAXA), kamiya.takeshi@jaxa.jp
**CRC Solutions Corp.

October 6th, 2004

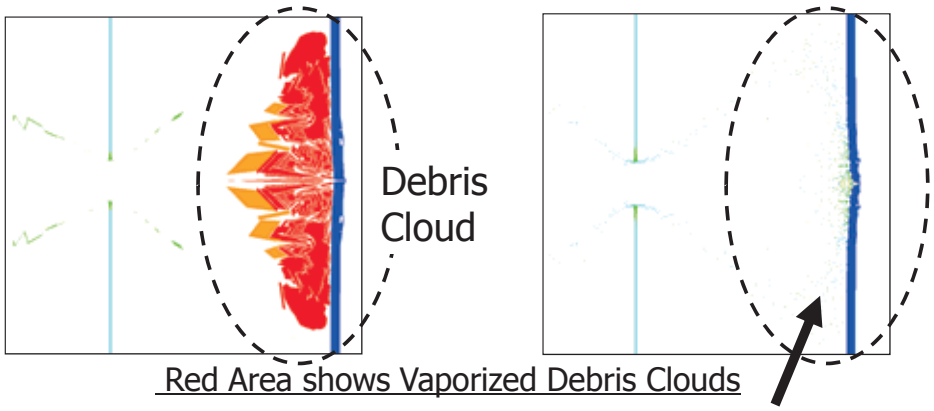
4. Simulation Results and Assessment

IAC-04-IAA.5.12.2.05

Comparison of Vaporized Area
between Lagrange and SPH at Vi=14km/sec

2-dimensional Lagrange Method (14μsec)

2-dimensional SPH Method (14μsec)



Red Area shows Vaporized Debris Clouds

■ There is no vaporization area in SPH because Debris Cloud in the SPH cannot hold the internal energy due to the feature of the SPH method.

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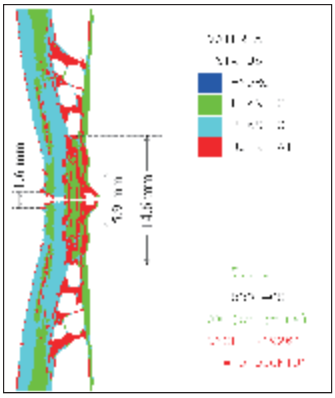
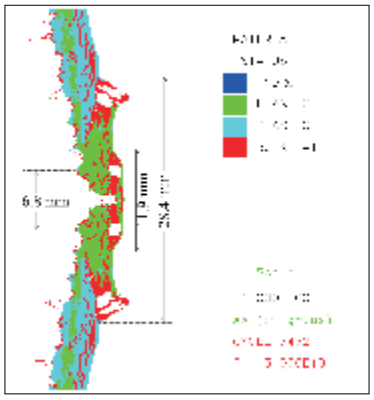
4. Simulation Results and Assessment *IAC-04-IAA.5.12.2.05*

Comparison of Vaporized Area between Lagrange and SPH at Vi=14km/sec

2-dimensional Lagrange Method

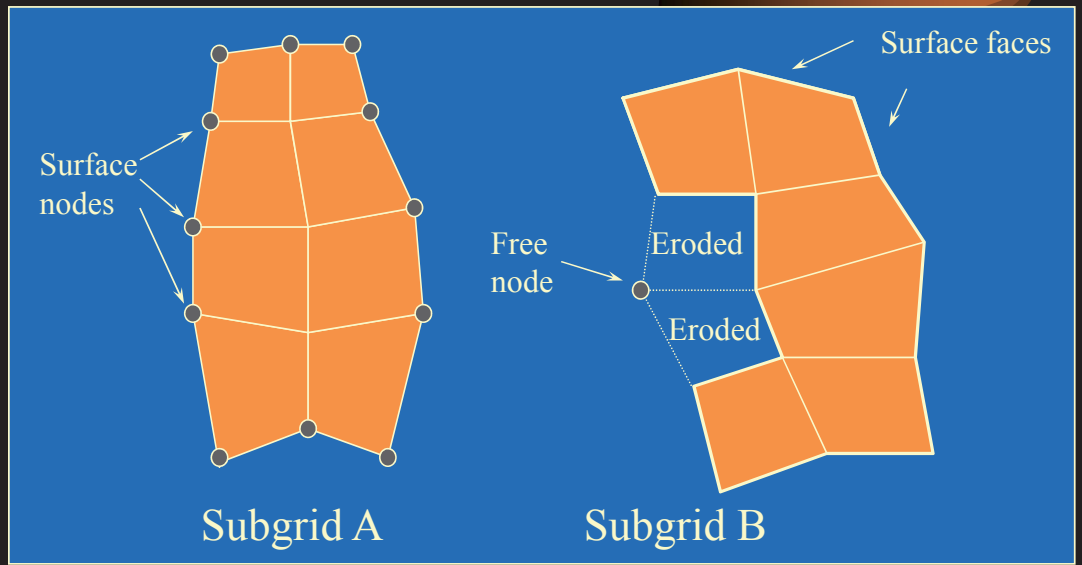


2-dimensional SPH Method



- The damage in SPH is severer than Lagrange because of less vaporization of Debris Clouds in SPH.

Numerical Erosion Option & Eroded Node Interactive with Lagrangian Grid



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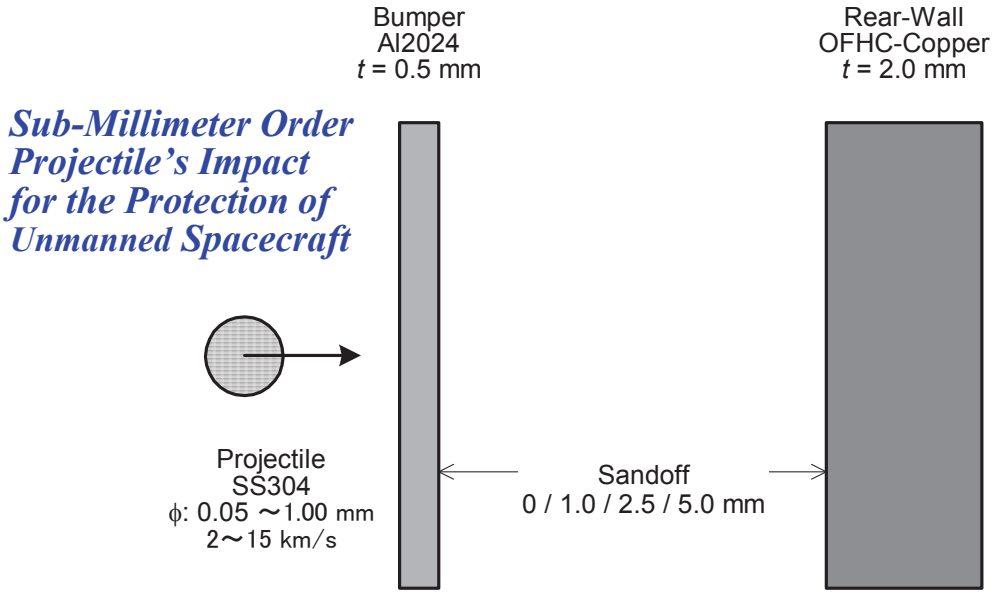
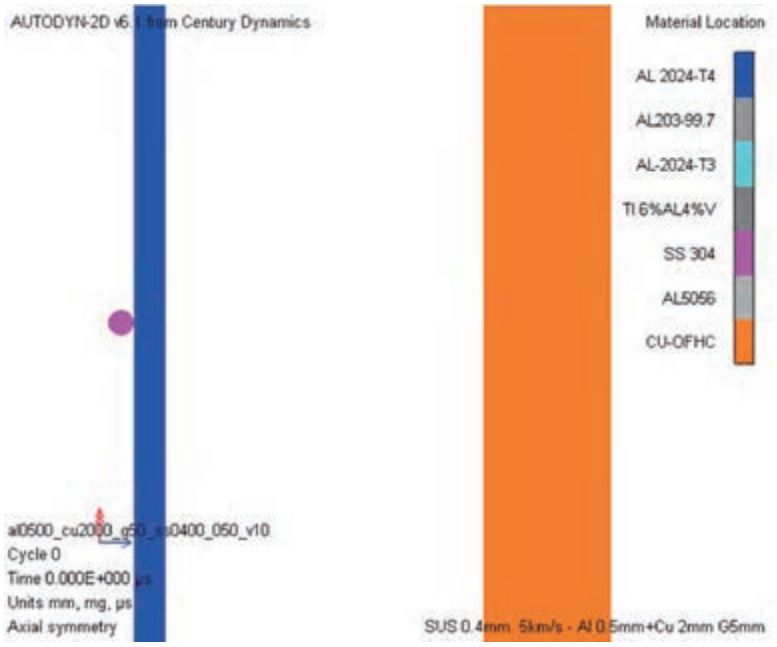
Ballistic Limit Curve of Double Sheet Targets Determined only by Numerical Procedures



The analytical models with different standoffs between the two sheets.

Ballistic Limit Curve of Double Sheet Targets Determined only by Numerical Procedures

Numerical Results



The analytical model with the standoff of 5.0 mm between the two sheets.

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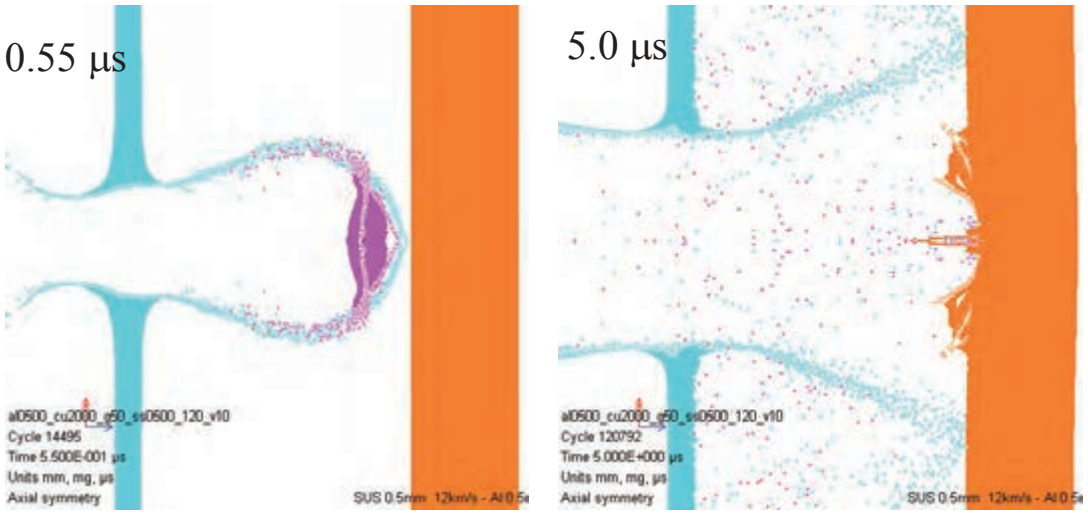
Ballistic Limit Curve of Double Sheet Targets Determinedbonly by Numerical Procedures

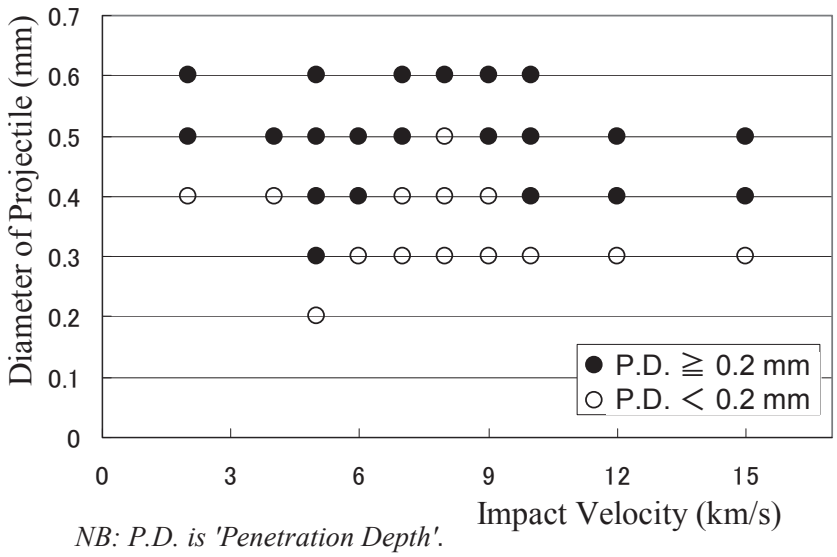
Numerical Results



The analytical model with the standoff of 5.0 mm between the two sheets.

Ballistic Limit Curve of Double Sheet Targets Determinedbonly by Numerical Procedures

Numerical Results



NB: P.D. is 'Penetration Depth'.

The analytical model with the standoff of 5.0 mm between the two sheets.

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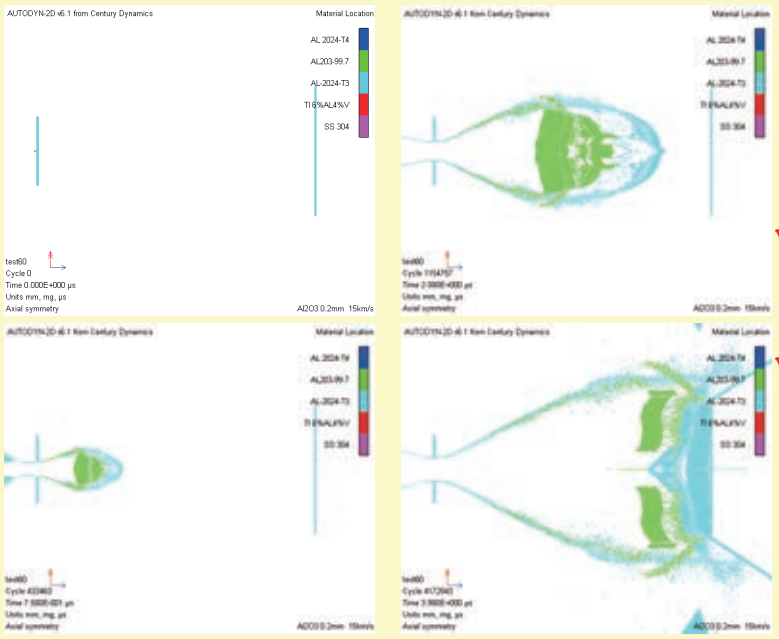
Expansioning Debris Cloud by Lagrangian Method

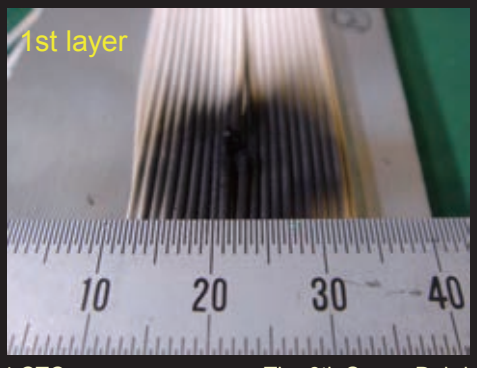


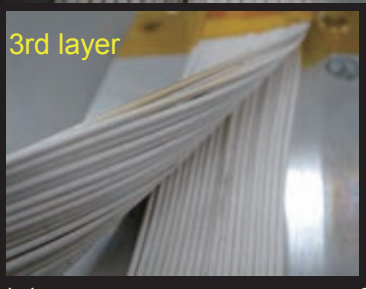
Problems

- ✓ Are there fragmentation or shattering processes actually in such a small system?
- ✓ It is difficult to be modeled by Eulerian method.

Power-Supply Harness Test by Two-Stage Light Gas Gun

- Projectile: 0.5 mmϕ Floatglass
- Impact Velocity: 4.35km/s





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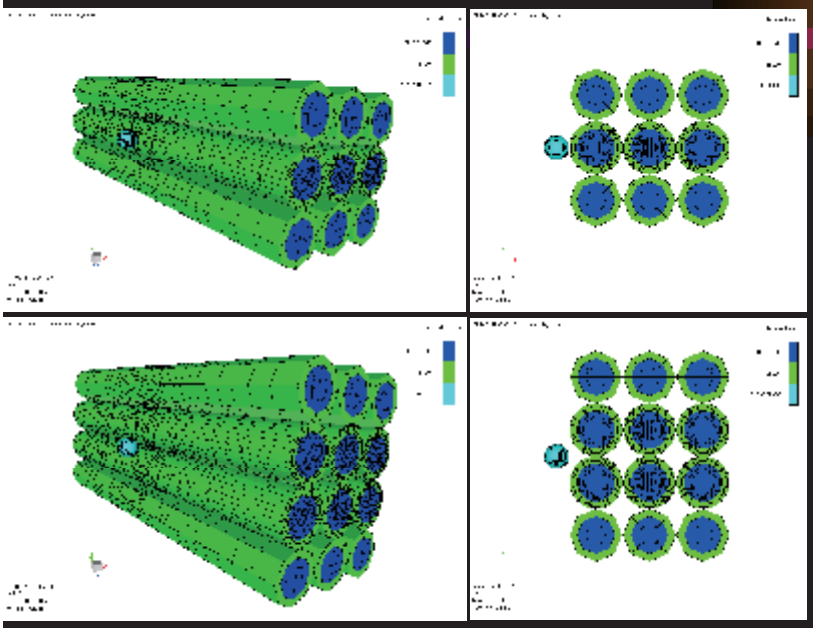
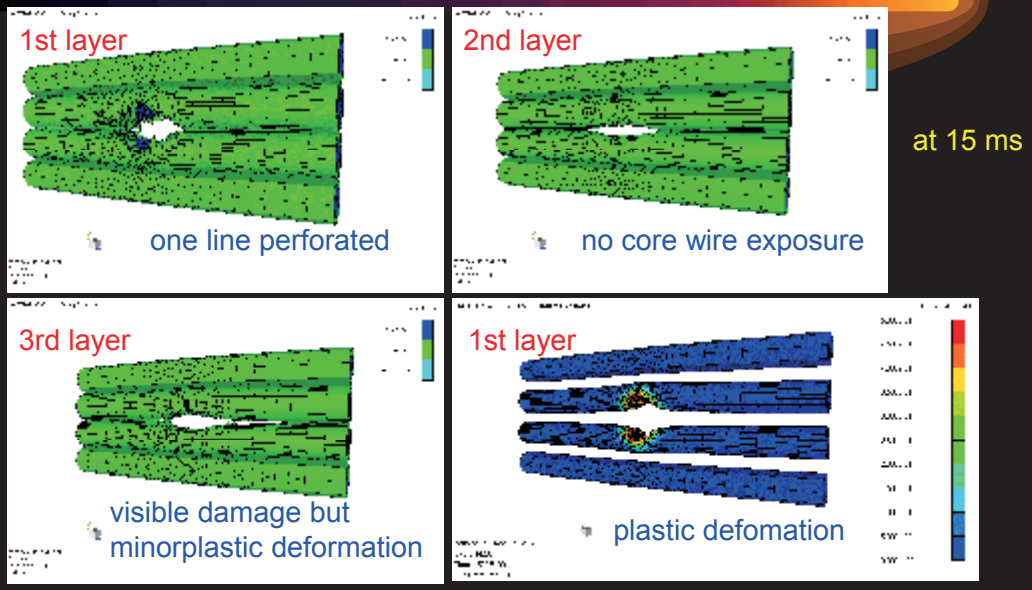
Power-Supply Harness Test by Two-Stage Light Gas Gun



- Projectile: 0.5 mmϕ Froatglass
- Impact Velocity: 4.35km/s
- Two-types of impact attitude
- Lagrangian method with the numerical erosion

Power-Supply Harness Test by Two-Stage Light Gas Gun (In-Between)



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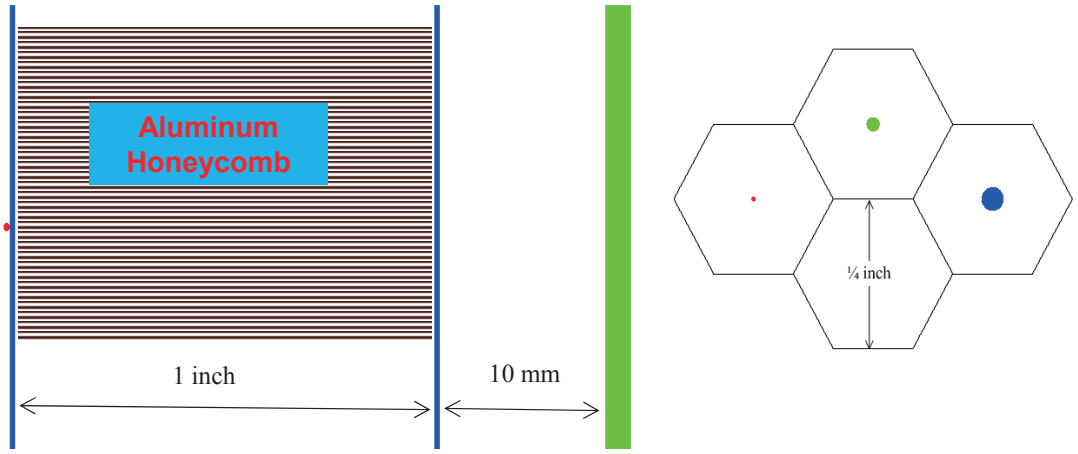
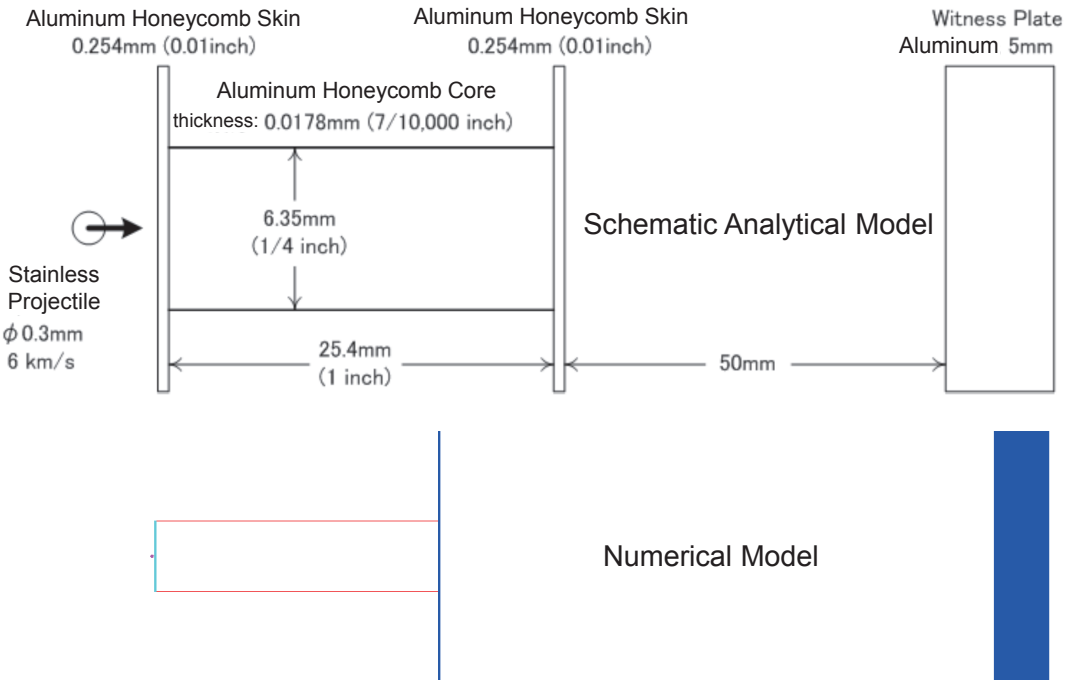
Analysis of Impact on Aluminum Honeycomb

- 0.25 mm-thickness aluminum skin
- 1 inch-thickness and 1/4 inch-cell size aluminum honeycomb
- Internal component (1.6 mm-thickness aluminum, stainless steel and titanium)
- Projectiles' (aluminum or stone) diameter: 0.2 mm
- Assumed to hit on the center of cell for the conservative estimation



Analysis of Impact on Aluminum Honeycomb



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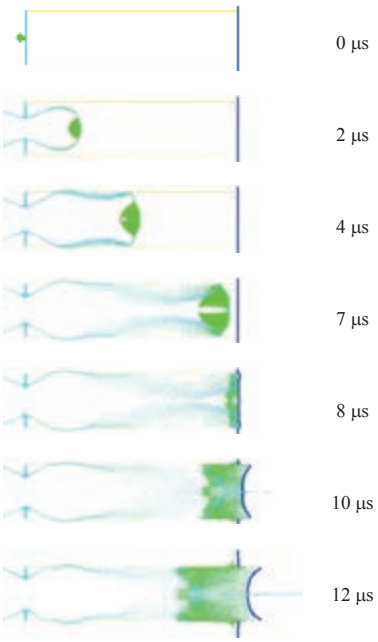
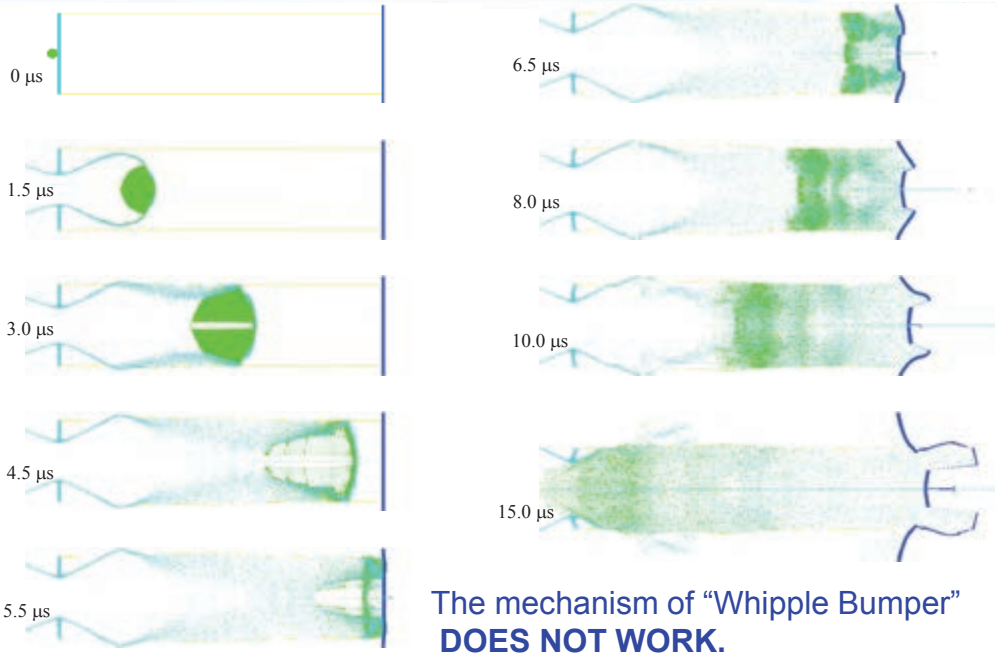
Analysis of Impact on Aluminum Honeycomb



Sequence of impact and perforation process (Alumina, 0.8 mmϕ, 4km/s)

Analysis of Impact on Aluminum Honeycomb



The mechanism of “Whipple Bumper”
DOES NOT WORK.

Sequence of impact and perforation process (Alumina, 0.8 mmϕ, 6 km/s)

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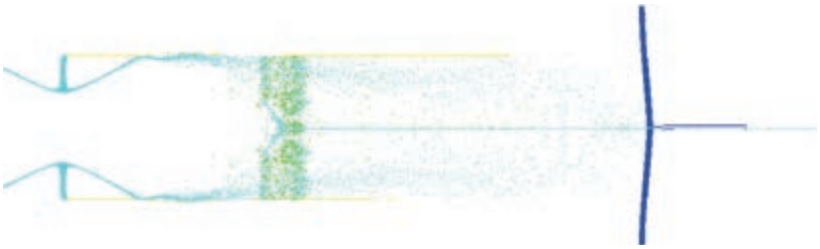
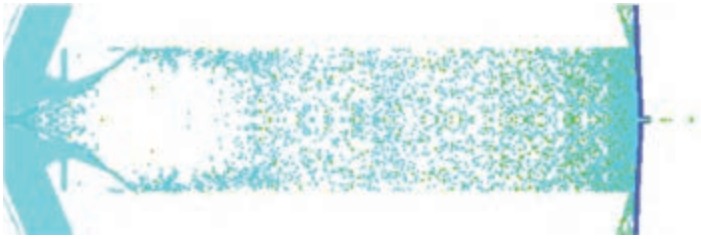
Analysis of Impact on Aluminum Honeycomb

Another problem



Result by Lagrangian method with the numerical erosion.



Result by SPH method.

Projectile: Alumina, 0.4 mmϕ, 6 km/s

CONCLUSIONS

- There are no almighty numerical analysis methods to solve the hypervelocity impact problem for the present protection assessment of spacecraft from the space debris impact.
- It is important to comprehend adequately the feature and characteristic of each numerical method in its merits and demerits, and to apply the best method to the each component in the target problem.

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Acknowledgement

This material contains a number of important numerical results obtained through the activity of preparation of “Design Manual for the Space Debris Protection” for the purpose of standardization of designing and developing satellites and probes by JAXA. Authors do specify the fact, at the same time they would like to acknowledge it gratefully.

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E6

イカロス探査機搭載ダスト検出器「ALADDIN」による地球・金星間の大型宇宙塵分布の直接計測

Direct Measurement of Large Meteoroid Distribution between the Earth and Venus by the ALADDIN Dust Detector onboard the IKAROS Spacecraft

○矢野創, 平井隆之 (JAXA 宇宙科学研究所), 岡本千里 (神戸大学),
藤井雅之(ファムサイエンス), 田中真(東海大学), IKAROS-ALADDIN チーム
○Hajime YANO, Takayuki HIRAI (JAXA/ISAS, Japan), Chisato OKAMOTO (Kobe University, Japan),
Masayuki FUJII (FAM Science), Makoto TANAKA (Tokai University), IKAROS-ALADDIN Team

2010 年 5 月に JAXA が打ち上げたソーラー電力セイル小型実証機「IKAROS」に展開された 0.54 m^2 の有効面積を持つ PVDF 型ダストその場計測器「ALADDIN」は、2010 年 6 月から 2011 年 11 月まで、地球～金星近傍空間を約 1.5 公転しながら、ほぼ連続的に宇宙塵フラックスを計測した。宇宙での実測データは厳密な信号スクリーニングと地上での超高速衝突校正実験を経ることにより、従来は黄道光の散乱光計測でのみ議論が可能だった、内惑星領域における数十ミクロン以上の大型宇宙塵のその場検出に成功した。本講演では、日本初の国産宇宙塵計測器である ALADDIN の機器構成、宇宙空間でのパフォーマンス、軌道上運用実績、検出された宇宙塵分布により明らかになった太陽系内の大型宇宙塵の分布構造とその科学的意義、および本ミッションの教訓を受け継ぐ次世代計測器の構想について論じる。

The ALADDIN (Arrayed Large Area Dust Detector for INterplanetary Space) is the first Japanese-design/built/ calibrated in-situ dust detector successfully operated in space, as an onboard instrument of the IKAROS solar sail demonstrator spacecraft launched in May 2010. With its 0.54 m^2 detection area of the PVDF film, it detected hundreds of large (>10-micron) micrometeoroids in the interplanetary space between the Earth and Venus, which were only observable as light scattering of the zodiacal cloud in the past, for 1.5 years, after careful data screening and ground impact calibration experiments. In this presentation, we discuss ALADDIN's instrumentation, in-flight performance, operational events, dust structure in the inner planetary region revealed by the large micrometeoroid detection and its scientific implications, as well as future plans of next generation meteoroid and debris detectors with heritages and lessons from ALADDIN.

図 イカロス探査機に搭載された ALADDIN のシステム構成

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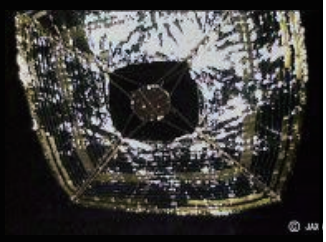
The 6th JAXA Space Debris Workshop

Direct Measurement of Large Meteoroid Distribution between the Earth and Venus by the ALADDIN Dust Detector onboard the IKAROS Spacecraft

イカロス探査機搭載ダスト検出器「ALADDIN」による地球・金星間の大型宇宙塵分布の直接計測

December 18th, 2014
ARD/JAXA, Chofu, Tokyo, Japan



Hajime YANO[1,2],
Takayuki HIRAI[1], Chisato OKMAOTO[3], Masayuki FUJII[4], Makoto TANAKA[5], and IKAROS-ALADDIN Team
1JAXA/ISAS; 2 JAXA/JSPEC; 3 Kobe University, 4 FAM Science, 5 Tokai University

○矢野創，平井隆之（JAXA/ISAS），岡本千里（神戸大学），藤井雅之（ファムサイエンス），
田中真（東海大学），IKAROS-ALADDINチーム

Agenda

- Dust Flux near the Earth and at 1 AU
- IKAROS, a Solar Sail Demonstrator
- ALADDIN System and Operation
- Initial Data Analysis
- Scientific Discovery (1) near Earth
- Scientific Discovery (2) near Venus
- Future Prospects
- Summary

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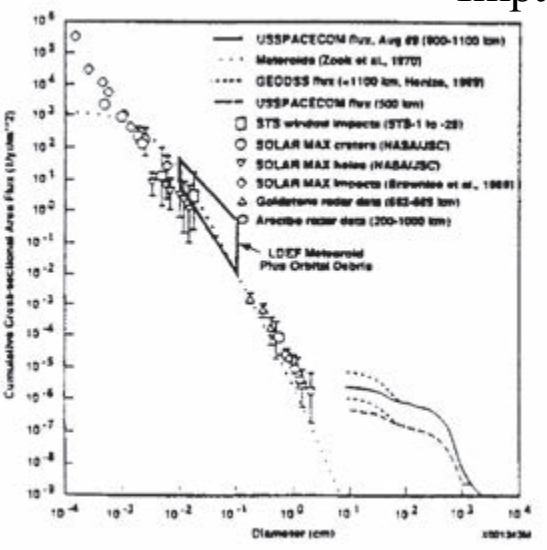
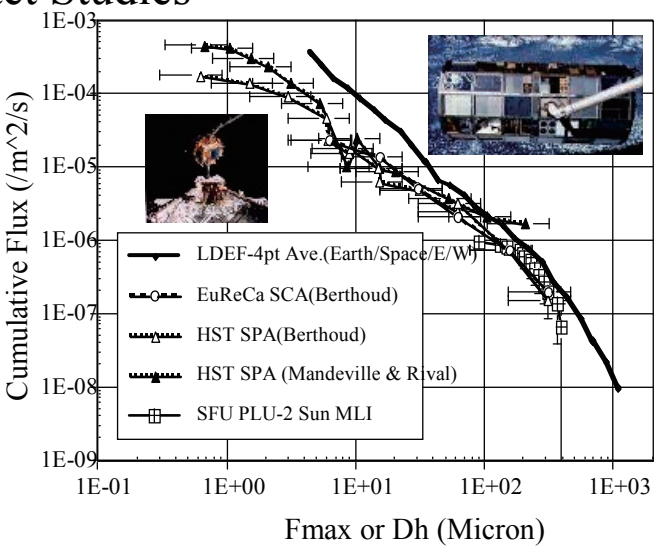
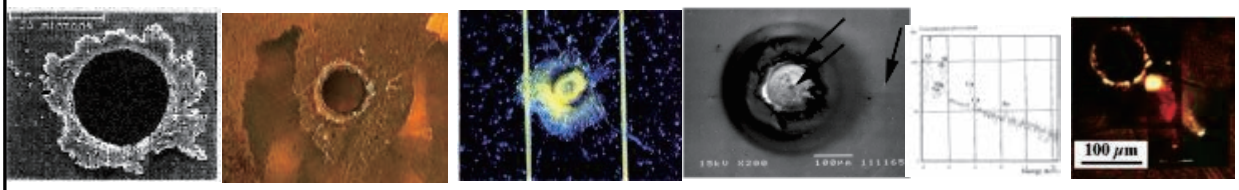
Direct Static Flux Measurements at 1 AU via Spacecraft Impact Studies



(Loftus & Potter, 1990)



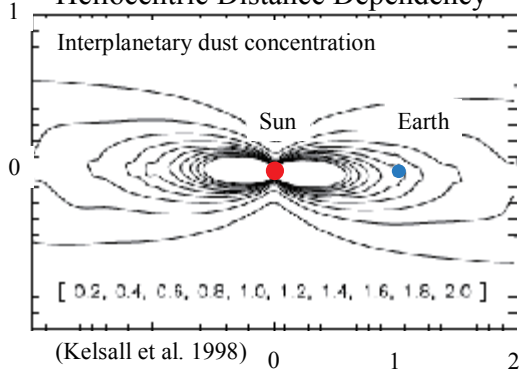
(Yano, 1995)



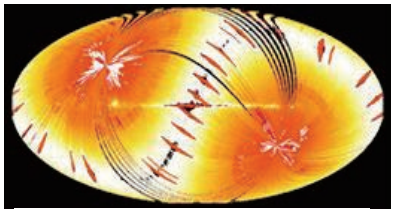
(All Impact Images courtesy: H. Yano)

Scientific Objectives: Dust Flux as a Function of the Heliocentric Distance and Local Structure nearby Planets in the Inner Planetary Regions

Heliocentric Distance Dependency

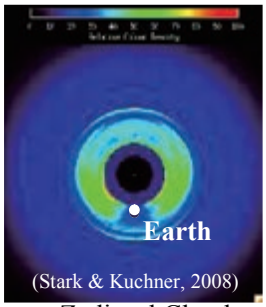


Zodiacal light observed by AKARI

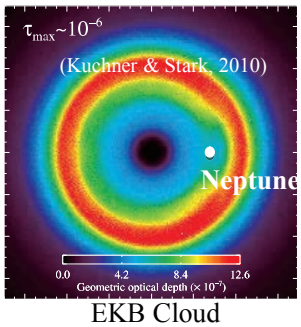


(© JAXA/ISAS Akari Team)

Local Dust Flux Enhancements Predicted by Numerical Models



Zodiacal Cloud
(Inner Region)

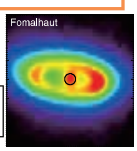


EKB Cloud
(Outer Region)

Validation by optical observation and in-situ measurement

e.g. IKAROS & Solar Power Sail

e.g. New Horizons



Exo-debris Disk Model

4

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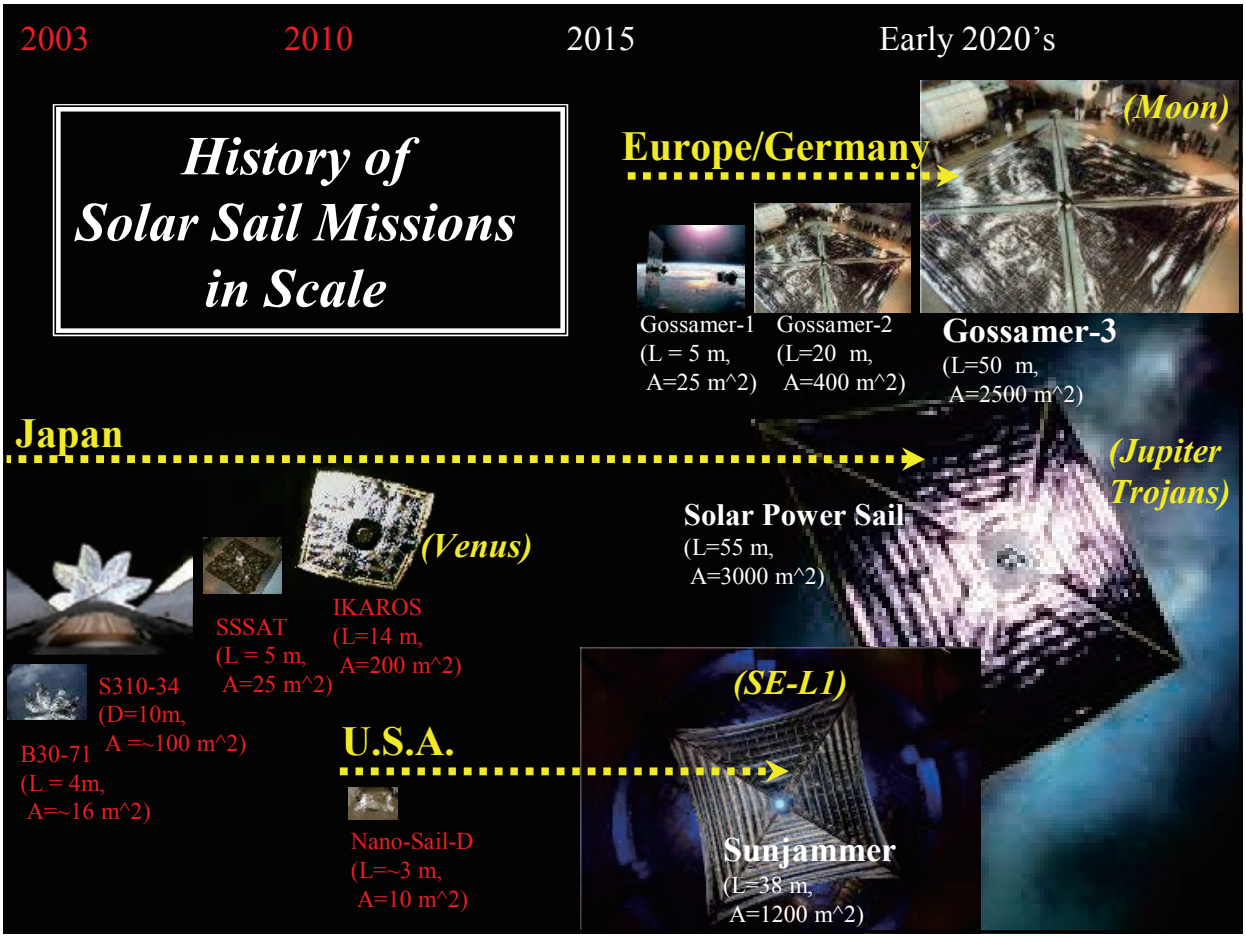
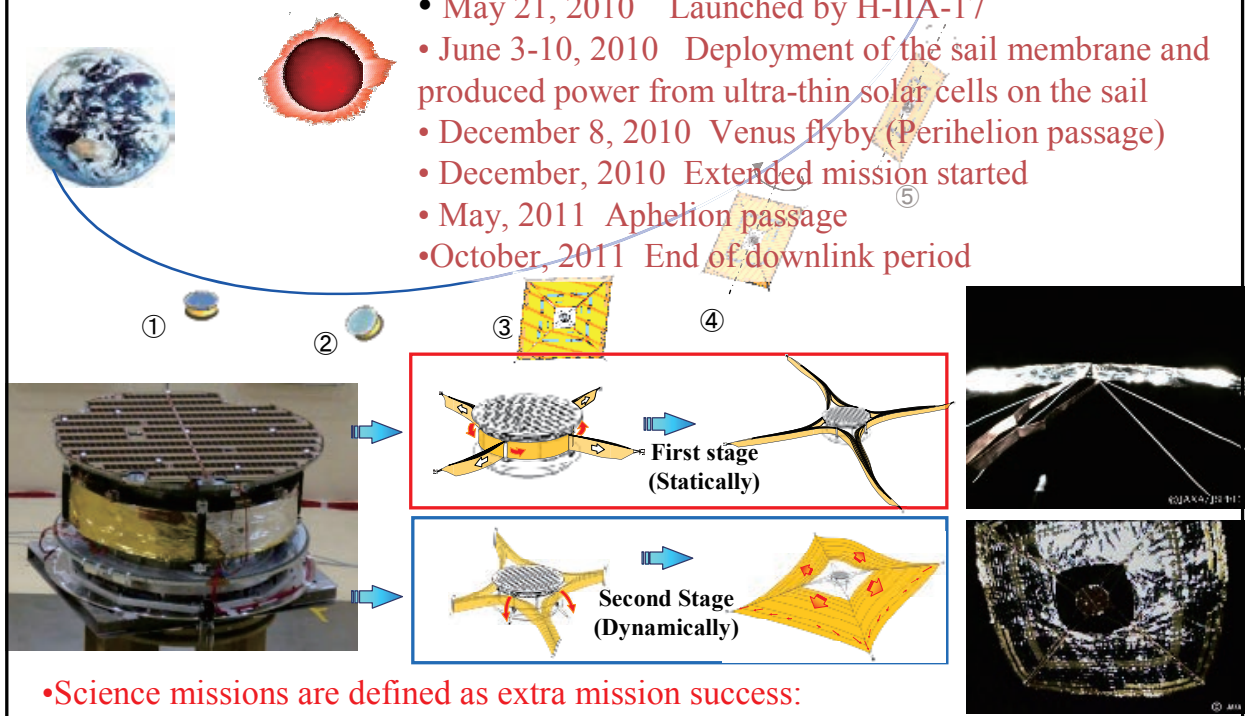


IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun)

- May 21, 2010 Launched by H-IIA-17
- June 3-10, 2010 Deployment of the sail membrane and produced power from ultra-thin solar cells on the sail
- December 8, 2010 Venus flyby (Perihelion passage)
- December, 2010 Extended mission started
- May, 2011 Aphelion passage
- October, 2011 End of downlink period



•Science missions are defined as extra mission success:
GAP (high energy astronomy) and **ALADDIN (solar system science)**

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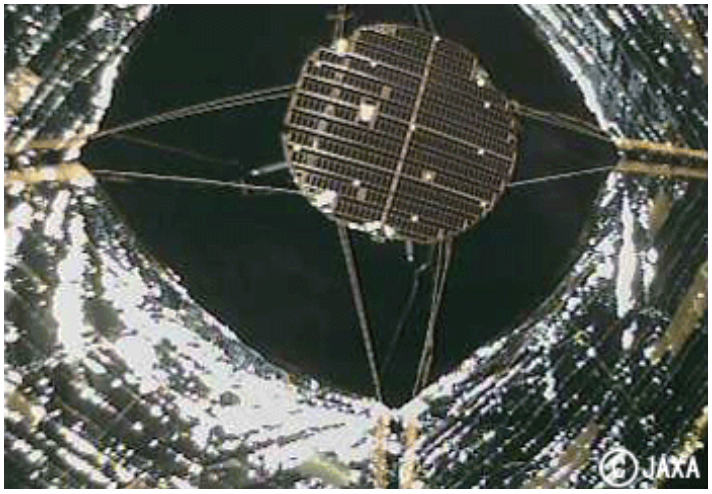
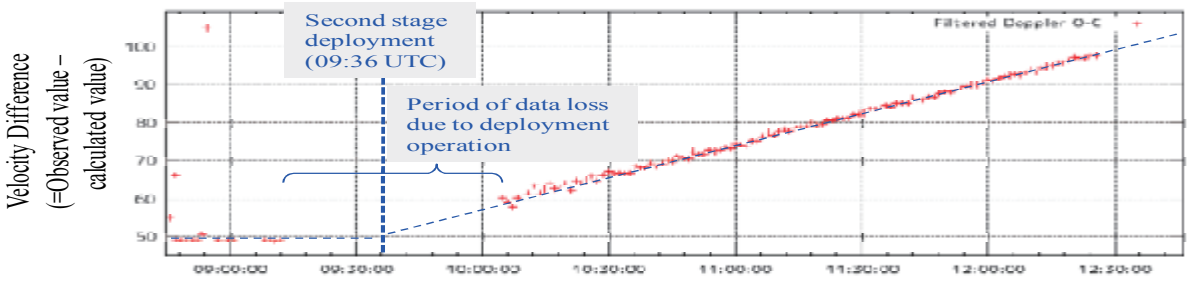
The Successful Deployment and Solar Photon Acceleration of IKAROS in Interplanetary Space in June 2010





(Mori, Tsuda, et al., 2011)

IKAROS Trajectory in the Inner Planetary Region Compared with Those of the Spacecraft with Dust Counters : Helios, Galileo, IKAROS

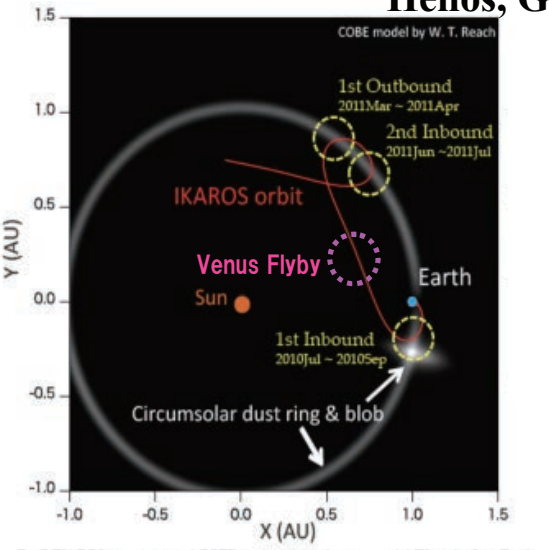
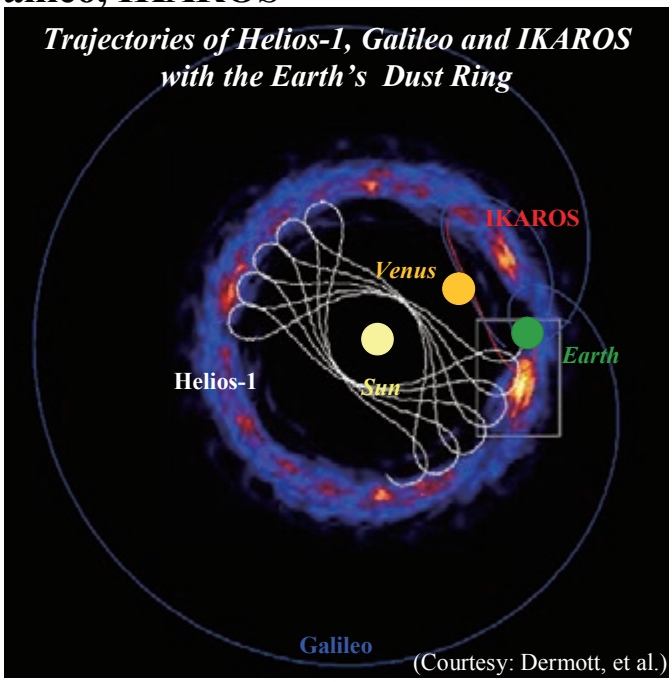


Fig.5 IKAROS trajectory and COBE cross section density model [2] in the Sun-Earth line fixed rotating frame. IKAROS entered into CDA region three times (the first one is the most dense region, blob and ring).

(Hirai, 2014)



(Courtesy: Dermott, et al.)

IKAROS passed the enhancement region of the Earth's circumsolar dust ring right after its launch

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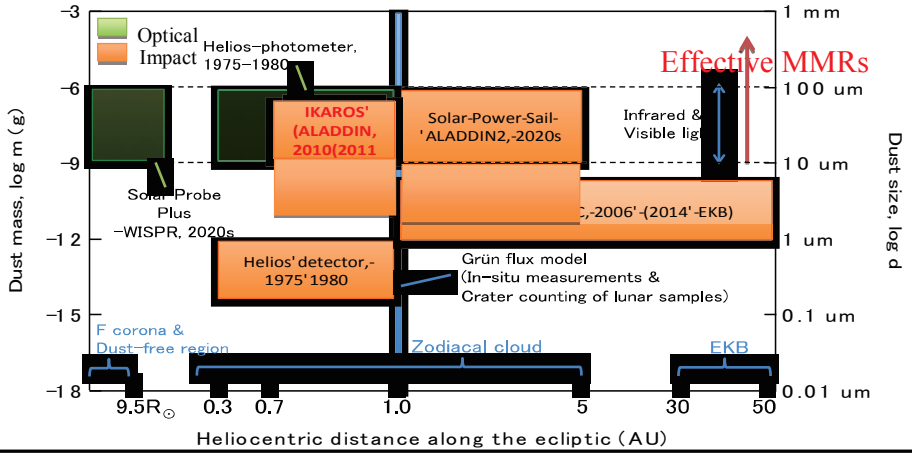
ALADDIN (Arrayed Large-Area Dust Detectors in Interplanetary space) onboard IKAROS

<Mission Objectives>

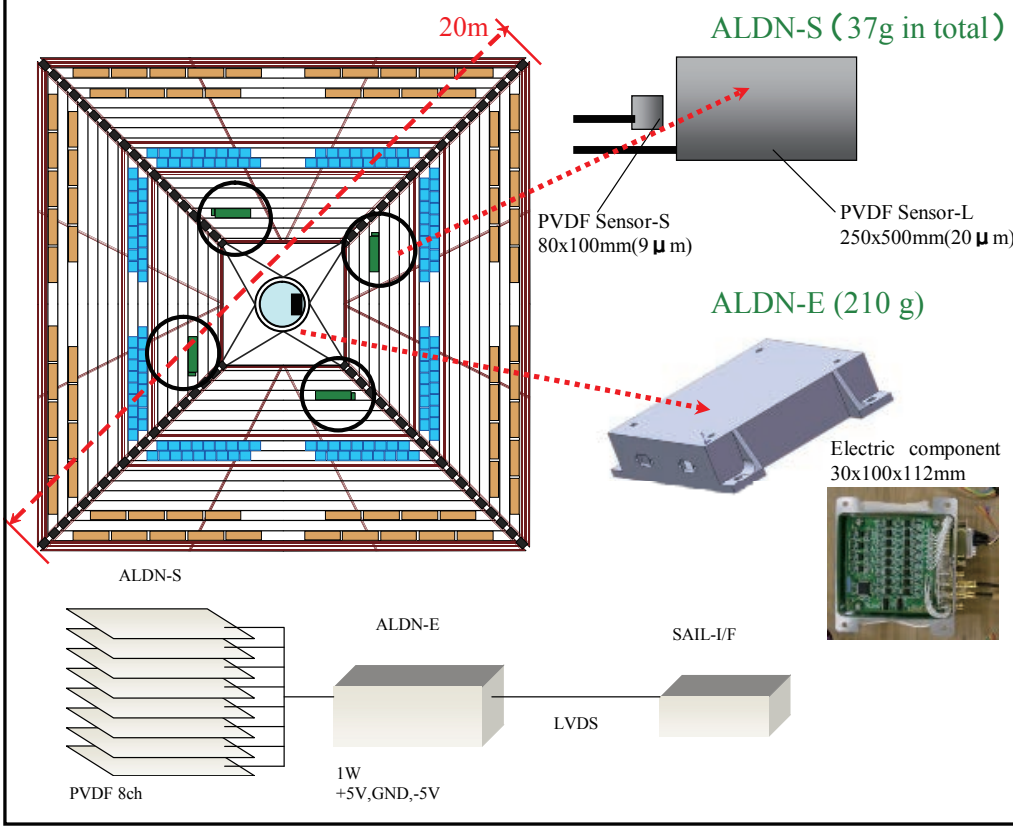
(1) Engineering demonstration of Japan's first and the world's largest dust detector to function in deep space, as a precursor of future outer planet exploration

(2) Measure dust flux variation in heliocentric distance inside 1 AU with statistically reliable data

Comparison with Past Dust Measurements



IKAROS-ALLADIN System



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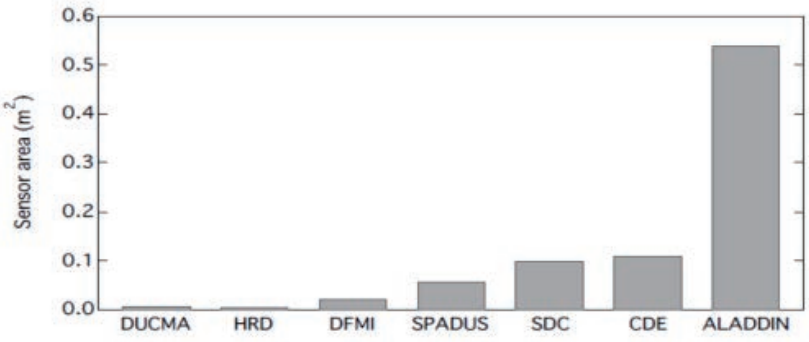
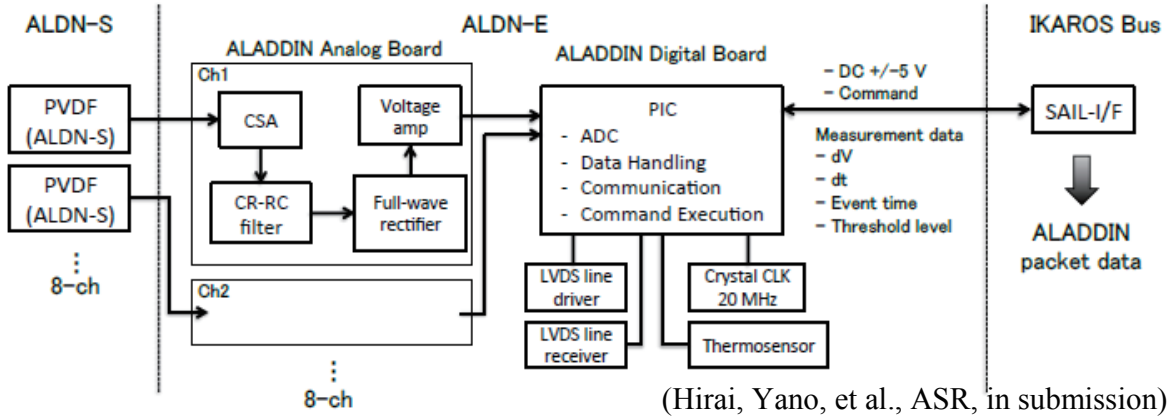
Sensor Area Comparison among Past Dust Detectors



ALDN-S/E System Block Diagram



(Hirai, Yano, et al., ASR, in submission)

Operation Record of IKARS-ALADDIN in 2010.06~2011.10.

<2010>

5/21 Launch

6/21 ALDN-E switched on、Started the initial operation

6/21-30 Health check and detection sensitivity validation of ALDN−E and -S

6/22 Detection of the first dust impact

6/30~ Nominal operation started; continuous measurement without RCD and SAP operations to avoid interference noise and out-of-communication periods

12/8 Flyby of Venus (Perihelion passage)

12-end Nominal operation ended and extended mission started

<2011>

4/27~5-end Aphelion passage

6/~ The second round of inbound cruising measurement started

10/ The last downlink of the ALADDIN data due to telecomm resource limit

<2012>

9/ The first resuming of telecom and health check after hibernation

<2013>

3/31 Official closure of the IKAROS project

6/ The second resuming of telecom and health check after hibernation

12

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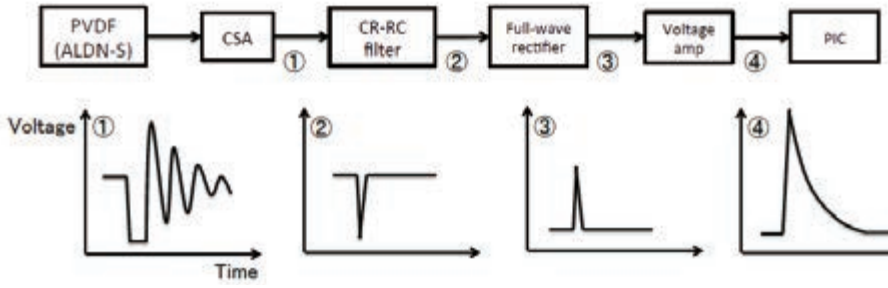
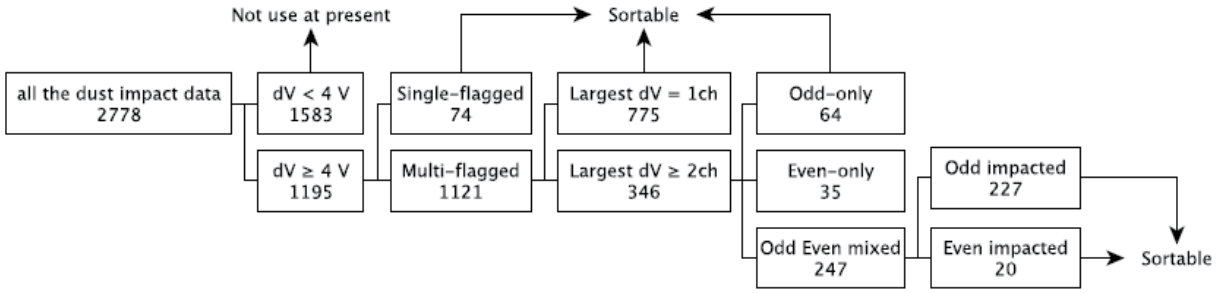
PVDF Impact Data Processing

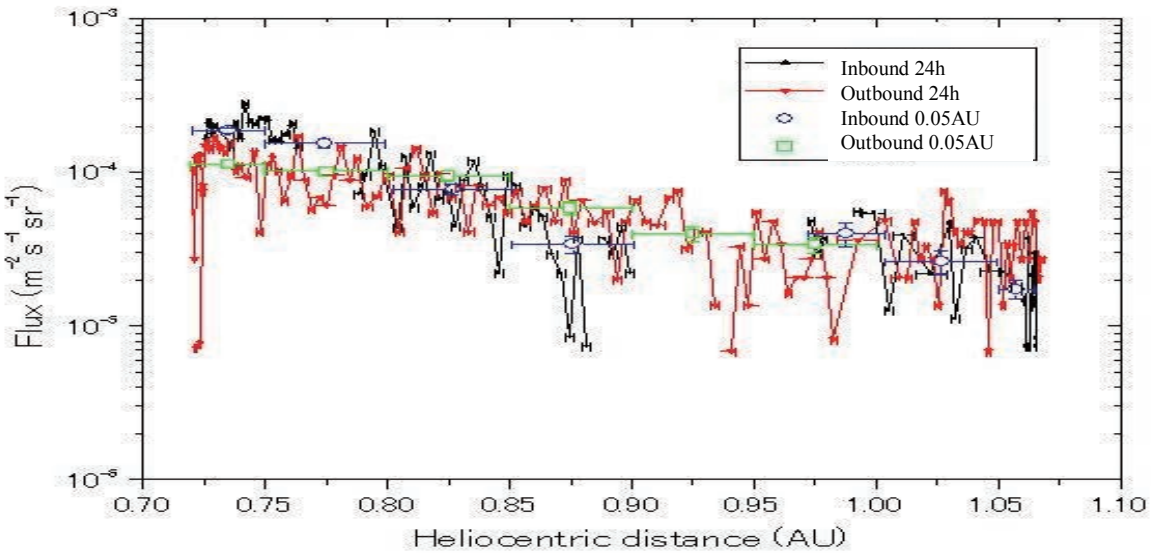


ALDN-S Acquired Data Screening & Deduction



(Hirai, Yano, et al., ASR, in submission)

Fine Temporal Measurements of Round-Trip Flux of IKAROS Trajectories between the Perihelion and the Aphelion in 24-hours Bin



(Yano, et al., 2011)

14

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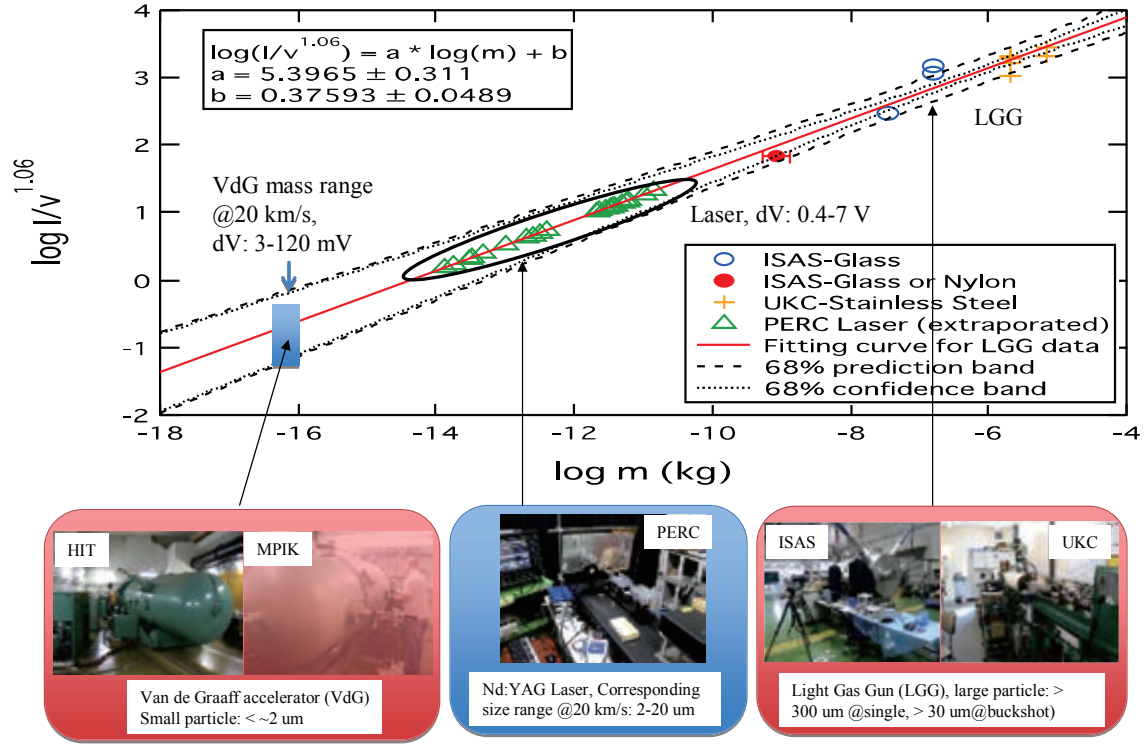
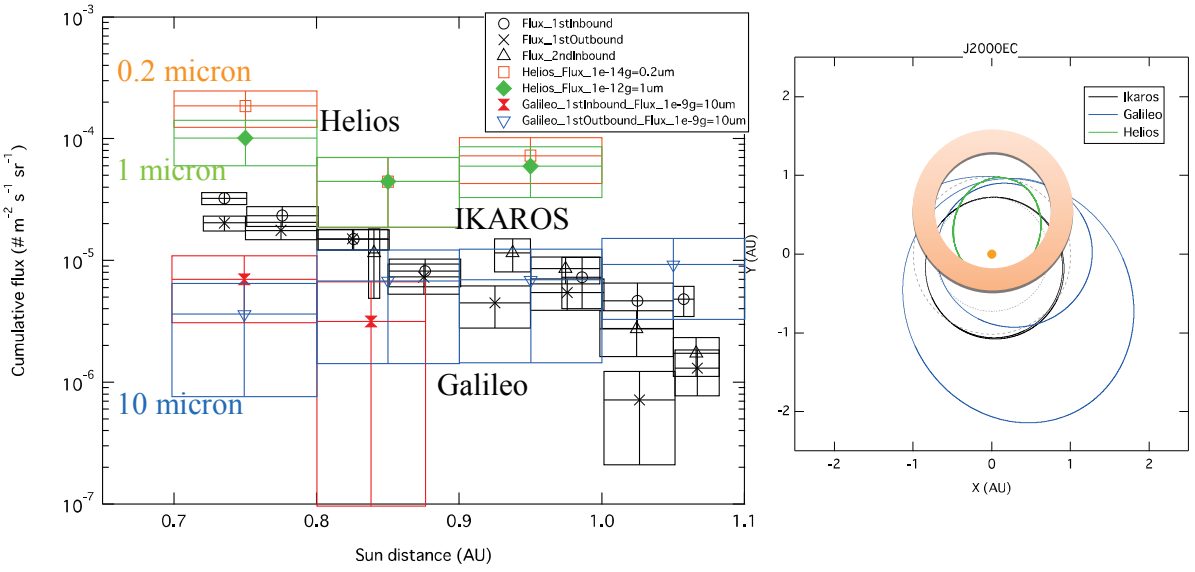
Wide-Range, Integrated Hypervelocity Impact Calibration Curve for ALADDIN PVDF Sensors



(Hirai, Yano, et al., PSS, 2014) 15

Flux Comparison of IKAROS-ALADDIN with Past Data in Different Size Range (HELIOS, Galileo) inside 1 AU



•ALDN Flux Data only selected for the dVmax > 4 V:
➔ Equivalent to 10 micron order impacts for inbound near Earth.

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Dust Flux Enhancement at the Earth's Trailing Blob

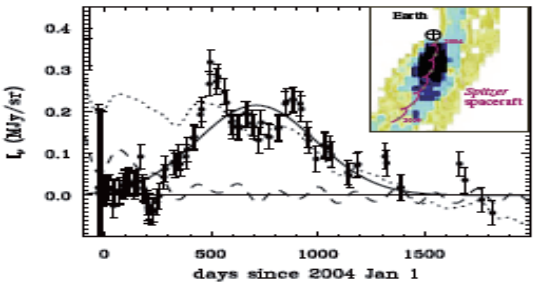
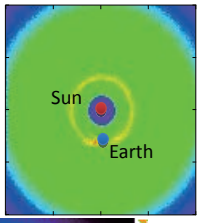


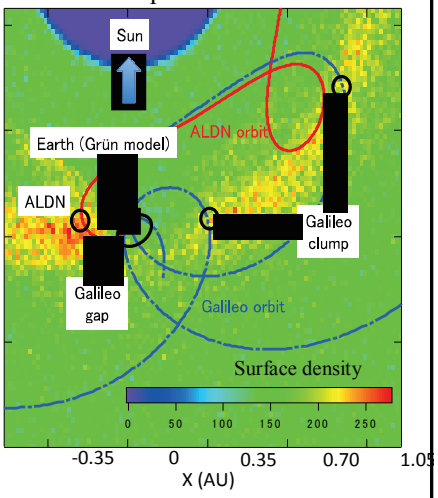
Fig.3 Brightness enhancement in the trailing dust blob measured by the Spitzer [3].

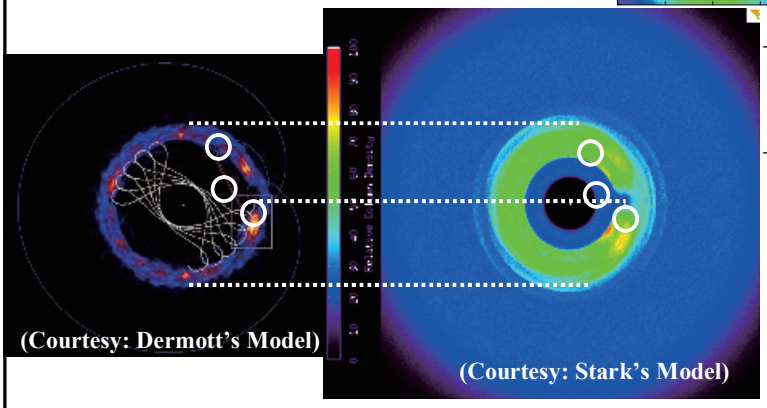
(Reach, et al., 2010)

Trajectory Comparison among the Earth's Mean Motion Resonance Dust Ring Models by Dermott et al. and Stark respectively

Test particle size = 10 micron

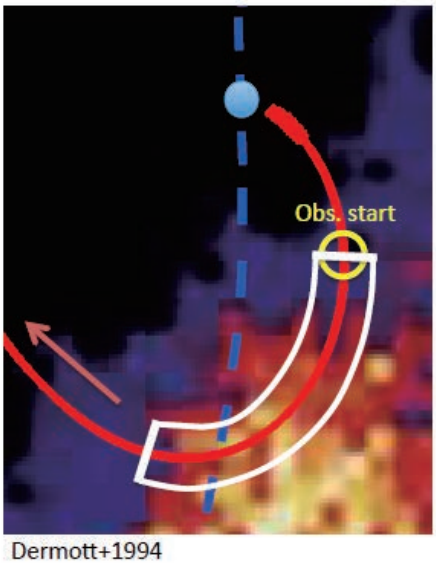




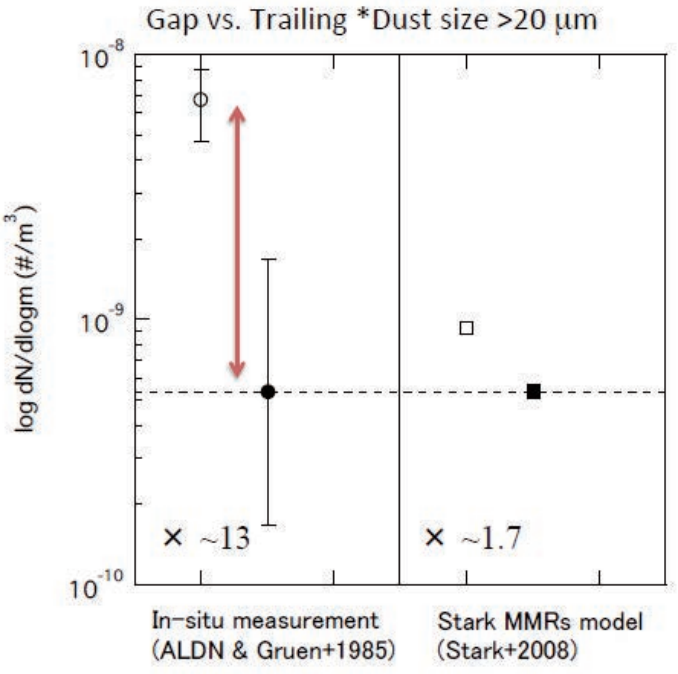


(Hirai, , 2014) (Yano, et al., 2014)

IKAROS Trajectory through the Earth's Circumsolar Dust Ring Blob Confirmed by ALADDIN



Dermott+1994



(Hirai and Yano, 2014)

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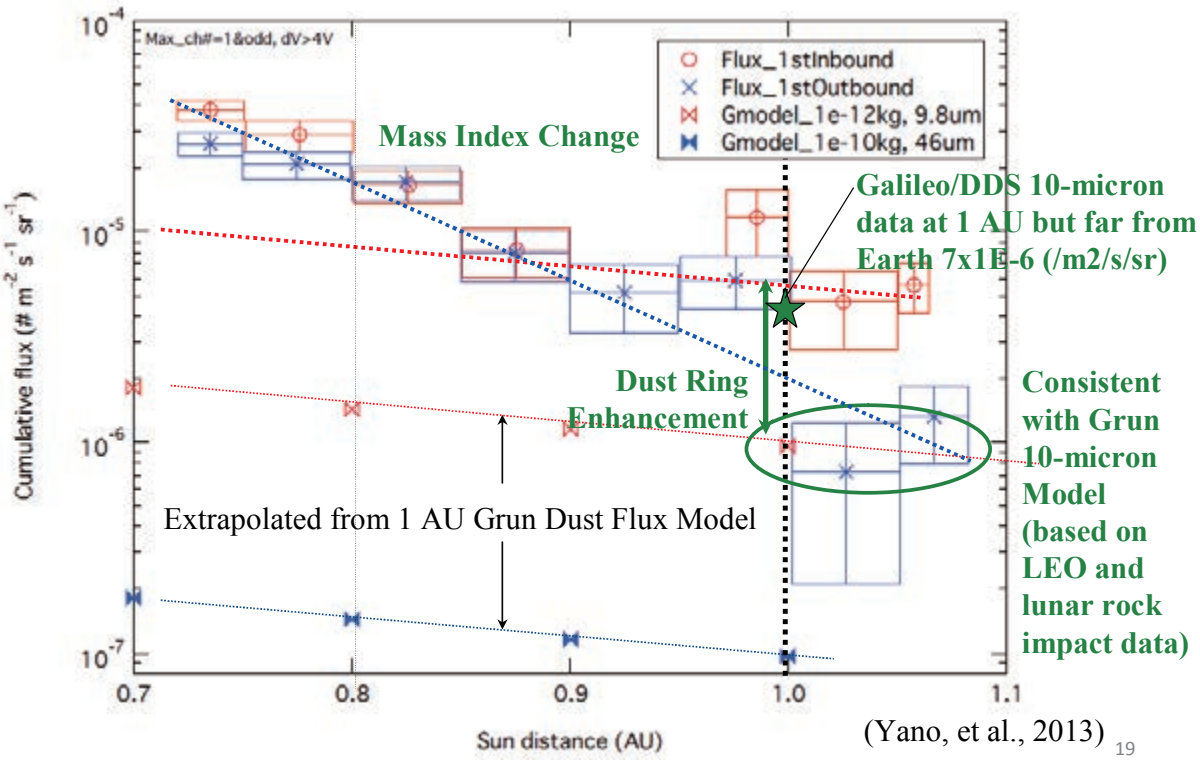
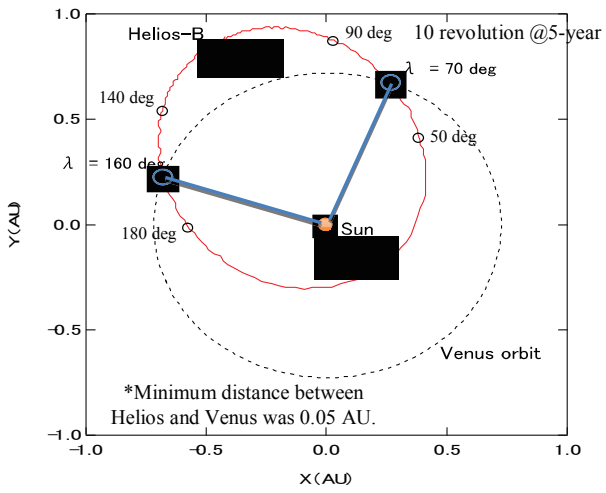
Direct Confirmation of Dust Ring Enhancement at the Earth's Trailing Blob

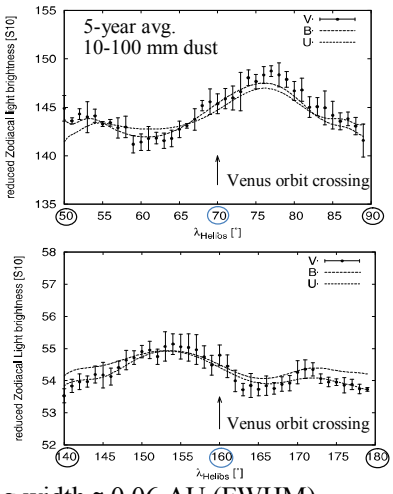


(Yano, et al., 2013)

Venus Circumsolar Dust Ring Detected by Optical Scattering by Helios-B and More Recently by STEREO

Cf. Optical observation by Helios-B photometer (Leinert&Moster, 2007)





Ring width ≈ 0.06 AU (FWHM)

(Also by Jones et al., Nature, 2014)

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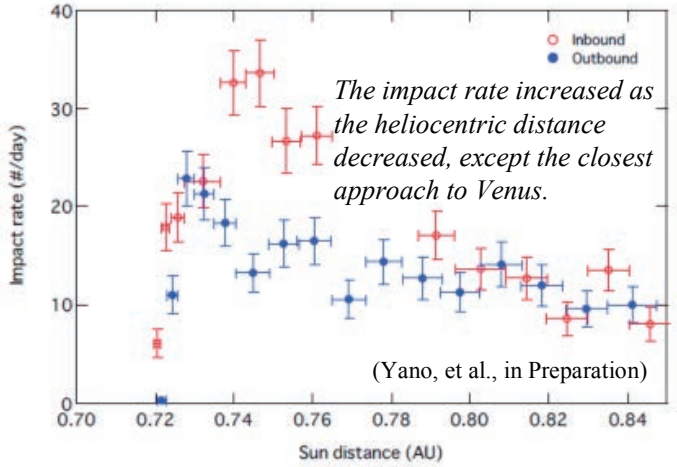
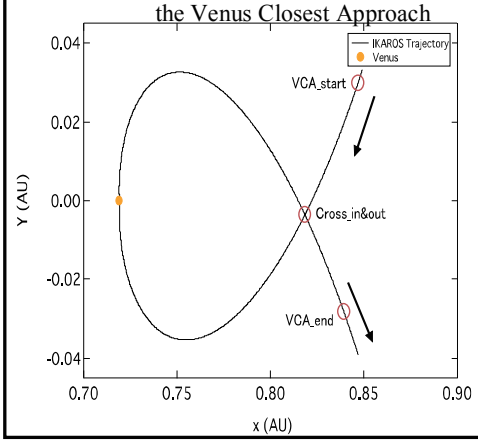
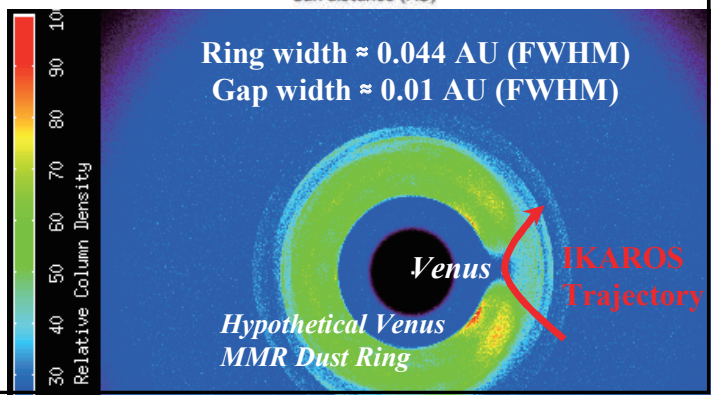
Impact Rate of IKAROS-ALADDIN near Venus



IKAROS Trajectory near the Venus Closest Approach





The S&K Model Predicts that Mean Motion Resonance near 1 AU Triggers Impact Fragmentation

Venus Earth

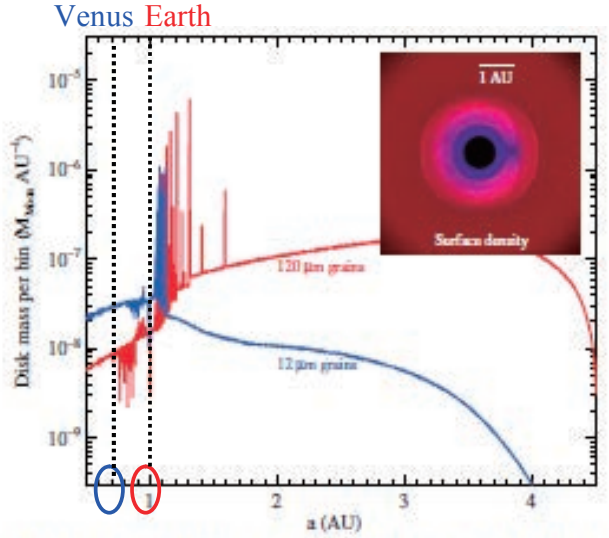
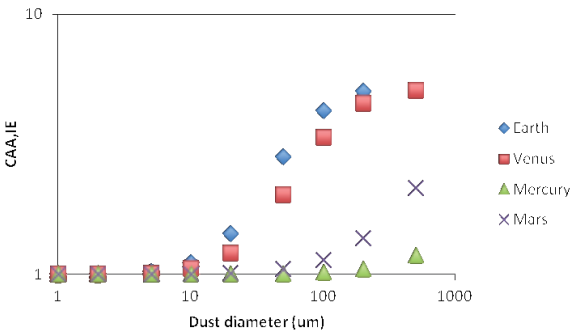


Figure 9. Disk mass (in Lunar masses) as a function of semimajor axis for a disk of fragmenting grains in the presence of an Earth-mass planet at 1 AU orbiting the Sun. The inset false-color image shows the face-on surface density of the disk. MMRs near 1 AU trigger fragmentation, a process which may explain the population of small warm dust interior to Fomalhaut's resolved ring structure (Stapelfeldt et al. 2004).

(Stark and Kuchner, 2009)

➔ Impact-induced, fragmented small meteoroids are expected to contribute flux enhancements inside the circumsolar dust ring near 1 AU

CAA,IE at 4 planets



➔ Surface Density Contrast Efficiency by Planets and Dust Size

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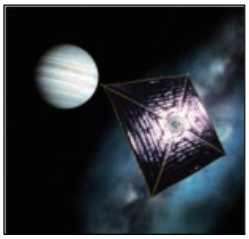
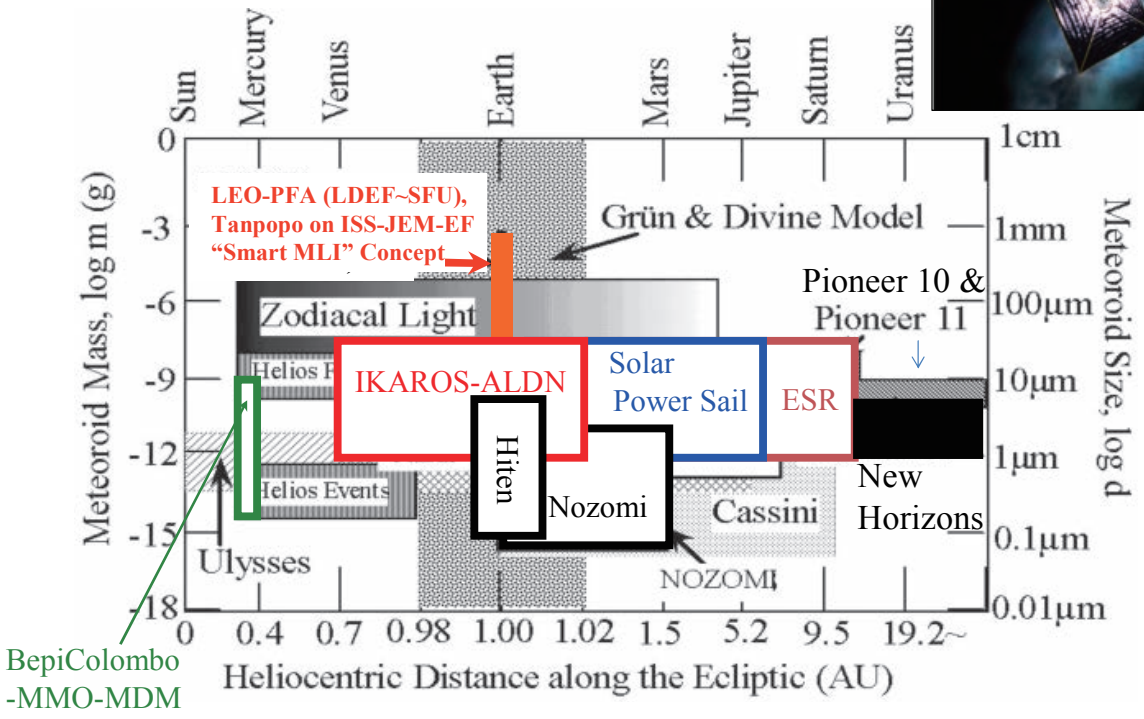
Meteoroid Measurement Opportunities by Japanese Space Exploration and Experiments





Summary

• ALADDIN is Japan's first interplanetary dust detector composed of 8 channel PVDF sensors deployed on the thin sail membrane at 0.54 m^2, the largest ever detection area in the history of cosmic dust detection.

•ALADDIN was successfully launched onboard the IKAROS solar sail spacecraft in May 2010 and recorded >2800 dust impact detections of >1-2 micron on the anti-Sun face in the Earth-Venus space (0.73-1.06 AU), between June 2010 and October 2011.

•ALADDIN results directly measured statistically significant increase of dust flux both by heliocentric distance decrease and the presence of circumsolar structure of 10-micron order dust for the Earth and Venus as well as the gap regions nearby the planets, which require a new dust model compliant with MMR dust ring and collisional evolutions.

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F1

京都大学におけるスペースデブリへの取り組み
～軌道・観測・低減～
Space Debris Related Research Activities at Kyoto University

山川 宏（京都大学）
Hiroshi Yamakawa (Kyoto University)

京都大学におけるスペースデブリへの取組みについて概要を述べる。軌道に関しては、微小なデブリに注目して、その軌道推移について検討しており、その初期検討結果について述べる。また、京都大学生存圏研究所のMU（Middle and Upper Atmosphere）レーダを用いたデブリ観測の可能性について、検討を開始しており、その概要について述べる。最後に、スペースデブリの低減に向けて、デブリを積極的に帯電させることで、軌道を変化させる可能性について、概要を述べる。

Space debris related research activities at Kyoto University are outlined in the presentation. As for the space debris trajectories, we pay attention to very small-scale debris clouds and their trajectory evolution. In terms of observation, we started observing large space debris using Kyoto University MU (Middle and Upper Atmosphere) Radar, whose summary will be presented. Finally, the possibility of mitigating space debris by positive charging will be discussed.

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京都大学におけるスペースデブリへの取り組み ～軌道・観測・低減～

Space Debris Related Research Activities at Kyoto University

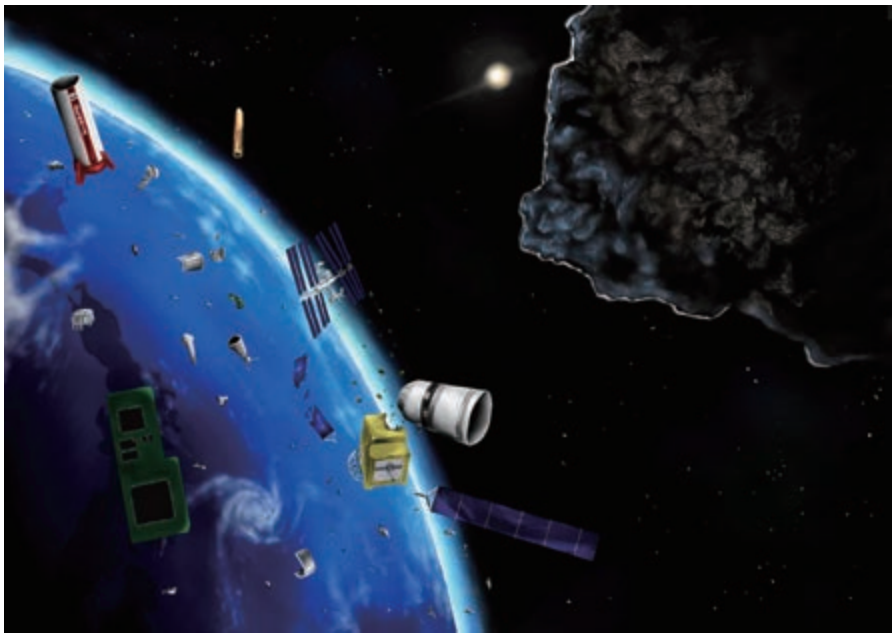
Hiroshi Yamakawa

Kyoto University

6th Space Debris Workshop

December 19, 2014, JAXA

Space Debris and Asteroids



京都大学 山口皓平氏

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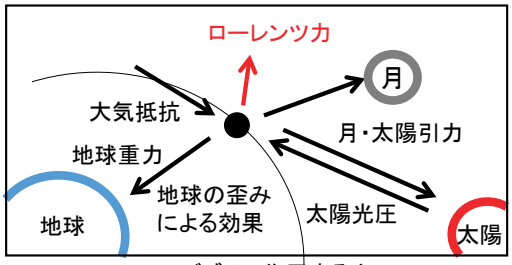
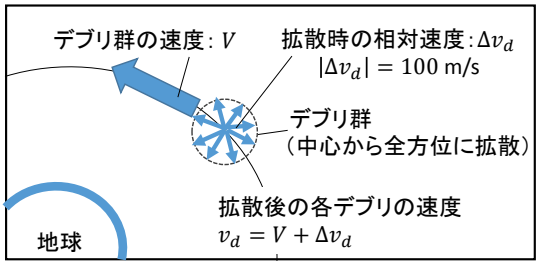
Charging Effect on Space Debris Orbital Evolution

1. 単一デブリの軌道シミュレーション



デブリに作用する力

2. デブリ群の軌道シミュレーション



拡散するデブリ群の様子

京都大学　植田有希子氏、増成一樹氏

Space Debris Observation

～Kyoto University MU Radar～

http://www.rish.kyoto-u.ac.jp/DCRP/MU.html

http://www.rish.kyoto-u.ac.jp/~mu/detail.html

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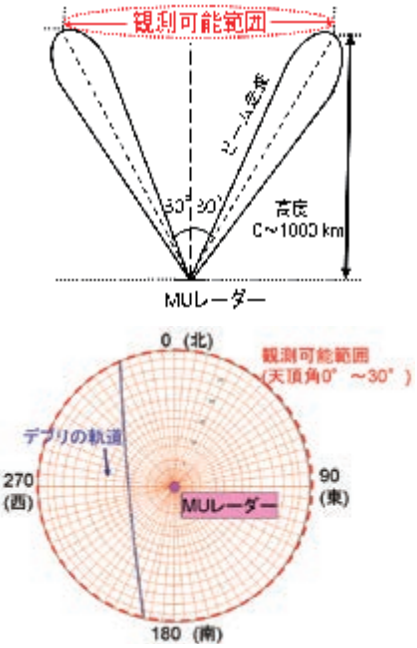
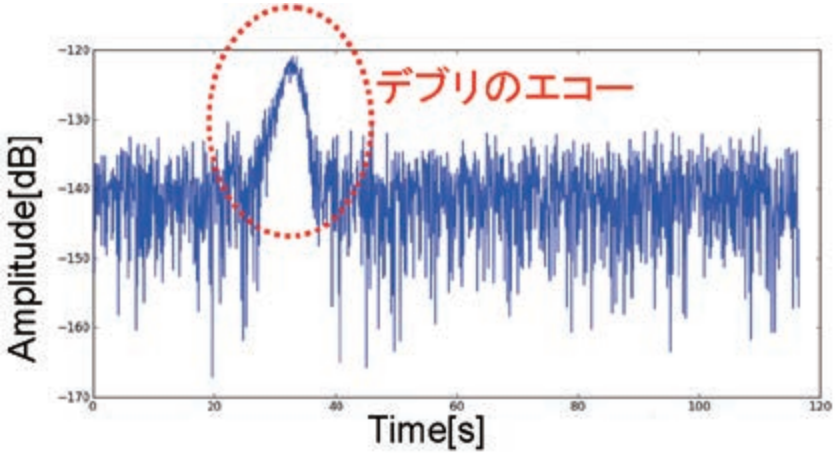
Space Debris Observation by MU Radar

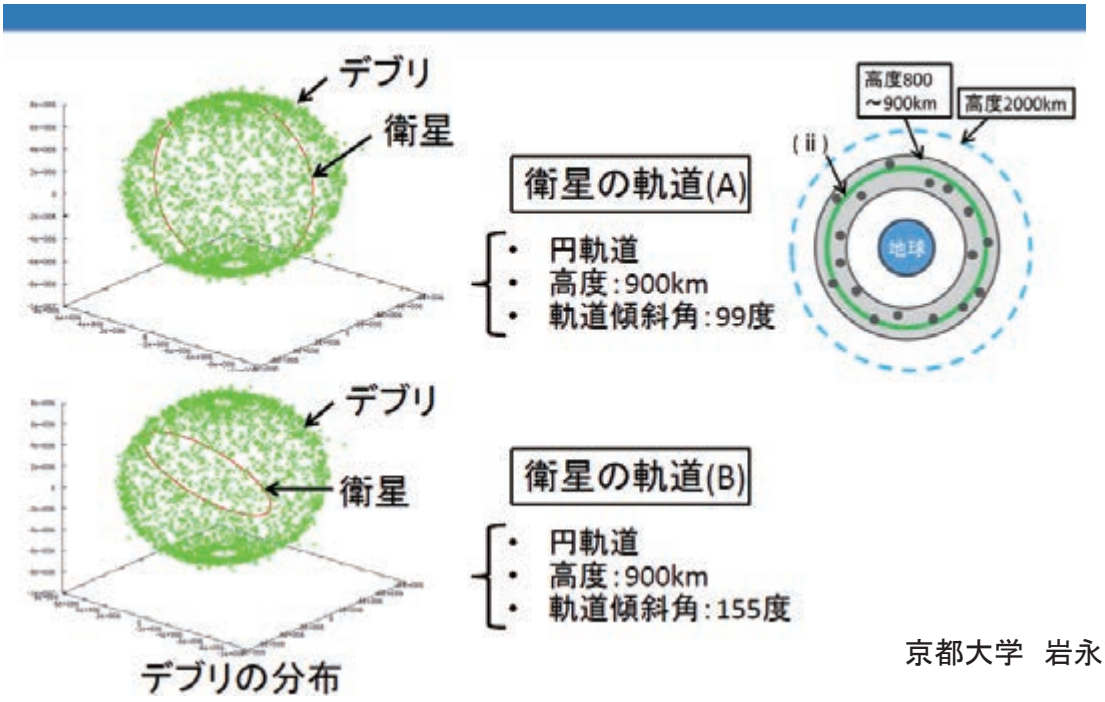




京都大学

河原淳人氏、増成 一樹氏、岩堀太紀氏

Space Debris On-Orbit Observatory Concept



京都大学 岩永直也氏

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Positive Charging of Satellites and Space Debris

スペースデブリに接近、帯電機器（電子エミッタなど）を取り付ける

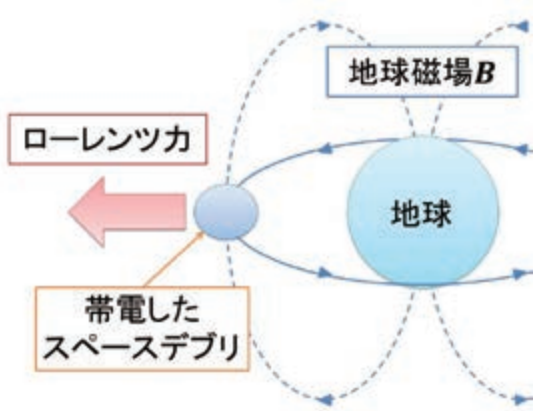
↓

帯電機器の動作によりデブリを帯電させる

↓

地球磁場との相互作用によるローレンツ力により軌道変更、衝突回避

† J. F. FENNELL et al. “A Review of SCATHA Satellite Results: Charging and Discharging”



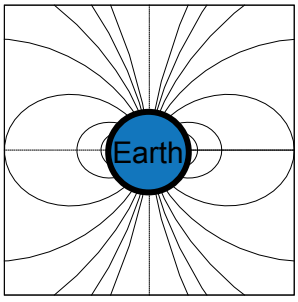
京都大学　星賢人氏 7

Space Debris & Satellite Orbit Simulation Model with Lorentz Force

$$\vec{F} = q(\vec{v} - \omega_E \vec{n} \times \vec{r}) \times \vec{B} + \vec{F}_{AD} + \vec{F}_G$$

q :帯電量(制御変数) $\vec{v}$:速度 $\vec{B}$:磁束密度

$\omega_E \vec{n}$:自転角運動量ベクトル



大気抗力　$\overrightarrow{F_{AD}} = -\dfrac{\rho(z) C_D S |\vec{v}|}{2} \vec{v}$

重力　$\vec{F}_G = -m \dfrac{MG}{r^3} \vec{r}$

磁場モデル：ダイポール磁場　$\vec{B} = \dfrac{B_0}{r^3} \left[3(\hat{z})\hat{r} - \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \right]$

京都大学　赤司陽介氏、中宮賢樹氏

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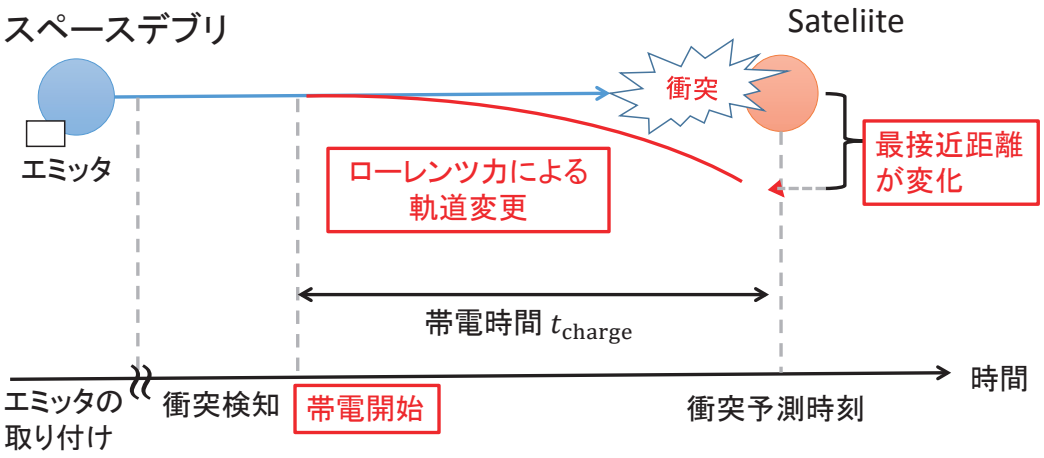
Debris Orbit Deviation by Positive Charging to Avoid Collision



京都大学 池田成臣氏

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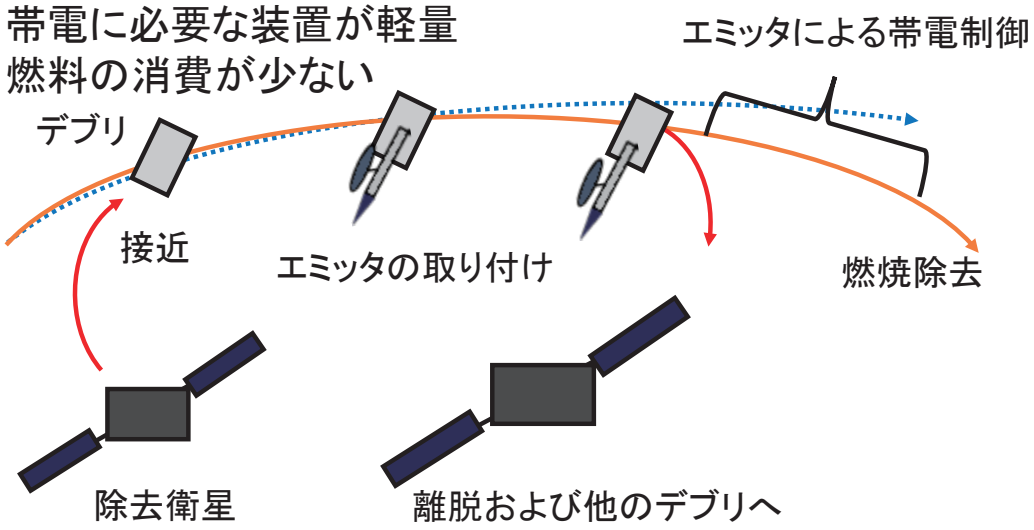
Debris Mitigation by Positive Charging

- 帯電に必要な装置が軽量
- 燃料の消費が少ない



京都大学 赤司陽介氏、中宮賢樹氏

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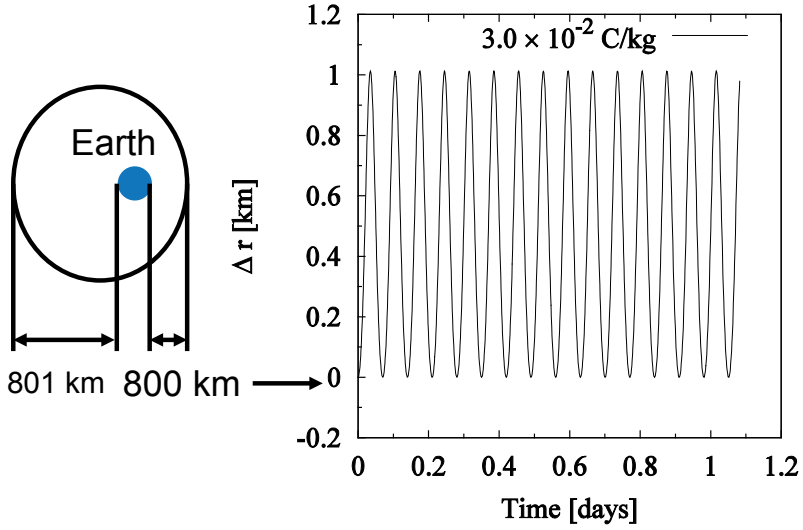
Orbital Evolution
~ Constant Charge Amount Case ~

周期的に、しかも、
わずかに高度が
変化する程度

一定帯電によるデブ
リ除去は困難

帯電量の制御を行
うことでデブリ除去
実現を目指す



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F2

GEO デブリの画像処理及び光度変動

Image-processing and light curve of orbital objects around GEO

○小田寛, 黒崎裕久, 柳沢俊史(JAXA), 田川真(九大)
○Hiroshi ODA, Hirohisa KUROSAKI, Toshifumi YANAGISAWA (JAXA),
Makoto TAGAWA (Kyushu Univ.)

スペースデブリ光学観測の画像処理、検出手法、および検出物体の光度変動の解析結果について報告する。 観測は地平座標固定モード(静止軌道物体は画像内で静止)で行い、一領域につき露光時間 3 秒で 32 枚撮像したものを 1 データセットとした。これらの画像に対して直線運動検出法を適用することで移動物体を検出し、検出された移動物体に対し測光を行い光度変動を調べた。その結果、検出物体が回転している可能性を示唆する光度変動を示すものが多数確認された。本講演ではこれらの解析結果について報告する。また、スペースデブリの回転を誘起させる機構についても議論する。

We report on image-processing, detection and light curve of space debris around the geosynchronous Earth orbit (GEO). In GEO survey observation, we employ the horizontal coordinate system, and set the exposure time to be 3 seconds. A dataset of an observation region consists of 32 successive light frames. We detect moving objects by applying the uniform linear motion detection method to the dataset, and perform photometry on the images to investigate the light curve. As a result, we found that a lot of the detected objects show the time variation in the light curve which provides information on the rotational state of the detected object. We also discuss the cause of the rotation of orbital objects.

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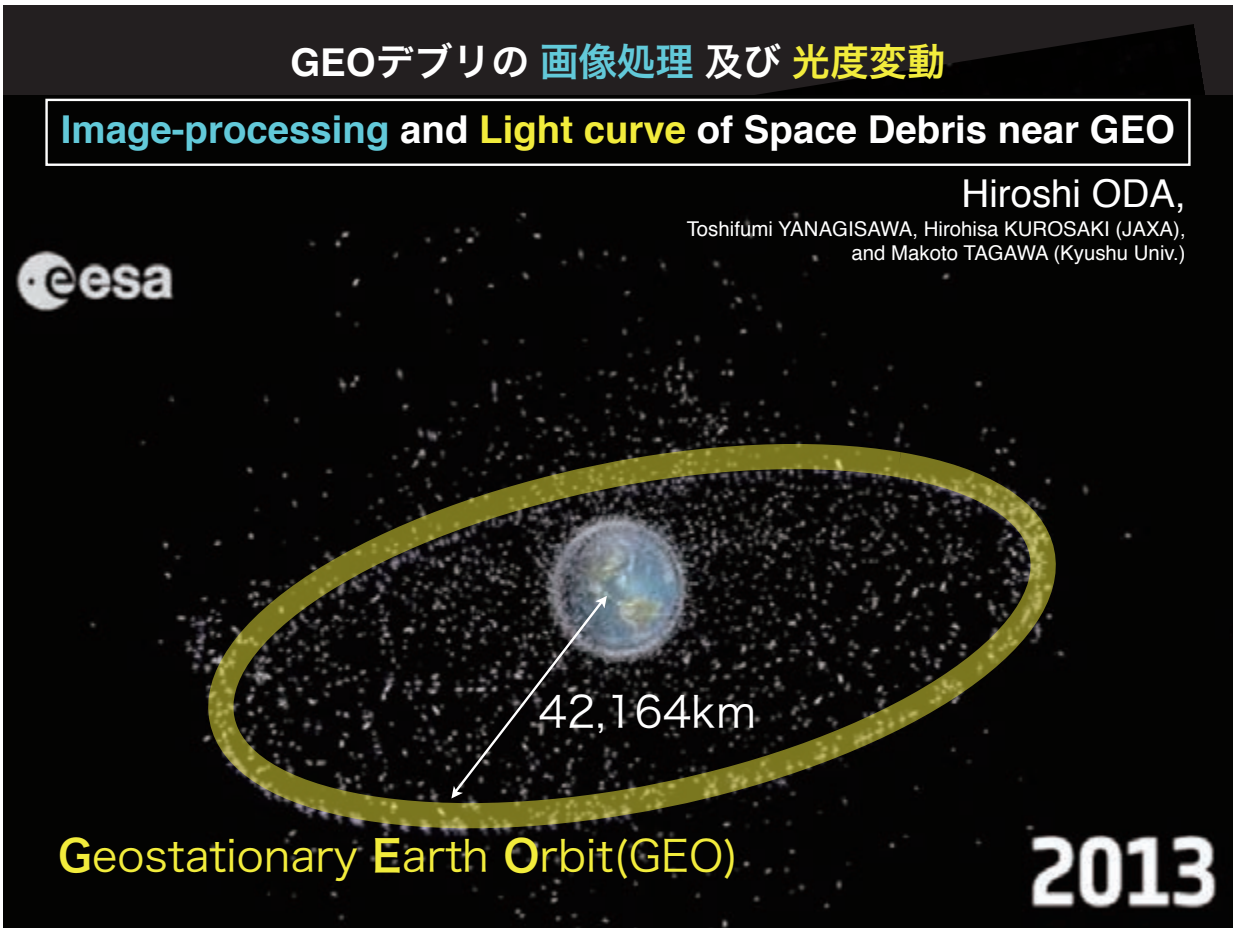

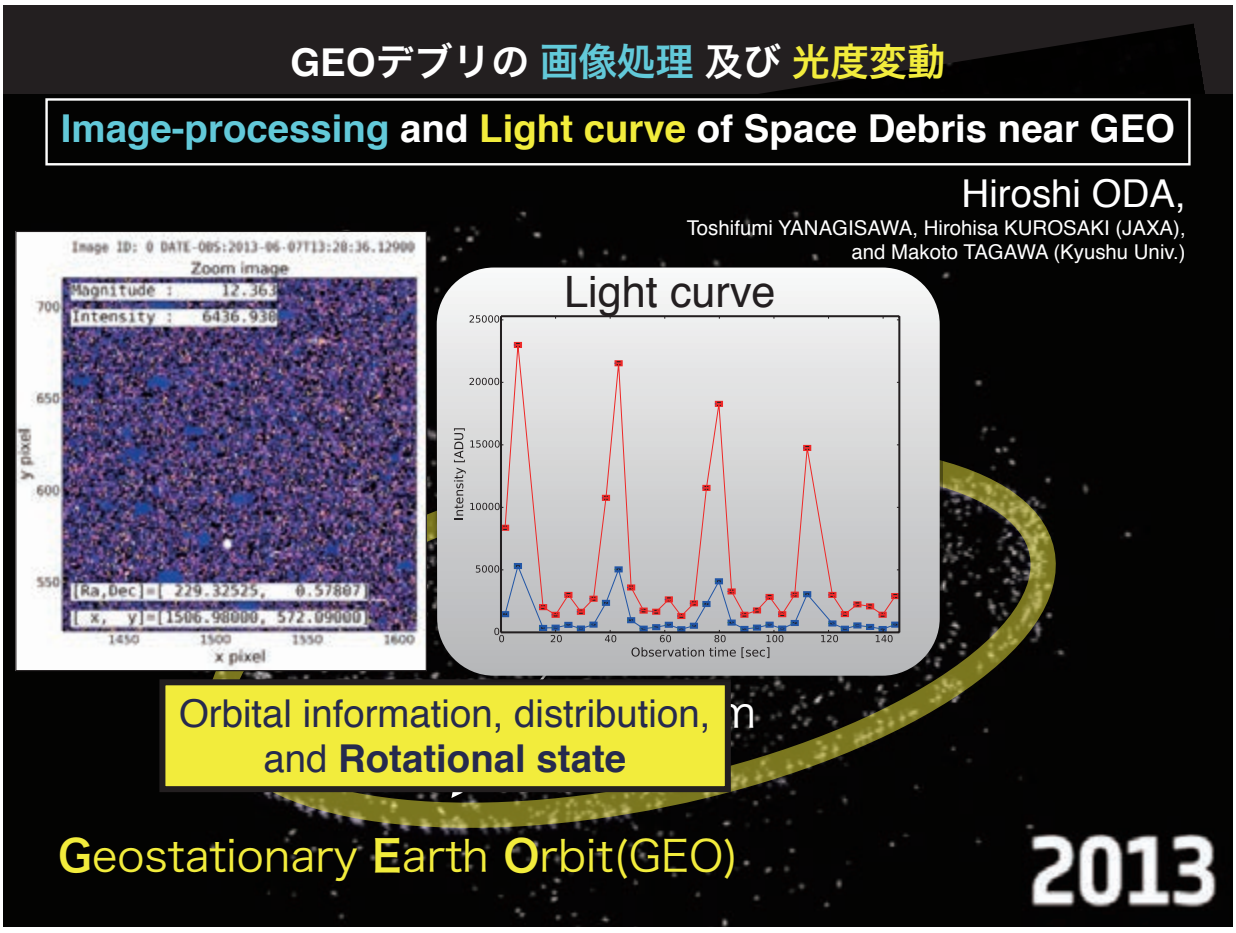

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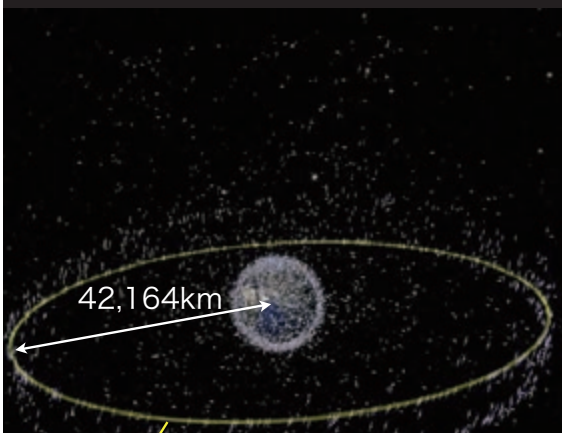
- Observation and dataset
  - Site and instruments
- Image-processing and detection algorithm
  - Dark-Bias, Flat, BKG, Diurnal motion object masking
  - Uniform linear motion detection
  - Photometry
- Highlight data
  - Number distribution
  - Light curves
- Summary and Future works
  - A lot of detected objects show a time variation
  - More detailed analysis is on going.



Geosynchronous **E**arth **O**rbit (GEO)

Orbital information, distribution, and **Rotational state**

Observation Site

Nyukasa Observatory

Dome 1
35cm telescope + CCD
FOV: 1.4° x 1.4°
GEO survey

Dome 2
25cm + CCD:
18cm + CCD:
LEO survey
NEO survey

Introducing and testing
2 CMOS Cameras

35° 40' 42" N
139° 33' 24" E
Alt. of 55m

35° 54' 16" N
138° 10' 08" E
Alt. of 1870m

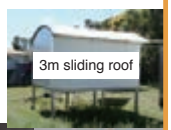
27° 26' S
151° 43' E
Alt. of 406m

Chofu Observatory

Tri-Axial Mount
35cm + CCD
FOV: 7.6′ x 6.1′
LEO tracking

Australia Remote Obs.

18cm (→ 25cm) + CCD
FOV: 3.17° x 3.17°
GEO survey
NEO survey



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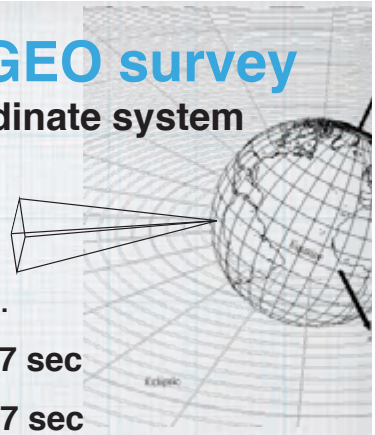
Observation and Dataset for GEO survey



* We employ **the horizontal (topocentric) coordinate system**
  - Stars move horizontally
  - Perfect GEO objects are stationary.
* Time interval: **3 sec exposure + Readout time**.
  - ARO: 3 sec exposure + 1.7 sec readout ~ **4.7 sec**
  - Nyukasa: 3 sec exposure + 2.7 sec readout ~ **5.7 sec**
* Duration: (4.7 or 5.7 sec) x 32 images **~150 sec**

Note: The dataset is optimised for detection efficiency but light curves

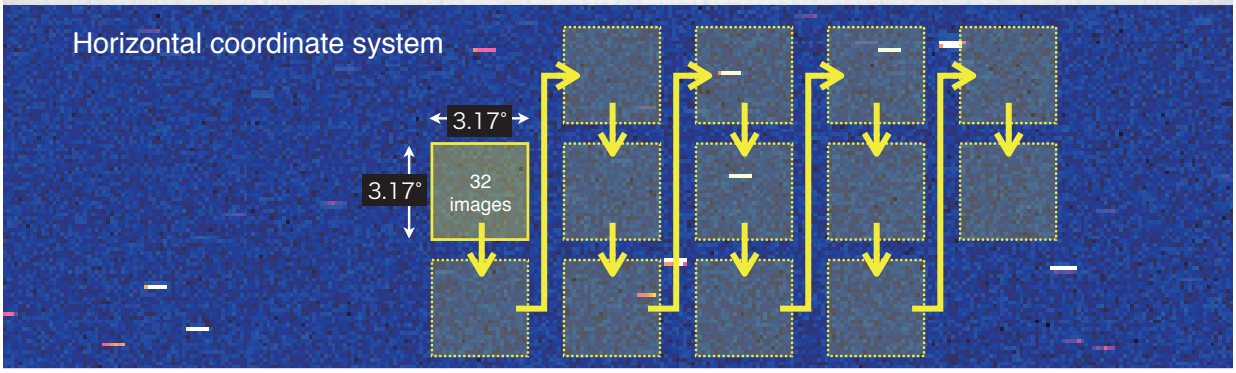
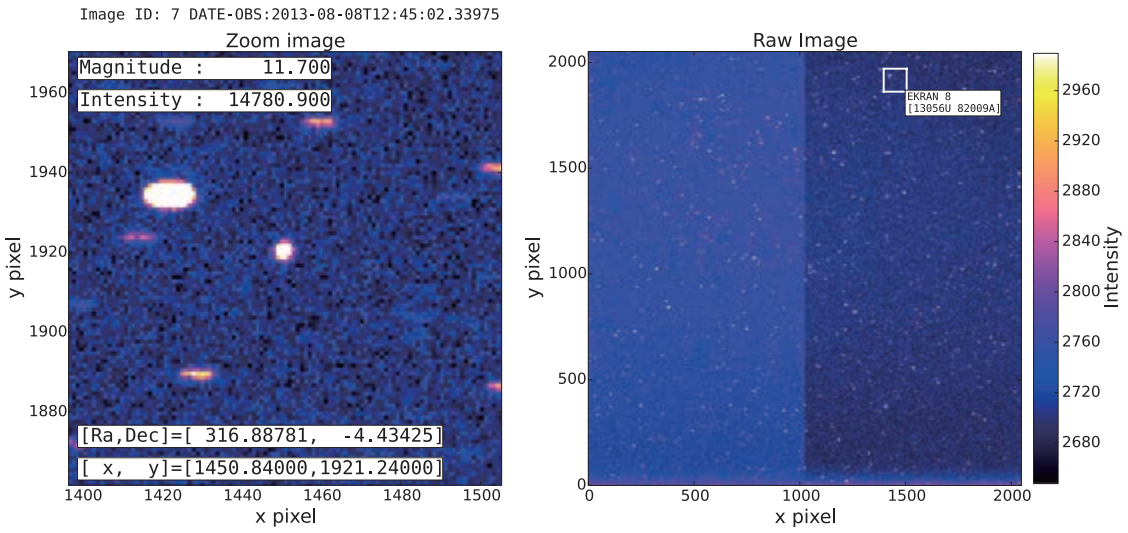


Image-processing

* Raw image
* Dark-Bias subtraction, Flat correction, BKG subtraction
* Diurnal motion object (star trail) masking



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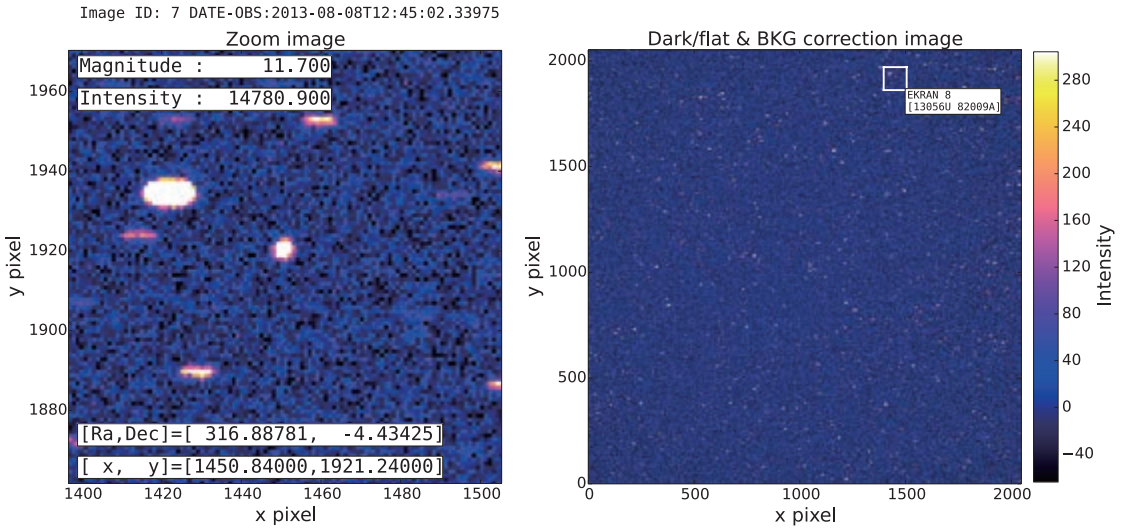

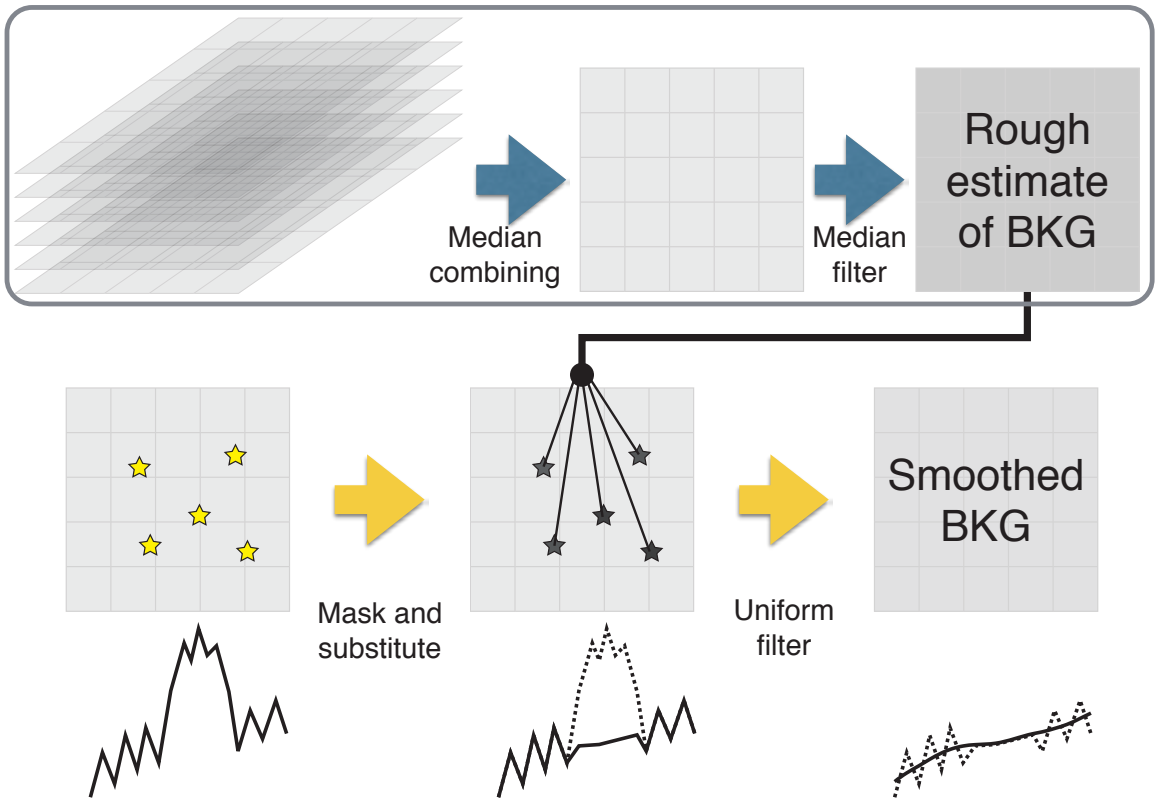

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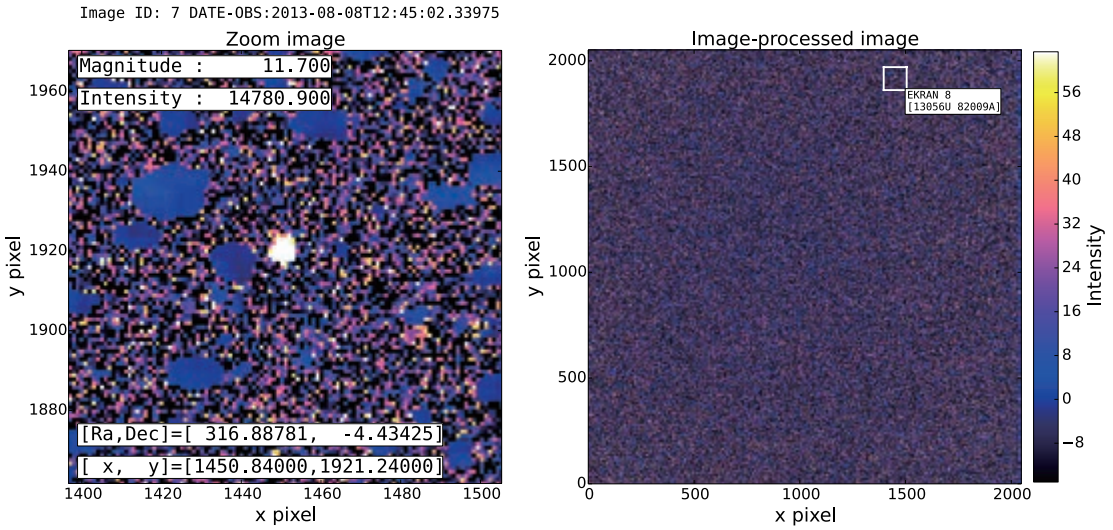
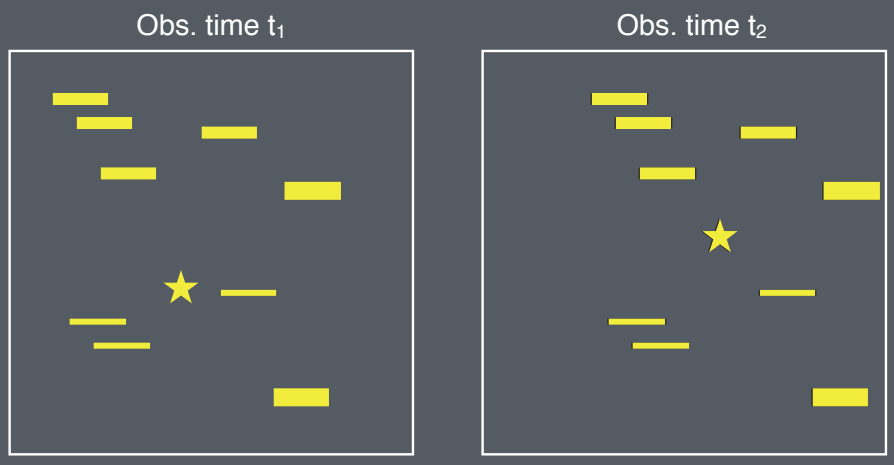


Diurnal motion object (star trail) masking

For the convenience in detection of orbital objects, we want to mask star trail…



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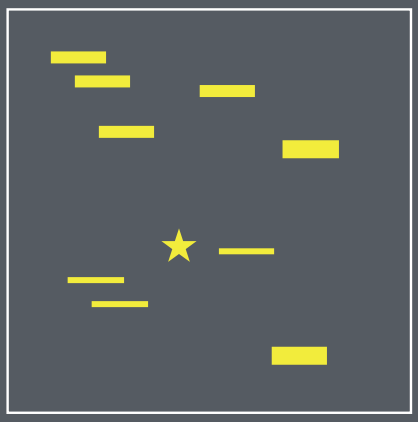
Diurnal motion object (star trail) masking

For the convenience in detection of orbital objects, we want to mask star trail…

Obs. time t_1



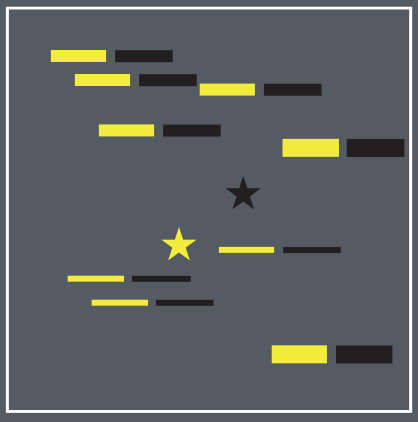
Obs. time t_2

Mask bright pixels

Diurnal motion object (star trail) masking

For the convenience in detection of orbital objects, we want to mask star trail…

Obs. time t_1



Overlay masked image

Obs. time t_2

Mask bright pixels

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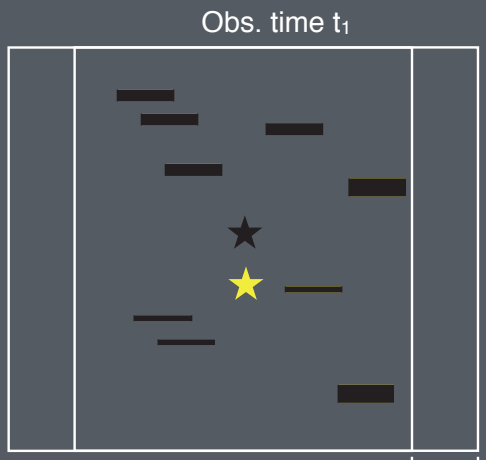
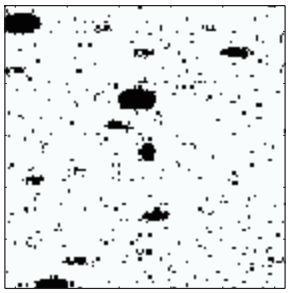
Diurnal motion object (star trail) masking

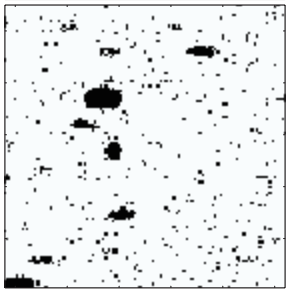
For the convenience in detection of orbital objects, we want to mask star trail…



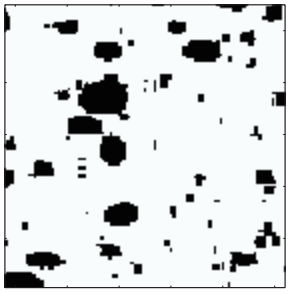
Mask bright pixels



Shift by the travel distance due to the diurnal motion



Shift by the travel distance due to the diurnal motion



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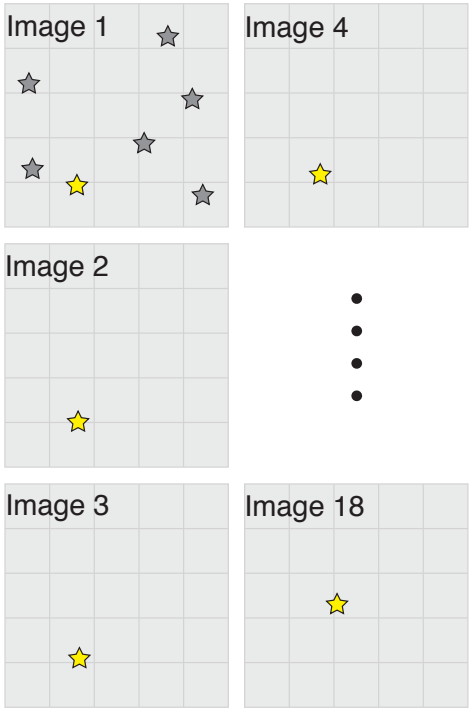
Detection algorithm: Uniform linear motion detection



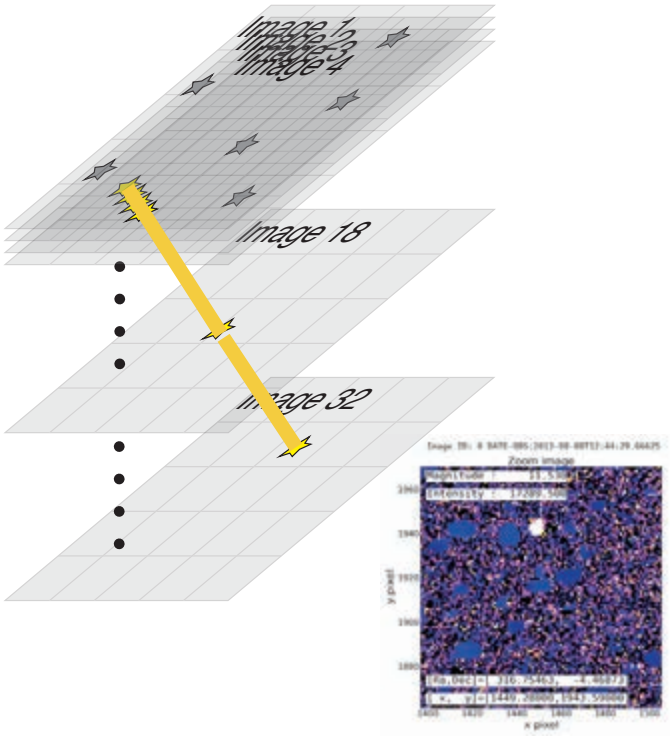
limited by the computational resources

▸ **Step1**
Select 500 candidates based on
- shape (blurred by atmospheric turb.)
- Intensity (brightest 500)

At this step,
noise, cosmic rays, etc… are included.

▸ **Step2**
Search objects showing the uniform linear motion
- 9 out of first 18 light frames

Detection algorithm: Uniform linear motion detection



limited by the computational resources

▸ **Step1**
Select 500 candidates based on
- shape (blurred by atmospheric turb.)
- Intensity (brightest 500)

At this step,
noise, cosmic rays, etc… are included.

▸ **Step2**
Search objects showing the uniform linear motion
- 9 out of first 18 light frames

▸ **Step3 (for lightcurve)**
extrapolate the detected path to the **32th image** and follow-up search

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Photometry

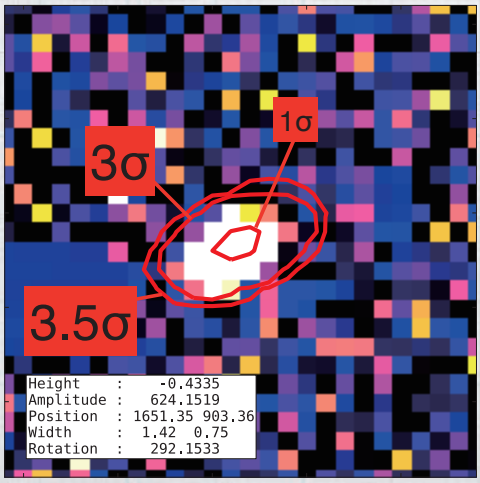
☑ Moving objects leave trailed image (**not circle and ellipse**)

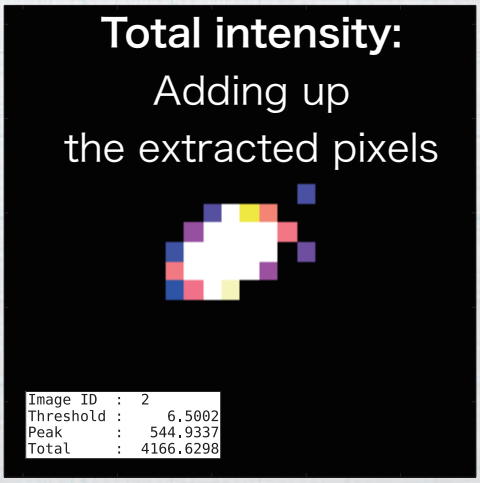
Extract pixels adequate for photometry using the 2D-Gaussian fit

*Step 1: Crop region surrounded by **3.5σ**

➡ apparently inadequate pixels are excluded.

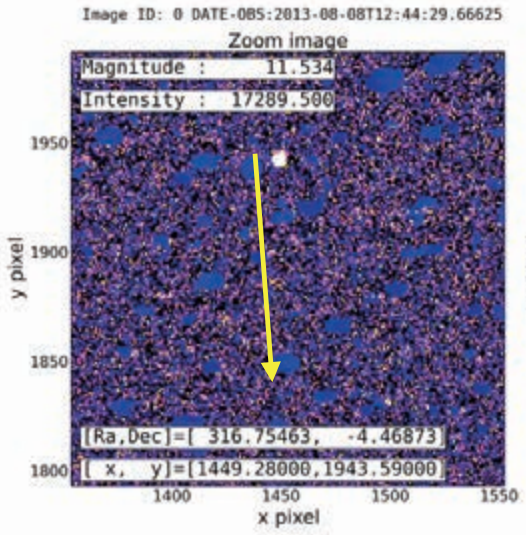
*Step 2: Extract pixels whose value greater than the value at **3σ**

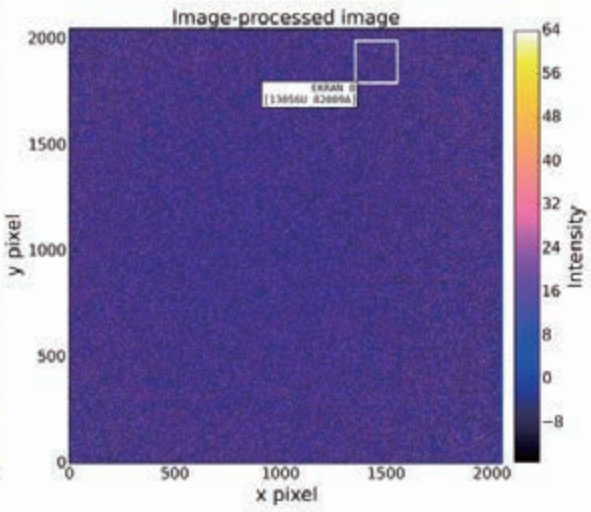




Example of a bright object

2013/08/08, region 027, object 0:
Mean mag. 11.79





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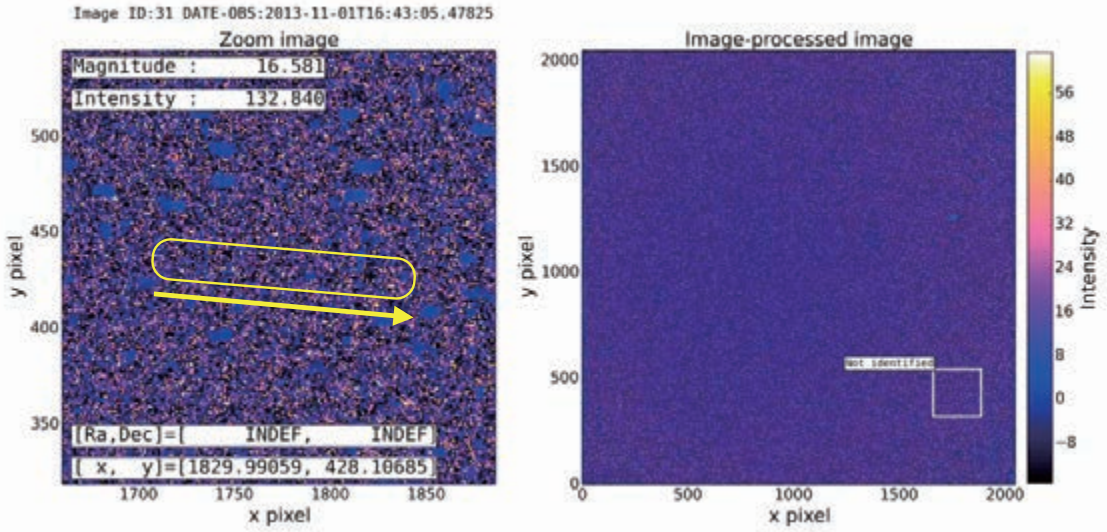
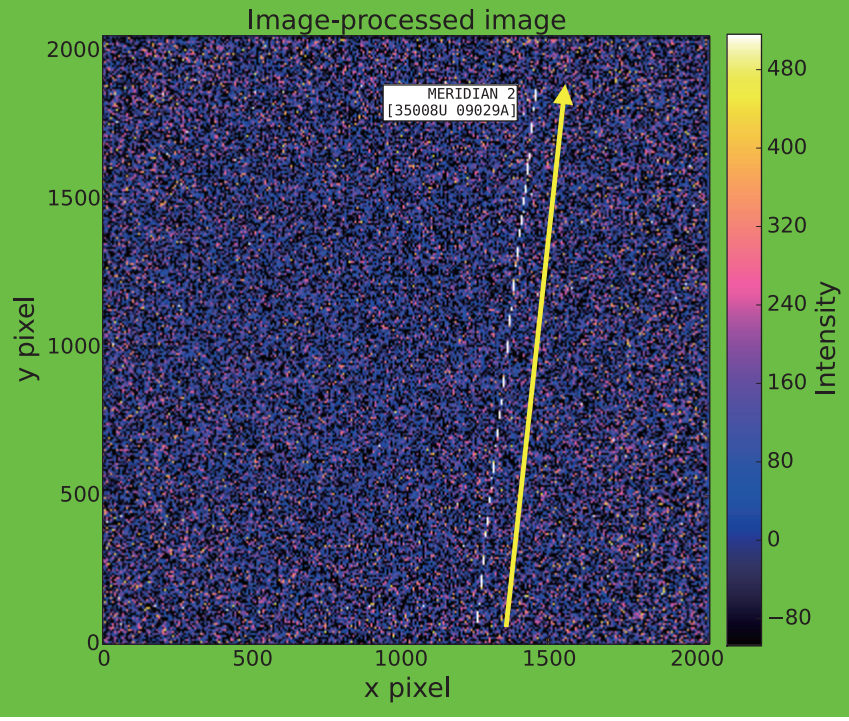
Example of a faint object

2013/11/01, region 049, object 0:
Mean mag. 15.11



Example of a fast (and bright) object

2013/11/01, region 058, object 0:
Velocity = 21.85 pix/sec(~ 0.034 deg/sec)



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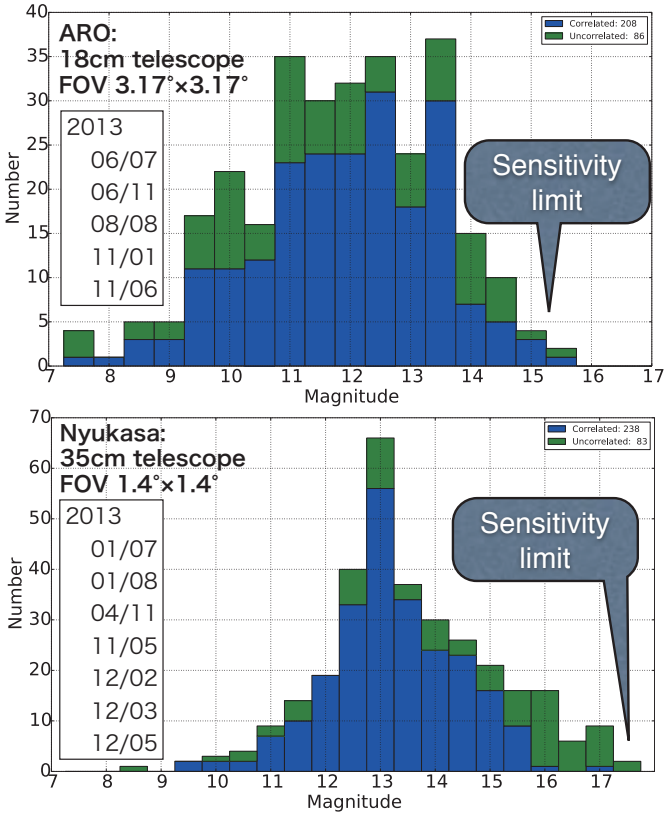
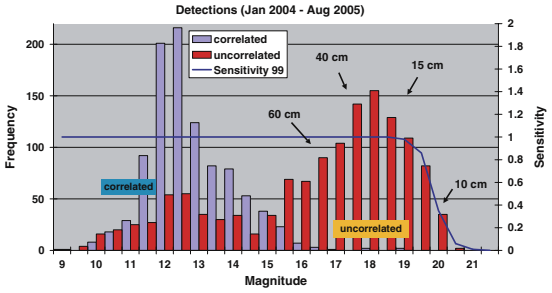
Magnitude-Number distribution



Peak at ~12-13 Mag.

- reflects the size distribution in the catalog.

ESA's 1-m telescope

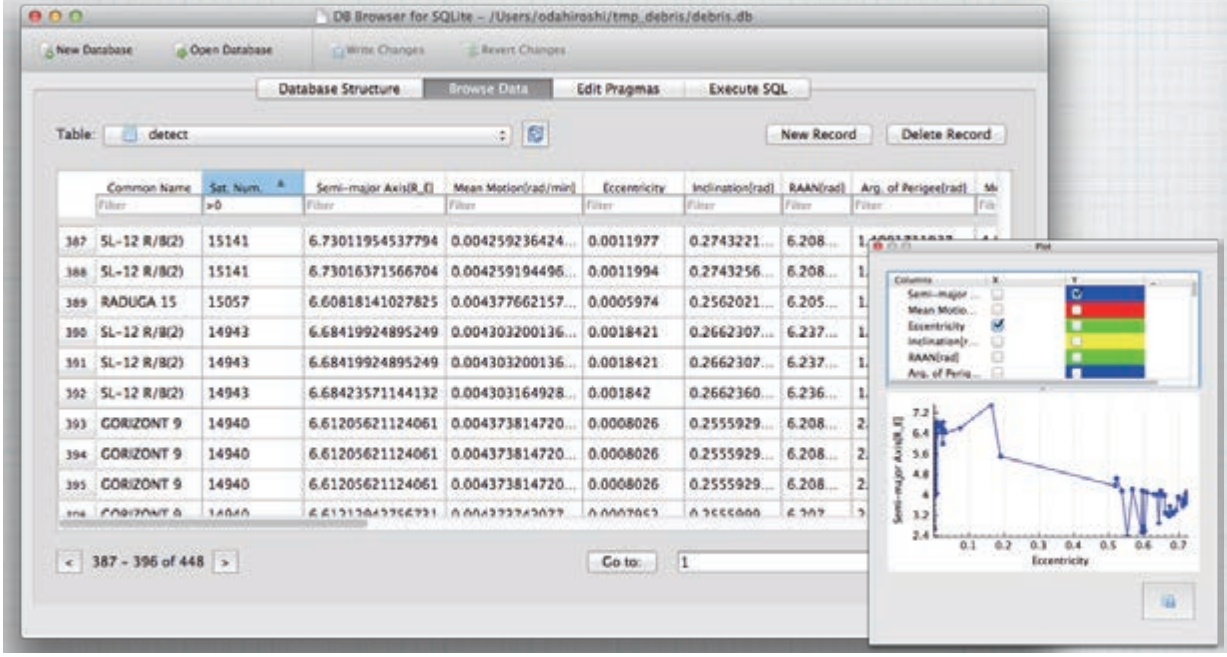


Schildknecht et al. 2004

Note: A lot of detected object shows a time variation in the light curve.
The "mean" mag. could not represent the proper size.

Database Management

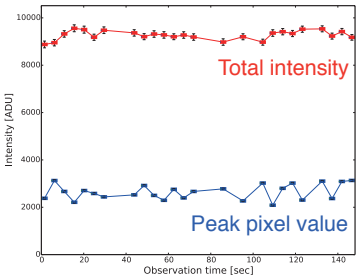
* **Database Language: SQLite**
  - Python standard library (Our codes are written in Python)
* **Database Structure**
  - Correlated objects: Orbital elements in TLE catalog + Astrometry + Photometry
  - Uncorrelated objects: Astrometry([RA, Dec], etc…) + Photometry(Mag., etc…)



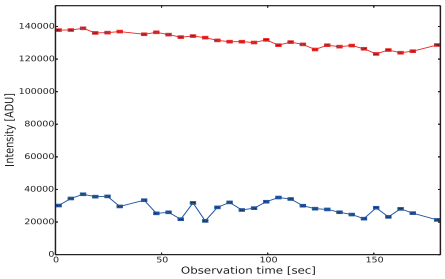
This document is provided by JAXA.

Light curve: Stable Example

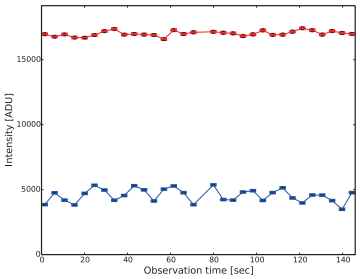
2013/06/11@ARO



2013/11/05@Nyukasa



2013/11/06@ARO

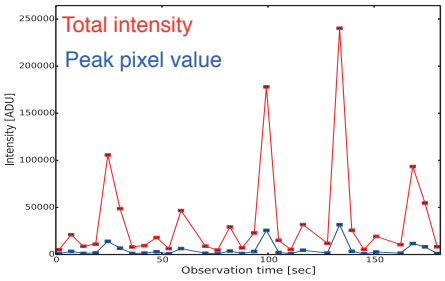


Correlated: JCSAT 5 [25067] - communication satellite

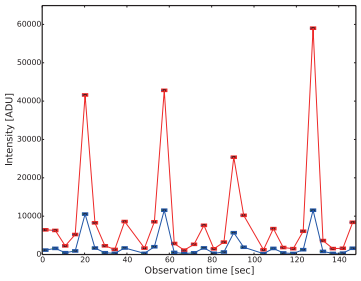
Date	Semi-major Axis[R	Eccentricity	Inclination [rad]	RAAN [rad]	Argument of Perigee[rad]	Mean Mag.
06/11	6.61	0.00046	0.0484	1.214	0.17	11.74
11/05	6.61	0.00053	0.0537	1.191	2.74	11.11
11/06	6.61	0.00053	0.0537	1.191	2.75	10.96

Light curve: Periodic Oscillation (Spike-like) Example

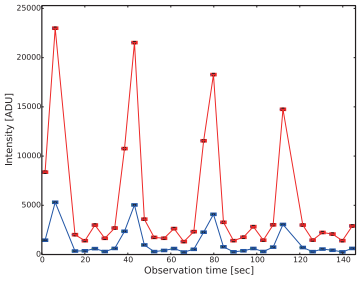
2013/01/07@Nyukasa



2013/06/07@ARO



2013/11/06@ARO



Period of about 40 seconds?
Constant period?

Correlated: SATCOM K2 [16276] - communication satellite, de-orbited in 2002

Date	Semi-major Axis[R	Eccentricity	Inclination [rad]	RAAN [rad]	Argument of Perigee[rad]	Mean Mag.
01/07	6.64	0.0008	0.224	0.678	2.00	11.77
06/07	6.64	0.0009	0.229	0.647	2.51	12.71
11/06	6.64	0.0012	0.232	0.615	2.62	12.76

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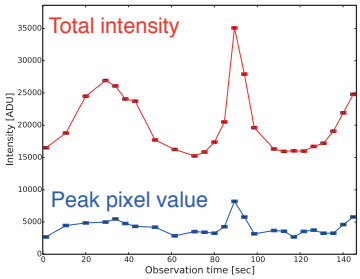
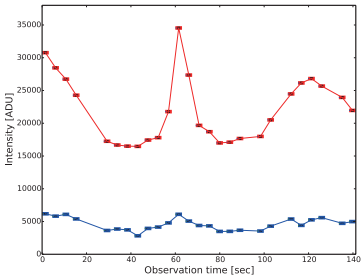
Light curve: (Moderately) Long Periodic Oscillation Example

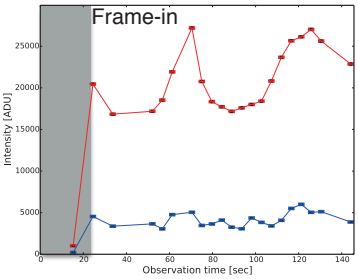
2013/11/01@ARO



2013/11/06@ARO



2013/11/06@ARO



© Gunter Dirk Krebs 1996-2014

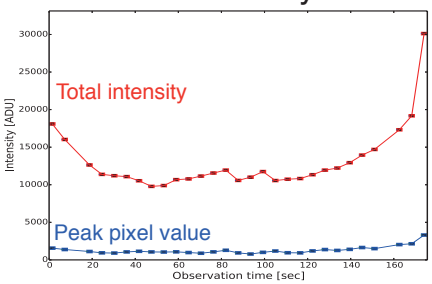
Period of about 120 seconds?
2 characteristic faces?

Correlated: EXPRESS 1 [23319] - communication satellite, launched in 1994

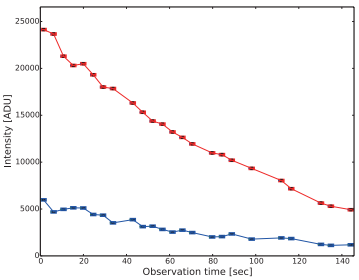
Date	Semi-major Axis[R	Eccentricity	Inclination [rad]	RAAN [rad]	Argument of Perigee[rad]	Mean Mag.
11/01	6.63	0.00074	0.1994	0.757	1.948	10.86
11/06	6.63	0.00073	0.1996	0.756	1.951	10.70
11/06	6.63	0.00073	0.1996	0.756	1.951	10.91

Light curve: (Likely) Long Periodic Oscillation Example

2013/04/11@Nyukasa

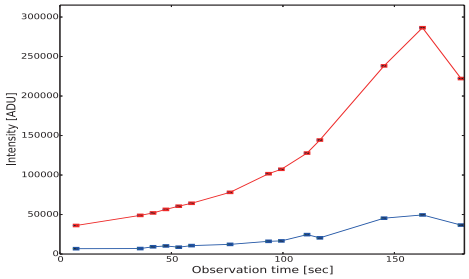


2013/11/01@ARO

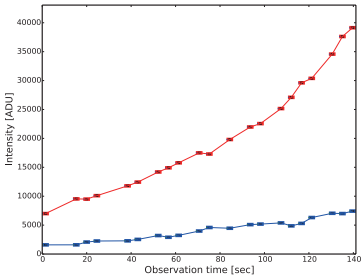


Period of about 200~300 seconds?
Longer observing time is required!

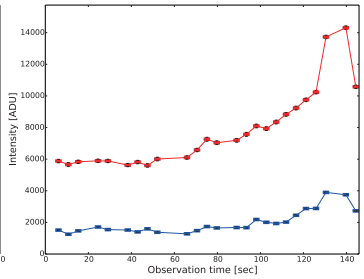
2013/11/05@Nyukasa



2013/11/06@ARO



2013/11/06@ARO



Correlated: RADUGA 1-7 [28194] - communication satellite, launched in 2004

Date	Semi-major Axis[R	Eccentricity	Inclination [rad]	RAAN [rad]	Argument of Perigee[rad]	Mean Mag.
04/11	6.606	0.0002635	0.1230	1.1023	0.1784	13.12
11/01	6.610	0.0004036	0.1301	1.0568	1.3865	11.71
11/05	6.610	0.0003984	0.1302	1.0561	1.4027	11.00
11/06	6.610	0.0003984	0.1302	1.0561	1.4027	11.32
11/06	6.610	0.0003984	0.1302	1.0561	1.4027	11.77

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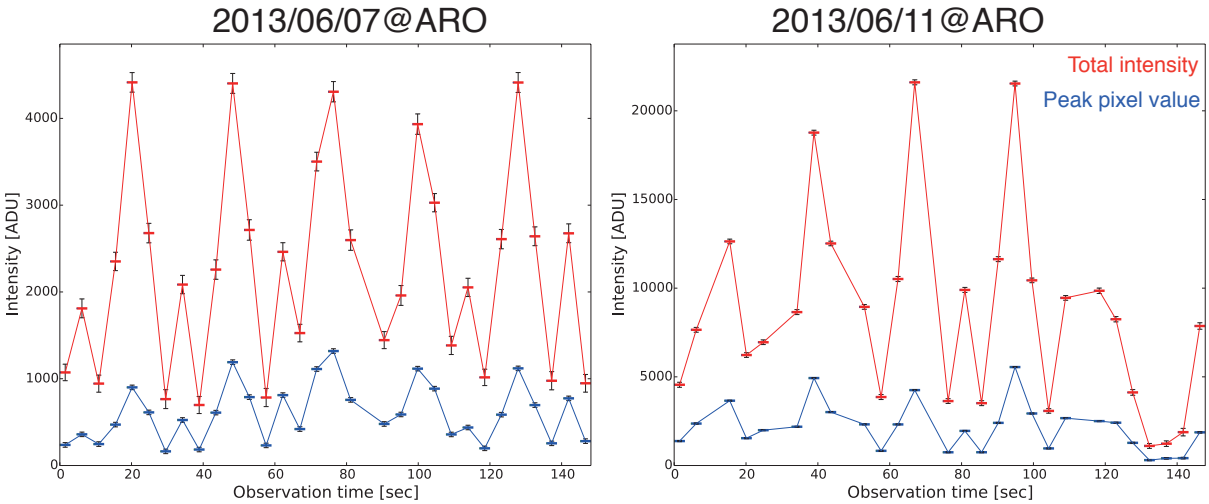
Light curve: Rapid Oscillation Example



Period of about less than 5~10 seconds?

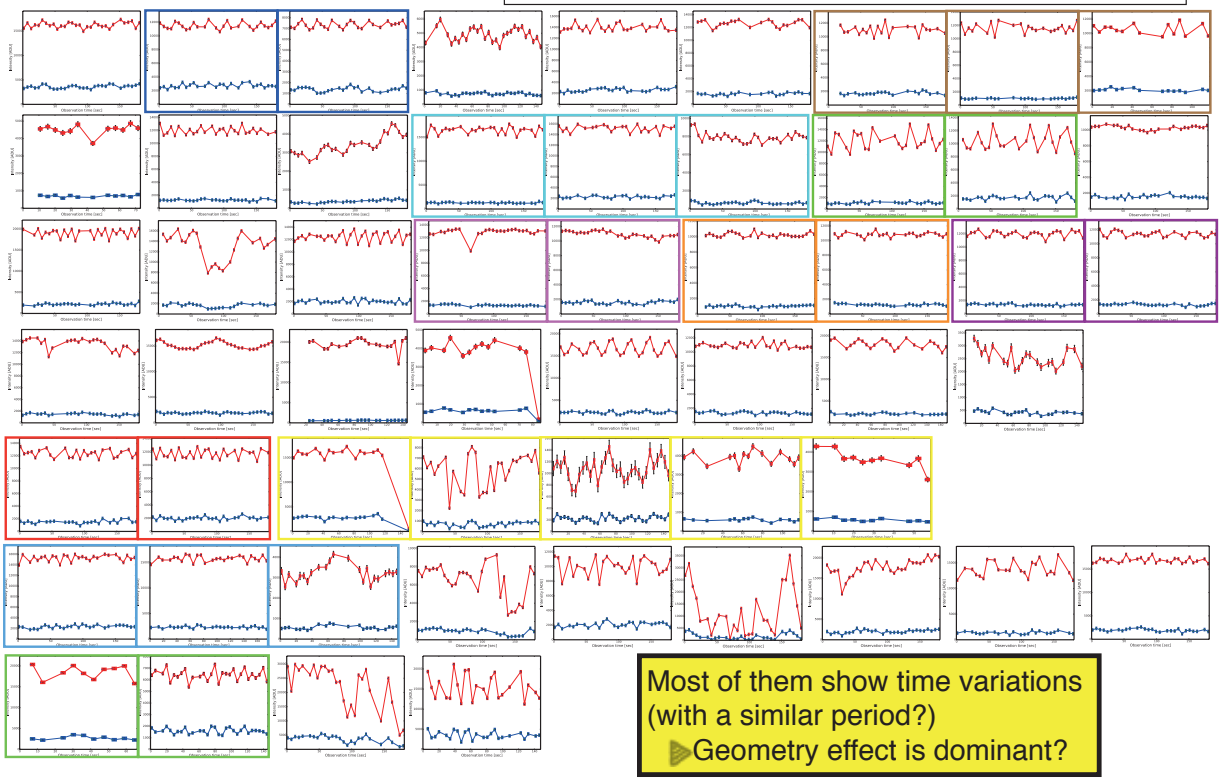
Shorter observation time interval is required!

Correlated: ARABSAT 3A [25638] - communication satellite, launched in 1999

Date	Semi-major Axis[R	Eccentricity	Inclination [rad]	RAAN [rad]	Argument of Perigee[rad]	Mean Mag.
06/07	6.615	0.000467	0.0707	1.1451	5.421	11.74
06/11	6.615	0.000478	0.0708	1.1446	5.406	12.11

Light curve: SL-12 R/B(2) series

$a \sim 6.5\text{-}6.7\ [R_E],\ e \sim 0.0043\text{-}0.0045$



Most of them show time variations (with a similar period?)
▶Geometry effect is dominant?

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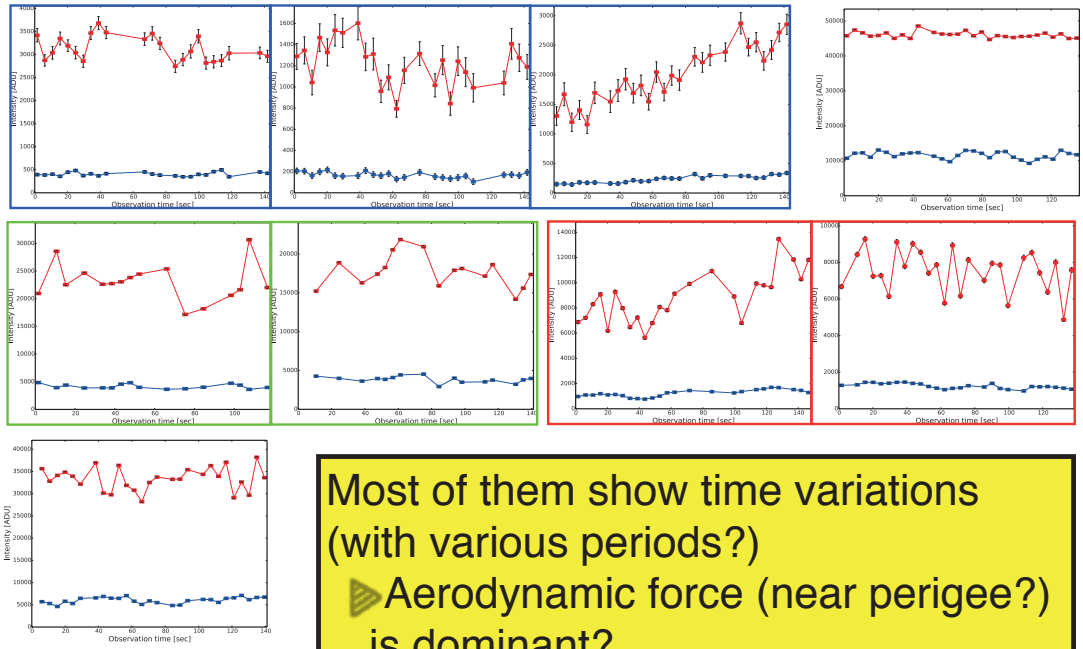
Light curve: ARIANE 5 R/B series

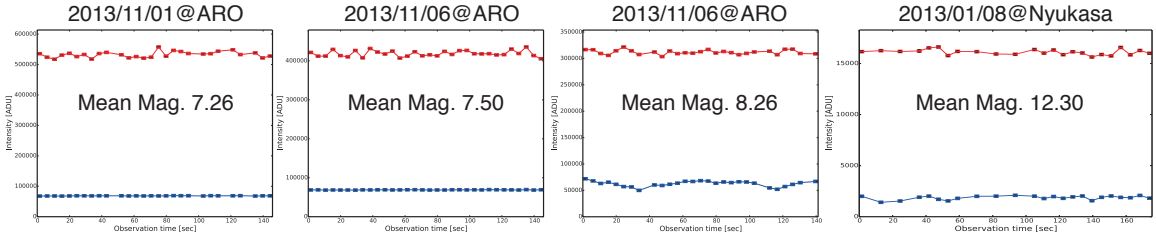
$a \sim 3.5\text{-}3.8\ [R_E],\ e \sim 0.71\text{-}0.72$



Most of them show time variations (with various periods?)
- Aerodynamic force (near perigee?) is dominant?

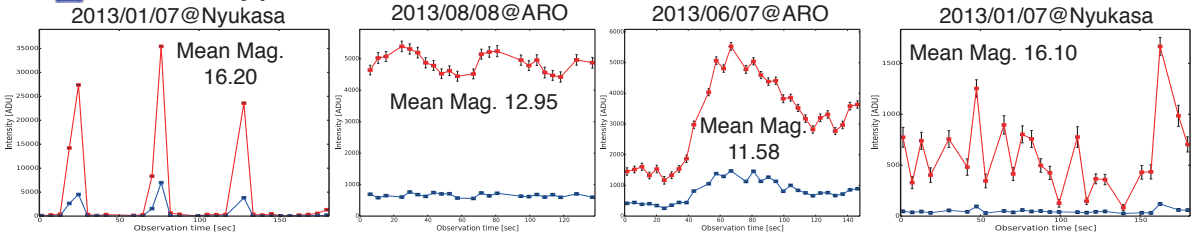
Light curve: Uncorrelated Objects

☑ Stable and bright



possibly operated, but just not listed in the catalog for some reasons?

☑ Various type of time variation



rotating debris?

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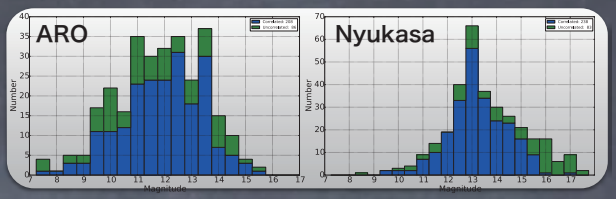
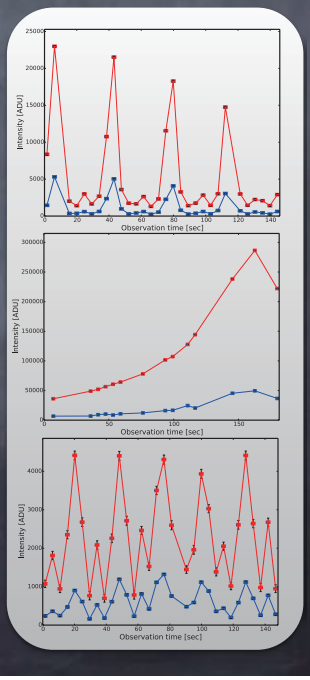
Summary



- **GEO survey observation**
  - 18cm telescope + CCD @ ARO
  - 35cm telescope + CCD @ Nyukasa
  - 32 images in a region (optimised for detection efficiency)
- **Image-processing, detection algorithm**
  - Dark/Flat, BKG subtraction, diurnal motion (star trail) masking
  - Uniform linear motion detection
  - Photometry (for motion blurred objects)
- **Detection result**
  - ARO: 208 correlated + 86 uncorrelated in 5 night data
  - Nyukasa: 238 + 83 in 7 night data
- Database management (using SQLite)
- **Light curve**
  - A lot of detected objects show a time variation
    - Longer observing time is required for long periodic oscillation.
    - Shorter time interval is required for short periodic oscillation.
  - Optimised observation and detailed analysis is on going.



Future works

- We replaced 18cm telescope with 25cm telescope in June 2014
  - Sensitivity limit must be improved (by a magnitude of 1?)
- **Improve detection algorithm: Stacking method**
  - Stack images shifted along to the **“all possible predicted”** moving direction.
    - Detection limit is expected to be improved by a magnitude of 2 empirically.
  - However, huge computational resources are required…
  - We plan to accelerate it by making use of GPU(e.g., NVIDIA Tesla K20).

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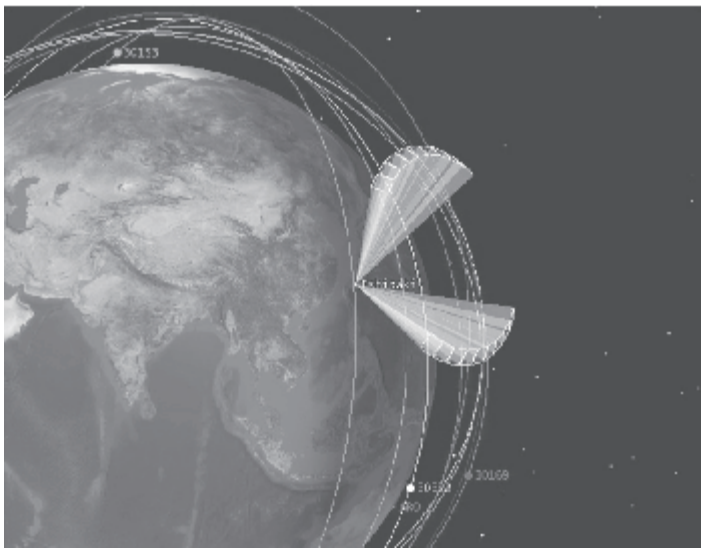
F3

低軌道デブリ地上光学観測システム
Ground-based Optical Observation System for LEO Debris

○黒崎裕久，柳沢俊史，小田寛（宇宙航空研究開発機構），田川真（九州大学）
○Hirohisa Kurosaki, Toshifumi Yanagisawa, Hiroshi Oda (JAXA)
and Makoto Tagawa (Kyushu Univ.)

我々は広大な空をカバーするために、たくさんの光学センサを使う低軌道物体を監視するための地上光学観測システムを提案している。この研究でシステム評価は STK ソフトウェアを用いて実行した。この結果は、サーベイのために二つの経度方向に離れたサイトと両極域の二つの追跡サイトで TLE オブジェクトの 60%以上検出してそれらの軌道を維持できることを示す。提案したシステムは、近い将来、宇宙状況認知のような低軌道物体監視のための現在のレーダー観測システムを補完するか置き換えることができるかもしれない。

We are proposing a ground-based optical observation system for monitoring LEO objects which uses a lot of optical sensors to cover the vast sky. In this study, the system evaluation was carried out using STK software. The results shows that two longitudinally separate sites for survey and two tracking sites located in both polar regions were able to detect more than 60% of TLE-objects and maintain their orbits. The proposed system may complement or replace the current radar observation system for monitoring LEO objects like a space situation awareness in the near future.



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6th Debris Workshop

Ground-based Optical Observation system for LEO Objects

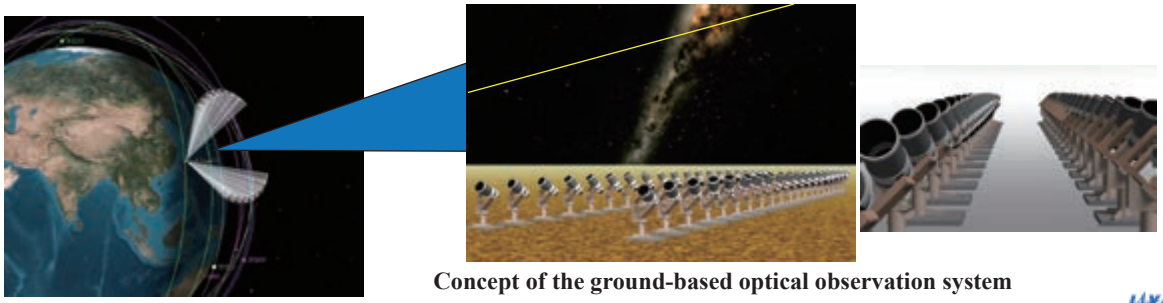
低軌道デブリの地上光学観測システムの検討

Japan Aerospace Exploration Agency(JAXA)
Innovative Technology Research Center
H.Kurosaki, T.Yanagisawa, H.Oda
and M.Tagawa(kyushu Univ.)
宇宙航空研究開発機構(JAXA)
研究開発本部 未踏技術研究センター
黒崎裕久, 柳沢俊史, 小田 寛(JAXA), 田川 真(九大)

Abstract

We are proposing a ground-based optical observation system for monitoring LEO objects which uses a lot of optical sensors to cover the vast sky. In this study, the system evaluation was carried out using STK software. The results shows that two longitudinally separate sites for survey and two tracking sites located in both polar regions were able to detect more than 60% of TLE-objects and maintain their orbits. The proposed system may complement or replace the current radar observation system for monitoring LEO objects like a space situation awareness in the near future.

我々は広大な空をカバーするために、たくさんの光学センサを使う低軌道物体を監視するための地上光学観測システムを提案している。この研究でシステム評価はSTKソフトウェアを用いて実行した。この結果は、サーベイのために二つの経度方向に離れたサイトと両極域の二つの追跡サイトでTLEオブジェクトの60%以上検出してそれらの軌道を維持できることを示す。提案したシステムは、近い将来、宇宙状況認知のような低軌道物体監視のための現在のレーダー観測システムを補完するか置き換えることができるかもしれない。



Concept of the ground-based optical observation system

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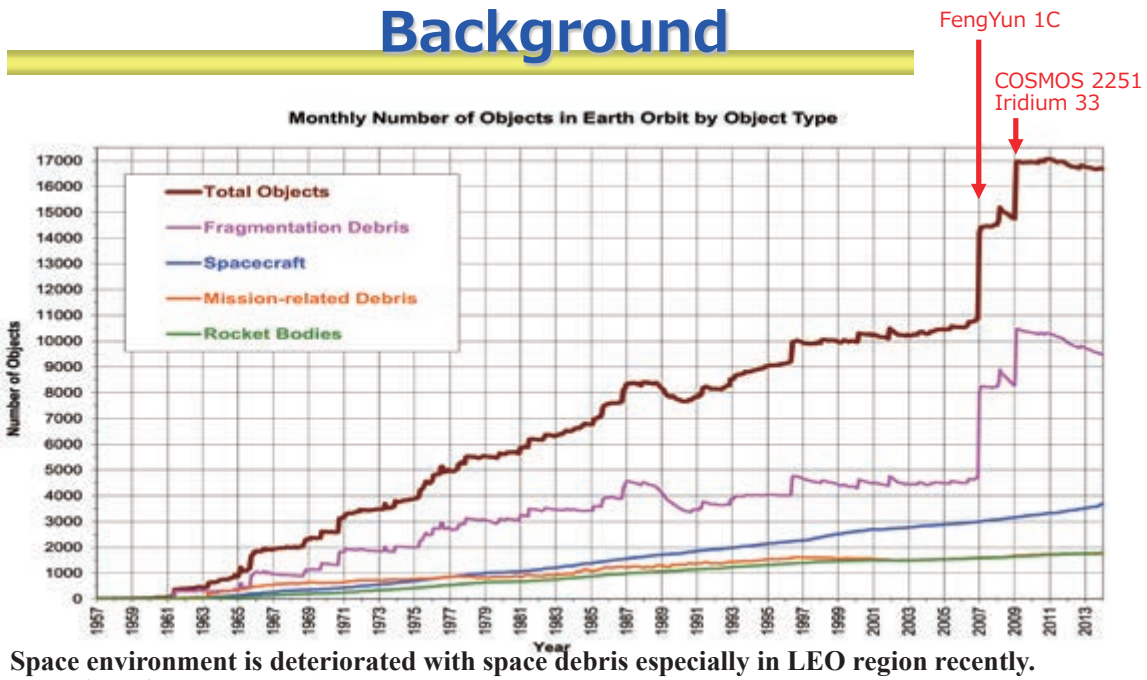
Background



Space environment is deteriorated with space debris especially in LEO region recently.
低軌道の環境は年々悪化の一途をたどっている。(衛星破壊実験、衛星同士の衝突等)

Dead zone problem. (a few mm to 10cm)
観測限界が10cmであるのに、宇宙機が防御できるサイズは数mm

Inaccuracy of TLE
軌道要素(TLE)の精度が悪い。

➡ Observation ability of LEO objects must be reinforced.
低軌道デブリの観測能力を強化する必要

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.
レーダー観測:米国のSSN。24時間365日。天候に左右されにくい。建設及び維持運用費がかかるという欠点

②Optical observation: ISON network of Russia. Observable time is limited by lighting condition of the sun and weather. Very cost effective.
光学観測:ロシアのISONネットワーク。1日数時間の観測、天候の影響受ける。建設及び維持運用費が安い。

- Optical Sensors(CCD, CMOS) are improving 光学センサー(CCD, CMOS) の発展、高性能で廉価
- PC performances are improving 計算機能力の著しい向上

Cost-effective ground-based optical observation system of LEO objects which is used for SSA will be possible.
廉価な低軌道デブリ用の地上光学観測システムを構築でき、宇宙状況監視にも貢献。

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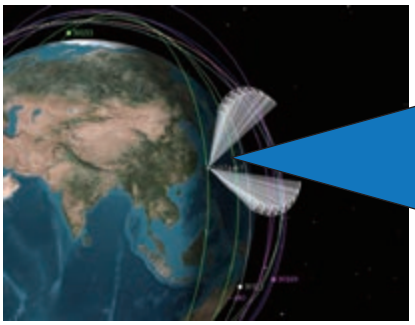
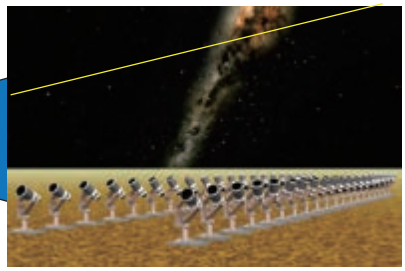
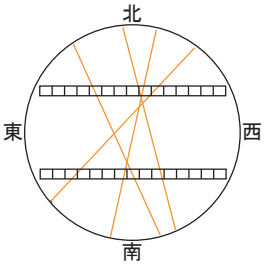
Ground-based optical observation system





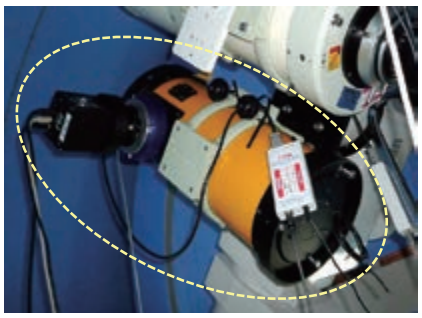


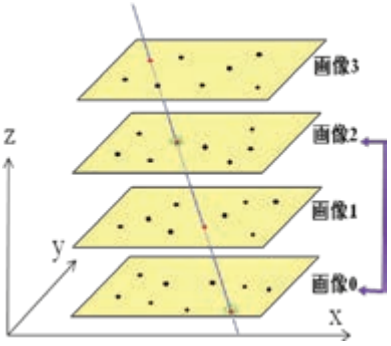
複数台によるＬＥＯデブリ監視システム

- About 40 optical sensors are installed to one site. 1サイトで40台の光学センサ
- 2 regions of the sky are monitored to get long arc. 長いアークを得るため天球上の2領域を観測
- 2 consecutive passes should be observed for accurate orbital determination.
  For this reason, 2 longitudinally separated sites are considered.
  2回の連続する2パスを観測→精度よい軌道決定が可能。経度の離れた2か所に観測サイトを配置。

1. Detection abilities and 2. orbital determination possibilities are investigated

Observation equipments and Data analysis





Many frames

↓

Candidates are searched using a threshold and a shape parameter

閾値、形状パラメータを利用して候補を探す

↓

Candidates which creates a straight line are detected as a moving object

直線上にのる移動物体を検出

Observation equipments:

- Takahashi ε180ED (D:180mm)
- FLI CCD camera ML23042 (Back Illuminated 2Kx2K)
  FOV : 3.5×3.5-degree

Data analysis software:

The linear motion detection algorithm
等速直線運動検出アルゴリズム

Survey observation was carried out using these equipments and software

本観測装置及び解析ソフトを利用、サーベイ観測を実施

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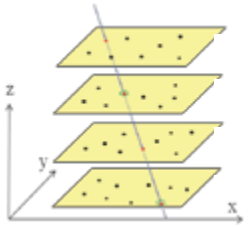
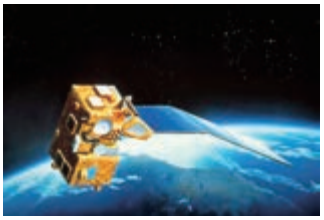
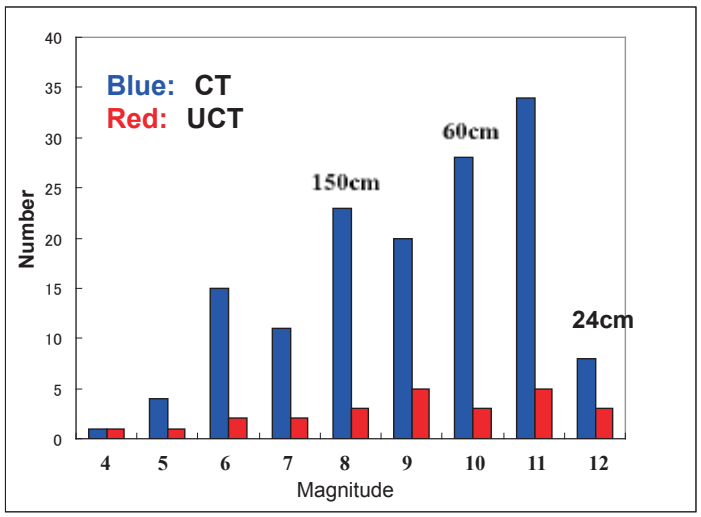
検出能力 Detection abilities





17525(MOMO-1)
exposure time： 50msec
interval ： 1.5 sec

検出能力 Detection abilities



Diffuse reflection with 90-degree phase angle and albedo 0.1
拡散反射、位相角90°反射率10%を仮定したサイズ

Result of 16 days' survey
16日間のサーベイ結果

About 30cm LEO objects are detectable
約30cmサイズの低軌道物体の検出が可能

About 15% of detected objects are un-cataloged
検出物体のうち約15%が未カタログであった。

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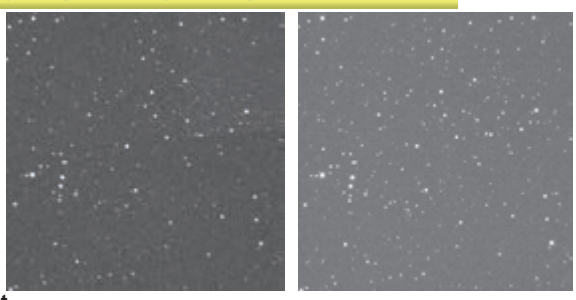
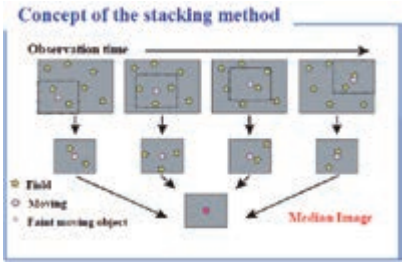
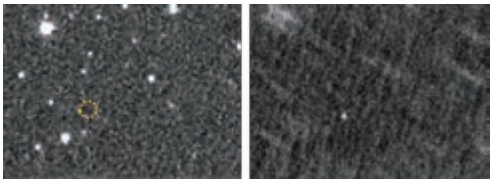
将来計画 Future Works

CMOS sensor for LEO observation. Readout time is 60 times faster than that of CCD
低軌道デブリ用CMOSセンサーの開発。
CCDと比較して60倍の読み出し速度。



Comparison between a CCD frame(left) and CMOS frame(right) in same condition
同一条件でのCCD画像(左)とCMOS画像(右)の比較



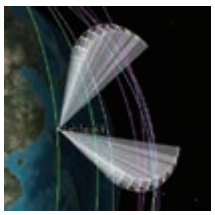


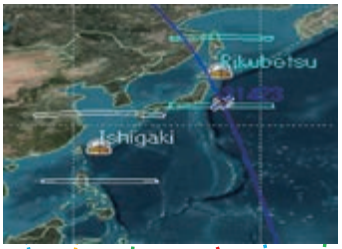
An asteroid detect with the stacking method. One CCD image (left) and the stacked image (right).
CCD 画像1枚(左) と重ね合わせ法で検出した小惑星(右).

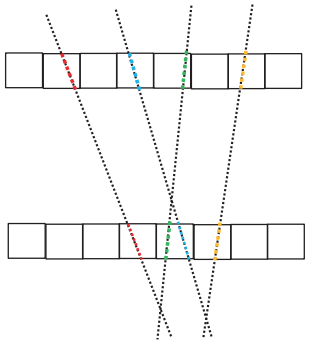
- Improve equipments: CMOS sensor will be used for the LEO survey observation
- Improve analysis method: Linear Motion Detection Algorithm → Stacking method
  装置と解析手法の改良　　線分検出法 → 重ね合わせ法

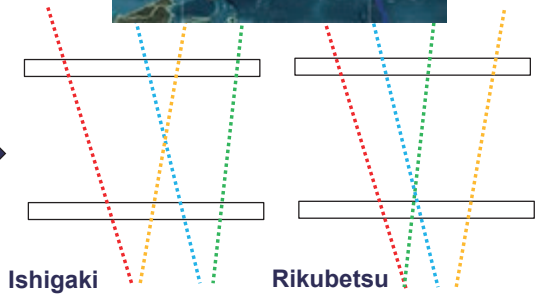
Aim to detect about 10cm LEO objects 10cm級のLEOデブリの検出を目指す

軌道決定能力 Orbital Determination Possibilities









Precise orbit determination
高精度軌道決定

Step1. Identification of same objects at one site
各局での同一物体の対応づけ

Step2. Identification of same objects at both sites
2局での同一物体の対応づけ

In order to carry out precise orbit determination, the identification of same object, which is extraction of 4 sets of data of same object from many observation data taken at 2 sites, must be done.
精度よい軌道決定をするため、それぞれの物体に対し、各局2回、合計4回のデータセットを、多数の観測の中から同一物体として対応づけなくてはならない。

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軌道決定能力
Orbital Determination Possibilities
-Observation Simulation-

Observation sites:

Ishigakijima Observatory (Okinawa)

Rikubetsu Observatory (Hokkaido)

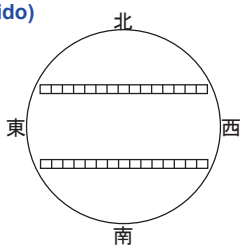
Observation equipments:

Takahashi ε180ED

＋

FLI ML4240

×40



20セット一列をAz 0°, El 50°
20セット一列をAz 180°,El 50°
各セットが東西に一列になるように指向.

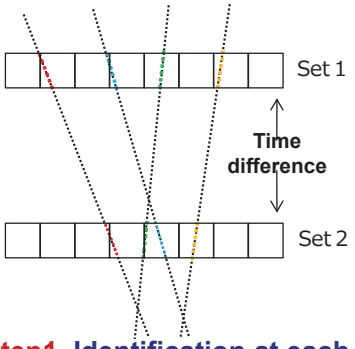
Observation date and time: Apr/11/2012 8:40-11:40(UT) Rikubetsu
Apr/11/2012 10:20-13:20(UT) Ishigaki

Targets: 14574 TLEs of Apr/11/2012 distributed at Space Track web site.

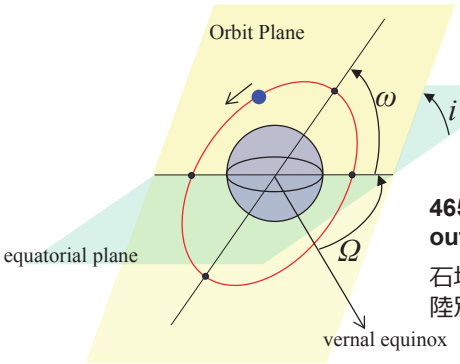
Observed coordinates(RA and Dec) of each object at each site are calculated every second using STK(Satellite Tool Kit) software.

軌道計算ソフトSTKを用いて各サイトで観測される物体のID（SSC番号）、観測位置（赤経、赤緯）を一秒間隔で計算.

軌道決定能力
Orbital Determination Possibilities
-Observation Simulation-



Step1. Identification at each site
各局での同一物体の対応付け



用いた軌道要素14574の物体のうち

石垣 セット１で872物体、セット２で636物体が検出.
両方で検出されたものは473物体.

陸別 セット１で916物体、セット２で934物体が検出.
両方で検出されたものは458物体.

Identification conditions
対応付け条件

①Difference of observation times: Less than 700-sec
観測時間差 700秒以内

②Change rate of circular radiuses: Less than 0.1
円軌道の軌道半径変化率 10%以下

③Difference of inclinations: Less than 1.0-degree
円軌道の軌道傾斜角の差 1.0°以下

④Difference of RAANs: Less than 1.0-degree
円軌道の昇交点赤経の差 1.0°以下

⑤Difference of direction cosines at the middle of observation time of 2 set: Less than 5.0-degree
両セットの観測中央時刻での両軌道の方向余弦の差 5°以下

465 objects out of 473 ones at Ishigaki (98.3%) and 454 objects out of 458 ones at Rikubetsu (99.1%) are identified.

石垣の473物体中465物体（98.3%）、
陸別の458物体中454物体（99.1%）が対応付けできた.

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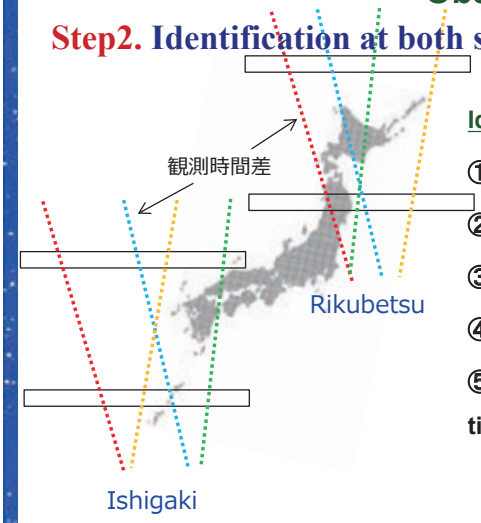
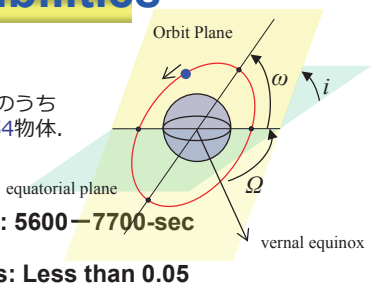
軌道決定能力
Orbital Determination Possibilities
-Observation Simulation-

Step2. Identification at both sites



石垣で対応付けされた465物体、
陸別で対応付けされた454物体のうち
両サイトで観測されたものは154物体.



Identification conditions
対応付け条件

①Difference of observation times: 5600－7700-sec
観測時間差 5600－7700秒

②Change rate of circular radiuses: Less than 0.05
円軌道の軌道半径変化率 5%以下

③Difference of inclinations: Less than 1.5-degree
円軌道の軌道傾斜角の差 1.5°以下

④Difference of RAANs: Less than 1.0-degree
円軌道の昇交点赤経の差 1.0°以下

⑤Difference of direction cosines at the middle of observation time of either of the two sits: Less than 90-degree
どちらのサイトでの観測中央時刻での両軌道の方向余弦の差 90°以下

143 objects out of 154 ones (92.9%) are identified
154物体中143物体（92.9%）の対応付けができた.

Same object identifications out of many observation data taken at 2 sets of observation units at 2 sites are possible.

Which means objects coordinates separating about 80-degree of 2 passes are available. Therefore, accurate orbital determinations will be carried out.

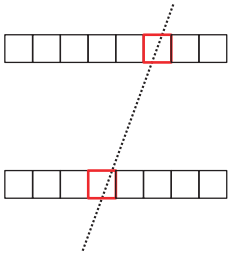
●2局の観測サイトそれぞれにある２つの観測装置のセットのデータから同一物体を高い確率で対応付けできることが分かった.
●2回のパスについて天球上の数十度離れた位置情報を得ることが可能になり、精度良い軌道決定が可能となる.

軌道決定能力
Orbital Determination Possibilities
-Test Observation-

Observation sites:

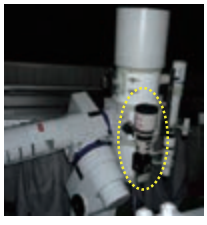
Ishigakijima Morita Observatory (Okinawa)

Rikubetsu Observatory (Hokkaido)

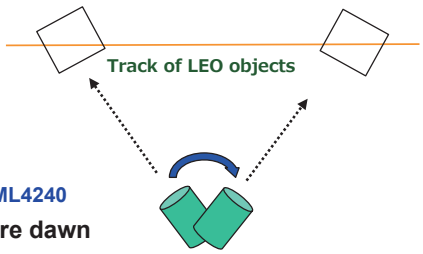


Observation equipments:

Canon 200mm F2 + FLI ML23042



Canon 300mm F2.8 + FLI ML4240



Observation date and time: Jul/27-28/2012 after dusk and before dawn

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

In order to mimic the observation using the optical array system described before, some TLE-objects were observed assuming one of the sensor of the system detects those objects with no TLE 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 was for evaluation of the accuracy of the orbit determination.

観測を模擬するため、いくつかの明るいTLE物体を経度の離れた2局において連続する2パスをそれぞれ１つの観測ユニットで観測した．各局ではTLE物体の通過位置2か所をTLEを基に計算して待ち受け観測を実施、得られた観測データ（時刻及び位置情報）をシステムの1台のユニットが観測したものと仮定する．２晩このような観測を各局で実施し１晩目のデータは軌道決定に、２晩目のデータは軌道決定精度の評価に利用した.

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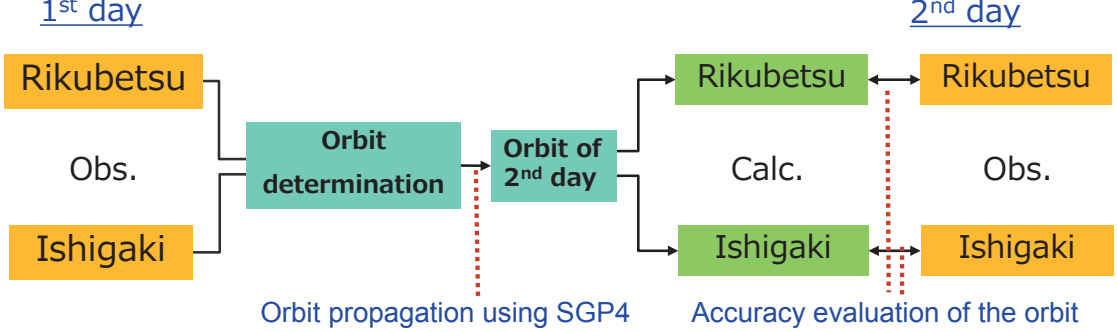
軌道決定能力
Orbital Determination Possibilities
-Test Observation-



Result of the accuracy evaluation(Obs. – Calc.)　軌道決定精度評価結果

SSC番号	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

FOV □7.65°

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.

評価結果から少ない観測数にも関わらず、翌日の追跡には十分な軌道決定の精度を達成していることがわかった．特に13589，20720では計算と実際の観測の差異が0.01°=36arcsec以下と極めて良い精度であった．これらの事実から提案する低軌道デブリ光学観測システムは未カタログのLEO物体の精度良い軌道決定に有効であることがわかる．

運用効率
Operational efficiency

今後、CMOSセンサーの開発、解析手法等の向上により、10cm級を検出できると仮定。本システムでいくつの軌道上物体を検出、軌道決定ができるかをSTKを使って調査。

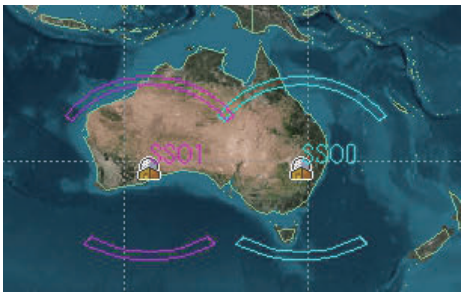
観測周期は？　追跡望遠鏡は必要？何個、どこに？

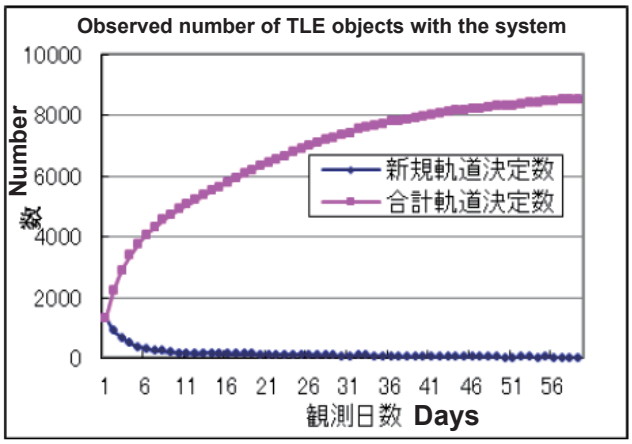
Sites: 豪州Siding Springs Observatoryと経度が25°離れた架空の観測サイト

Equipments: 18cmTelescopes＋ Optical Sensors　40sets (each sites)

Objects: TLE（About 14900）

Date and time: 2014/1/1-　4 months





●4ヶ月後には9100個（TLE全体の約60％）でほぼ一定となった。

●天候の影響は考慮していない。

●検出、軌道決定の頻度は各物体で様々
- ほぼ毎日
- 10日程度の空白期間をおいて数日
- 数日観測された後は全く観測されない

↓

追跡観測の必要性

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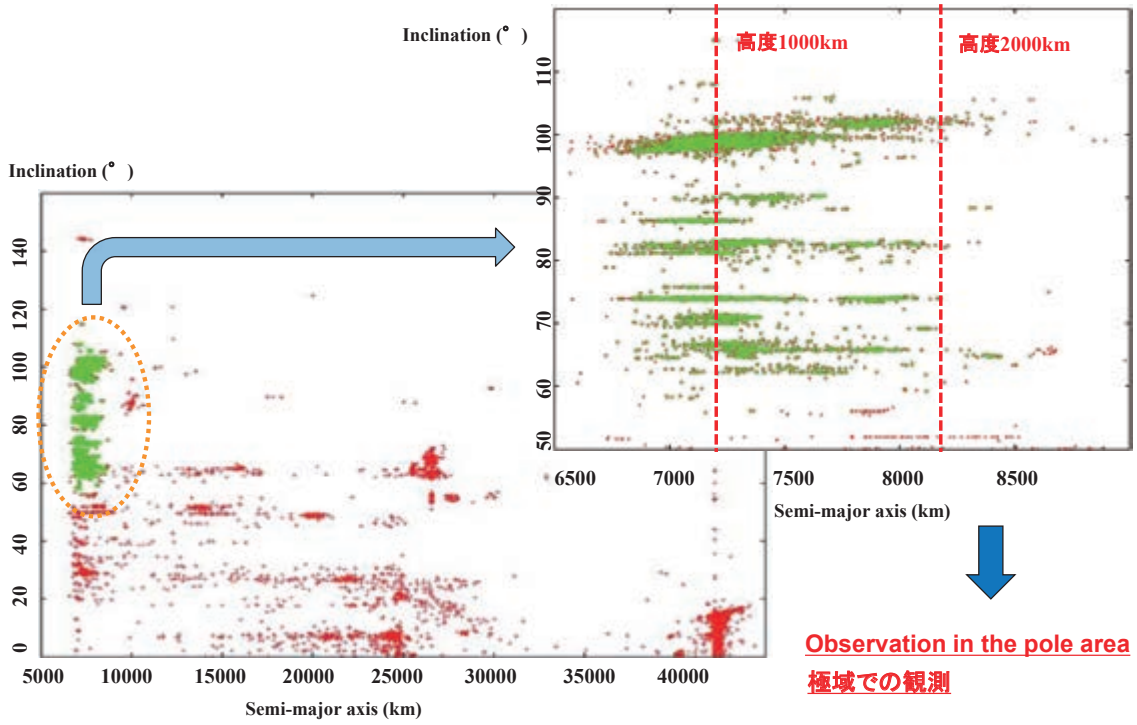
追跡観測

Tracking Observation

本システムで検出可能な軌道上物体の軌道長半径 - 軌道傾斜角分布



Tracking Observation Sites

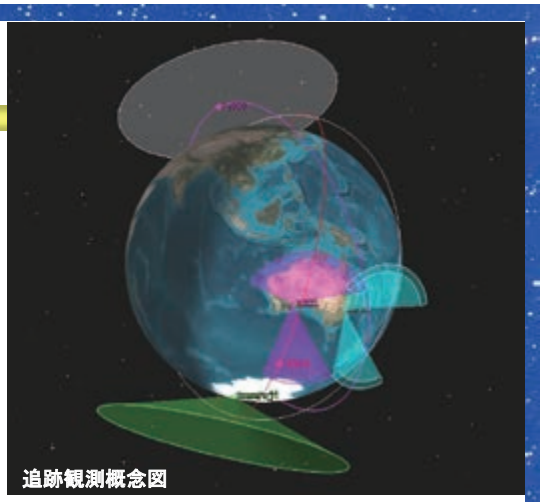
北極域及び南極域に追跡用の光学観測施設を設置、本システムで軌道決定できる物体のうち典型的な軌道の7物体の可視観測時期をSTKを使って調査した。

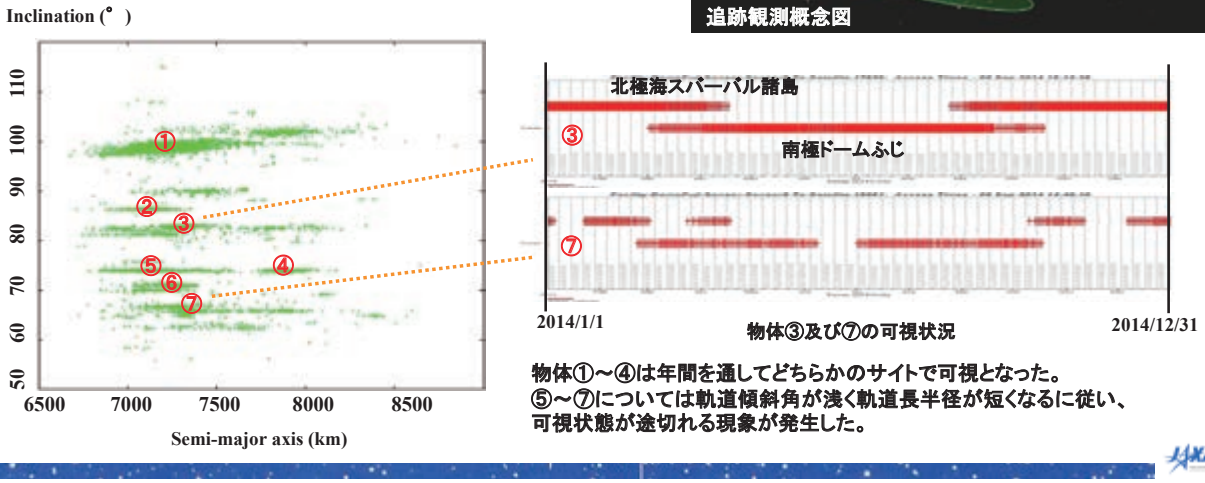
Sites: 南極ドームふじ及び北極海スバールバル諸島

Equipments: 18cm Telescope＋Optical Sensor (each sites)

Objects: 7 本システムで軌道決定される低軌道物体（7個）

Date and time: 2014/1/1- 1 year





物体①～④は年間を通してどちらかのサイトで可視となった。
⑤～⑦については軌道傾斜角が浅く軌道長半径が短くなるに従い、可視状態が途切れる現象が発生した。

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Summary

We are proposing a ground-based optical observation system for monitoring LEO objects which uses a lot of optical sensors to cover the vast sky. In this study, the system evaluation was carried out using STK software. The results shows that two longitudinally separate sites for survey and two tracking sites located in both polar regions were able to detect more than 60% of TLE-objects and maintain their orbits. The proposed system may complement or replace the current radar observation system for monitoring LEO objects like a space situation awareness in the near future.

低軌道物体を監視するため、多数の光学センサーを利用して天球上の広い領域をカバーする地上光学観測システムを提案している。STK softwareを利用したシステム検討から経度方向に離れて設置した2局のシステムにより公開されている軌道物体の約60%の軌道決定が独自で可能であり、さらに南北の極域にそれぞれ1局づつ追跡観測施設を設置することにより軌道決定した物体の多くを追跡可能であることが分かった。提案システムは将来、宇宙状況監視において現在米国が運用しているレーダー観測網を補完するような機能を持ちうる。

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F4

スペースデブリの軌道上光学観測

Space Based Optical Observation of Space Debris

○松本晴久（宇宙航空研究開発機構）、泉山卓（IHI）
○Haruhisa Mastumoto (JAXA), Taku Izumiyama (IHI)

米国 JSpOC は、2009 年 9 月から、軌道上の全ての運用衛星の接近解析を実施し、接近注意警報を各衛星運用機関に送信しているが、解析プロセス、情報品質、提供タイミング、検出サイズ等で課題がある。第 5 回スペースデブリワークショップでは、デブリ密度の高い低軌道デブリの軌道観測ミッションについてその有効性を報告した。今回は、利便性が非常に高く、かつ実用衛星が数多く運用されている静止軌道に対する光学センサによる数 10cm 級のデブリ検知、軌道決定及びデブリ回避システムの可能性について、回避実例を交えたシステムの検討結果について報告する。

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スペースデブリの軌道上光学観測

松本 晴久(JAXA)、泉山 卓(IHI)

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- 研究の背景
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  - 開発スケジュール
  - 特徴と懸念事項と素子の選定
- まとめ

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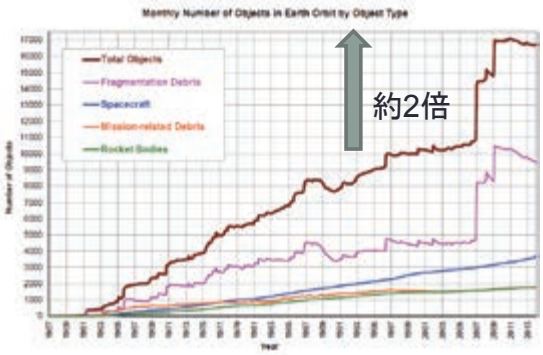
研究の背景

- 1957年以降、2014年9月4日までに6,983個の衛星が打ち上げられた。運用中の衛星は、1,340個。軌道上登録物体は（低軌道で大きさ10cm以上）、1993年に約8,000個であったのに対して2013年に約17,000個、直近の20年で約2倍と悪化。約92%がスペースデブリ。

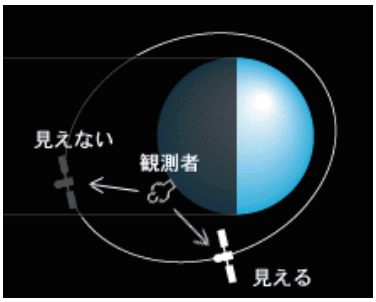


軌道上デブリの数量変化（NASA/JSC提供）

1cm~10cmのデブリは、10万個、
1mm~1cmのデブリは、3,500万個と推定されている。

軌道上観測のメリット(1/2)

- **24時間/7時間が可能： 観測制限がない、**
- **例えば**
  - **天気**（雲、雨、エアロゾル、吸収）
  - 昼/**夜** サイクル
  - 月の光, 光害
- **地理的制限がない**
  - 地上観測は、場所が問題となる



- **運用の柔軟性**
  - 目的とする軌道に対して、幾つかの観測方法が存在する
  - 地上観測より長い時間にわたる追跡が可能でカバー範囲が広い
- **短時間のデブリ検出と高い再検出率は、「準追跡」を可能にする**
  - 未知デブリのカタログ作成
  - 衝突回避、破砕事故等への早い対応
  - 地上観測より早く検知できる

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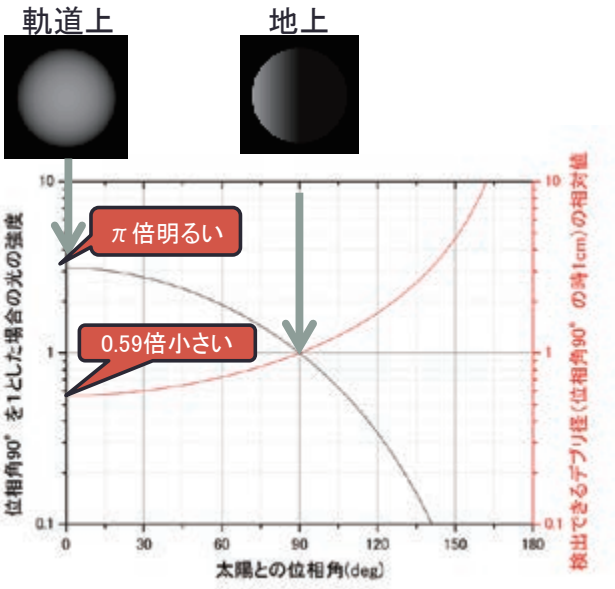
軌道上観測のメリット(2/2)

効率の良いデブリ検出と計測の正確さ

・バックグラウンド・ノイズの減少（大気がない）
　→感度の向上、より小さな物体の発見

・光学系の回折限界（大気は分解能を低下させる）
　→感度の向上と空間的分解能

・デブリの明るさ（地上より明るい場合が多い）
　→位相角を小さく
　　デブリまでの距離が短いものが多く存在する



位相角90°より位相角0°は、π倍明るく観測できる。
径は、0.59倍程小さいものが見える。

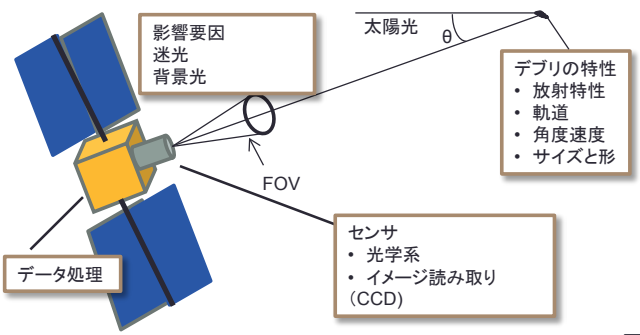
低軌道デブリ観測の概要

目的

衛星に衝突しそうな物の軌道を正確に決定する。破砕事故が起きた場合、全体の広がりを把握する。日本の衛星が多数運用されている600～800kmの軌道上物体（1cm以上）のカタログを作成する。

概要

物体が満月(位相角=0°)でセンサーの視界に現われる場合、位相角は最適化となる。例えば、反太陽指向で昼夜の明暗境界線近くの太陽同期軌道を使用する。さらに、衛星の軌道は、600kmとする。(800～1000kmの高いデブリ密度は避ける。)



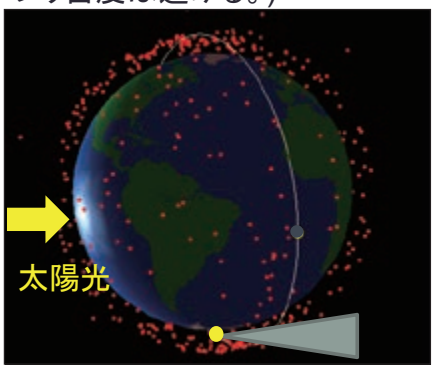


図1　低軌道デブリ観測衛星（案）(STK出力)

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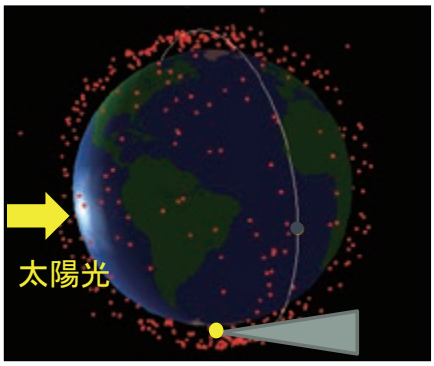
シミュレーション条件

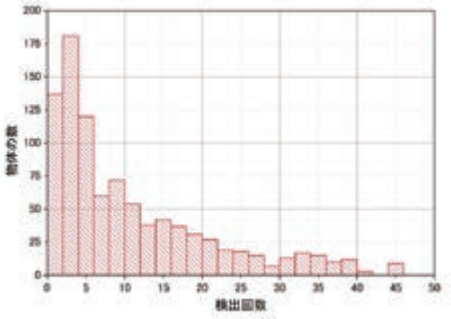
衛星: 高度600kmの昼夜境界軌道
物体: 高度600~800km、離心率0.002以下の967個
計算期間:2013/01/15　0:0:0から10日間
光学センサ:
　視野方向:反太陽方向
　FOV(全角): 15.8°　×15.8°
　露光時間:　1秒撮影



解析結果

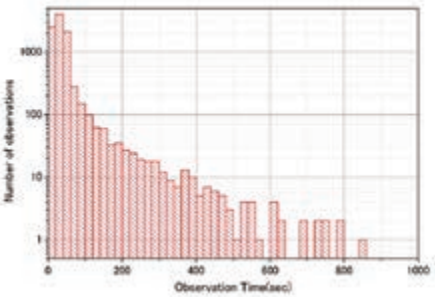
時間ごとの物体の検出数

検出時間	物体数数	パーセント
1day	585	60.5%
2days	792	81.9%
3days	855	88.4%
4days	883	91.3%
10days	937	96.9%



2013/01/15　から3日間の検出回数、
3日間連続して観測できる物体は315個(32.6%)

1日から3日間及び10日間を比較した場合、
3日間でほぼ検出できることから、
以後3日間で検討する。



物体の観測時間

但し、デブリ回避やカタログ化するには、技術的課題が大きい。

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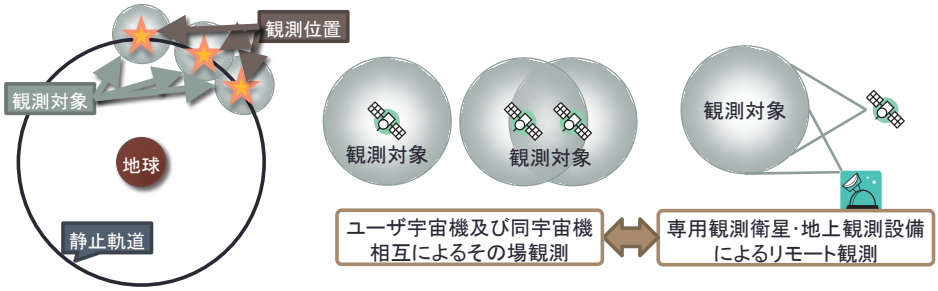
静止軌道デブリ観測

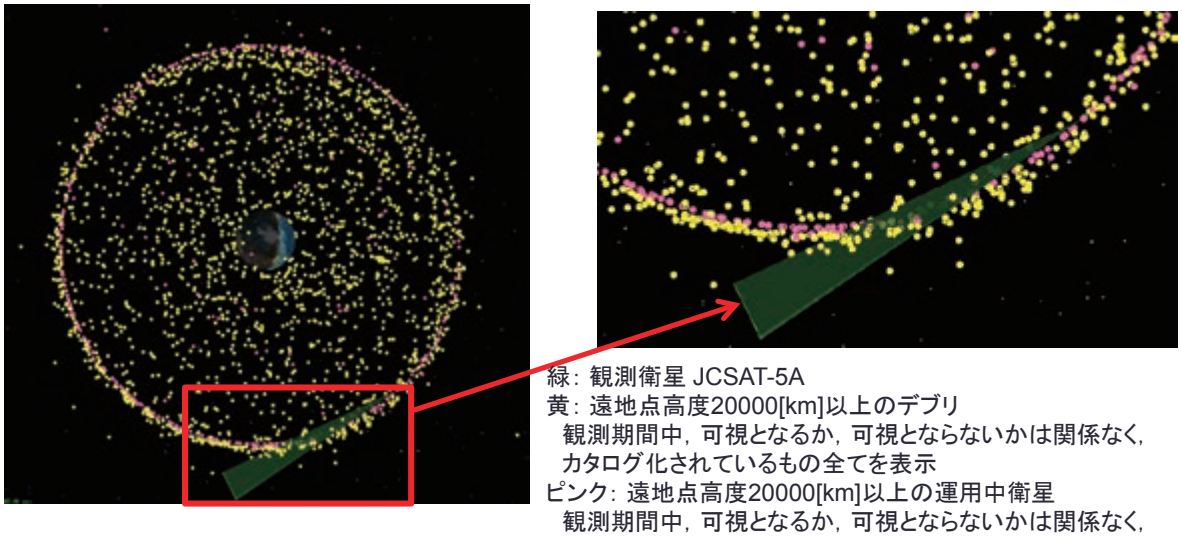
- **目的**
  - EISCAT（欧州非干渉散乱）レーダーなどでも、低軌道2cmのデブリの検知、軌道決定が可能である。
  - しかし、静止軌道での数cm級のデブリ観測は、地上観測では困難である。静止軌道は、利便性が非常に高く、かつ実用衛星が数多く運用されており低軌道より早く実現すことが重要であると判断した。
  - また、デブリ回避運用を実現する。
  - 観測手段として、静止衛星（ユーザ宇宙機）自身による「その場観測」を検討している。



デブリがどの様に見えるか（例１）

- 観測衛星(カメラ搭載衛星) JCSAT-5A (衛星番号29045)
- 観測期間 2013/11/1 00:00:00 ～ 2013/11/8 00:00:00 UTC
- カメラ
  - 視野角：7×7 [deg]
  - 視野方向：Azimuth 185[deg]，進行方向と逆側
  - Elevation 15[deg]，地心と反対側

拡大



緑：観測衛星 JCSAT-5A
黄：遠地点高度20000[km]以上のデブリ
観測期間中，可視となるか，可視とならないかは関係なく，
カタログ化されているもの全てを表示
ピンク：遠地点高度20000[km]以上の運用中衛星
観測期間中，可視となるか，可視とならないかは関係なく，
カタログ化されているもの全てを表示

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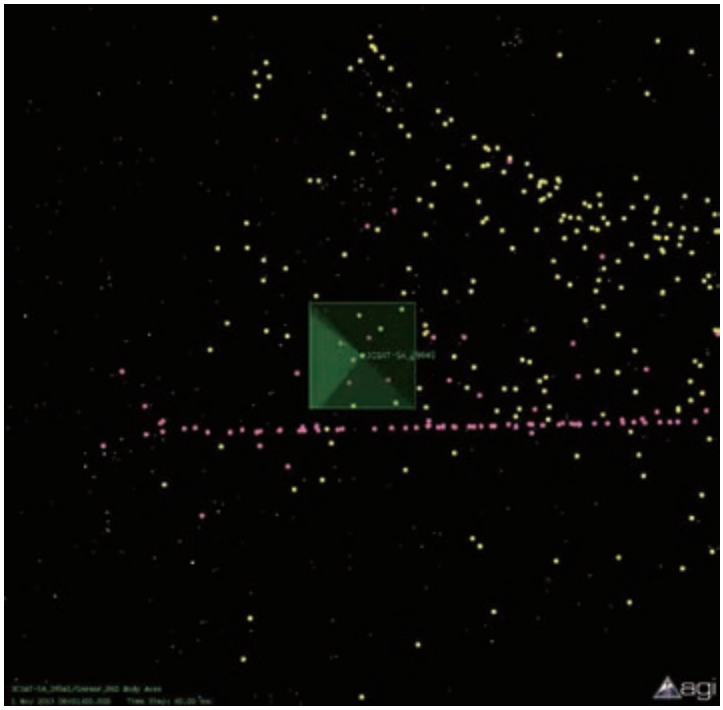
シミュレーション（例１）



一番近い運用衛星は、約150km

デブリがどの様に見えるか（例2）
-回避運用した例-

- 観測衛星(カメラ搭載衛星)　Superbird_A3 (衛星番号24880)
- 観測期間　2012/12/16 00:00:00 ～ 2013/1/17 00:00:00 UTC
- 視野角：13.28 × 13.28 [deg]
- 視野方向：
  - Azimuth 180[deg], 進行方向と逆側
  - Elevation −5[deg], 地心側
- 動画上の物体識別
  - 緑：観測衛星 Superbird_A3
  - 黄：観測期間内に観測衛星から距離5000km 以内で視野に入るデブリ
  - ピンク：観測期間内に観測衛星から距離5000km 以内で視野に入る運用中衛星
  - 白：観測期間内に視野内に入るが、観測衛星から距離が5000km 以上のデブリおよび運用中衛星
  - 青：観測対象軌道上物体 Express_2

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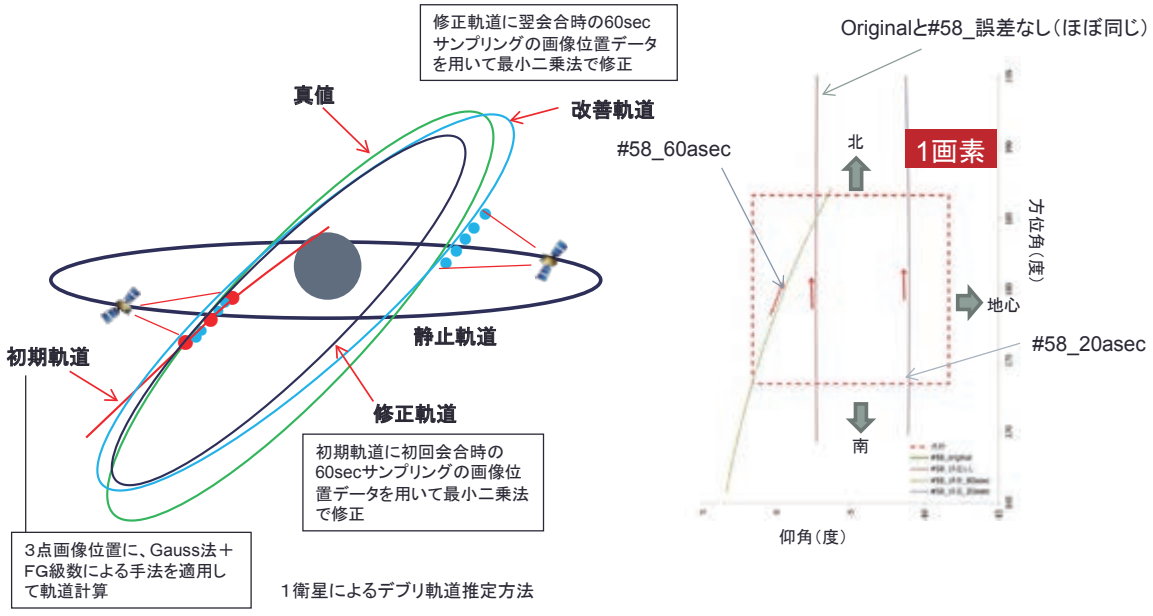
シミュレーション（例2）

デブリ回避の可能性



1衛星によるデブリ軌道推定方法

・視野を南北方向 約25度とすることで、次回観測で軌道上物体を同定可能なレベルの軌道決定が可能となる。
・最接近時刻・距離の正確な推定には、1回の観測では困難である。
・したがって、次回観測で軌道上物体を同定して、複数回観測により精度向上を行うアプローチをとる必要がある、

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開発スケジュール

- 撮像素子選定
  - 耐久性(動作時間、動作温度)、限界照度、感度の均一性、宇宙用のカスタマイズ(工程の一部変更)
- 工程変更の検討
  - 分光感 度特性、マイクロレンズ不採用(揮発性質量損失及び黄変対策)、パッケージ交換、接着剤の見直し等
- 粒子追跡法等の処理アルゴリズムの作成
- 研究モデルの製作
- CMOSの詳細なデータ取得
  - リニアリティー
  - ダークフレーム
  - ホットピクセル
  - 読み出しノイズ計測
- 恒星模擬装置Ⅲのソフトウェアを改修し、デブリを表示できるようにする。

撮像素子選定

-静止軌道デブリ観測の特徴と懸念事項等-

- 特徴
  - 画像内に輝度の低いもの、高いものの異なるものが混在する。
    - 現在、想定している視野方向(ラム又はウェイク)では、運用衛星が約150kmと近くに存在し、非常に明るい疑似星(＞1等星)となる。
    - 一方、観測しようと考えている10cm以下のデブリは、12等級~15等級と暗い。
    - また、カメラを搭載する衛星が、静止衛星の運用初期の場合、衛星は、ほとんど位置(緯度、経度、高度)が変化しない。
  - 視野方向(ラム又はウェイク)の場合、星は、＋X方向、デブリは主に±Y方向に移動する。

- 懸念事項
  - スミアやブルーミング
  - 焼き付き

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撮像素子の比較

	CCD	EMCCD	CMOS	I. I.+CCD(CMOS)
画素数	△	△	◎	CCD又はCMOSに同じ
構造(ｼﾝﾌﾟﾙさ)	△	△	◎	同上
消費電力	×	△	◎	同上
画質	◎	◎	○	同上
量子効率	◎	◎	○	同上
電子シャッタ	◎	◎	△	同上
ブルーミング	×	×	○	
スミア	△	△	○	同上
リニアリティー	◎	△	◎	×
寿命	ー	ー	ー	I.I.明るい光に弱い
読み込み速度(rt)	＞0.1sec程度	＞0.1sec程度	0.03～0.01sec	数10ns～数ms
低ノイズ(高SN)	◎	フォトンカウンティング領域	○	フォトンカウンティング
評価結果	△(rt>0.1sec)	×	◎(trt<0.1)	△(明るい光に対する対策)

センサ候補

- 民生品のCMOSセンサ、長時間動作可能な阻止、2/3インチ以上、ADC12ビット以上、ダイナミックレンジ80dB程度

項目	A社	B社	C社
サイズ	2/3インチ	1インチ	2/3インチ
分解能	1920×1080	4144×3063	1280×1024
ピクセルサイズ	5μm×5μm	3.1μm×3.1μm	7.1μm×7.1μm
シャッター	グローバルシャッタ	ローリングシャッタとグローバルリセット	ローリングシャッター
	カラー	カラー、モノクロ	カラー、モノクロ
ADC	12bit（14.7fps)、10bit（22.5fps）	12bit(24fps) 10bit(60fps)	18bit
ダイナミックレンジ	60dB	79dB	80dB
QE	60～70% 0.005lux	68%(カラー:Green) 80%(モノクロ)	約70% 0.0001lux
スピード	59.94fps	24fps,60fps	30fps,50fps
ノイズ	<2e-～<3e-程度	<2e-程度	<1e-1@30fpc64回積分

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静止軌道デブリ観測カメラ(案)

Lambertian 球、距離 2300km, アルベド 0.1
位相角=0°, デブリ速度 0.4°/sec,

項目	レンズ
検出素子	3.1μm×3.1μm 4144×3063 CMOS
焦点距離(f)(mm)	60
Fナンバー(Fn)	1.2
全角(FOV)	12° ×9°、対角15°
有効口径(D)(mm)	50
波長域(⊿λ)	0.2μm(450~650nm, 基準波長:550nm)
光学特性	0.35
S/N(dB)	2(目標)
リードノイズ	2e-
検出直径(重ね合わせ法) (理論値)	7(3)cm
台数	3台

まとめ

- 静止軌道衛星に光学カメラを搭載することにより、デブリ回避の可能性が確認できた。
- 視野を南北方向 約25度することで、初期軌道推定後、次回の観測で軌道上物体を同定可能なレベルの軌道決定が可能である。
- 今年度中に素子の選定及びデータ処理アルゴリズムの基本部分を開発する。

- 謝辞

本ミッション構想を検討するに際し、チーフエンジニア室 ミッションデザイン支援グループにご協力を頂きました。

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F5

JAXA 衛星に対するスペースデブリ接近解析の現状

Current Status of Conjunction Assessment for JAXA satellites

○阿部 旬也、松田 郁未、池田 人、池田 沙織、
坂本 拓史、田島 徹（統合追跡ネットワーク技術部）
○Junya Abe、Ikumi Matsuda、Hitoshi Ikeda 、Saori Ikeda、Takushi Sakamoto、
Toru Tajima (Consolidated Space Tracking&Data Acquisition Department, JAXA)

近年、スペースデブリの増加が著しく、人工衛星はスペースデブリとの衝突の危険が高まっている。JAXA では、人工衛星をスペースデブリとの衝突から守るため接近解析を日々実施しており、接近解析によって衝突の危険性が高いと判断した場合には、必要に応じて衝突回避運用を実施している。この衝突回避運用の実施に当たっては、衛星寿命やミッションの成立性を考慮し過剰な実施は避けるべきであり、確度の高い接近解析および効果的な軌道制御運用に取り組む必要がある。本講演では、JAXA によるスペースデブリの接近解析に基づく衝突回避運用の事例を紹介する。

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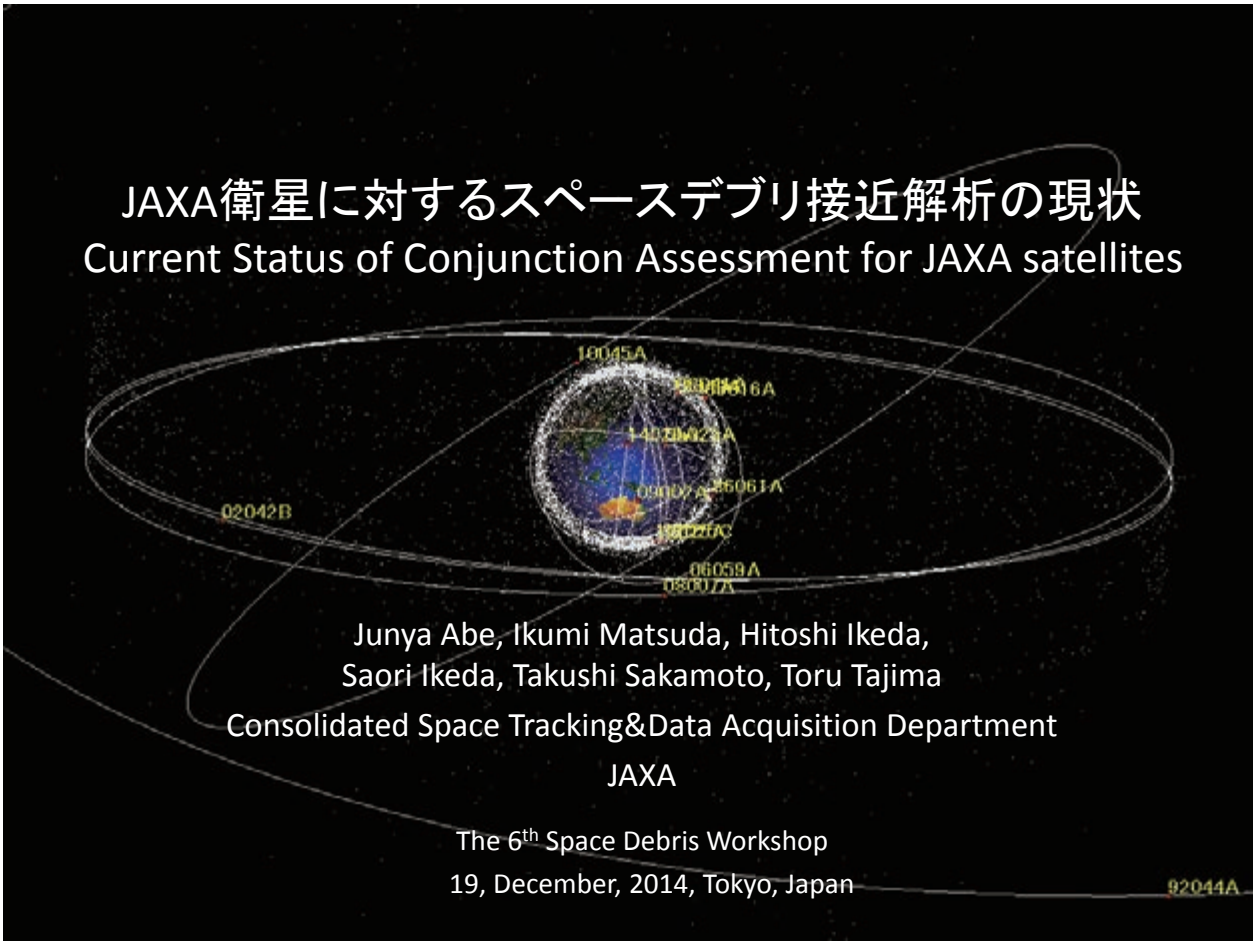
JAXA衛星に対するスペースデブリ接近解析の現状
Current Status of Conjunction Assessment for JAXA satellites



Junya Abe, Ikumi Matsuda, Hitoshi Ikeda,
Saori Ikeda, Takushi Sakamoto, Toru Tajima
Consolidated Space Tracking&Data Acquisition Department
JAXA

The 6th Space Debris Workshop
19, December, 2014, Tokyo, Japan

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3. Conjunction Assessment (CA)
4. Collision Avoidance Maneuver (CAM)
5. Practical Example of CAM Operation
6. Summary

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1. Introduction

- On-orbit collisions pose deterioration of space environment.
- The activities for collision risk identification and mitigation are necessary to preserve sustainable space development.

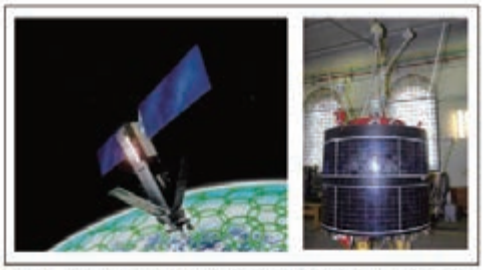


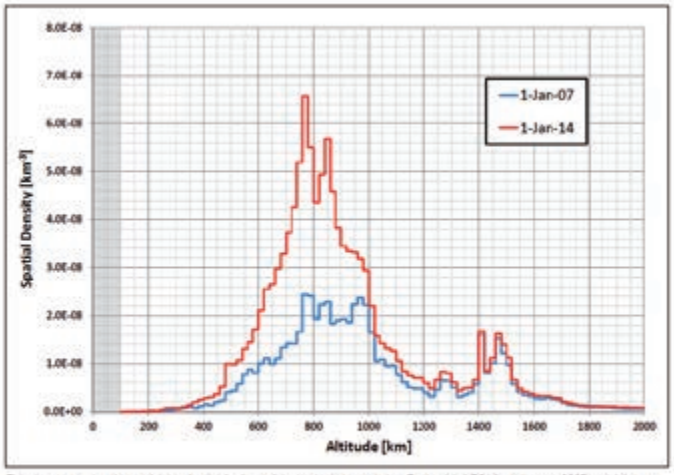
Figure 2. Configurations of an Iridium satellite (left) and the class of Cosmos satellite (right) involved in the collision of 10 February 2009.

Table 1. A summary of recent major breakups (based on the 25 June 2009 catalog data).

Event	Event Time	Cause	Total Catalogued Fragments*	Number of Catalogued Fragments with RCS data	Number of Catalogued Fragments Remaining In Orbit
Fengyun-1C	Jan 2007	Collision (deliberate)	2680	2680	2630
Briz-M	Feb 2007	Explosion	69	69	67
Cosmos 2421	Mar 2008	Unknown	506	506	40
Iridium 33	Feb 2009	Collision (accidental)	349	349	335
Cosmos 2251	Feb 2009	Collision (accidental)	809	809	785

*some tracked objects have not been added to the catalog.

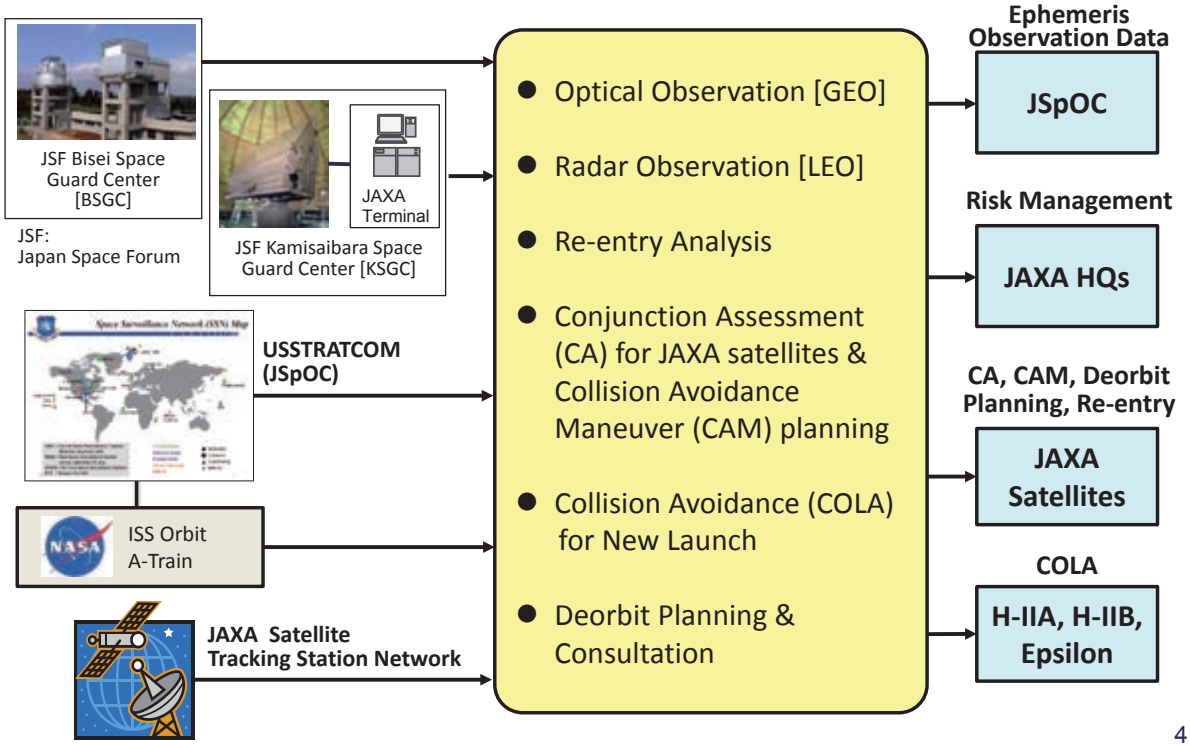
Ref. ODQN Vol. 13, Issue 3, July 2009



This chart compares the spatial density distributions of the tracked objects in low Earth orbit (LEO) for 1 January 2007 and 1 January 2014. The increase below 1000 km altitude is approximately 115.4%. Fragments generated from the Fengyun-1C anti-satellite test conducted by the People's Republic of China in 2007 and the accidental collision between Iridium 33 and Cosmos 2251 in 2009 account for most of the increase.

Ref. ODQN Vol. 18, Issue 2, April 2014

2. Overview of JAXA Activities for SSA



This document is provided by JAXA.

3. Conjunction Assessment

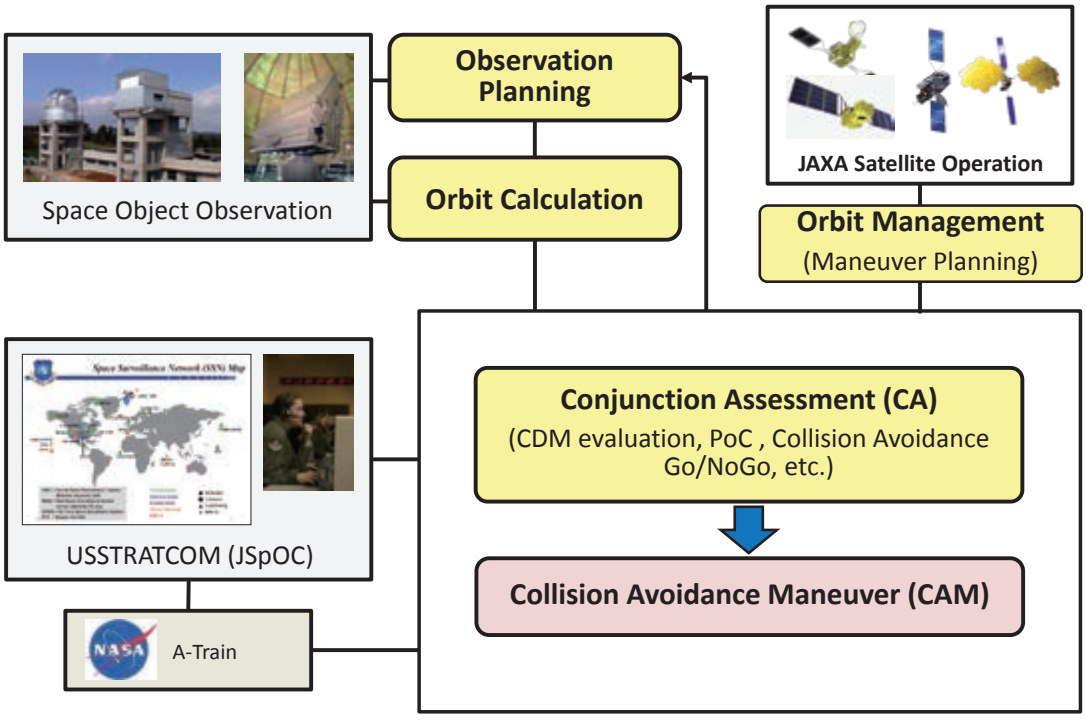
CA History and Practice Summary

- **HISTORY**
  - The 1st generation CA tool validation was accelerated by the IRIDIUM 33 and COSMOS 2251 accidental collision in February 2009
  - The 1st collision avoidance maneuver (ALOS vs. COSMOS 2251 DEB) in July 2009
  - SSA Sharing Agreement in May 2013

- **CA Practice Summary**
  - 3 GEO, 1 QZ, 1 HEO, and 10 LEO JAXA Satellites
    - Maneuverable satellites' orbit information including regular maneuvers has been informed to JSpOC
  - CA and CAM（Collision Avoidance Maneuver)
    - 22 CA notifications with initial evaluation were made within a month.
    - 4 collision avoidance maneuvers were executed in LEO since April 2014

5

3. Conjunction Assessment



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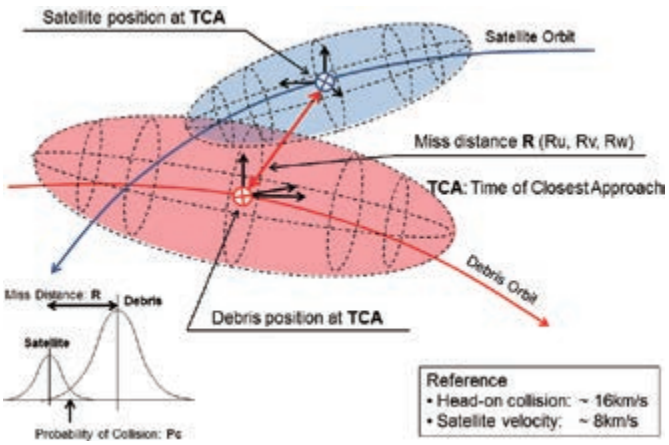
3. Conjunction Assessment

Assessment Point for CAM

■TCA Information

- Miss distance
- Geometry（Radial, In-track, Cross-track）
- Orbital error covariance
- Collision probability
- Orbit Determination(OD) quality
- Close approach to same objects at other timing
- Close approach to other objects



■Operational Capability

- Constraint of orbit keeping
- Feasibility of CAM operation (e.g., operation timeline, tracking station assignment)

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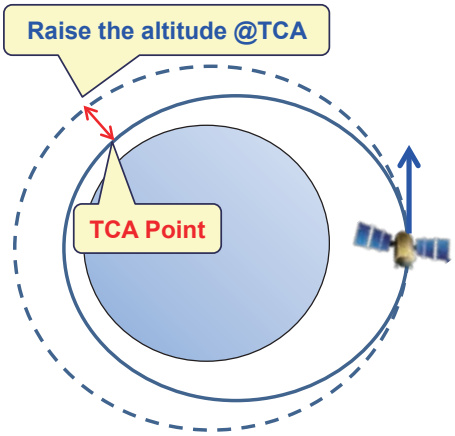
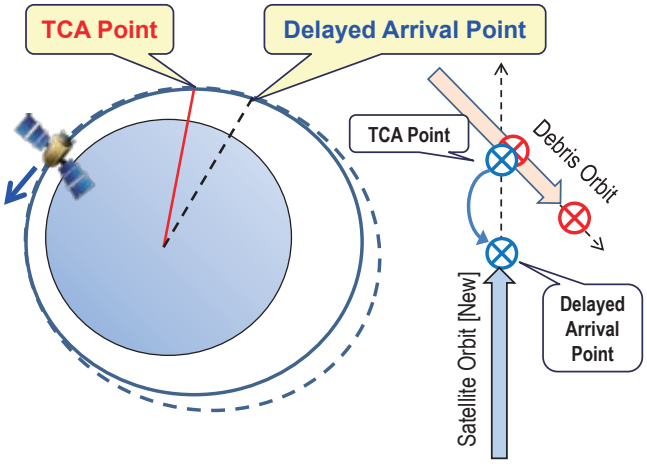
4.Collision Avoidance Maneuver

Altitude Separation



Advantage : can enlarge a miss distance rapidly
Disadvantage : need flexible maneuverability for an effective CAM operation

Phase Separation



Advantage : can accept a constraint of s/c maneuverability (e.g., attitude, direction)
Disadvantage : need relatively long duration time to obtain phase separation

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4.Collision Avoidance Maneuver

Strategies for CAM planning

- Risk mitigation to leverage routine Orbit Control Maneuvers (OCMs)
  - Cancel
  - Change an execution timing
  - Adjust a magnitude of ΔV
- Control Autonomous OCMs
  - Figure out planned OCMs calculated by onboard computer to decide following operations
  - Send a Enable/Disable command to ensure a schedule of CAM operation
- Additional OCM Planning
  - In the case of no routine OCMs, additional OCM is planned as CAM
- CA Screening
  - S/C trajectories after a CAM operation (nominal, backup) are also assessed again

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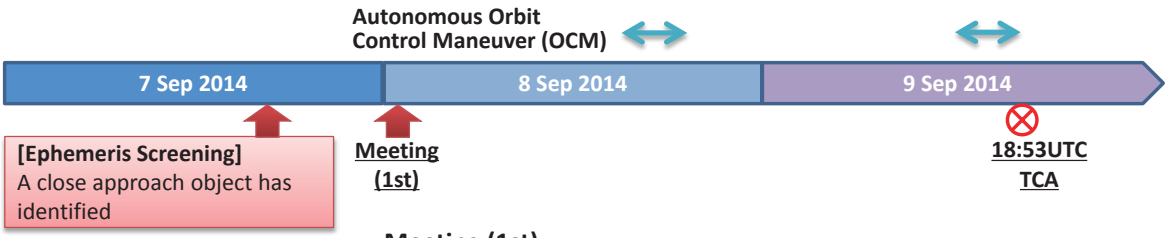
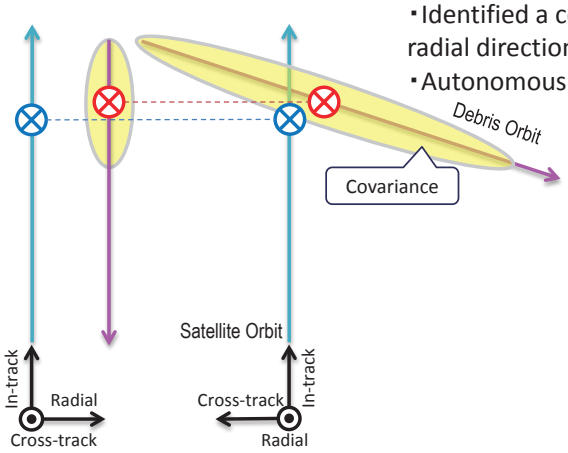
5. Practical Example of CAM Operation

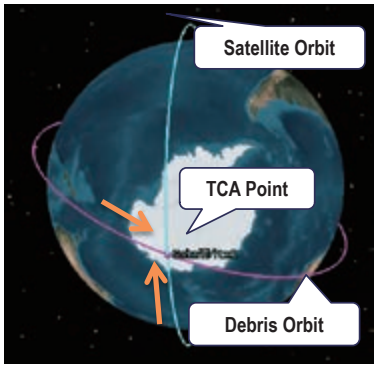


Meeting (1st)

・Identified a conjunction: secondary object is located above in radial direction, large prediction error

・Autonomous OCMs had planed to maintain operational orbit.





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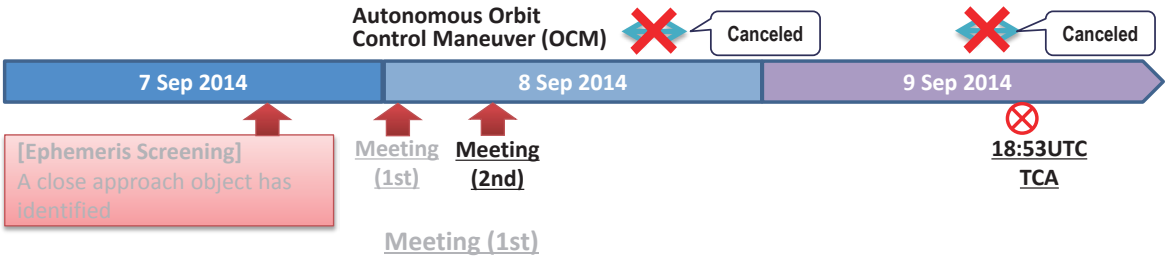
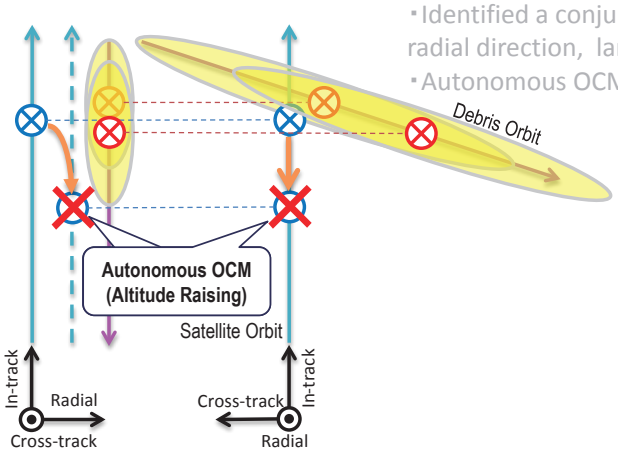
5. Practical Example of CAM Operation



Meeting (1st)

・Identified a conjunction: secondary object is located above in radial direction, large prediction error

・Autonomous OCMs had planned to maintain operational orbit.



Meeting (2nd)

・Radial miss distance are still close and the autonomous OCMs yields increased risk.

⇒ Autonomous OCMs are canceled.

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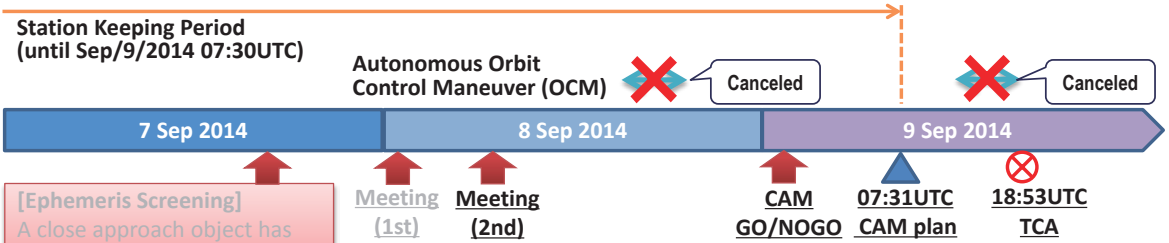
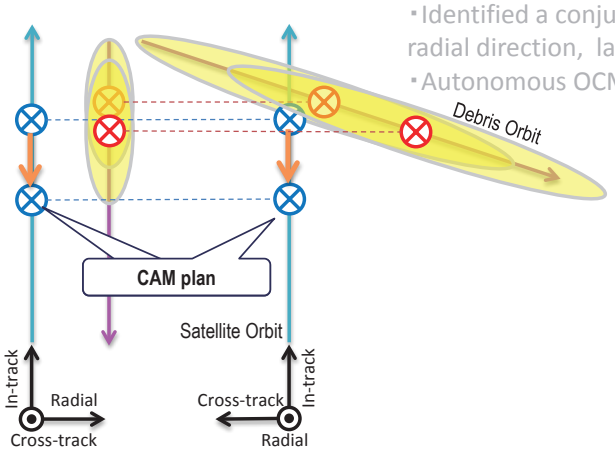
5. Practical Example of CAM Operation



Meeting (1st)

・Identified a conjunction: secondary object is located above in radial direction, large prediction error

・Autonomous OCMs had planned to maintain operational orbit.



Meeting (2nd)

・Radial miss distance are still close and the autonomous OCMs yields increased risk.

⇒ Autonomous OCMs are canceled.

・Additional OCM needs for station keeping.

⇒ We will perform CAM at the same argument of latitude of the TCA to separate orbital phase and to prevent the decrease of radial miss distance.

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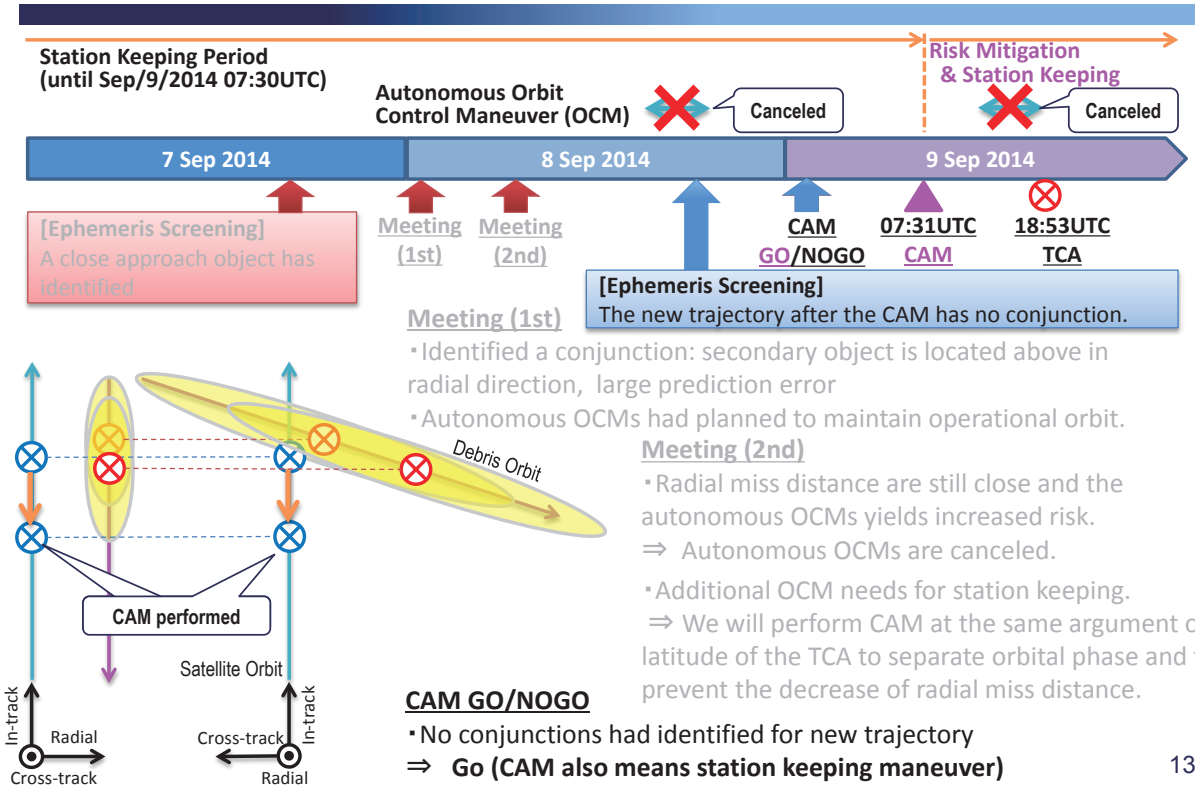
5. Practical Example of CAM Operation



Meeting (1st)

・Identified a conjunction: secondary object is located above in radial direction, large prediction error

・Autonomous OCMs had planned to maintain operational orbit.

Meeting (2nd)

・Radial miss distance are still close and the autonomous OCMs yields increased risk.

⇒ Autonomous OCMs are canceled.

・Additional OCM needs for station keeping.

⇒ We will perform CAM at the same argument of latitude of the TCA to separate orbital phase and to prevent the decrease of radial miss distance.

CAM GO/NOGO

・No conjunctions had identified for new trajectory

⇒ **Go (CAM also means station keeping maneuver)**

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6. Summary

- The overview of SSA activities for JAXA satellites are presented.
- Current status of conjunction assessments and collision avoidance maneuver operation are also described with some practical examples.
- The steady CA and CAM operation are necessary to accomplish a sustainable space environments.
- To save the fuel consumption caused by CAM, precision and stable CA techniques are necessary.
- We will continue consistent effort not only to improve accuracy of conjunction assessment but also to perform effective CAM operation.

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Thank you for your attention.

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G1

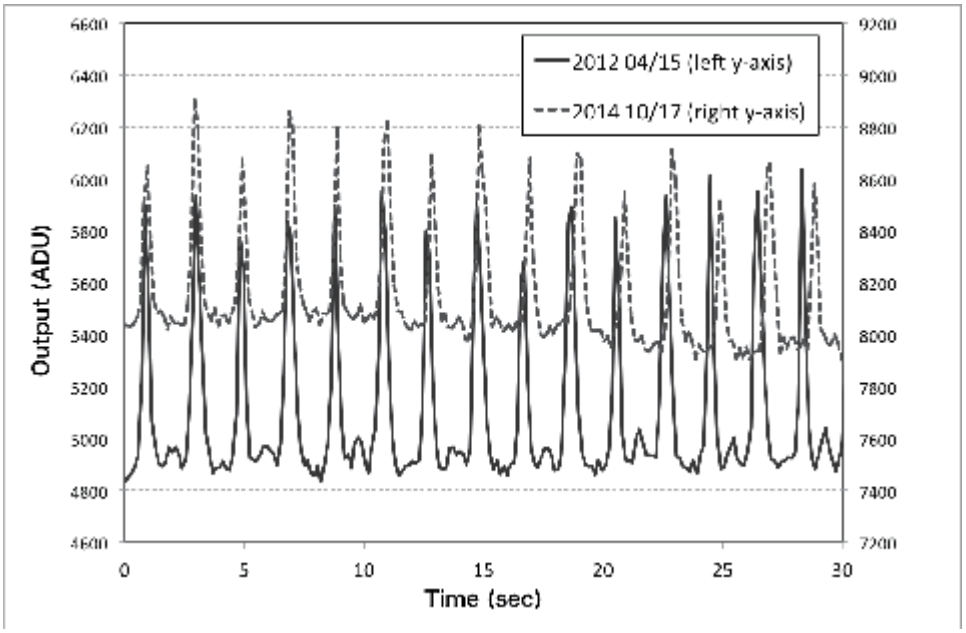
美星スペースガードセンターにおけるスペースデブリ光学観測への取り組み

Status of the optical observations of space debris at the Bisei Spaceguard Center

○奥村真一郎, 西山広太, 浅見敦夫, 浦川聖太郎, 坂本 強, 橋本就安, 高橋典嗣 (JSGA)
○Shin-ichiro Okumura, Kota Nishiyama, Atsuo Asami, Seitaro Urakawa, Tsuyoshi Sakamoto, Nariyasu Hashimoto, and Noritsugu Takahashi (JSGA)

美星スペースガードセンターは日本スペースガード協会が旧科学技術庁に働きかけ、日本宇宙フォーラム、NASDA(現 JAXA)と協力して建設した世界初のスペースデブリと地球接近小惑星の専用観測施設である。ここでは2000年から3台の光学望遠鏡(1m, 50cm, 25cm)を用いたデブリの光学観測を実施している。主たる観測対象は静止軌道物体であるが、1m と 50cm の望遠鏡は高速駆動が可能であり低軌道衛星などの高速移動物体を追尾する能力も有している。静止軌道物体の観測では 0.2-0.3 秒角(静止軌道上で約 40m)の精度で位置測定が可能である。最近では研究観測も重視しており、独自の手法を用いてデブリの短時間光度変化の観測などを実施している。図は運用を終えたある衛星の秒スケールの光度変化を示すものであり、この 2 年間で回転もしくはタンブリングの状態が変化していることが確認できる。

Bisei Spaceguard Center was built as a facility for the purpose of the optical observations of space debris and near Earth asteroids. Since 2000, observations have been carried out with three telescopes (1 m, 50 cm and 25 cm). Although main targets are GEO objects, the telescopes have the tracking capability for high-speed moving objects at LEO. The accuracy of the positional measurement is about 0.2-0.3 arcsec, which corresponds to the distance of 40 m at GEO. We are also working on research observations of space debris in recently. For example, the figure shows a short-term light curve of a retired satellite. Two light curves were obtained in 2012 and 2014. It shows that the rotation or tumbling status has varied in these two years.



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美星スペースガードセンターにおける スペースデブリ光学観測への取り組み

Status of the optical observations of space debris at the Bisei Spaceguard Center

○奥村真一郎、西山広太、浅見敦夫、
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（日本スペースガード協会）
○Shin-ichiro Okumura, Kota Nishiyama, Atsuo Asami,
Seitaro Urakawa, Tsuyoshi Sakamoto, Nariyasu Hashimoto,
Noritsugu Takahashi
(Japan Spaceguard Association)

Contents

· About the Japan Spaceguard Association & the Bisei Spaceguard Center

· Status of the space debris observations
  - Survey, follow-up（methods and examples）
  - Research

· Future plans

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Japan Spaceguard Association (JSGA)

- Non-profit organization established in 1996
- to protect the Earth's environment
  from a disastrous near-Earth object (NEO)
  collision
  by studying and observing
- Number of members: 400
  activity: observations, research, and education
  about “spaceguard”

Bisei Spaceguard Center (BSGC)

- Built using a grant from the former Science and Technology Agency by the request from JSGA
- Construction began in 1998, with the cooperation of the Japan Space Forum, NASDA, and JSGA
- The first astronomical facility in the world, optimized for the observations of space debris and near Earth objects
- Constructed in 1999, 25cm and 50cm telescopes were installed and observations started from 2000
- 1m telescope and wide-field mosaic camera were installed in 2001

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Bisei Spaceguard Center (BSGC)

- Building is administered by JSF
  Funded by NASDA(JAXA)
  Observations and research work by JSGA
- Discovery/followup/research observations of artificial objects
- Discovery/followup/research observations of near Earth objects
  - more than 1100 newly discovery
    (460 of “numbered asteroids”)
  - Follow up observations for more than 900 newly discovered near Earth objects

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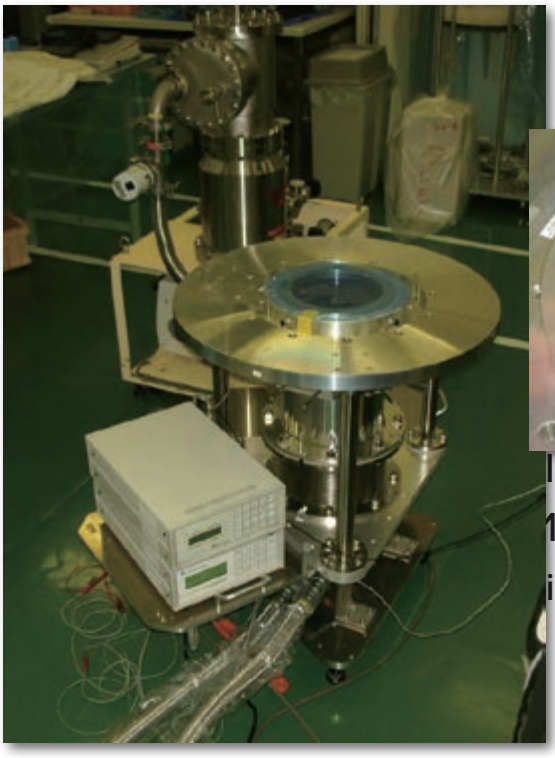

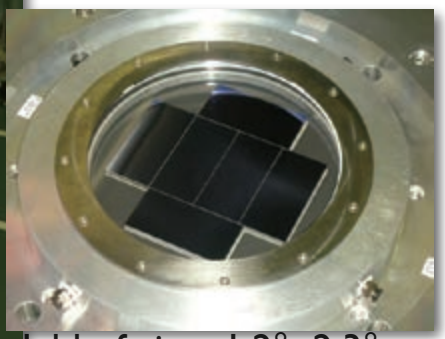

ield of view 1.2°×2.3°

laximum tracking speed 2.5°/s

imitng magnitude
18.7 (exp. of 2 min)
17.0 (exp. of 4 sec)

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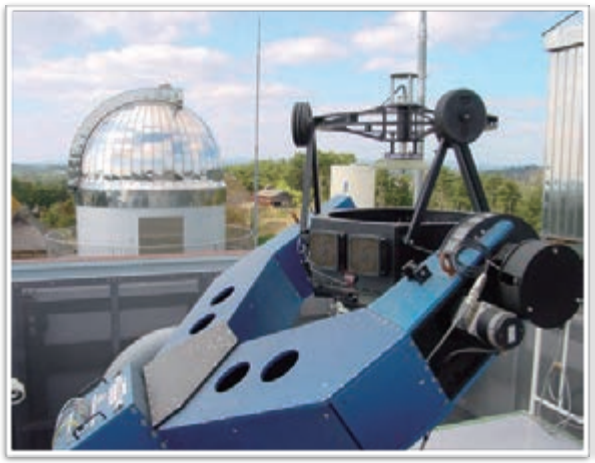

50cm telescope
- Fork-mounted Equatorial
- Cassegrain
  focal length: 1000mm (F2)
- Fields of view:1.7°×1.7°
- Maximum tarcking speed 5°/s
- Limiting magnitude
  17mag（2min）

25cm telescope
- Deutch Equatorial
- Baker-Ritchey-Chrétien
  focal length:1250mm （F5）

Status of the space debris observations (organization)

- daily observation
  …two JSGA members are in shift every night
  (average 255 days over a year)

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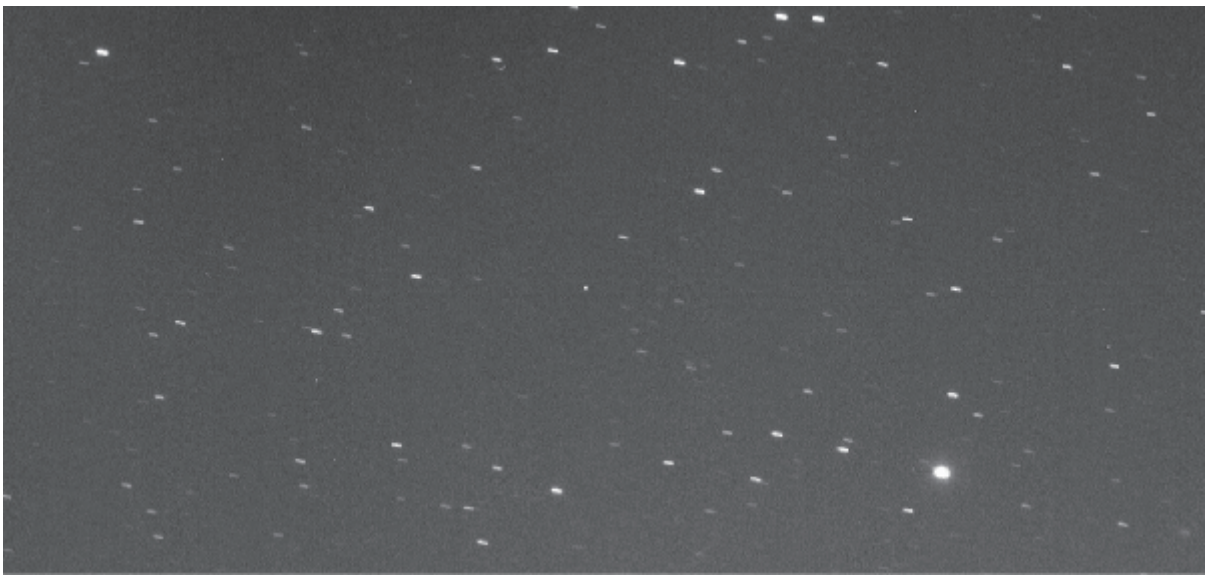
Status of the space debris observations (Survey and follow-up)

- Main target
  …Space objects at the geosynchronous orbit
- Survey observations and followup observations by the request from user (JAXA)

Observation method（GEO object）



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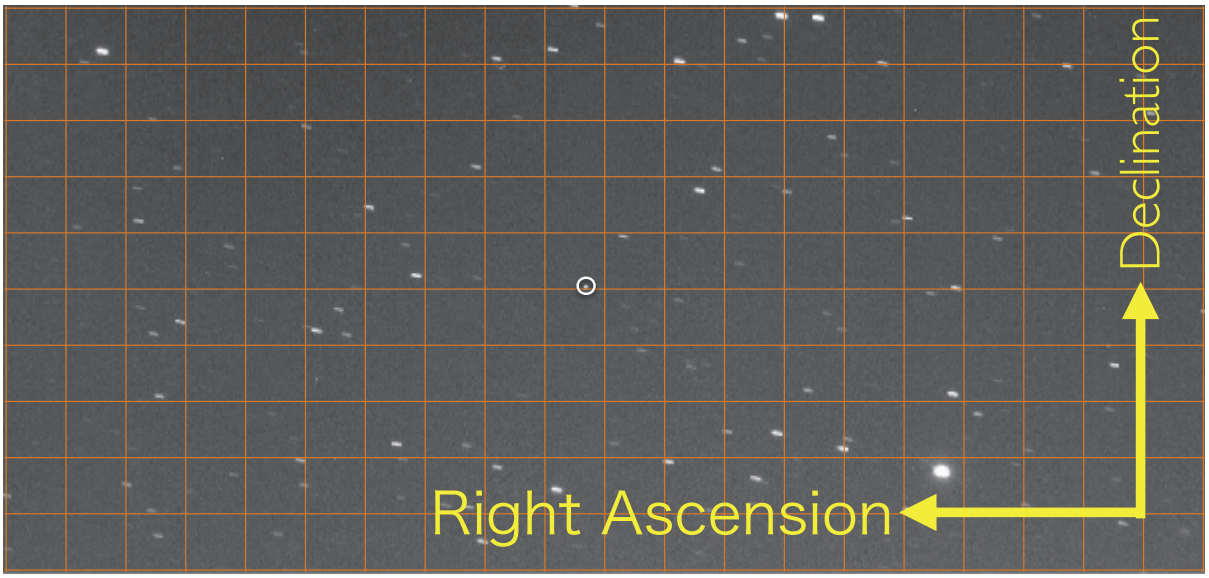
Observation method（GEO object）



Status of the space debris observations (Survey and follow-up)

- Main target…Space objects at the geosynchronous orbit
- Survey observations and followup observations by the request from user (JAXA)

Positional accuracy for the GEO objects…0.2-0.3 arc sec (約40m@36000km (GEO))

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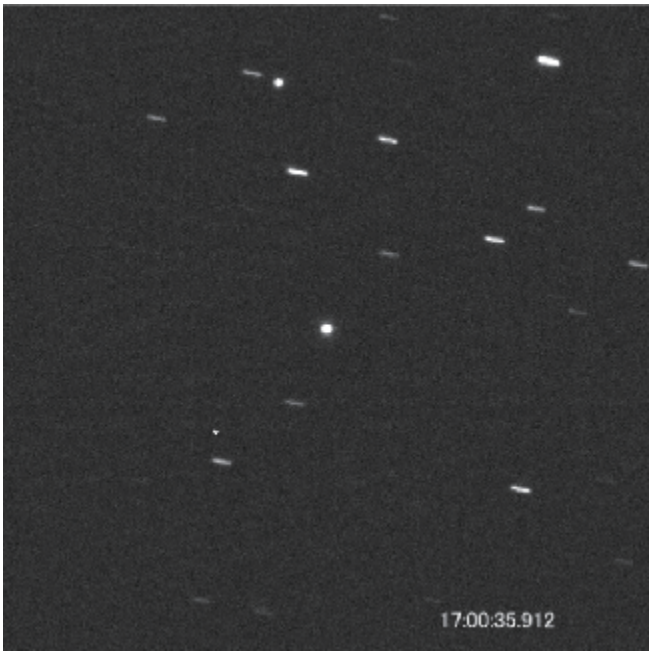
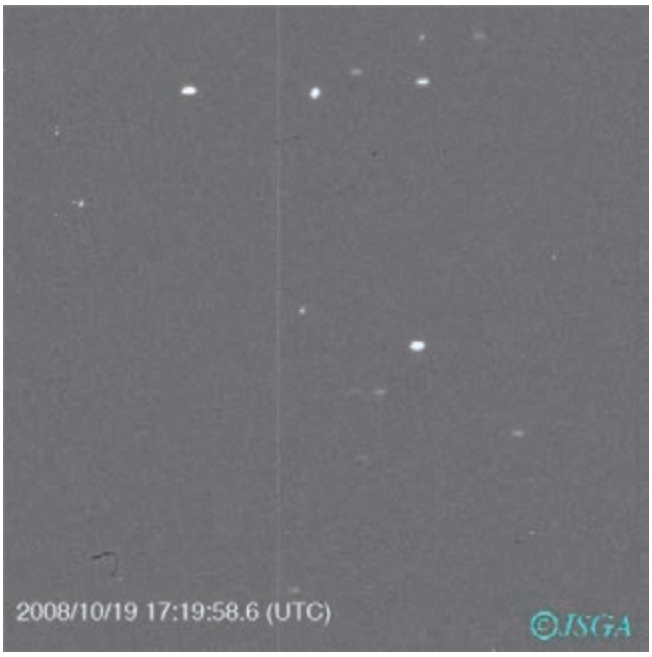
Example image（GEO）



Example image（GEO）



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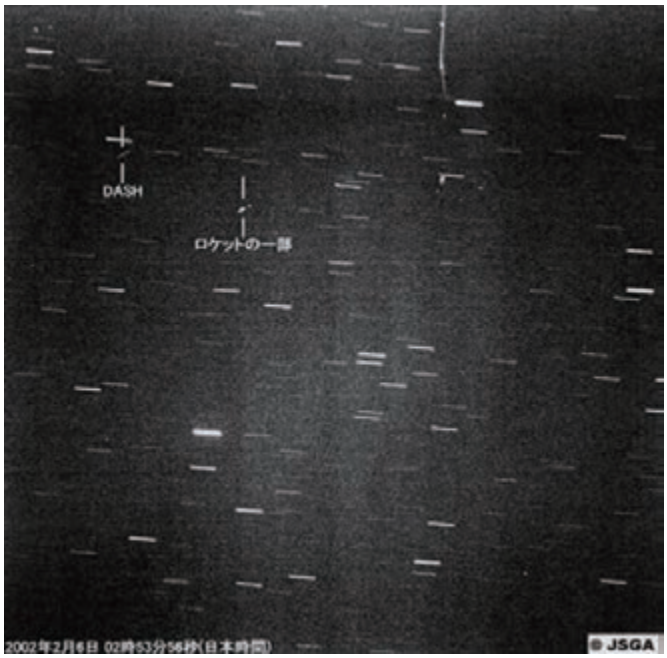
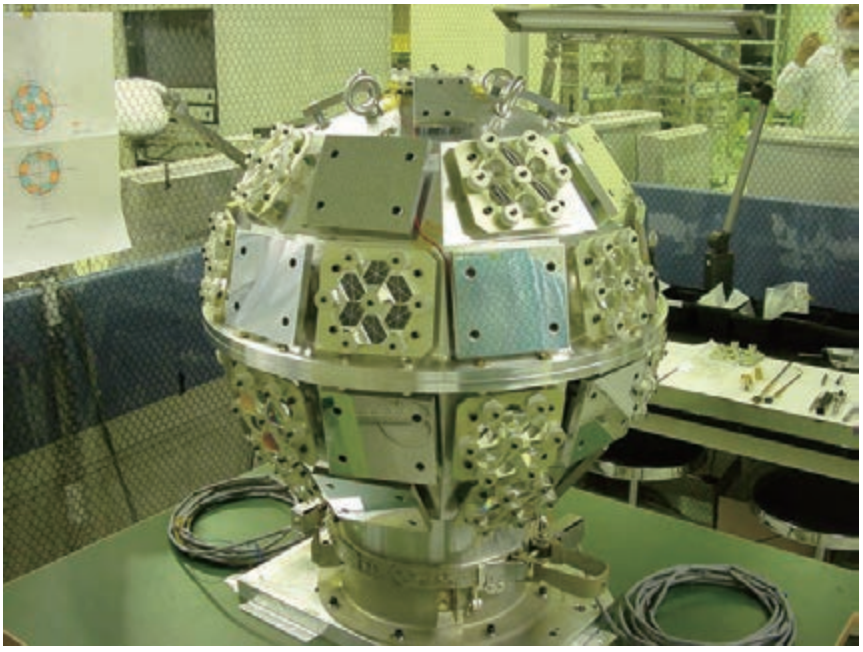
Example（DASH & rocket body）



Example
(Laser Reflecting Equipment: LRE)



from「LRE Photo Gallery」http://god.tksc.jaxa.jp/lr/lre.html

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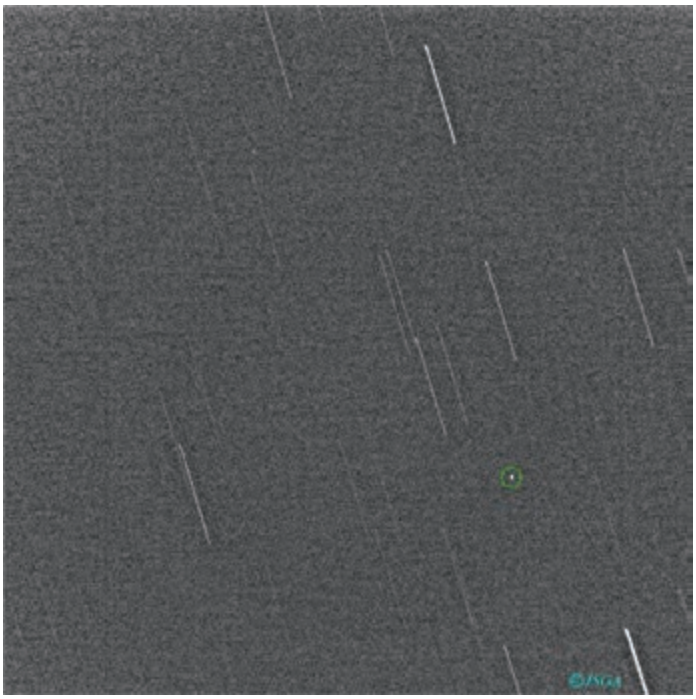
Example
99025AK（FENGYUN 1C debris)



Status of the space debris observations (Research)

- Luminosity vs Phase angle with the Sun
- Test observations of Low-Earth orbit objects
- Estimation of shape or motion form its light curve
- Short-period light curve by the application of TDI mode

etc., …

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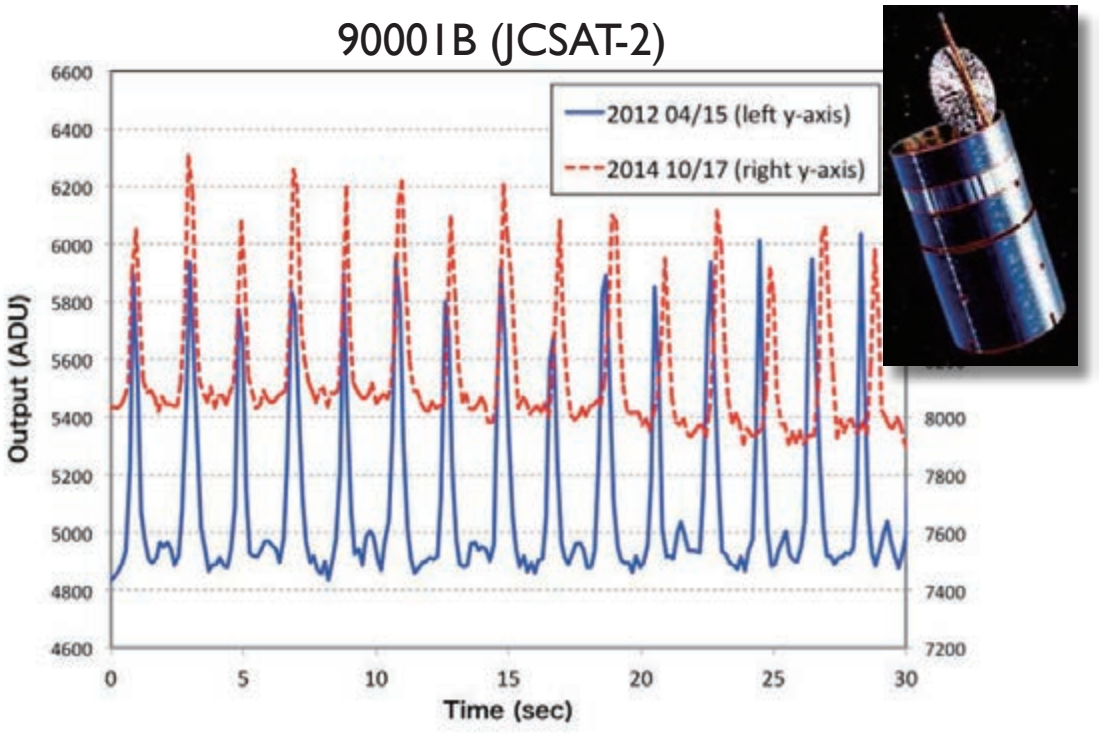
Example：research observation



Future plans

- Discovery and followup for smaller debris
  →larger telescope
- More efficiently
  →wide field
- For LEO object
  →light weight, fast tracking

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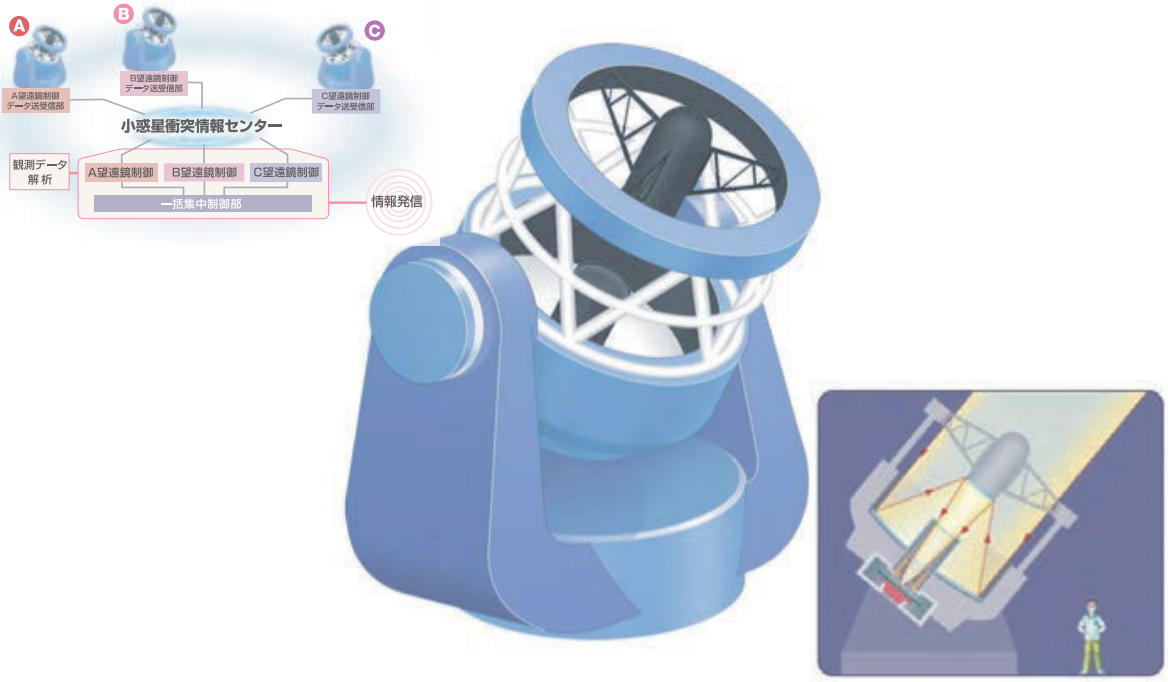
Plan of 3m-class wide-field and light-weight telescope for space debris and near Earth object



Summary

- Bisei Spaceguard Center
  - ★ **The first facility for the observations of space debris and near Earth objects**
- Status of the space debris observations
  - Survey and follow-up observations
    - ★ **GEO objects (positional accuracy～40m@36000km)**
  - Research
    - ★ **Light curve of space debris, etc.,**
- Future plans
  - ★ **3 m-class telescope**

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G2

静止軌道の宇宙状況監視技術の開発
−小型光学望遠鏡での挑戦−

Space Situational Awareness System for Resident Space Objects in GEO Belt
– Challenge of Small Optical System –

○泉山 卓、樋川 治、平井 健二、北澤 幸人、橋本 こずえ (IHI)
○Taku Izumiyama, Osamu Hikawa, Kenji Hirai, Yukihito Kitazawa, Kozue Hashimoto (IHI)

IHI では、20 年以上前から宇宙デブリに関する研究開発を実施してきた。 主として、宇宙空間でのその場観測や、宇宙システムに対する防護、また宇宙デブリの除去に係る技術の研究開発であったが、数年前からそれらの研究に加えて、自社内に望遠鏡口径 50cm 以下級の小型の光学観測設備を導入して、地上からの観測を開始している。現在、IHI 相生事業所に固定・据置型装置を、IHI エアロスペース富岡事業所内に可動式装置を設置し、観測を行っている。装置の設置位置は GPS により計測しているため、富岡の装置は、各地に持ち込んで出張観測も可能である。相生事業所に設置した装置では、遠隔操作による自動観測を実施可能であり、富岡の IHI 事務所や IHI 本社等から遠隔運用を行っている。 現在、これらの装置、特に相生の装置を使用して、主として静止軌道帯の物体（人工衛星、宇宙デブリ）の観測を通して、観測技術の研究を行っている。 相生の観測装置は、遠隔・自動運用を実現するため、望遠鏡・架台、カメラといった通常の観測装置の他に、各種センサを装備し、機器の状態、気象状況や周囲環境が遠隔での操作者がモニタできるようになっている。 通常の運用では、夕方までに観測対象を選定し、観測計画を作成した後、装置にシーケンスを投入までを操作者が実施している。 その後、翌朝までの観測は装置が自動実行する。観測中に、例えば降雨等があった時は、装置は安全化処置がとられる。 また、翌朝の観測終了時には、観測ドームは閉じられ、装置はホームポジションに移動する。観測により取得した画像から、恒星位置を基準として、物体の位置（赤経・赤緯）を算出し、物体の軌道決定を行っている。現在、相生に設置した観測装置の性能評価を実施している。 静止軌道帯の観測範囲として、位置が既知である静止衛星を観測することで、インド洋上空から太平洋上空まで約 120 度の観測幅を有することを確認した。また、観測から軌道決定までの、観測システム全体としての評価のため、マヌーバを行わないことが分かっている宇宙物体を追跡している。 観測により決定した軌道を伝播し、数ヶ月間の軌道を予測し、数ヶ月後に実際の観測で得られた物体位置との比較を行う、という再帰観測により評価を行っている。 再帰観測の結果、軌道伝播による予測結果と観測結果は良い一致を示すことを確認した。今後、再帰観測の期間をさらに延ばし、評価を継続するとともに、様々な対象の観測を通して、遠隔・自動観測システムにおける観測技術の開発を継続する予定である。

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Doc.#: JGM1-14 0576

第6回スペースデブリワークショップ

静止軌道の宇宙状況監視技術の開発
ー小型光学望遠鏡での挑戦ー

Space Situational Awareness System for Resident Space Objects in GEO Belt
- Challenge of Small Optical System -

2014年12月19日

株式会社IHI
宇宙開発事業推進部／宇宙防衛事業企画グループ
泉山 卓、樋川 治、平井 健二、北澤 幸人、橋本 こずえ

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はじめに

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近年、運用終了した衛星・ロケット上段や衛星の破片等、制御できない軌道上物体（宇宙デブリ）が増加している。デブリとの衝突は、人工衛星を損傷するばかりではなく、新たなデブリを産み出し、持続的な宇宙開発・利用を困難とする。 特に、静止軌道は、多くの実用衛星が利用する、軌道上物体が静止して見える唯一無二の特殊な軌道であるため、大規模な汚染で使用できなくならないように保全しなければいけない。 静止軌道の環境保全のためには、先ずはデブリの軌道／分布状況の把握が重要である。

IHIでは、20年以上前から、宇宙空間でのその場観測や、宇宙システムに対する防護等、デブリに関する研究開発を行ってきた。 宇宙環境保全への貢献が日本の宇宙開発を担ってきた企業としての責務であると考え、数年前から宇宙環境保全への取り組みとして、自社内に望遠鏡口径 50cm以下級の小型の光学観測設備を導入して、地上からのデブリ／軌道上物体の観測を開始した。

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軌道上物体の推移

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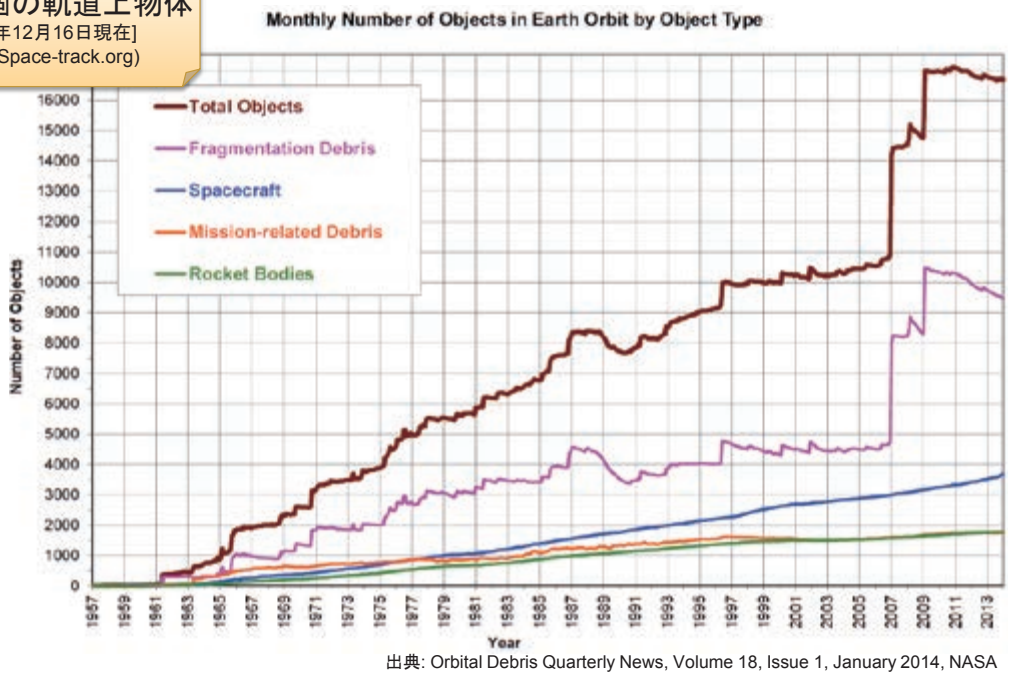
17,154個の軌道上物体
[2014年12月16日現在]
(出典: Space-track.org)



出典: Orbital Debris Quarterly News, Volume 18, Issue 1, January 2014, NASA

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IHIの観測アプローチ: 小型光学望遠鏡の活用

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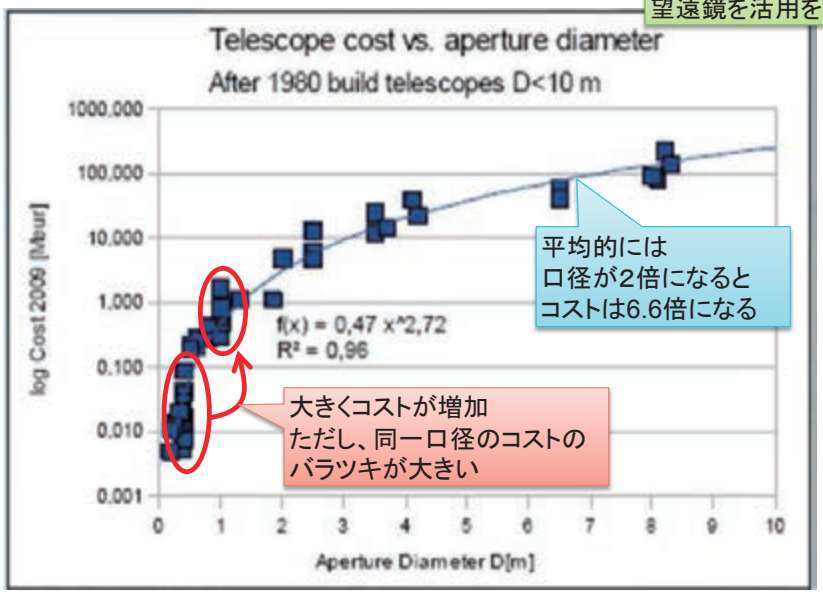
- 光学望遠鏡口径 1m級前後で価格が飛躍的に増加 ⇒ 導入コストを抑えるため、サブメートル（50cm以下）級望遠鏡を活用を目指す



出典: A. Vananti et al., Preliminary Telescope Design Analysis for the Optical Space Surveillance Subsystem, 2010, 61st IAC, Prague

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IHI光学観測装置

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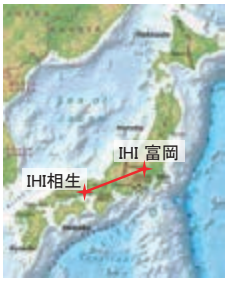
2地点に小型光学監視システムを設置: IHI相生観測所、およびIHI富岡観測所

IHI相生観測所

恒久観測設備(固定・据置型):

IHI相生事業所の造船所区域に接する山の上に設置

緯度	34.790143 deg N
経度	134.456717 deg E
高度	33 m



IHI富岡観測所

移動式観測設備:

通常の観測は、㈱IHIエアロスペース富岡事業所に設営

- 必要に応じて、観測場所を変更可能
- 装置の位置はGPSにより計測

緯度	36.301501 deg N
経度	138.933860 deg E
高度	207 m

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IHI相生観測所: 装置と観測範囲

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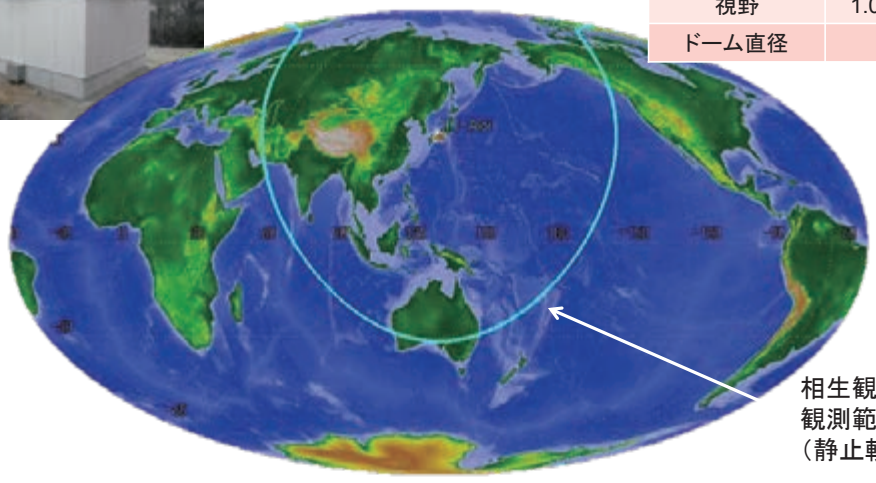
相生観測所

観測装置は固定され、天体観測ドーム内に格納

項目	仕様
望遠鏡口径	400mm
視野	1.0×1.0 deg
ドーム直径	3m



相生観測所からの観測範囲(静止軌道帯)

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IHI相生観測所: 観測範囲の確認

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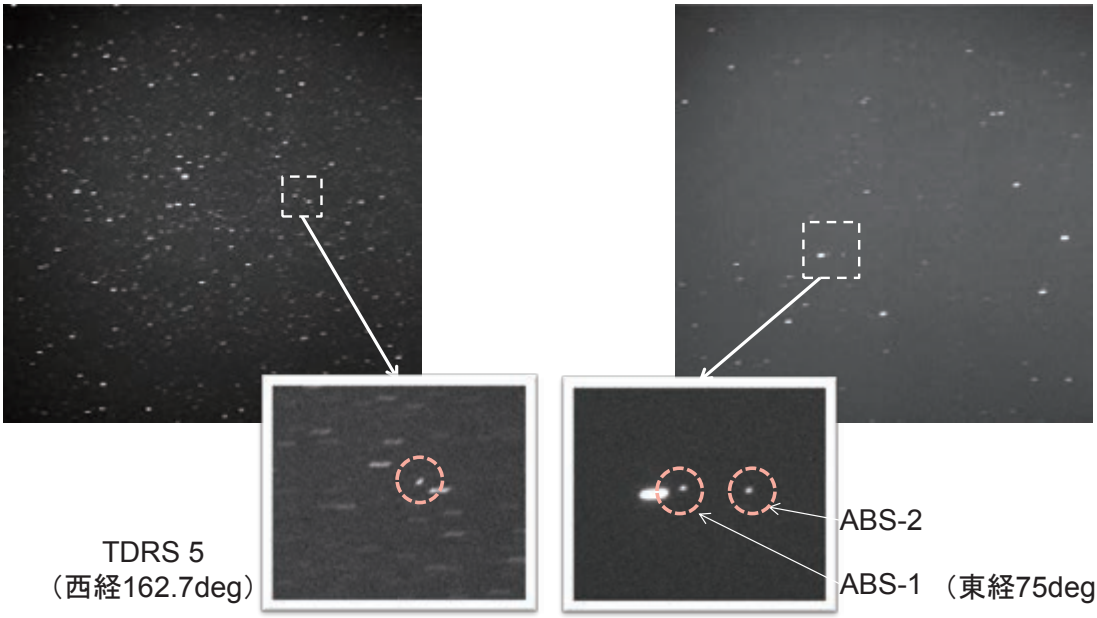
- **静止経度が既知の衛星を観測することで、観測範囲を確認**
  - 赤道上空の経度120度の範囲以上を観測可能なことを確認



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相生光学観測装置の特徴

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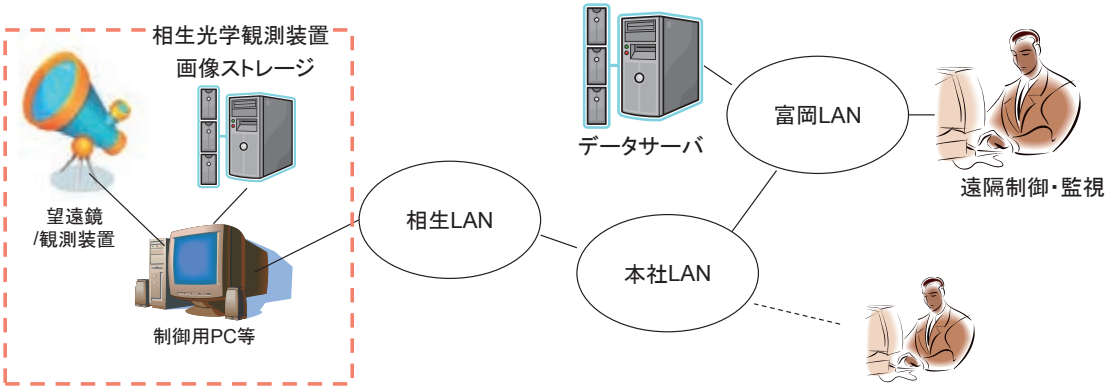
- **特徴: 遠隔自動観測の実現**
  - IHI社内ネットワークに接続したコンピュータ(IHI富岡等)から光学観測装置を制御、動作状態をモニタ
  - 遠隔観測を実現するため、観測装置周囲に各種センサを設置
  - 観測計画投入により、自動観測。翌朝、観測終了後、ホームポジションに復帰。
  - 天候の変化に対して、外部環境をモニタし、自動で安全化処置を実施。
  - 観測データの解析処理を自動化(継続開発中)。必要なデータのみIHI富岡に伝送



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IHI光学観測システム（相生）実証・運用

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- **相生光学観測装置: 3月から本格的に運用を開始**
  - 3/2～6にかけて試験観測を実施（3/4夜は雨天のため観測せず）
    - 自動シーケンスにより 約90領域／晩を撮影
      （途中、動作状況の確認のため、ブレークをとって実施）

設定したシーケンスに従い、自動観測／撮影の実行を確認

  - 観測スケジューリング機能等についても確認
    - 観測対象の撮影のため、光学観測システムの時刻毎の動作方向の決定
    - 決定したシーケンスをシステムに投入

短時間でシーケンス設定／投入可能なことを確認

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IHI光学観測システム（相生）観測状況

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- **7月から観測体制を整備し、定常的な観測を開始**
  - IHI夏期休業明けの8/18夜から基本的に毎晩、装置を稼働（～8/11はトライアル期間と位置づけ）

8月の観測結果

	データ取得	備考
8/1	-	夏期休業
8/2	-	夏期休業
8/3	-	夏期休業
8/4	×	
8/5	×	
8/6	×	
8/7	○	
8/8	×	
8/9	×	
8/10	○	

	データ取得	備考
8/11	○	
8/12	-	夏期休業
8/13	-	夏期休業
8/14	-	夏期休業
8/15	-	夏期休業
8/16	-	夏期休業
8/17	-	夏期休業
8/18	○	
8/19	○	
8/20	○	

	データ取得	備考
8/21	○	
8/22	○	
8/23	○	
8/24	×	
8/25	○	
8/26	○	
8/27	×	
8/28	○	
8/29	○	
8/30	○	
8/31	○	

観測計画日数	データ取得日数	データ取得率
22日	15日	68%

本年度は、全国的に天気不良にもかかわらず本格観測において高いデータ取得率を実現

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再帰観測

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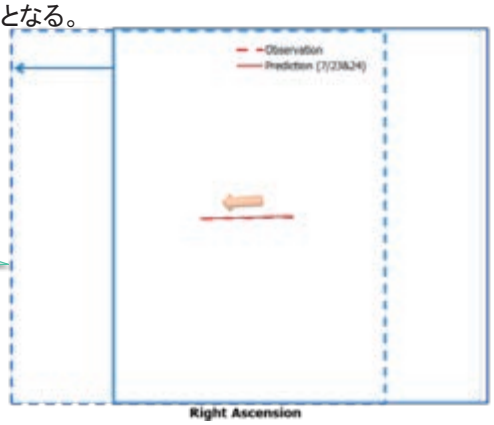
- **観測から軌道決定までの、観測システム全体としての評価のため、再帰観測を実施**
  - マヌーバしない物体を相生光学観測装置の可視範囲で追跡（数週間から数ヶ月）
  - 観測初期のデータで軌道推定。
  - 推定軌道を軌道伝搬させて、数日後、数週間後、数ヶ月後の観測データと比較し、誤差を評価
    - 観測視野内に捉えられるかが、一番のポイントとなる。

- **ケースA:**
  7/23と24の観測データで軌道決定

望遠鏡/赤道儀を停止して観測をしているため、赤経赤緯(RA-dec)平面では、カメラ視野が動いて見える



予測と観測結果は、ほぼ一致

15日後（8/7)の予測と観測結果 (RA-dec面）

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再帰観測:

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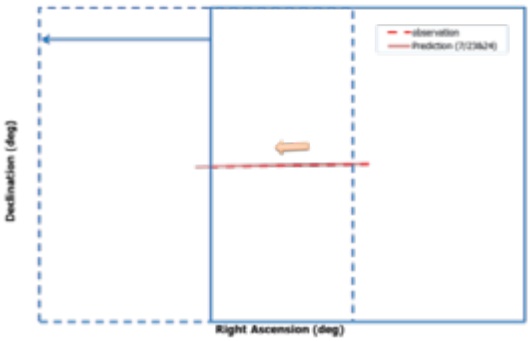
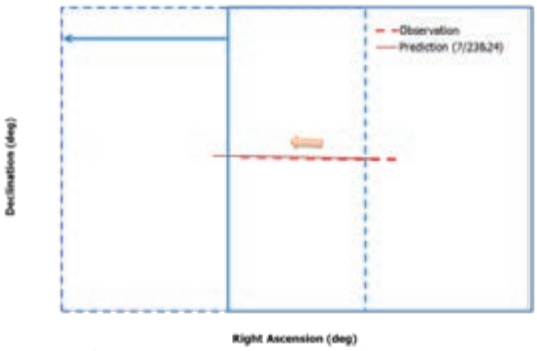
- **ケースA:（続き）**



37日後（8/30)の予測と観測結果 (RA-dec面）



56日後（9/18)の予測と観測結果 (RA-dec面）

観測後、約2週間後、5週間後、8週間後まで軌道伝播して位置を予測した結果、予測と観測結果は、ほぼ一致

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再帰観測:

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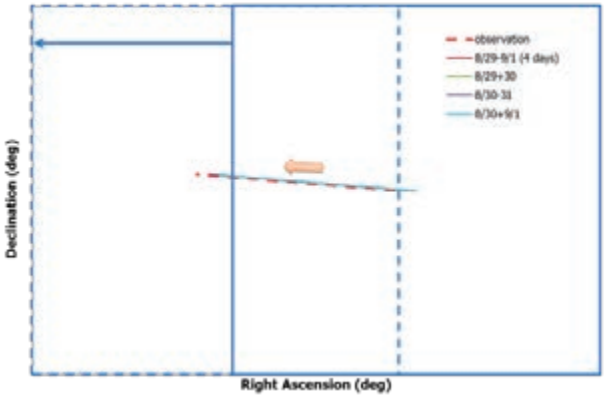
- **ケースB:（ケースAとは別物体）**
  8/29～9/1の観測データで軌道決定
  4日間のデータを使用した場合と2日間のデータを使用した場合で比較



約70日後（11/10)の予測と観測結果 (RA-dec面）

観測データの使用数/間隔を変えて大きな差はない
軌道伝播による約10週間後の位置予測結果と観測結果は、ほぼ一致した

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まとめ

IHI Realize your dreams

- **静止軌道上の物体（人工衛星、宇宙デブリ）を観測するために、IHIが開発した小型光学観測装置について紹介した。**
  - **◆ 本装置は、遠隔・自動観測が可能であり、効率的に軌道上物体を観測可能なことを実証した**
  - **◆ 事前設定した観測計画に基づき、夜間に自動実行させているが、今夏のように気象条件が悪い状況でも、かなり高い可観測率を記録することができた。**

- **観測から軌道決定までの全体のシステムの評価を再帰観測により実施した。**
  - **◆ 再帰観測対象とした2つの軌道上物体とも、数週間から数ヶ月（現時点では最大70日）後の軌道位置を精度良く予測できた。**
  - **◆ 観測データ数を変えた場合についても、評価を行い、今回のケースでは大きな差が生じないことを確認した。**

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今後の予定

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- 相生光学観測装置による定常的な遠隔・自動運用を継続し、観測データを蓄積していく計画である。
- また、観測データの評価のため、再帰観測の期間をさらに延ばし、評価を継続するとともに、様々な対象の観測を通して、遠隔・自動観測システムにおける観測技術の開発を継続する予定である。

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ご清聴ありがとうございました

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G3

Remediation of cm-size space debris from the International Space Station

○Toshikazu Ebisuzaki^1, Mark N. Quinn^2, Satoshi Wada^1, Lech Wiktor Piotrowski^1, Yoshiyuki Takizawa^1, Marco Casolino^1,^3, and Mario Bertaina^4, Philippe Gorodetzky^5, Etienne Parizot^5, Toshiki Tajima^2,^6, Remi Soulard^2 and Gerard Mourou^2
1 RIKEN, 2-1, Hirosawa Wako, 351-0198, Japan
2 IZEST, EcolePolytechnique, 91128, Palaiseau, France
3 INFN
4 University of Torino
5 APC-CNRS/Paris7 University, 10 rue A. Domon et L. Duquet, 75013 Paris, France
6 Dept. of Physics and Astron. University of California at Irvine, Irvine, CA 92697

We present here a plan in 3 steps to design an orbiting debris remediation system comprised of a super-wide field-of-view telescope and a novel laser system operating from the International Space Station (ISS). The EUSO (Extreme Universe Space Observatory) telescope has been designed for operation onboard the ISS for the detection of ultra-high energy cosmic rays. Equipped with 2.5 m optics and a field of view of ±30 degrees, the EUSO module can also be utilized for the detection of high velocity fragmentation debris in orbit near the ISS. Once detected, the CAN laser system will deliver a sequence of pulses to the debris surface inducing ablation and hence momentum impulse to reduce its velocity. The range of the detection/removal operation can be as large as 100 km. We will use a step by step approach employing ISS : 1) Proof of principle demonstration of the detection (and, if possible, laser impulse technology) with ISS based small prototype 2) Technical demonstrator debris removal that consists of the EUSO telescope for the detection and a 1.5 m Cassegrain telescope with a space CAN laser for tracking and impulse delivery for debris re-entry, and 3) A free-flyer mission dedicated to debris remediation in a polar orbit with the alititude ~800 km.

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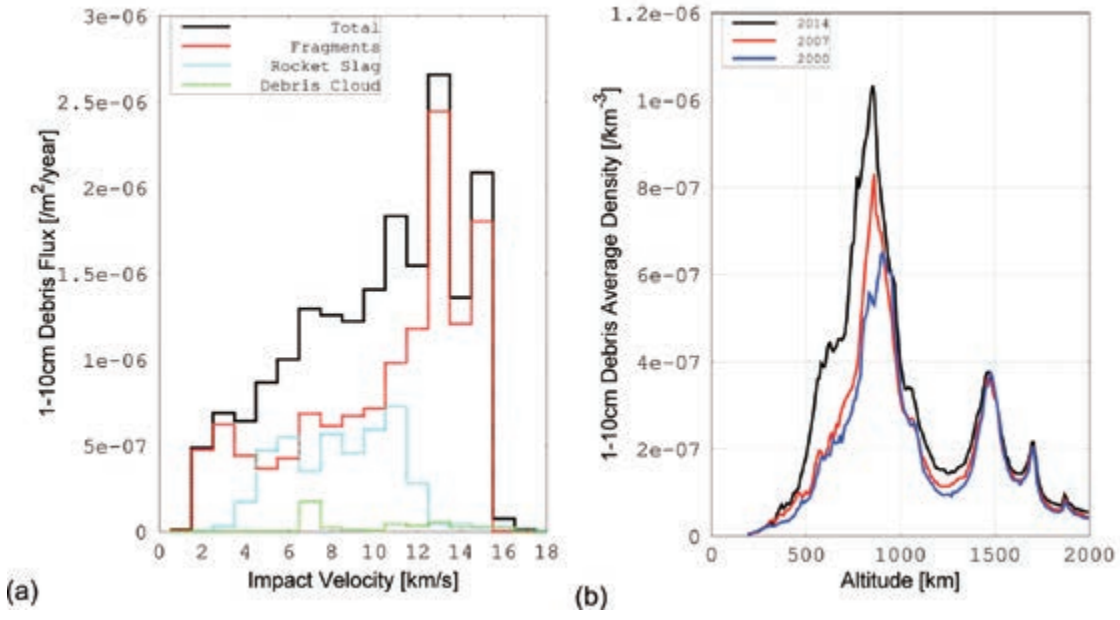
Remediation of cm-size space debris from the International Space Station

Toshikazu Ebisuzaki , S. Wada, L.W. Pitrowski, M. Casolino (RIKEN), R. Soulard, M. N. Quinn, G. Mourou (IZEST, Ecole Polytechnique, France)

Results of simulations for 1-10cm size debris, performed with the MASTER 2009



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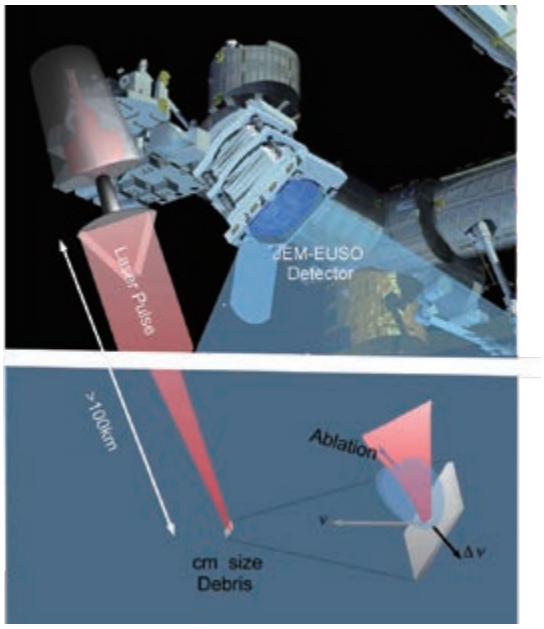
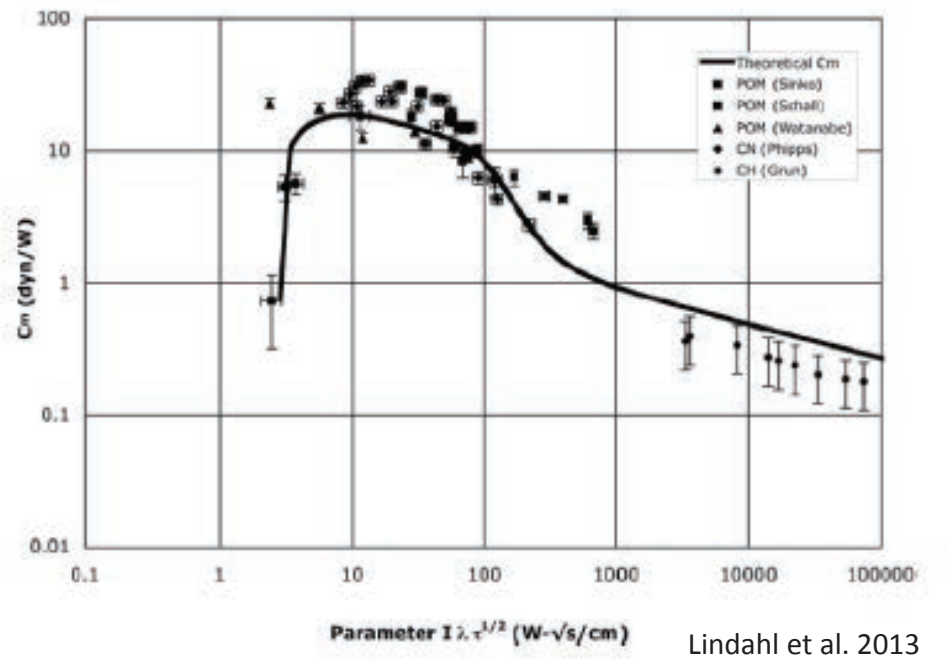
Concept of our technical demonstrator of the laser removal



- EUSO
  - Detection
  - Position and velocity
    - Crude determination
- CAN laser system
  - Search beam
  - Position and velocity
    - Fine determination
  - Shooting Operation

アブレーションによる反力



Lindahl et al. 2013

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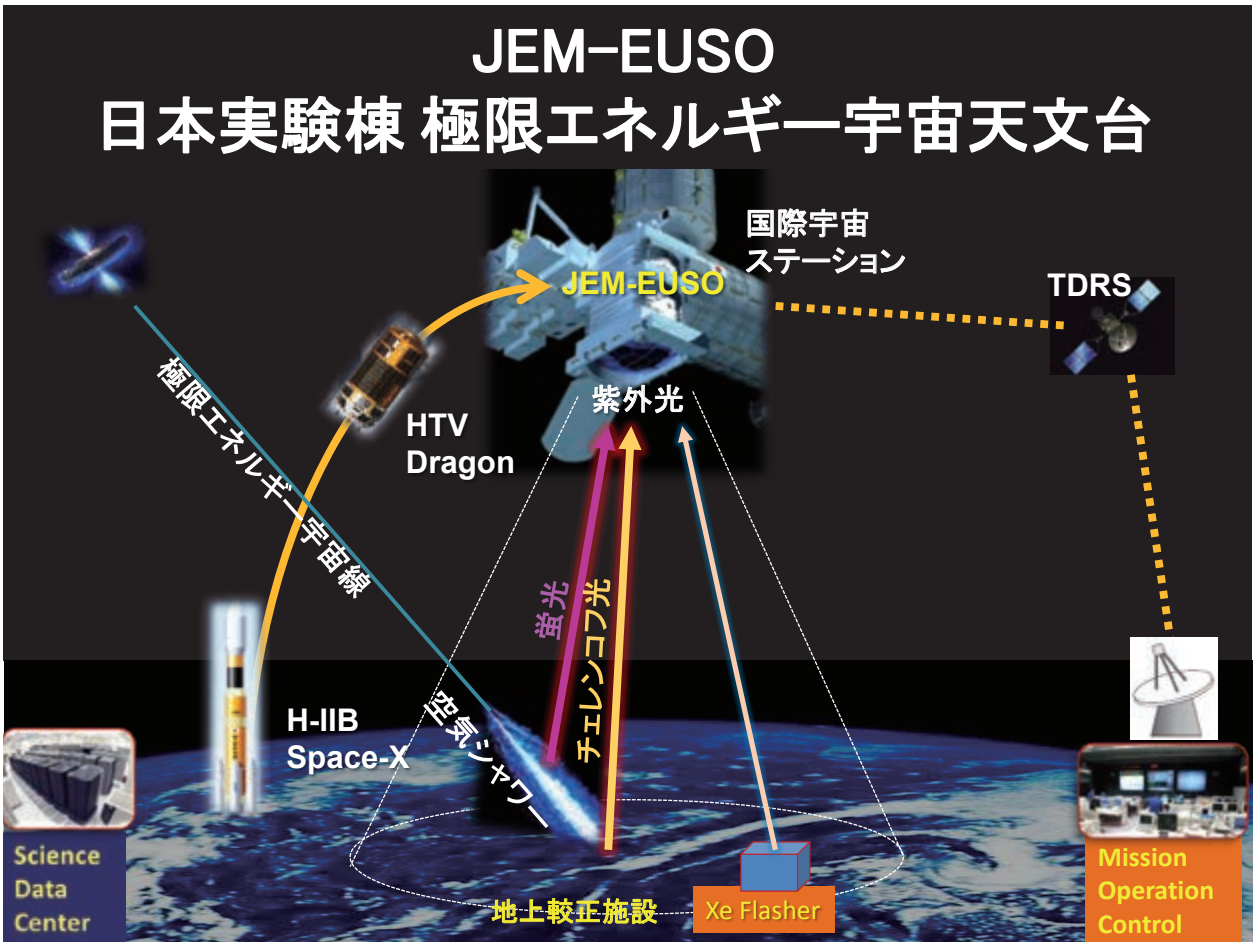

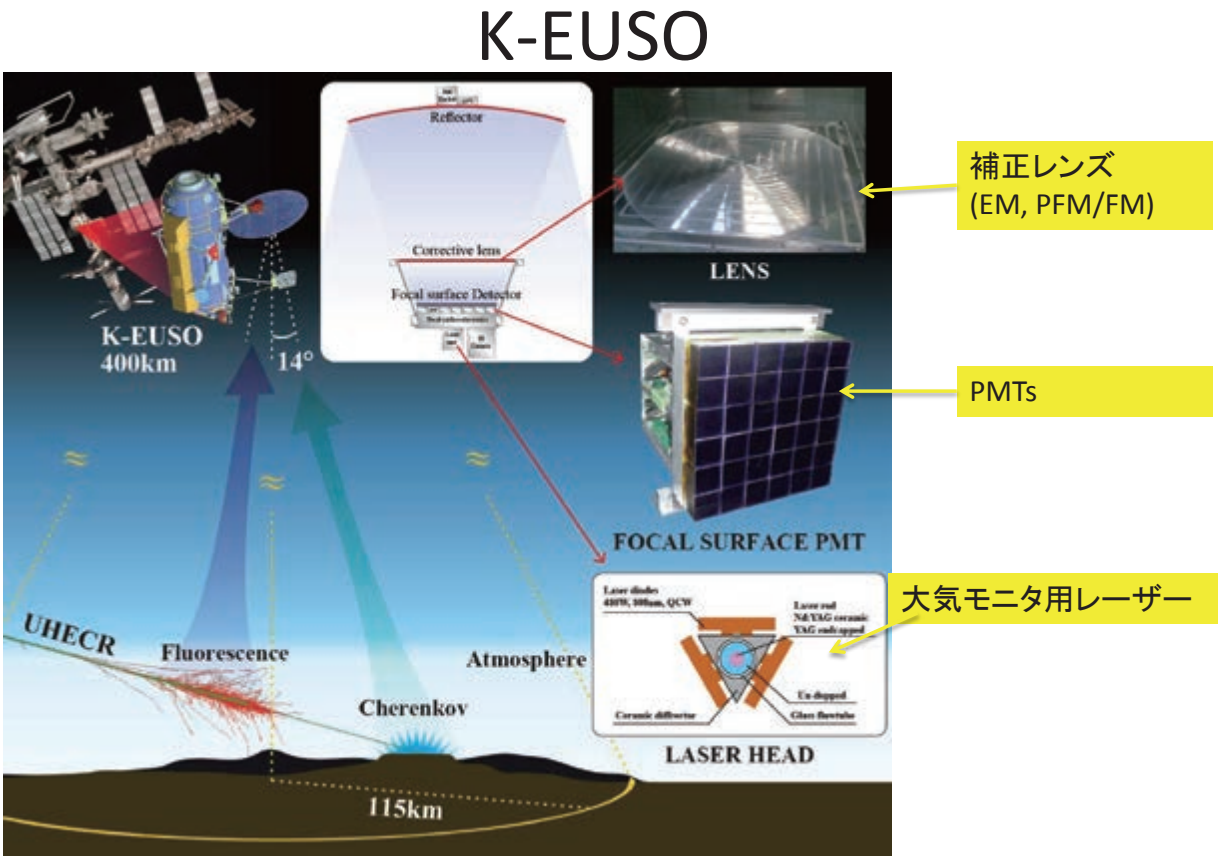

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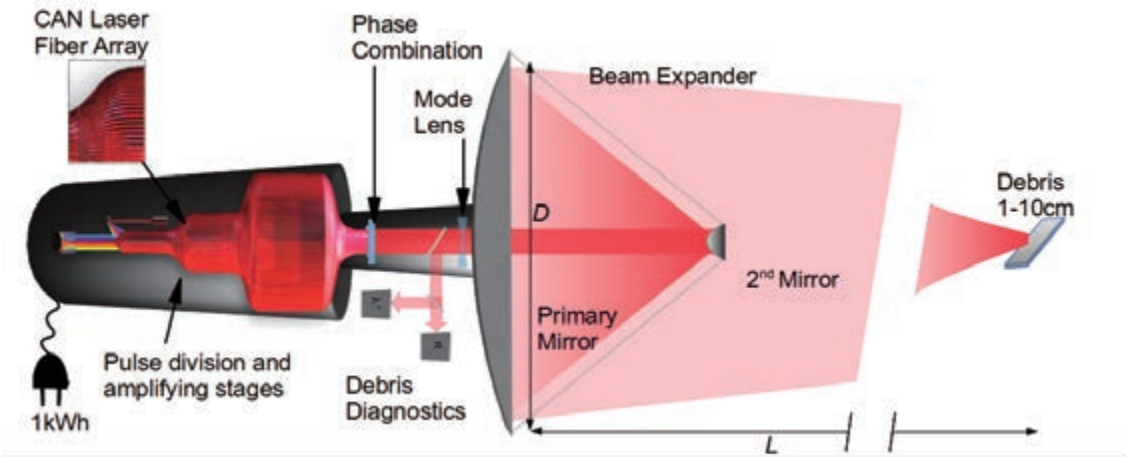
CAN (Coherent Amplification Network) Laser System

Mourou et al. 2013, nature Photonics, 7, 258-261

Space CAN laser system
CAN=Coherent Amplify Network



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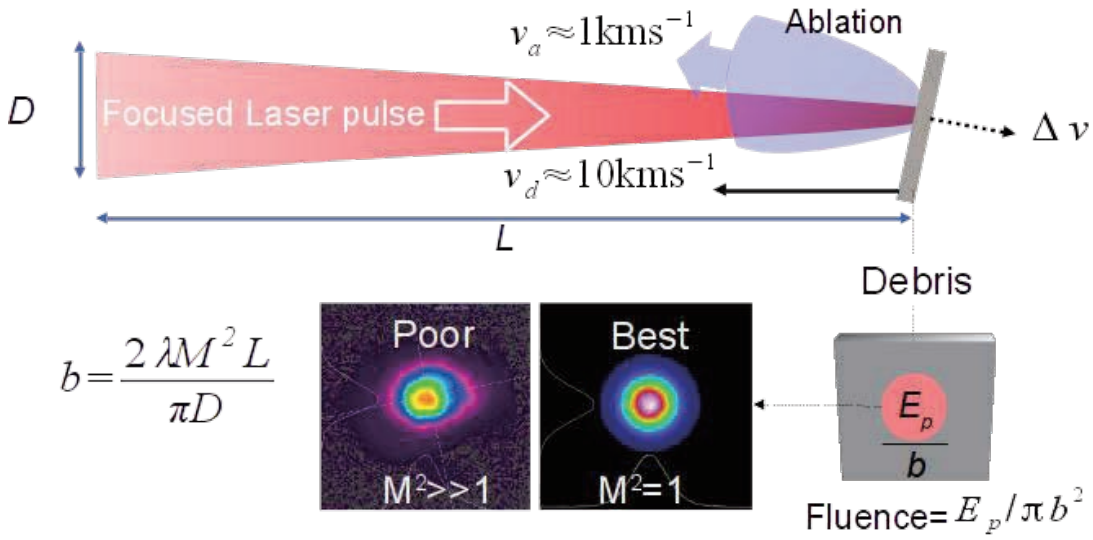
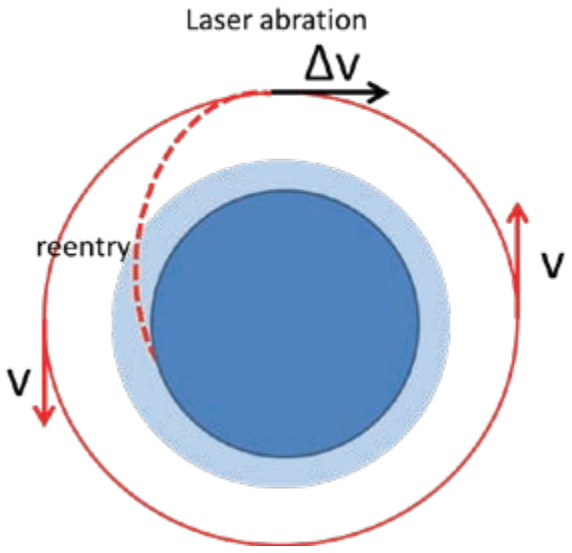
Reaction Force by Laser Abration



Reentry by reaction force of laser ablation



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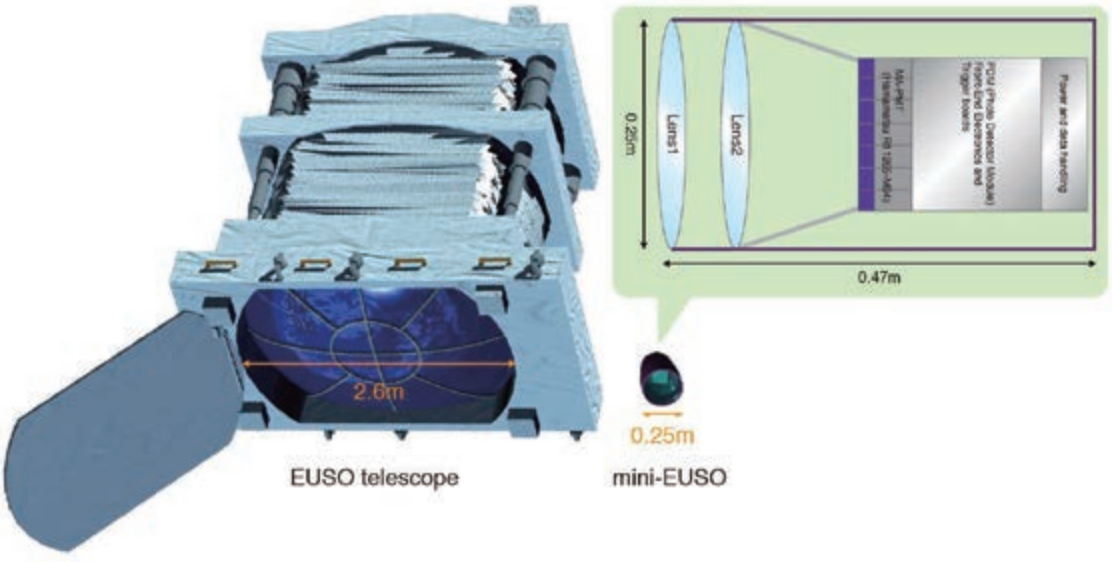
Three steps of debris removal

- Target Debris
  - a=1-10 cm、d～100 km、v_{rel}～1-10 km
- Detection（～0.1 seconds）
  - EUSO telescope ±30°
  - position（Δθ<0.07° ）and velocity (1%)
- Tracking（～1 seconds）
  - Cssegrain telescope（1.5m）（～1 seconds）
  - Pencil beam illumination（Δϕ～0.07° Δτ～1ns）
  - position（Δθ<10^{-6} rad, ΔR～1 km）
- Laser Shooting（～10 seconds）
  - E_p～10 J、R_p～10^4 Hz

JEM-EUSO and Mini-EUSO



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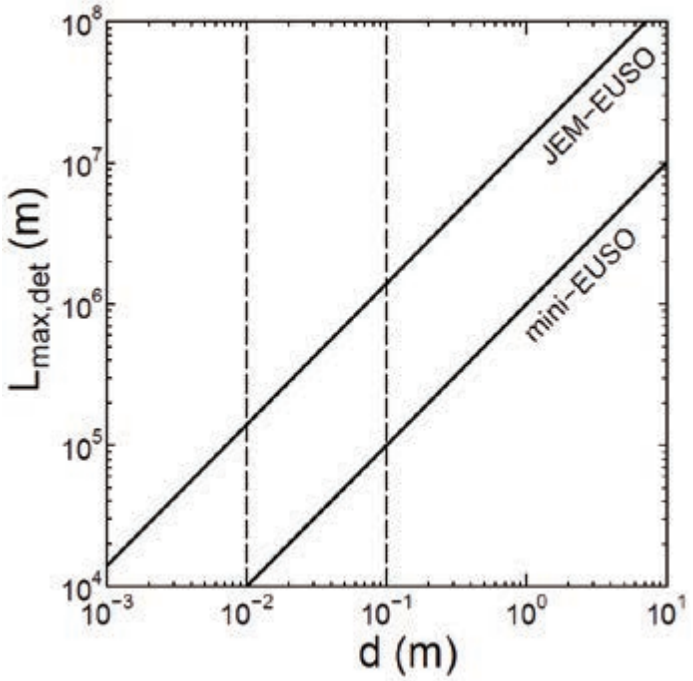
Detection Limit



Three steps of demonstration

1. Mini-EUSO on ISS
   - Proof of Principle Mission
   - 25 cm UV telescope
2. EUSO class telescope (K-EUSO) on ISS
   - Technical Demonstrator for Laser Removal
   - 2.5 m UV telescope CAN Laser System
3. Dedicated Removal Mission
   - Dedicated system of Laser removal

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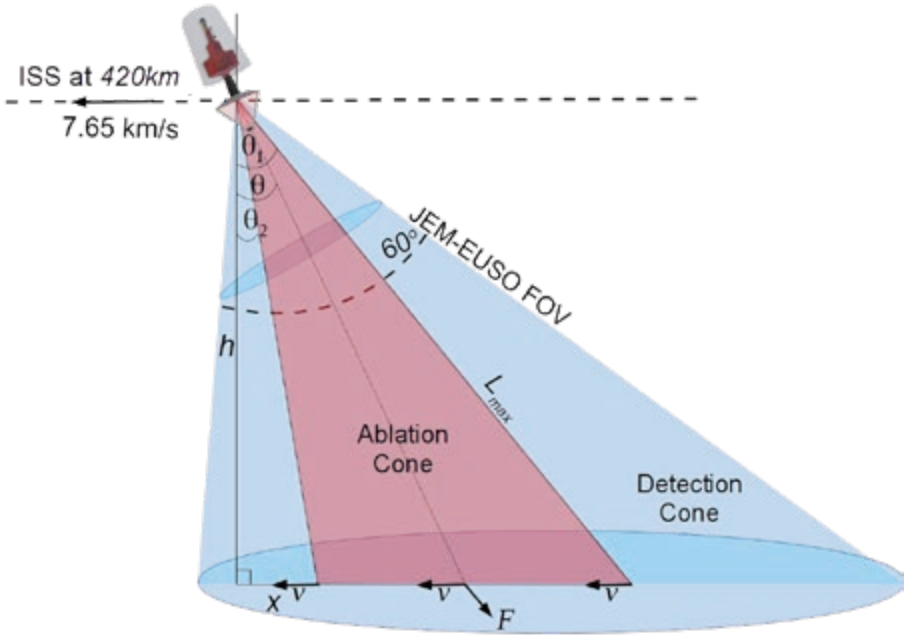
Laser Shooting Operation



1. Mini-EUSO

- Proof of principle system
- Selected by ASI asVUS-2 (Human Space Flight 2)
- Russian International Collaboration mission
  - long-term program of space experiments on the ISS
- Detection
- Tracking
  - and Irradiation by Lidar (if possible)

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Mini-EUSO mechanics

- Experiment "Relaxation" on the

Mechanical interface with UV window could be similar.

Decision

- From the May, 26 the experiment is included in the long-term program of space experiments on the ISS

Координационный научно-технический совет
Федерального космического агентства
по программам научных и прикладных исследований и экспериментов
на пилотируемых космических комплексах
ул. Пионерская, 4, г. Королёв, Московская обл., 141070

УТВЕРЖДАЮ
Председатель КНТС Роскосмоса
В.А. Соловьев
«26» мая 2014 г.

РЕШЕНИЕ № 5

О введении космического эксперимента «УФ атмосфера» в «Долгосрочную программу научно-прикладных исследований и экспериментов, планируемых на Российском сегменте МКС»

В соответствии с п.3 Приложения 2 к «Долгосрочной программе научно-прикладных исследований и экспериментов, планируемых на Российском сегменте МКС» (версия 2012 года) о порядке изменения Долгосрочной программы и учитывая, что для космического эксперимента «УФ атмосфера» полностью выполнены требования, установленные процедурой введения новых космических экспериментов в «Долгосрочную программу научно-прикладных исследований и экспериментов, планируемых на РС МКС», принимается

РЕШЕНИЕ:

Ввести космический эксперимент «УФ атмосфера» в «Долгосрочную программу научно-прикладных исследований и экспериментов, планируемых на Российском сегменте МКС».

И.о. учёного секретаря
КНТС Роскосмоса Б.В. Загреев

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Three steps of demonstration

1. Mini-EUSO on ISS
   - Proof of Principle Mission
   - 25 cm UV telescope
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   - 2.5 m UV Telescope CAN Laser System
3. Dedicated Removal Mission
   - Dedicated system of Laser removal

2.EUSO class telescope (K-EUSO) on ISS

- Technical demonstrator of Laser Removal
- 2.5m UV telescope FoV=±30°
- 1.5 m Cassegrain for tracking
- CAN laser system 100 kW and 10^4Hz
- Operation Range: 100 km
- 10 (Backward)-300 (forward) debris

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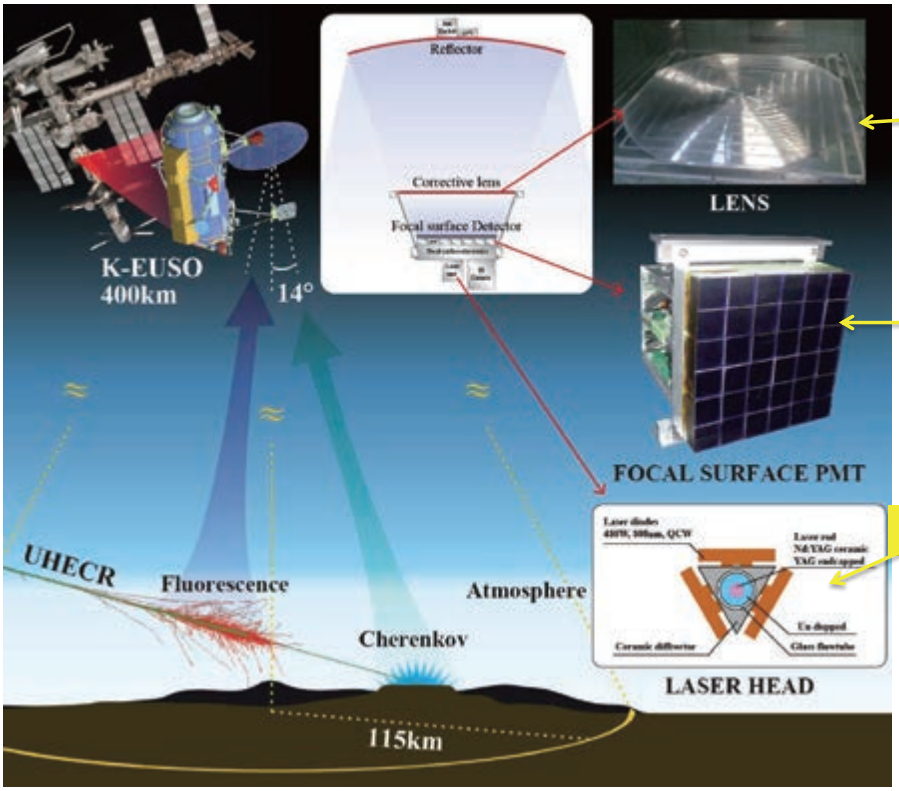
K-EUSO

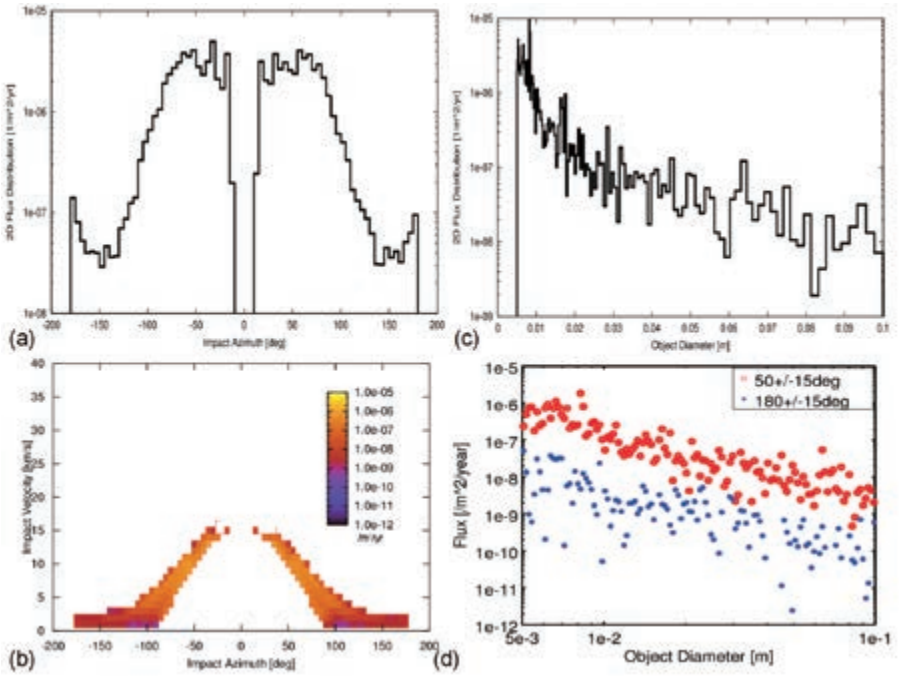


補正レンズ
(EM, PFM/FM)

PMTs

大気モニタ用レーザー

Debris Flux at ISS orbit (~400 km)



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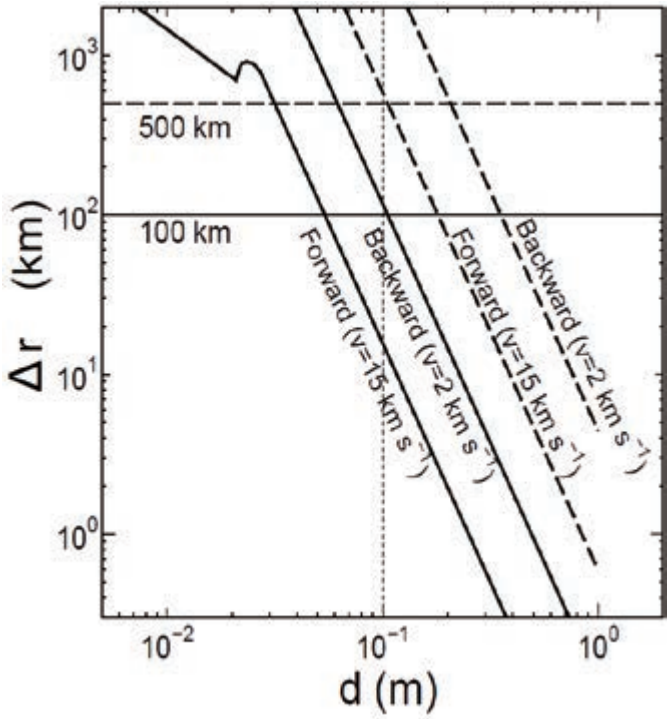
Reduction in orbit radius by an operation



Three steps of demonstration

1. Mini-EUSO on ISS
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3. Dedicated Removal Mission
   - Dedicated System of Laser Removal

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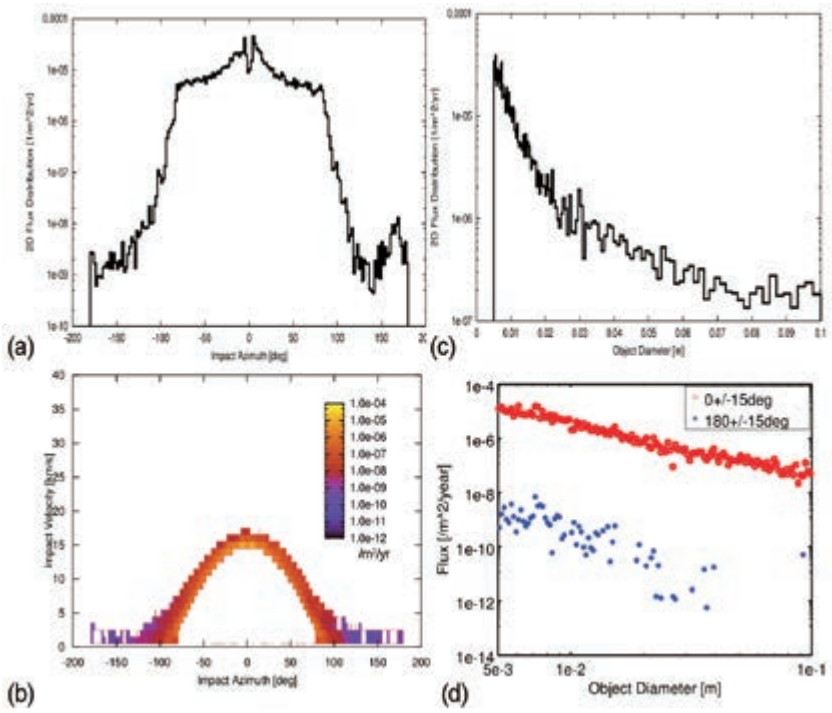
3. Dedicated Debris Removal System

- Polar orbit from 1000 km→600 km
- 2.5 m EUSO + Space CAN laser (500 kW)
- Operation Range: 100km
- 10^3(backward)-10^5 (forward) operation
- Most of debris (1-10 cm can be remove)

Polar orbit (~800 km)



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Parameters of Systems

	Prototype on ISS	Technical Demonstrator on ISS	Dedicated system
Target Debris Size (cm)	>1	10>a>0.5	10>a>0.5
Target Debris Distance (km)	10-100	100	100
EUSO Aperture (m)	0.25	2.5	2.5
EUSO FoV	±14°	±30°	±30°
Tracking Optics (m)	0.1	1.5	1.5
Laser system	Solid state	10^4 fibre	10^4 fibre
Pulse Energy (J)	0.1	10	10
Pulse Duration (ns)	1	0.1	0.1
Repetition rate (kHz)	0.1	10000	50000
Average power (kW)	0.001	100	500
Event per year	20-30 (detection) 2-3 irradiation)	10 (backward) 300 (forward)	10^5(forward) 10^3(backward)

Summary

- Reentry by Laser Ablation: 1-10 cm
- Laser ejection from Space craft
  - Detection EUSO telescope
    - Super wide field（～60° ）, super high speed （~microseconds）
  - Tracking system of 1.5 m and CAN laser (100-500 W)
- Three steps
  - Mini-EUSO: IUV window on ISS
  - EUSO+ CAN laser on ISS
  - Dedicated free flyer polar orbit 1000 km→500 m
- Rotation suppression: ~1W

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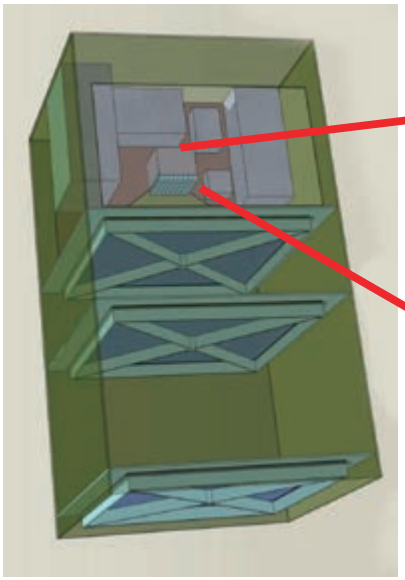
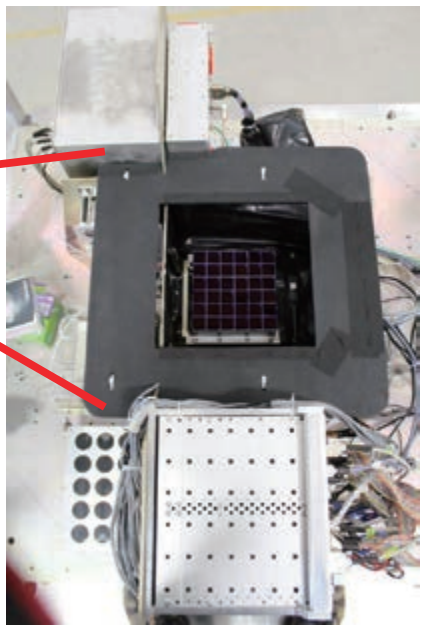
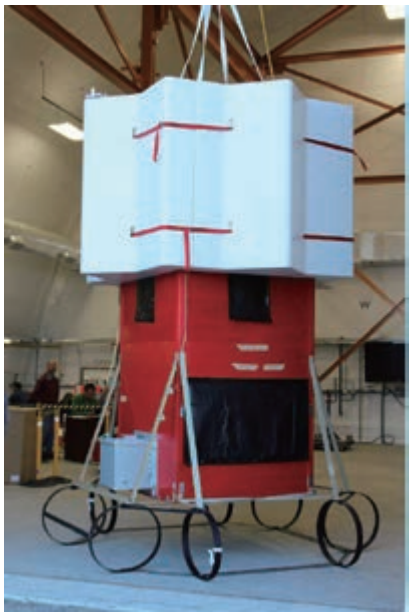
気球実験
CNES+JEM-EUSO Collaboration

気球飛行 2014 August 23

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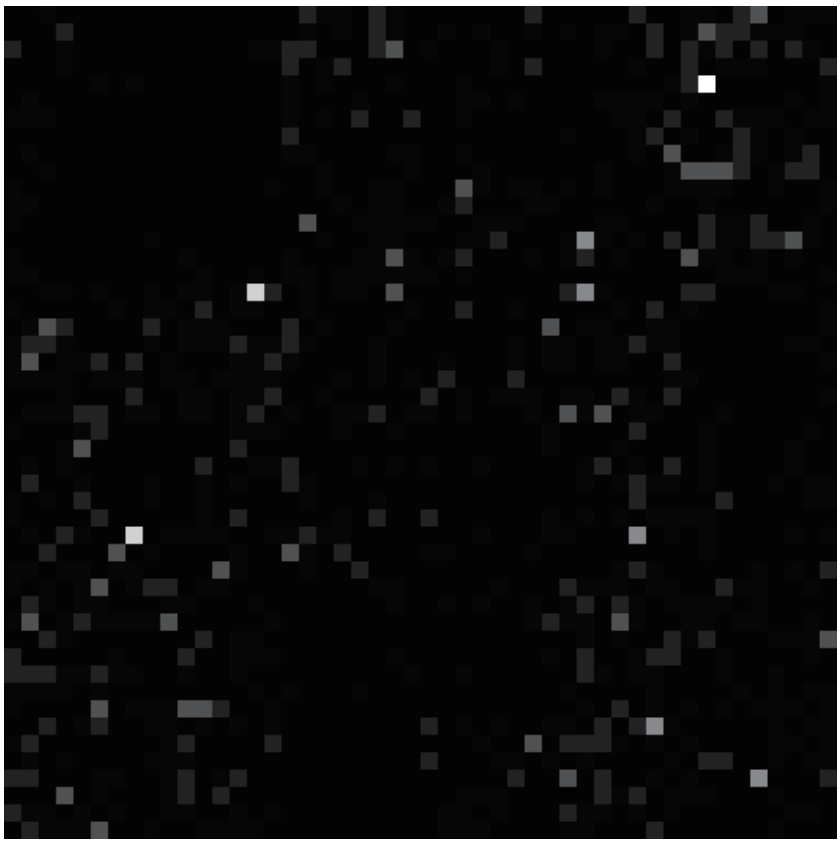
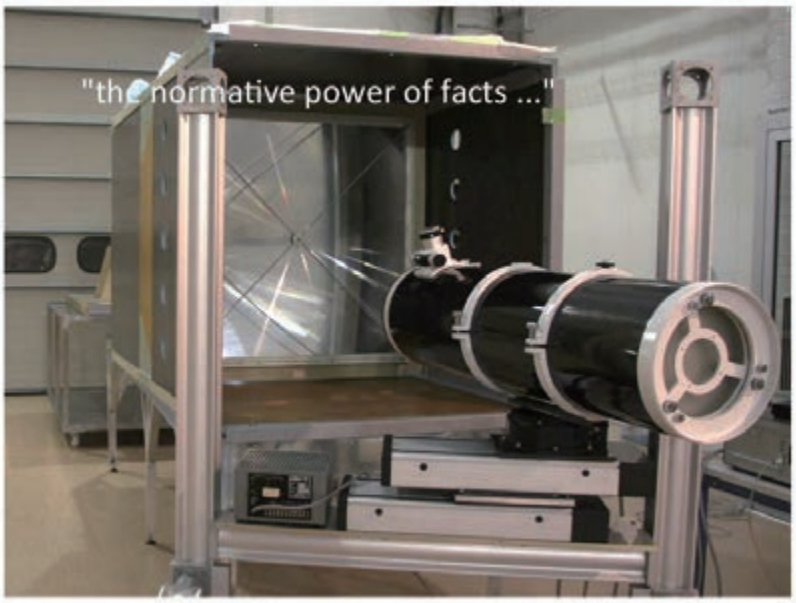
Laser flasher event



光学試験



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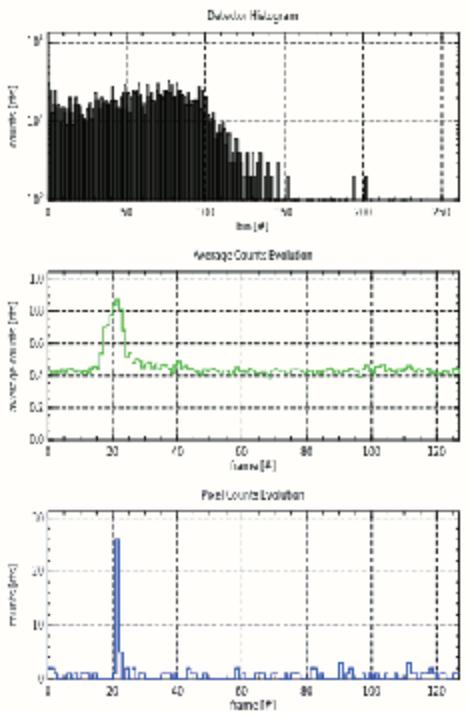
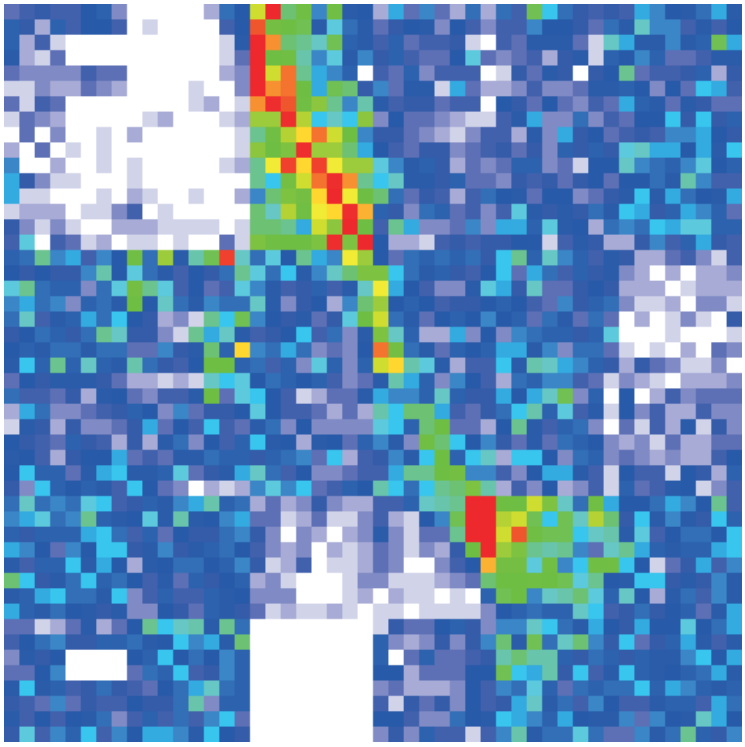
Laser track

Event profile





Helicopter equipped with laser and xenon flasher (NASA funding)

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無事着水

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G4

デブリ軌道アーカイブの逆問題的解析と微光デブリの追跡に関する研究紹介

Researches on inversion analyses of debris orbit archive and tracking of faint debris

○上津原正彦, 樋口知之(統計数理研究所)
○Masahiko Uetsuhara, Tomoyuki Higuchi (The Institute of Statistical Mathematics)

スペースデブリの画像や軌道の時系列データを解析する上で統計的手法は必須である. 今後, 光学センサやレーダーなどのデブリ観測システムの性能向上によりデブリに関する時系列データのもつ情報量が爆発的に増加することが予想されることから, 統計的手法の応用は更に重要となる. 本発表では, 著者が取り組んでいる大量のデブリ観測データを解析する研究について2つのトピックを紹介する. 1つ目は, 低軌道デブリの軌道を記録している米国 NORAD のカタログを利用した研究である. 本研究ではカタログに記録された低軌道デブリの平均運動変化率データを用いて, 低軌道物体の高度低下率を一時的に増大させる要因である地磁気嵐由来の超高層大気変動の特徴を明らかにしようとしている. 2 つ目は, 時系列画像上に映った微光デブリを追跡する研究である. 本研究では, CCD/CMOS カメラで捉えた微光デブリを逐次的に効率良く追跡するアルゴリズムの確立を目指している.

Space debris observation data will be explosively increased as sensor performance improvements in near future. This presentation introduces two topics about big data analyses of space debris observation data. The first topic is an inversion study utilizing NORAD catalog to characterize upper atmospheric fluctuations induced by geomagnetic storms. The second topic is a development of sequential tracking algorithm for faint debris images taken by optical sensors.

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Researches on inversion analysis of debris orbit archive and tracking of faint debris

Masahiko Uetsuhara, Tomoyuki Higuchi
The Institute of Statistical Mathematics

Outline

- Space debris observation data will be explosively increased as sensor performance improvements in near future. This presentation introduces two topics about big data analyses of space debris observation data.

1. inversion study utilizing the SSN catalog to characterize upper atmospheric fluctuations induced by geomagnetic storms

2. development of sequential tracking algorithm for faint debris images taken by optical sensors

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Inversion study utilizing the SSN catalog to characterize upper atmospheric fluctuations induced by geomagnetic storms

Motivation and objective

- Making use of space debris as in-situ sensors of upper atmospheric fluctuations of several days time scale induced by geomagnetic storms
  - Orbit time series of LEO debris in the SSN catalog (i.e., TLE) can be such in-situ measurement data
  - SSN catalog archives thousands of LEO debris orbit time series with (semi-)daily frequency
    - e.g., >1400 LEO debris are archived in 1998 with 0.5~1 day period

- For better understanding of the mechanism of upper atmospheric fluctuation, this study aims at establishing inversion methods which make full use of information in the TLE data of LEO debris

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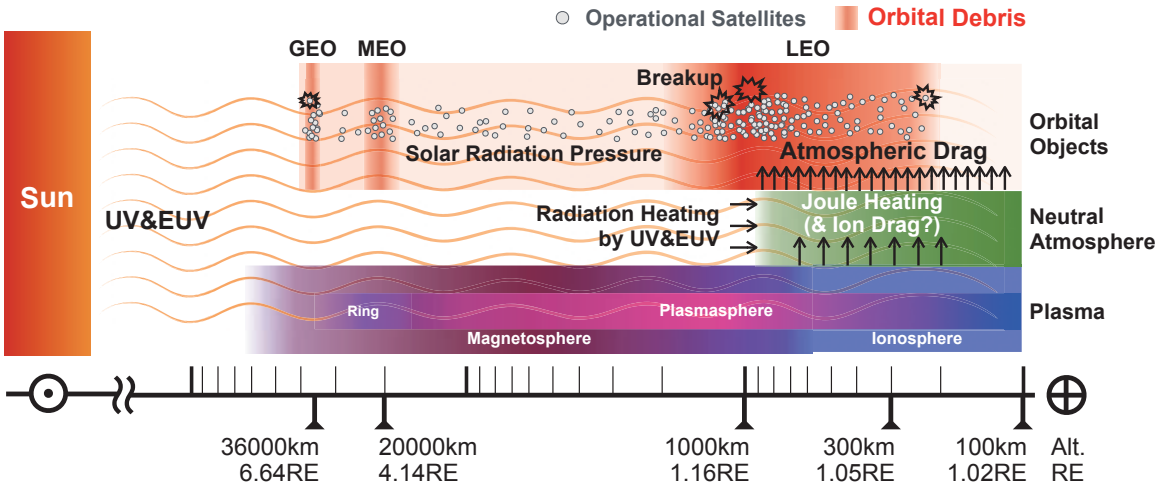
Research overview



5

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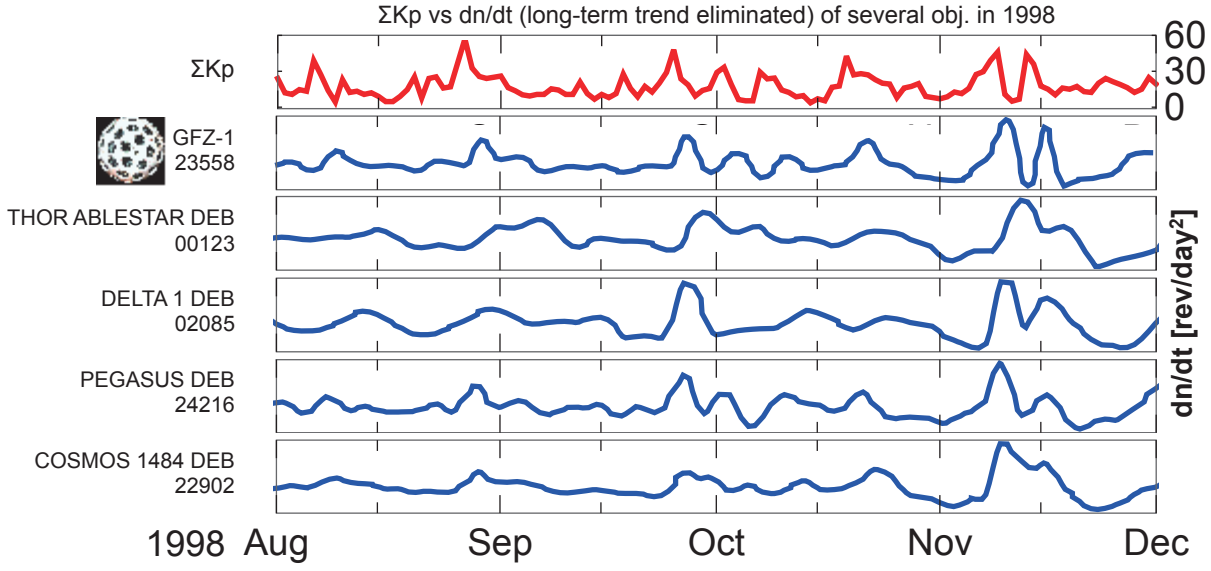
The Institute of Statistical Mathematics

Relationship between geomagnetic storm and orbital decay

Storm-driven upper atmospheric fluctuation results in the sudden orbital decay of LEO debris. The sudden orbital decay is recorded in the time series of the mean motion change rate dn/dt [rev/day^2].



6

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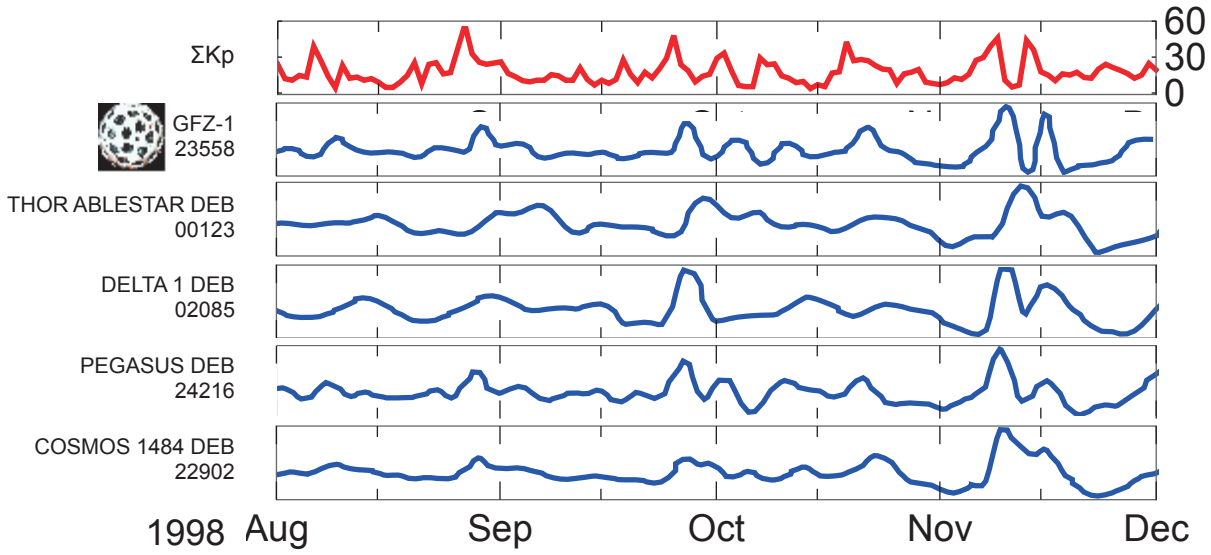
Subject of this work

In this work, we conduct cross correlation analysis between ΣKp and dn/dt of LEO debris to estimate the spatial-temporal pattern of the sudden orbital decay during a storm phase on the late September 1998.



7

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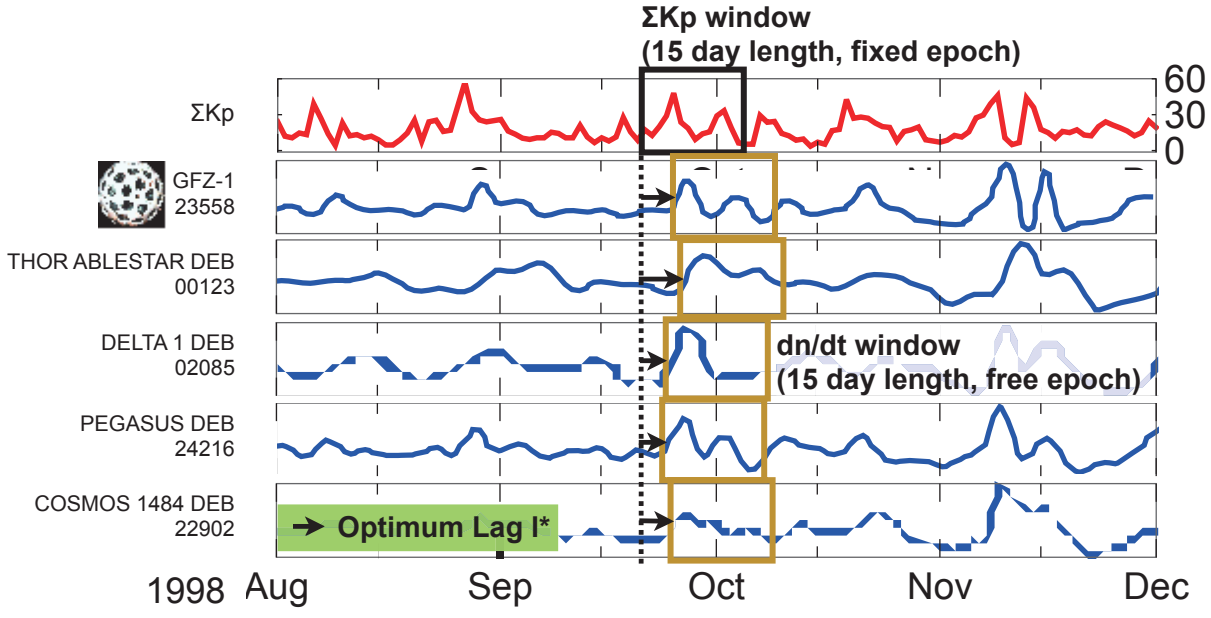
Analysis scheme

For each LEO debris we evaluate the optimum lag (l*) at which the cross correlation coefficient becomes maximum



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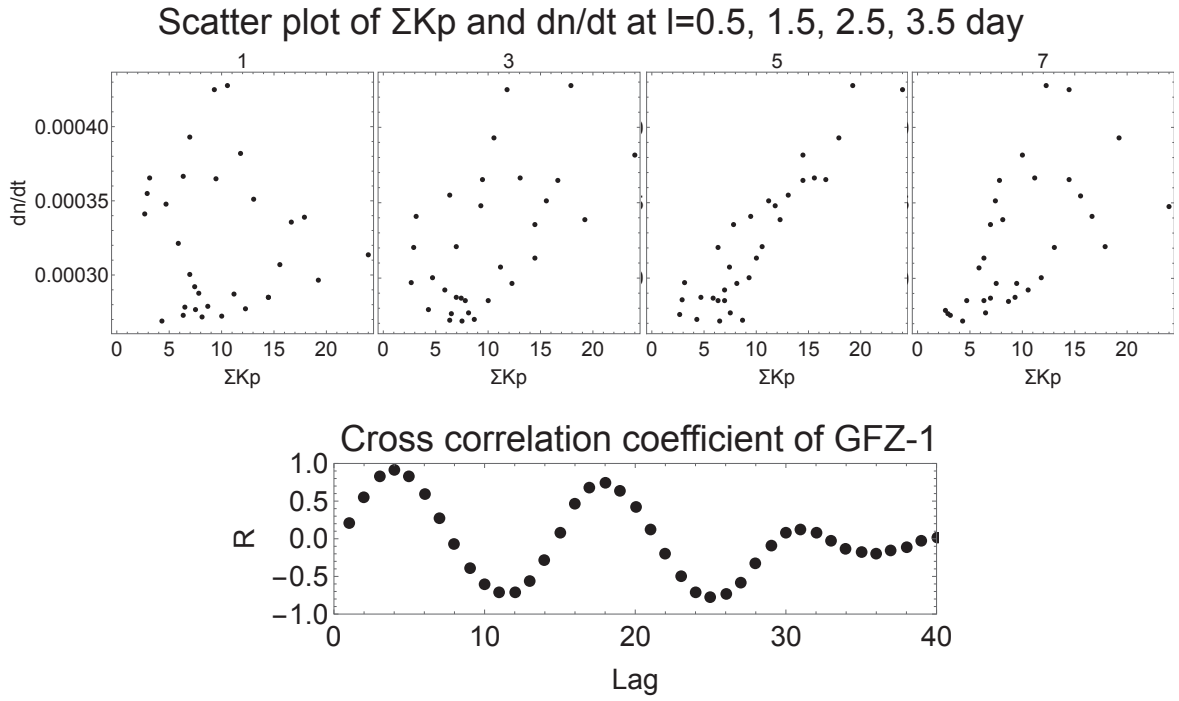
Cross correlation analysis result – GFZ-1



9

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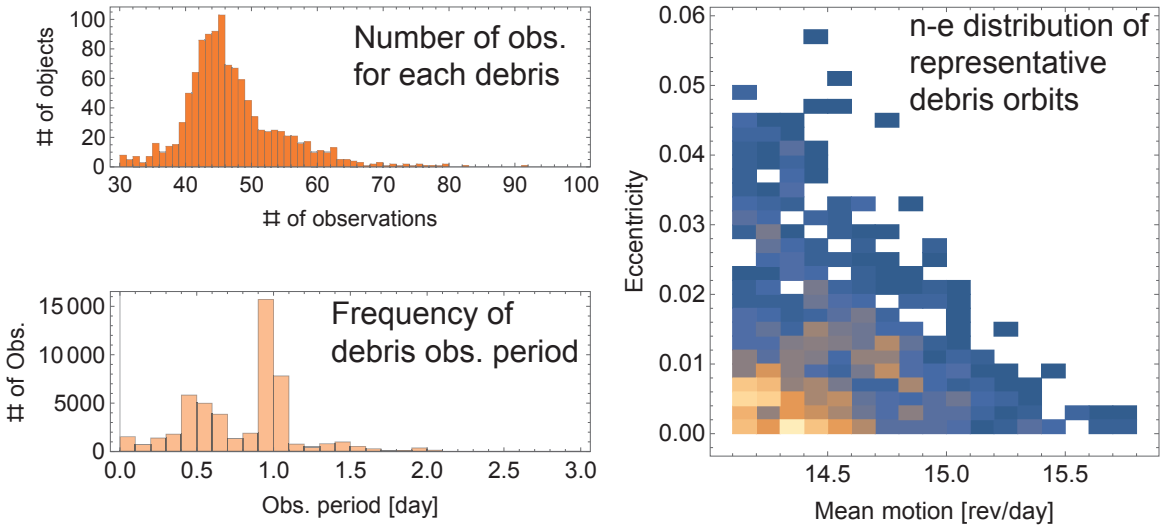
The Institute of Statistical Mathematics

Statistics of debris orbit data applied to cross correlation analysis

- 1130 LEO debris are available during the event period
- We regard the orbit at the l* epoch of each debris as its representative orbit



10

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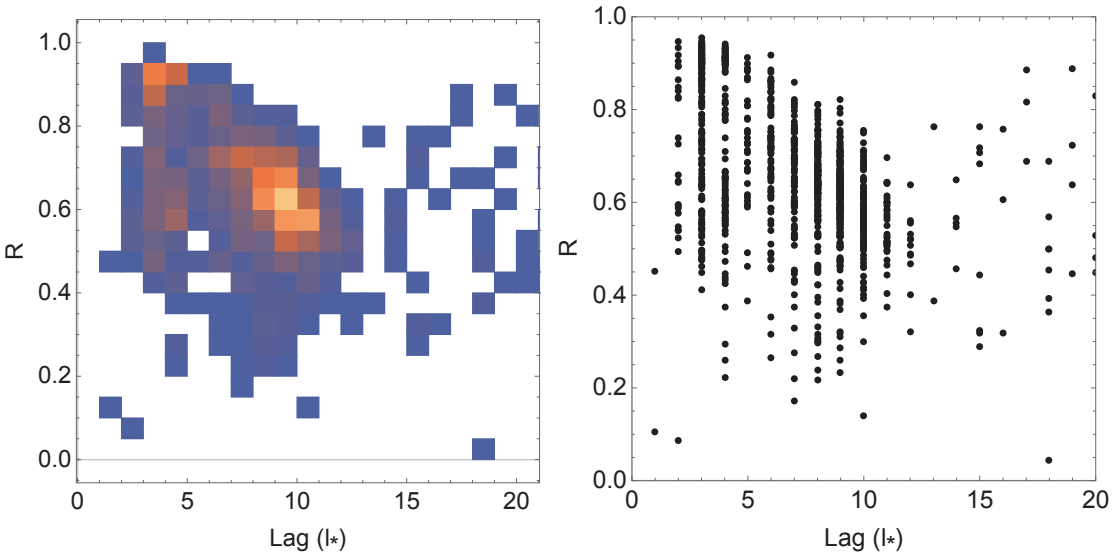
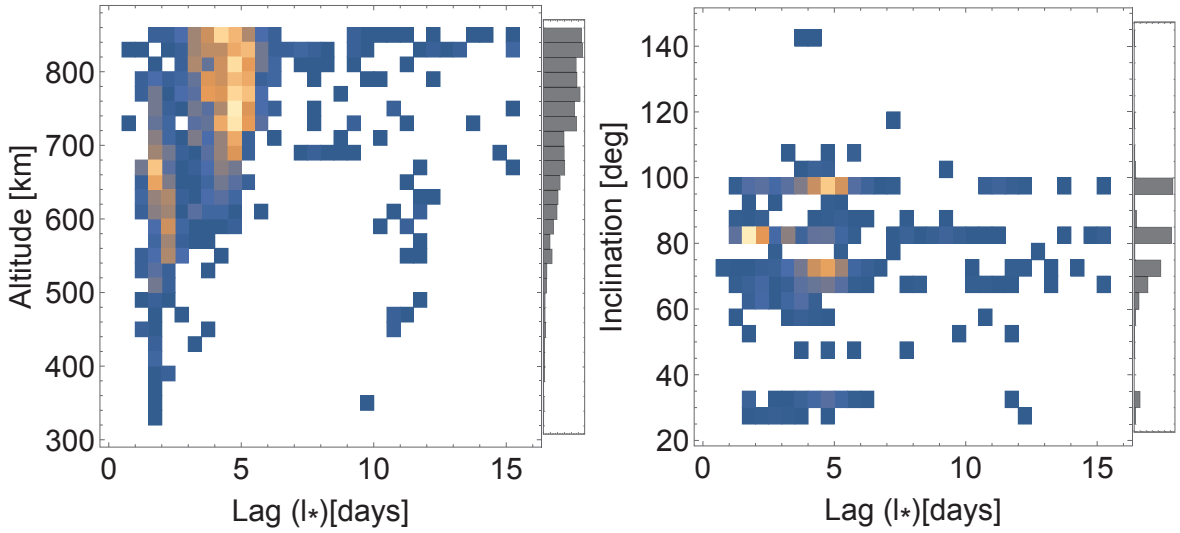
Cross correlation coefficient of I*



Cross correlation analysis result



- Alt. 500-700km & incl. 80deg region respond to ΣKp with 1.5~2 day lag
- Alt. 700-800km & incl. 70deg・100deg region respond to ΣKp with 3~5 day lag

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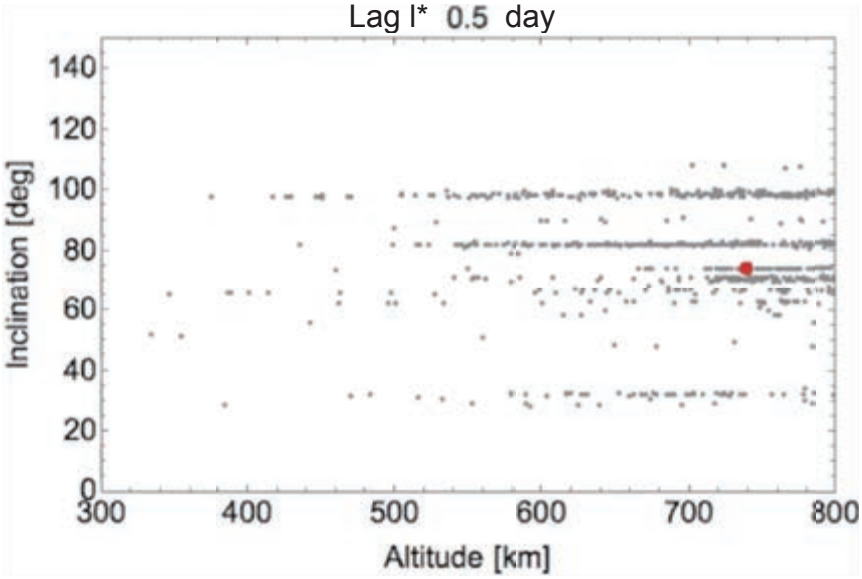
Cross correlation analysis result



Summary and future works

- This work estimated time lag of dn/dt to ΣKp during a storm period in the late September 1998 for each of 1130 LEO debris
- When mapping the estimation result into the altitude-inclination space, it was found that debris passing through polar region at mid altitudes first respond to the storm with 1~2 days lag then debris in lower/higher altitudes and lower latitudes

- Future works will include
  - mapping to the inertial space and/or geomagnetic coordinates
  - establishing an estimation scheme based on the state space model (data assimilation)

- Acknowledgement
  - This work was supported by JSPS KAKENHI Grant Number 26・3204

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Development of sequential tracking algorithm for faint debris images taken by optical sensors

Background

- **CCD → CMOS**
  - Readout time of CMOS is very rapid (100x CCD) and epoch registration accuracy is very precise (100x CCD)
    →Tracking of *O*(1deg/sec) debris will become easier for small FOV telescopes & Orbit determination accuracies will be improved
  - R&D topics on CMOS camera for debris observation:
    Sensor design・**Detection method**・Orbit determination・
    Sensor operation…
- **Enthusiastic trend of applying ground-based optical sensor network for space debris monitoring**
  - SSN, ISON, Asia-Pacific networks, ComSpOC, etc...

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Objective

This study aims at establishing a faint debris tracking method which is

- capable of handling a large number of sequential images such as CMOS camera's images
- customizable for a variety of observation plans

→Tracking states (position and velocity) of faint debris in image sequences based on the state space model consisting of motion model & observation model

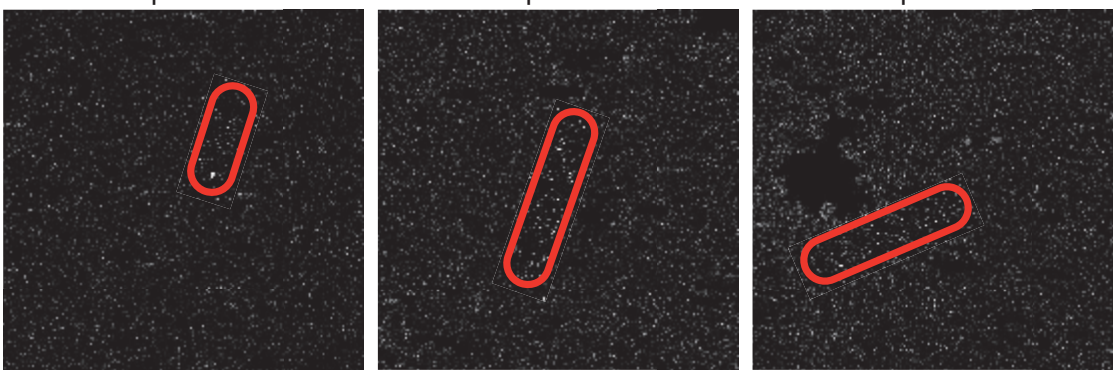
- Motion model describes motion of targets to predict the states
- Observation model evaluates the "debris-ness" (likelihood) of predicted states

Test targets

Image intensity

$CDF^{-1}\mathbf{y}(1\sigma) \leq$ $\leq CDF^{-1}\mathbf{y}(2\sigma)$

Sequence 1 | Sequence 2 | Sequence 3



Vmag=16.70 | Vmag=17.68 | Vmag=18.22

- 5.9sec exp.・2.7sec readout × 29 images × 3 sequences
- Captured by Φ50cmTAOS telescope at the Lulin observatory in Oct. 2011
- A single faint GEO debris appears in each sequence
- Image size is 300×300px cut from 2k2k original images
- Image reductions are applied beforehand (bias & vignetting correction・star masking)
- Presence of each target has been double-checked by the JAXA FPGA stacking method

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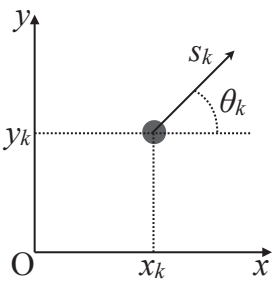
Motion model $\mathbf{x}_k=\mathbf{f}(\mathbf{x}_{k-1},\mathbf{v}_k)$

The motion model describes time evolution of state vector $\mathbf{x}$ during a time step assuming target's motion is linear. Uncertainties of position and velocity are also considered.



State vector
$\mathbf{x}_k=[x_k\ y_k\ s_k\ \theta_k]'$

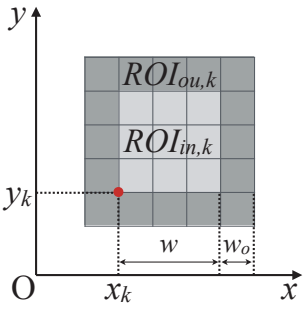
$$\mathbf{x}_k=\mathbf{f}(\mathbf{x}_{k-1},\mathbf{v}_k)$$
$$x_k = x_{k-1} + \Delta t_k s_{k-1}\cos\theta_{k-1} + v_{x,k}$$
$$y_k = y_{k-1} + \Delta t_k s_{k-1}\sin\theta_{k-1} + v_{y,k}$$
$$s_k = s_{k-1} + v_{s,k}$$
$$\theta_k = \theta_{k-1} + v_{\theta,k}$$

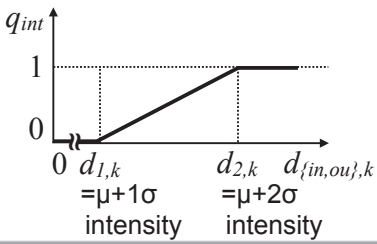
Uncertainty
$\mathbf{v}_k = [v_{x,k}\ v_{y,k}\ v_{s,k}\ v_{\theta,k}]^{\mathrm{T}}$
$\mathbf{v}_k \sim \mathbf{N}(\mathbf{0},\mathbf{Q})$
$\mathbf{Q}=\mathrm{diag}[\tau_x^2\ \tau_y^2\ \tau_s^2\ \tau_\theta^2]$

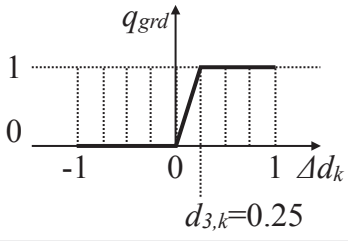
Observation model $w_k = h(\mathbf{y}_k|\mathbf{x}_k)$

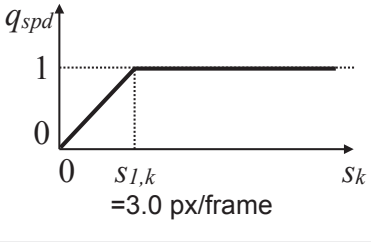
The observation model evaluates the likelihood w_k of the current state $\mathbf{x}_k$ with respect to the current image $\mathbf{y}_k$

$$w_k = h(\mathbf{y}_k|\mathbf{x}_k)$$
$$h(\mathbf{y}_k|\mathbf{x}_k) = q_{int}(d_{in,k}) \times q_{grd}(\Delta d_k) \times q_{spd}(s_k)$$
$$d_{in,k} = \mathrm{ave}(\mathrm{ROI_{in,k}})$$
$$d_{ou,k} = \mathrm{ave}(\mathrm{ROI_{ou,k}})$$
$$\Delta d_k = q_{int}(d_{in,k}) - q_{int}(d_{ou,k})$$









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Tracking algorithm (Particle Filter, PF)

- Motion model and observation model are nonlinear
  →solve by the particle filter

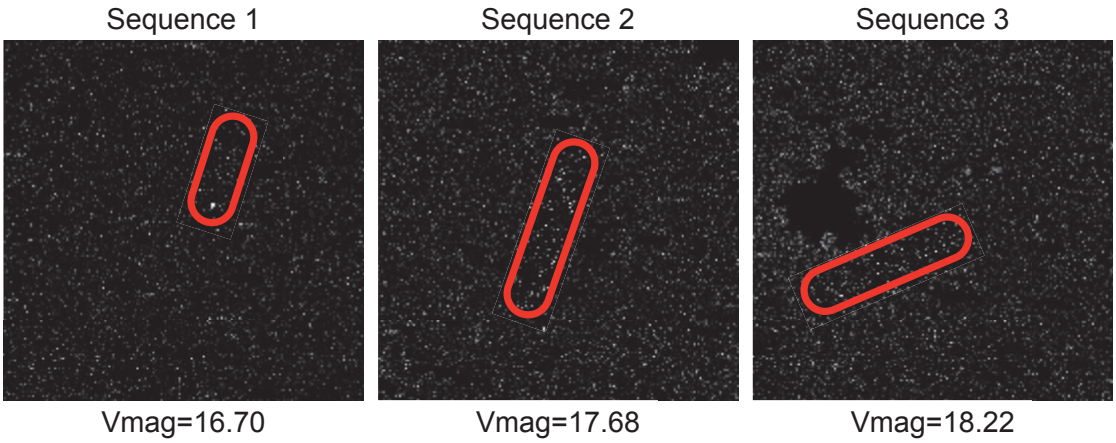
1. Sampling N initial particles from the initial distribution
   $\{\mathbf{x}_0^{(1)}, \ldots, \mathbf{x}_0^{(i)}, \ldots, \mathbf{x}_0^{(N)}\} \approx p(\mathbf{x}_0)$

   Repeat the following procedures for each image ($k = 1,\ldots,T$)

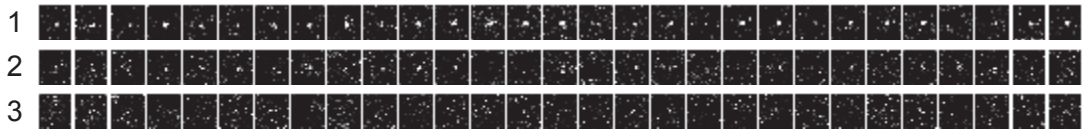
2. Prediction; $\mathbf{x}_k^{(i)}=\mathbf{f}(\mathbf{x}_{k-1}^{(i)}, \mathbf{v}_k^{(i)})$
3. Likelihood evaluation; $w_k^{(i)}=h(\mathbf{y}_k|\mathbf{x}_k^{(i)})$
4. Resampling; $\mathbf{x}_k^{(i)}\sim\{\ldots, \mathbf{x}_k^{(i)}, \ldots\}$ with prob. $\{\ldots, \beta_k^{(i)}, \ldots\}$
   where $\beta_k^{(i)} = w_k^{(i)}/\Sigma(w_k^{(i)})$

Test images w/ target proximity snapshots

Image intensity
CDF^{-1}**y**(1σ)≤ ≤CDF^{-1}**y**(2σ)



Snapshots of target proximity (30px by 30px)



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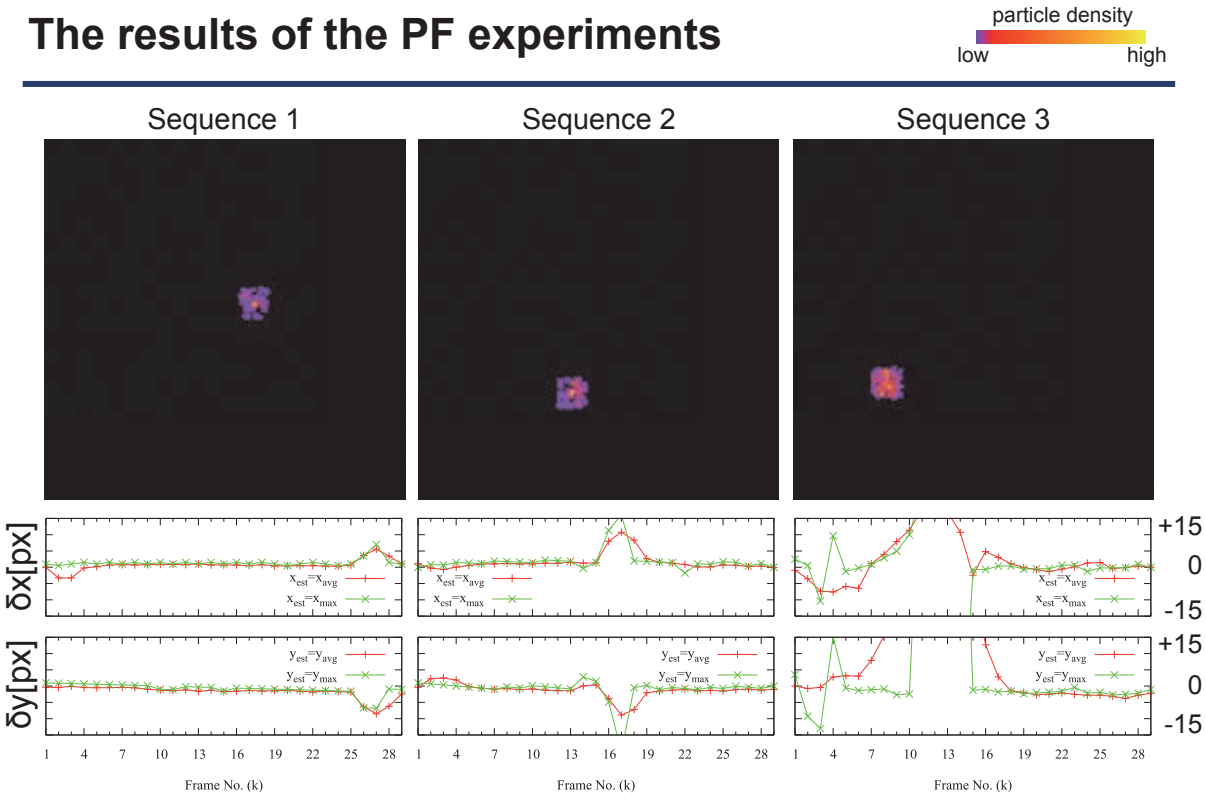
The results of the PF experiments



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The Institute of Statistical Mathematics

Initial state search algorithm (Evolutional Algorithm, EA)

- Sometimes the initial distribution $p(\mathbf{x}_0)$ is unknown (or has very large uncertainty) such as in survey observation
  - ➡ Modifying PF to apply EA which iterates heuristic search of initial distribution $p(\mathbf{x}_0)$
- Modification plan
  - ➡ To keep initial particles which have "not so bad" likelihood
  - Change the period of likelihood evaluation from image-by-image (short-term) to a set of images (long-term)
    $w_k \rightarrow \Sigma w_k$ (k=1,…,T)
  - At the beginning of each iteration, generate initial particles which consist of
    - the new particles sampled by a uniform distribution
    - the surviving particles resampled by the previous iteration result (= likelihood evaluation result)

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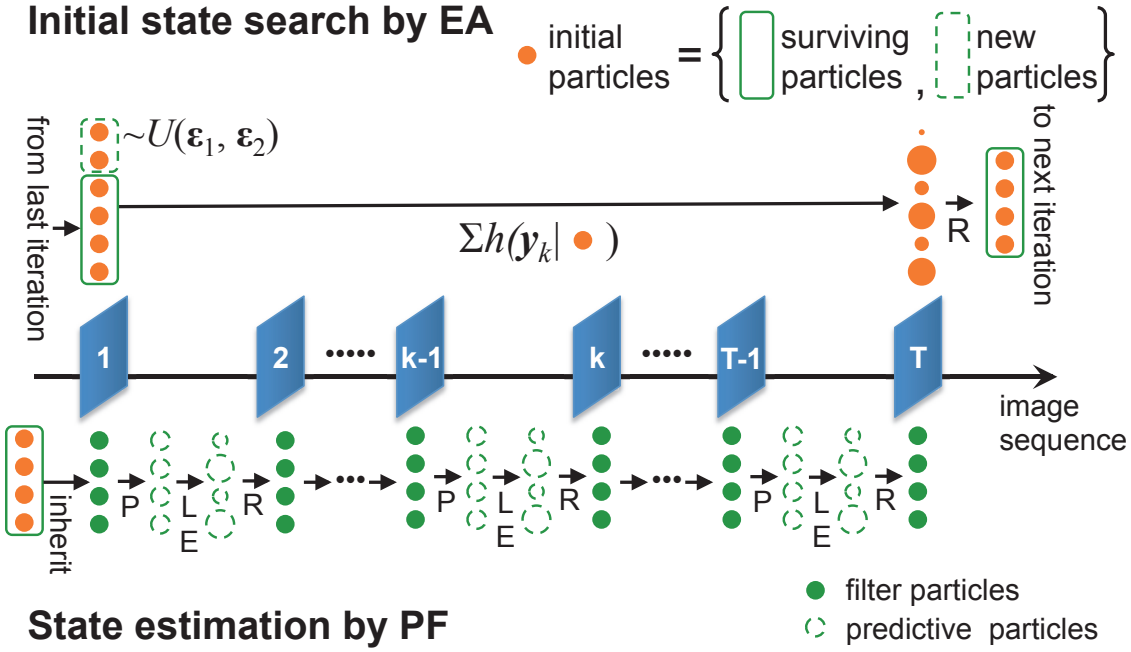
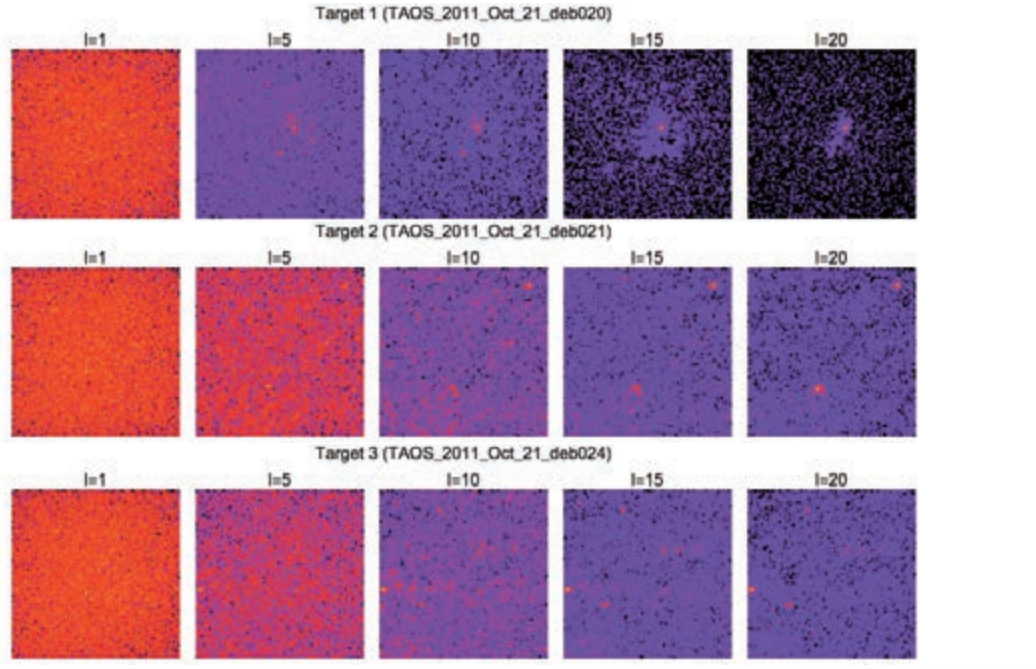
Algorithm's workflow



The results of the EA experiments (20 EA itr.)



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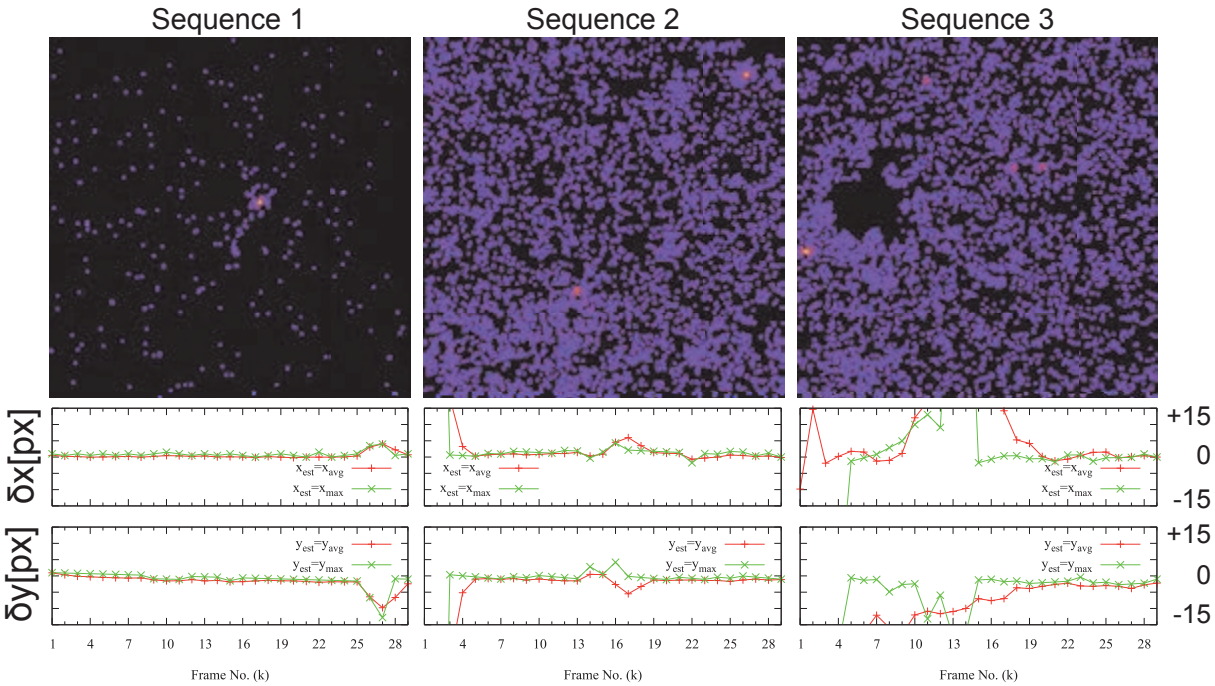
The results of the EA experiments (20 EA itr. then PF)



Summary and future works

- This work proposed a faint debris tracking method which is capable of tracking a single target and confirmed the capability through experiments
- Future works will include
  1. Estimating target presence
  2. Tracking multiple targets
  3. Refining the initial state search to online estimation
  4. Parallel processing

- Acknowledgements
  - The authors wish to acknowledge Dr. Toshifumi Yanagisawa for providing the image sequences for this study
  - Grateful acknowledgement is given to Dr. Andrew Wang for coordinating the TAOS telescope's operation in the observations in 2011
  - This study is supported by JSPS KAKENHI Grant Number 26820374

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G5

軌跡を用いた軌道上物体検出手法の提案と適用結果

Orbital object detection algorithm using streaks

○田川真（九大），柳沢俊史，黒崎裕久，小田寛（JAXA），花田俊也（九大）
○Makoto Tagawa (Kyushu Univ.), Toshifumi Yanagisawa, Hirohisa Kurosaki,
Hiroshi Oda (JAXA), Toshiya Hanada (Kyushu Univ.)

軌道上物体の光学観測において，見かけ上比較的高速で移動する対象を高感度で検出できる手法を提案する．本手法は画像中を高速移動する物体の軌跡内の信号を積算することで検出感度を向上させている．本手法の有効性を確かめるために，オーストラリア・リモート観測所（ARO）での観測データを用いて解析を行った．暗い物体の検出結果より，軌跡を構成するピクセル一つ一つの平均信号強度が背景雑音よりも小さい場合であっても検出可能であることが確かめられた．本発表では比較的暗い物体についての解析結果を報告する．

This study proposes a new image processing algorithm to detect objects using their apparent streaks. A faint streak can be improved its noise-to-signal ratio with the root square of its pixel length by compression. We apply this algorithm to datasets observed at Australia remote observatory in order to confirm validity. As a result, we confirmed that the algorithm can detect object appeared with streaks fainter than background noise.

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Orbital object detection algorithm using streaks

軌跡を用いた軌道上物体検出手法の提案と適用結果

○Makoto Tagawa (Kyushu Univ., JSPS research fellow)
Toshifumi Yanagisawa, Hirohisa Kurosaki, Hiroshi Oda (JAXA) and
Toshiya Hanada (Kyushu Univ.)

Space debris workshop (Chofu, 2014/Dec./17-19)

Abstract

- We developed a new image processing algorithm.
- We can detect an object appeared as streaks with a signal intensity weaker than 1.0 σ_{bkg}.
- We find objects that are not detected by a conventional method.

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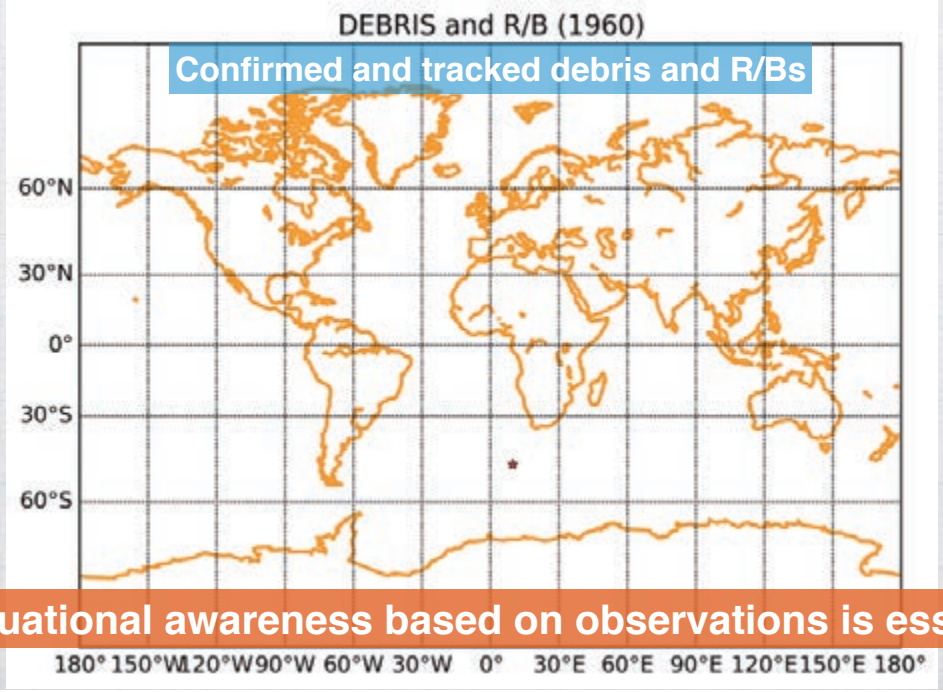
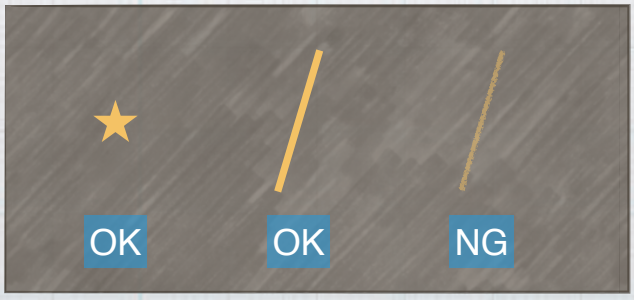
Evolution of the orbital environment



A situational awareness based on observations is essential.

Introduction

- JAXA has conducted survey observations for geosynchronous orbit (GSO) objects.
- The survey may misses objects appeared as faint streaks.



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Introduction

- We developed a new image processing algorithm.
- The algorithm focuses on apparently moving objects.
- The algorithm improves a signal-to-background-noise ratio (SNR).

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Object detection flow

1. Image preprocessing (noise reduction, flat correction and star elimination)
2. Image morphing (Skewing processing)
3. Image compression (Summing signals along vertical axis)
4. Steak position determination (Moving average)
5. Object search (correlation between streaks)

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Object detection flow

1. Image preprocessing (noise reduction, flat correction and star elimination)

Streak detection in an each image

2. Image morphing (Skewing processing)
3. Image compression (Summing signals along vertical axis)
4. Steak position determination (Moving average)
5. Object search (correlation between streaks)

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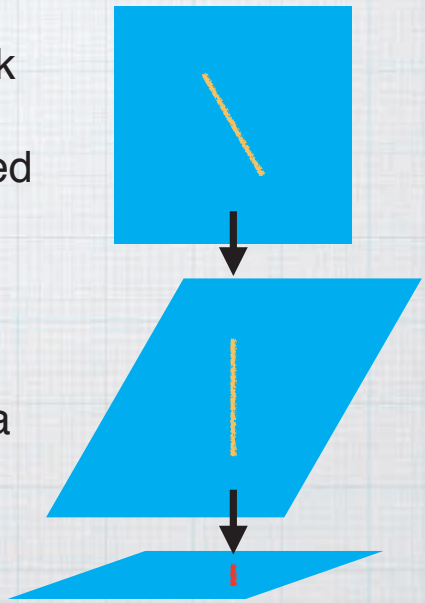
SNR improvement

A. Morphing an image to align a streak along the vertical axis.
(This sequence is repeatedly applied with various skewing angles to search unknown streaks.)

B. Compressing the image along the vertical axis. Compression means a local summing calculation.

SNR improvement
$\propto \sqrt{n_{pix}}$



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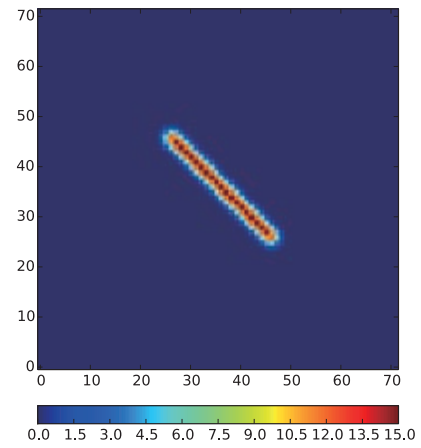
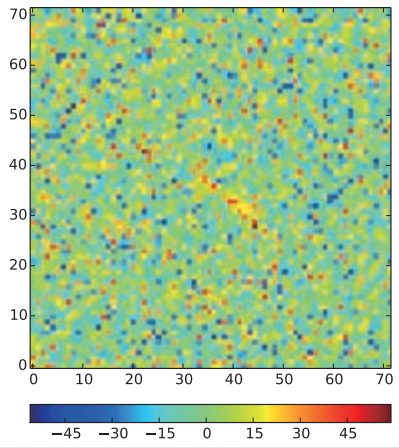
Exemplification using a theoretical streak



+ noise =



Signal intensity of 1.0 σ_{bkg}

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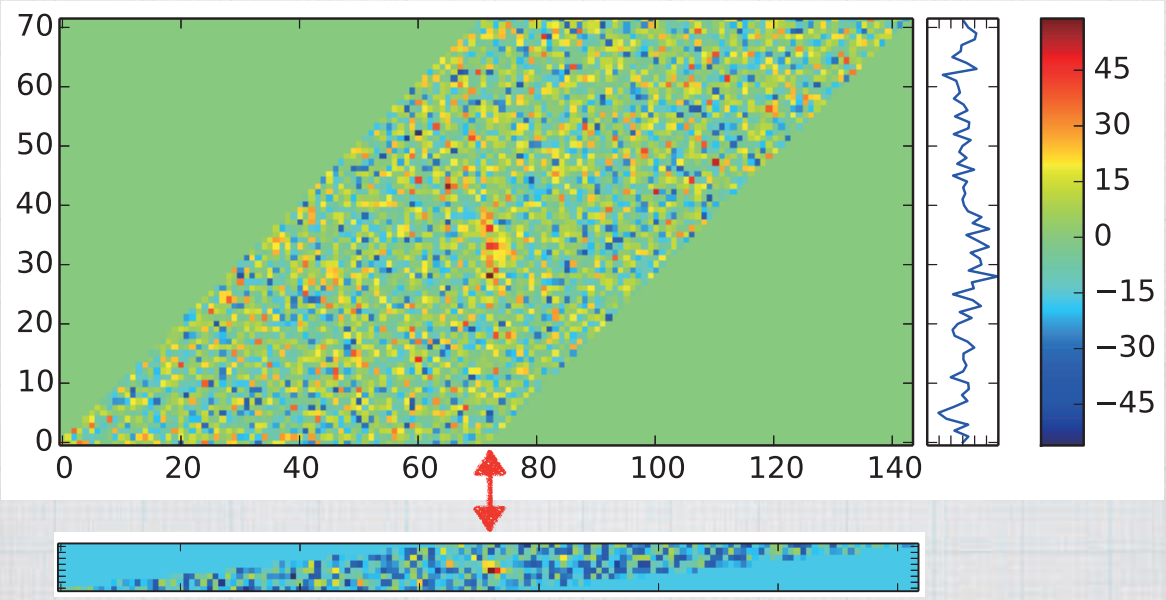
Exemplification of the skewing and the compression sequences



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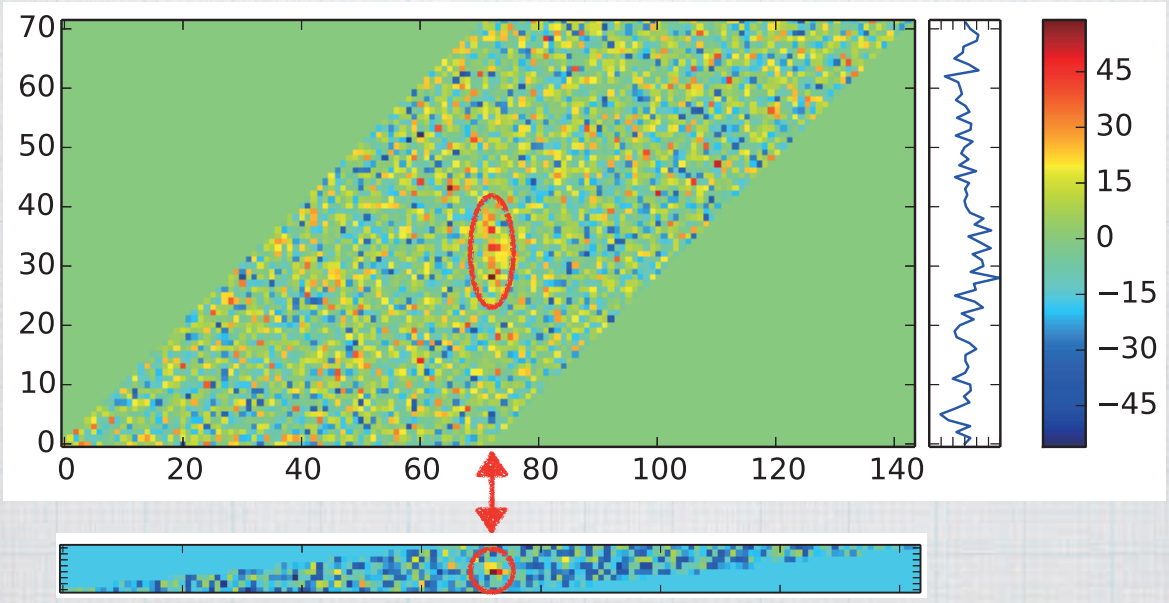
Exemplification of the skewing and the compression sequences



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Object detection flow

1. Image preprocessing (noise reduction, flat correction and star elimination)
2. Image morphing (Skewing processing)
3. Image compression (Summing signals along vertical axis)
4. Steak position determination (Moving average)
5. Object search (correlation between streaks)

Streak position determination
↓
Object search using time-series images
(False alarm rejection)

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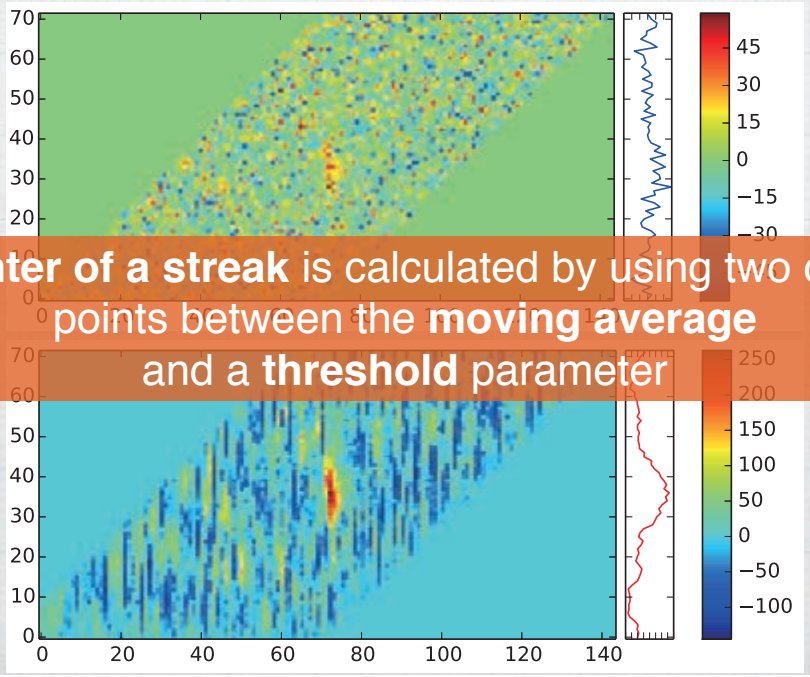
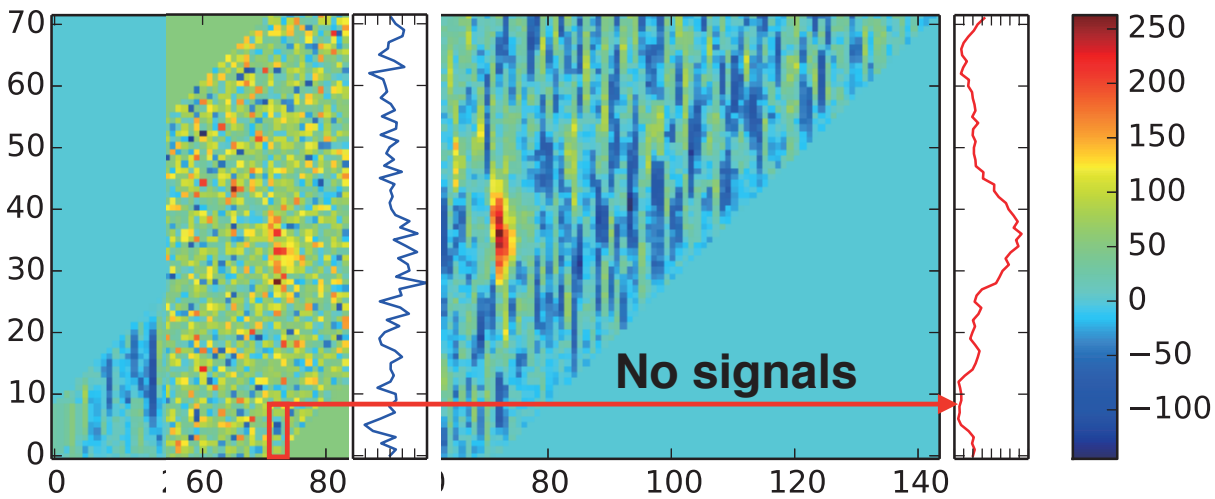
Streak position determination



The **center of a streak** is calculated by using two crossing points between the **moving average** and a **threshold** parameter

Streak position determination



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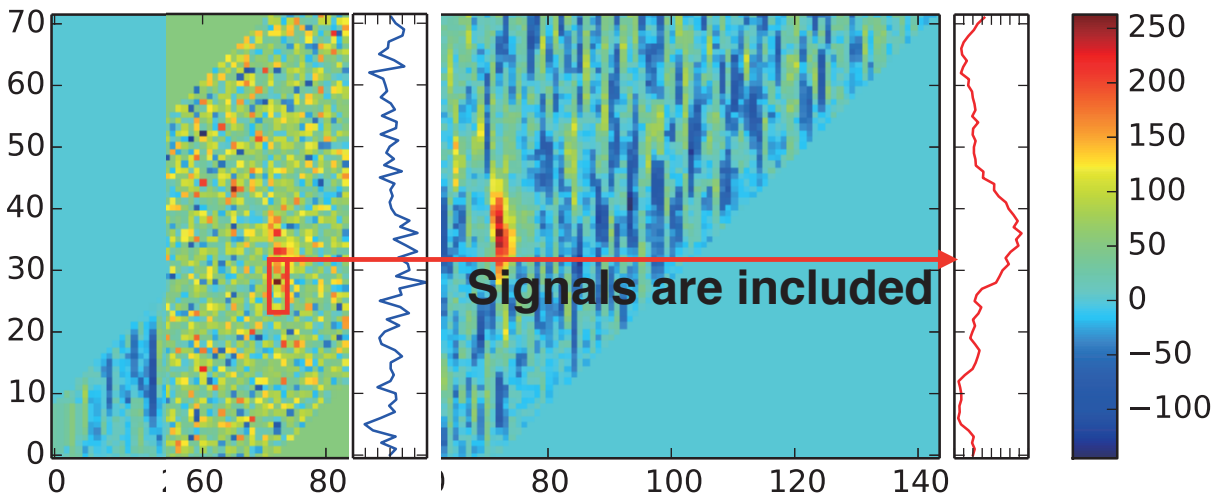
Streak position determination



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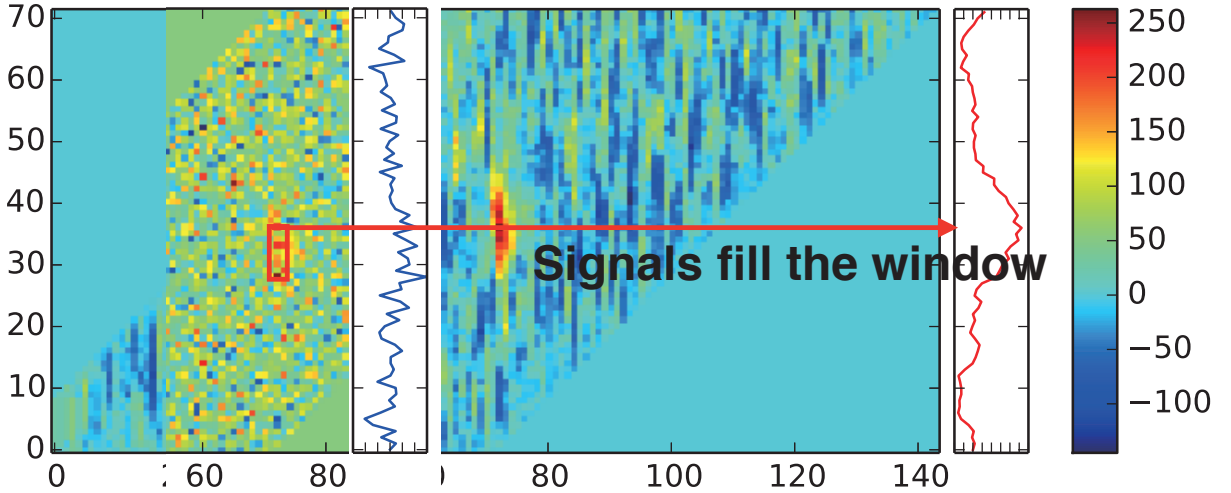
Streak position determination



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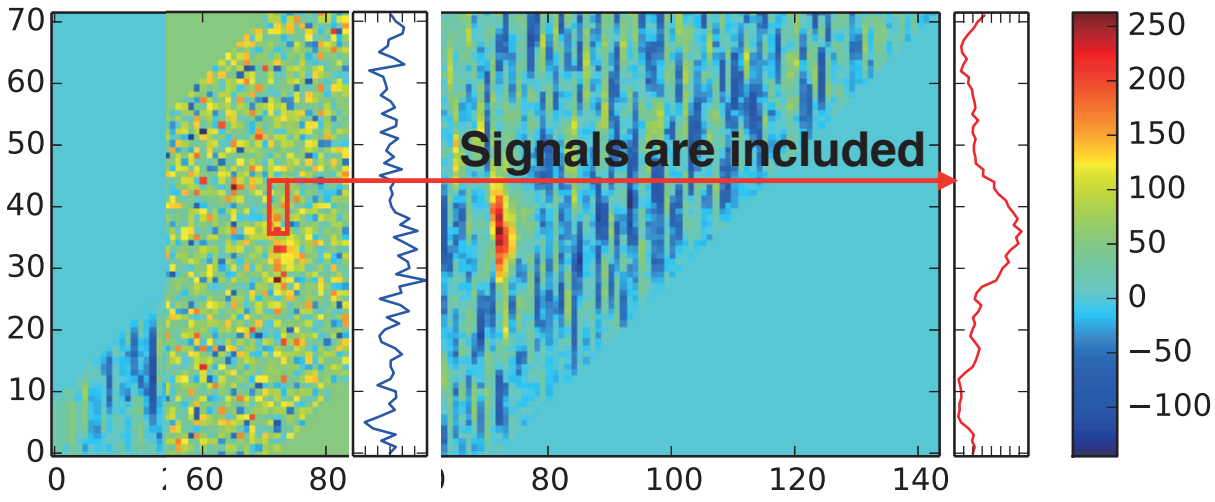
Streak position determination



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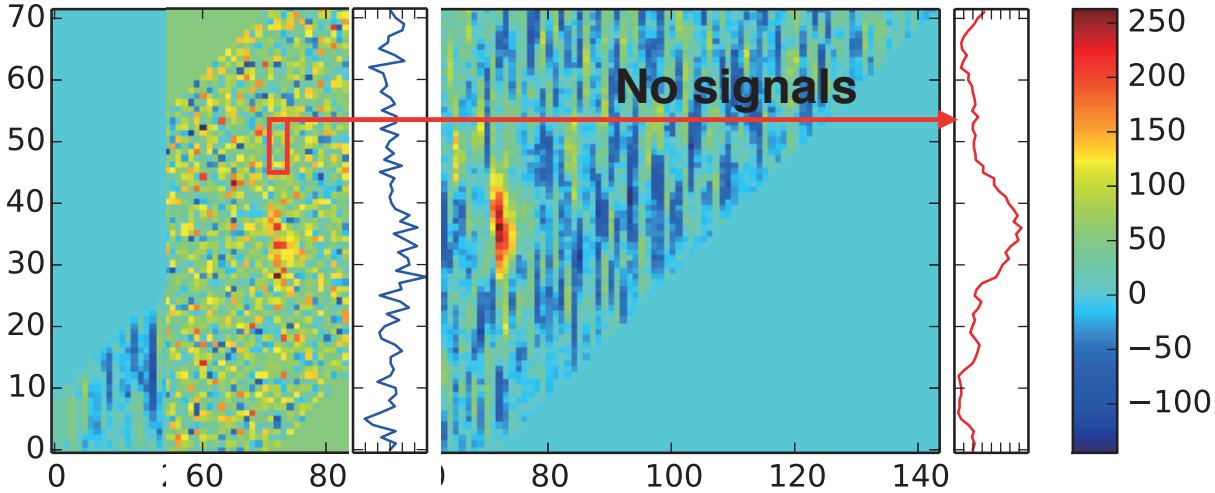
Streak position determination



An ascending and a descending **crossing points**, and a **window width** yield the **center of a streak**.

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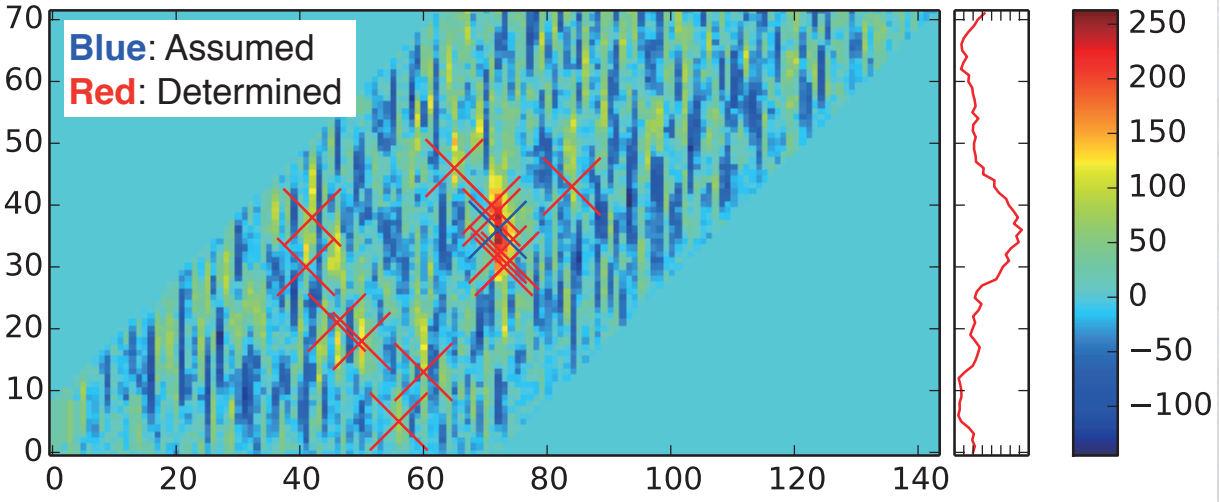
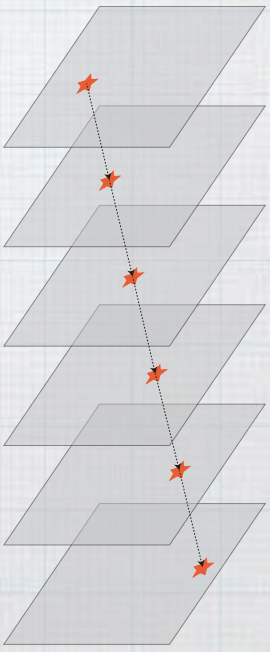
Exemplification of the determination sequence



There are false detections caused by noise.
→A lot of false detections from an image
→**False alarm rejection using images**

Object search

- Correlating determined centers' positions
- Likelihood assessment
  - A number of correlated centers
  - Uniformity and linearity



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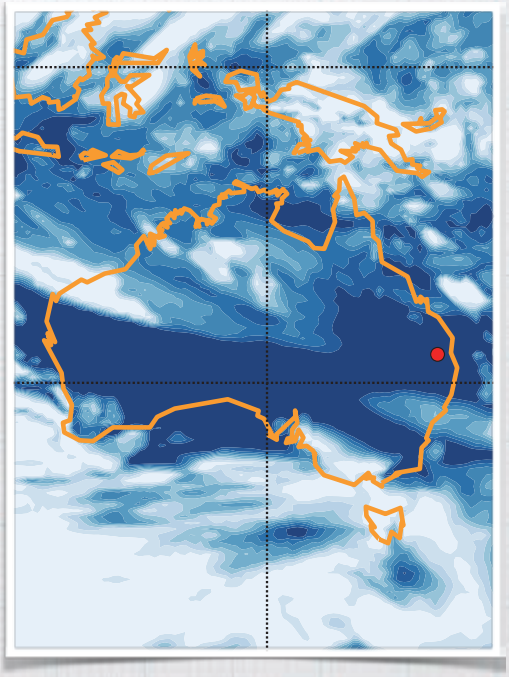
Empirical confirmation

- Australia Remote Observatory (ARO)
- GSO surveys
- Target: Mid-Earth Orbit (MEO) objects (e.g., navigation sat.)
- 18-cm aperture
  Apparent vel.: approx. 5 pixel/s
- 25-cm aperture
  Apparent vel.: approx. 7 pixel/s



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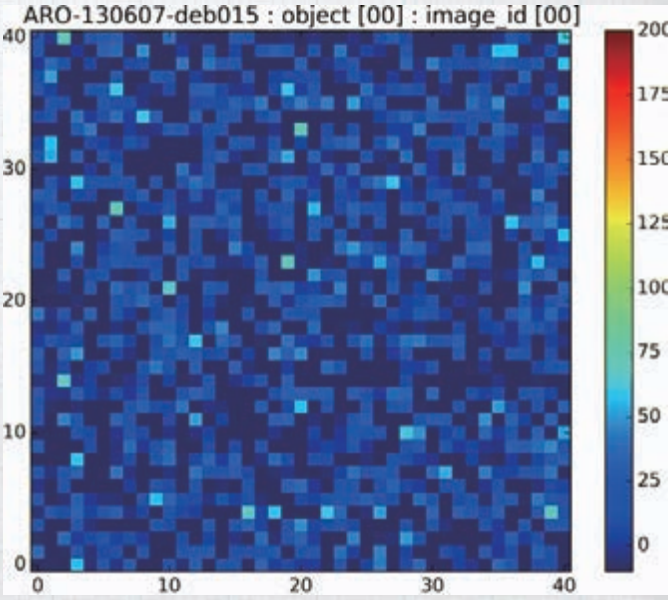
The darkest result

- Skewing angles
  : 1.6 degrees step,
  21 loops (±16 degrees)
- Compression widths
  :(18-cm aperture)
  9,18 pixels
- Contributed image IDs
  7 8 9 10 11 12 13 14 15 16 17



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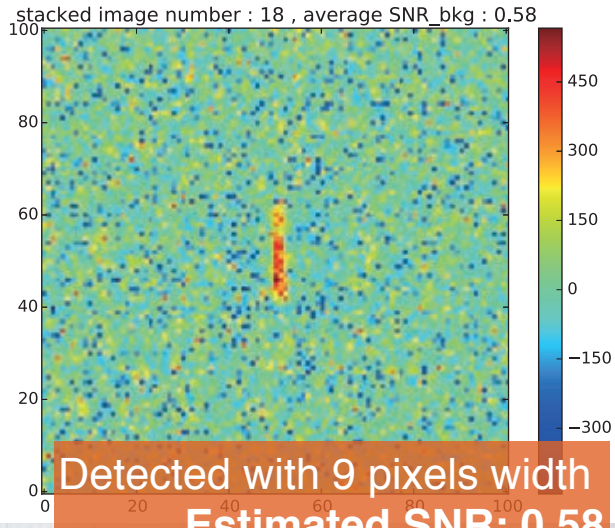
The darkest result

- COSMOS 2456 (Russian navigation sat.)
- Integrating all 18 frames focusing around the center of streaks.
- It confirms detection and estimates the SNR.



Detected with 9 pixels width
Estimated SNR: 0.58
(Threshold parameter 2.0)
(Detection limit 0.67)

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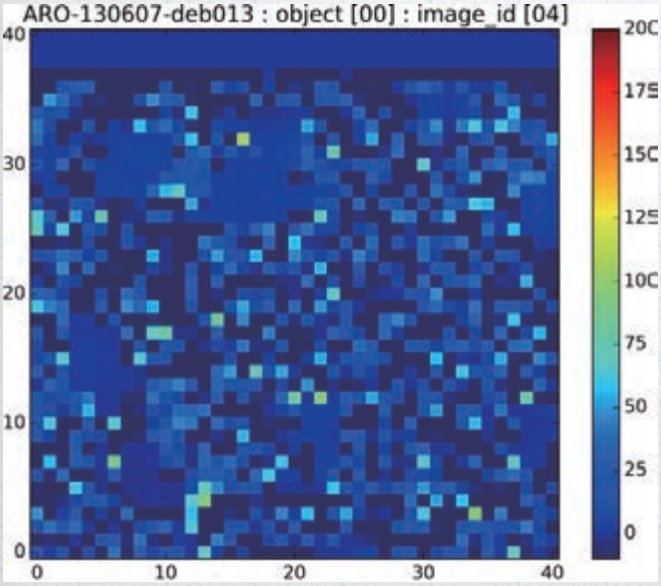
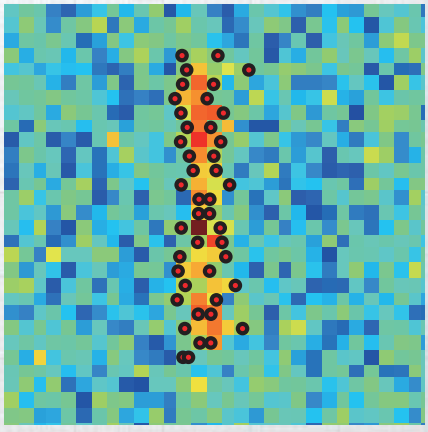
Other results: fainter than 2.0 σ_{bkg} (18-cm aperture)





COSMOS 2456
SNR: 0.79

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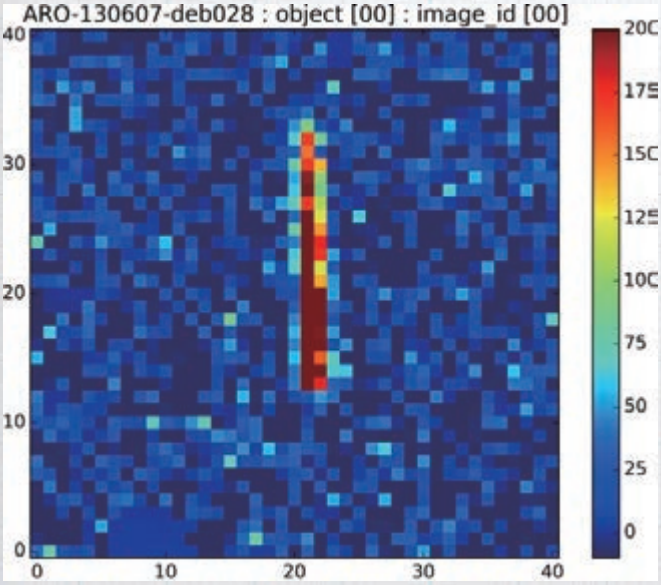
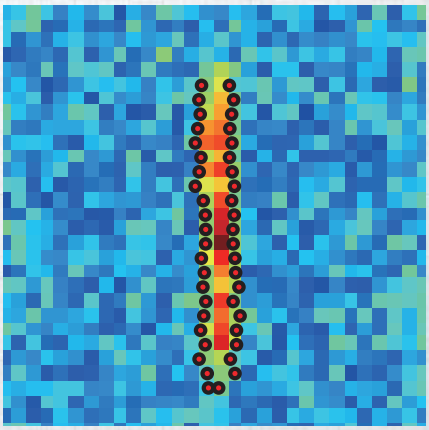
Other results: fainter than 2.0 σ_{bkg} (18-cm aperture)

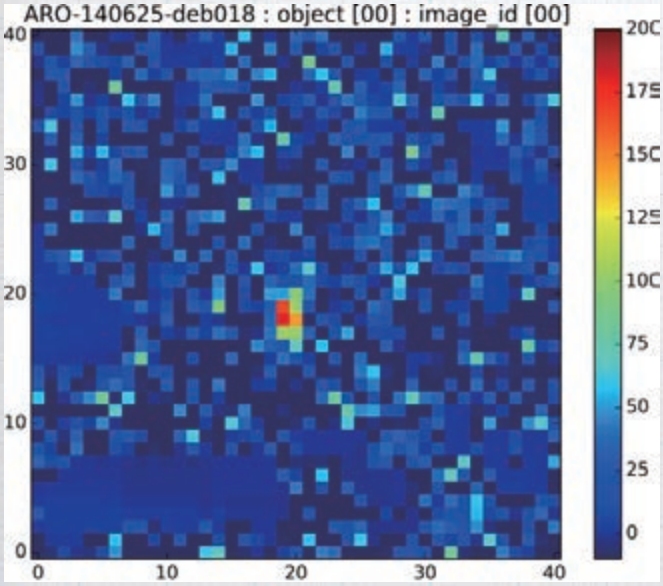


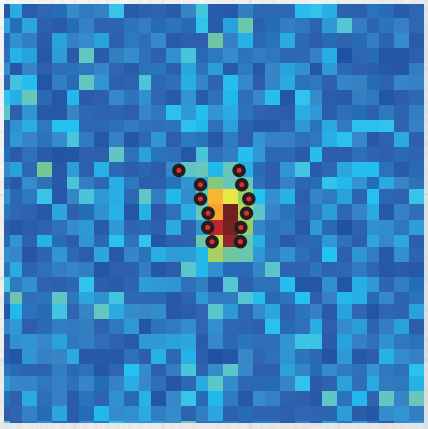


COSMOS 1650
SNR: 1.27

25

Other results: fainter than 2.0 σ_{bkg} (25-cm aperture)





Fengyun 2A AKM
SNR: 1.74

26

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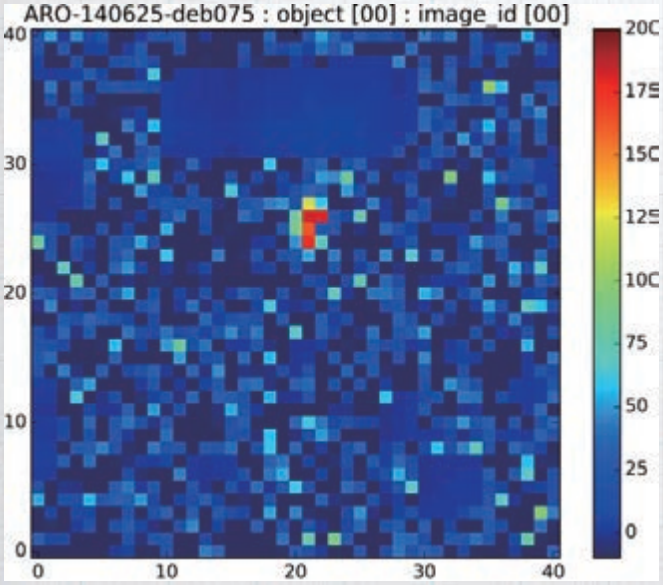
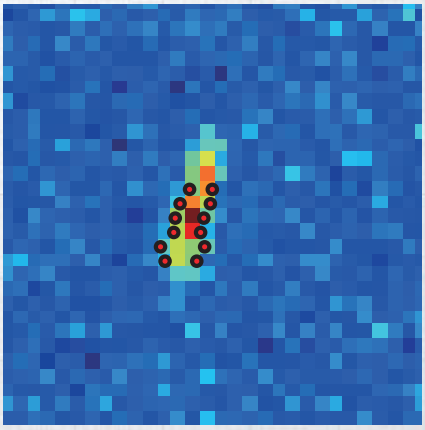
Other results: fainter than 2.0 σ_{bkg} (25-cm aperture)

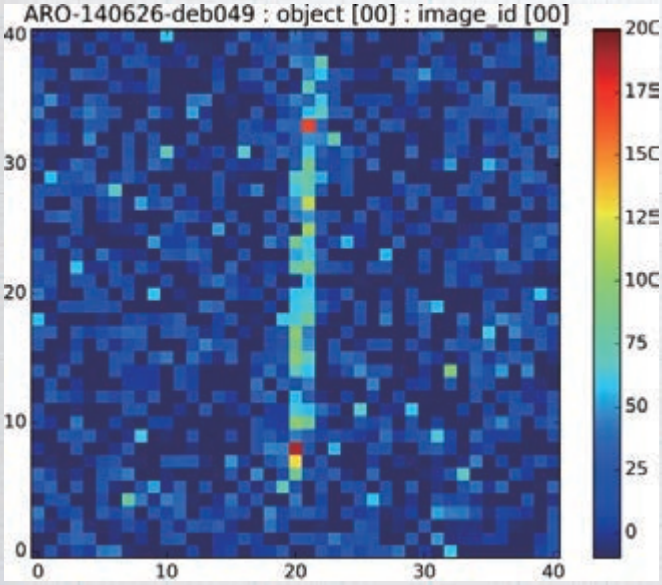


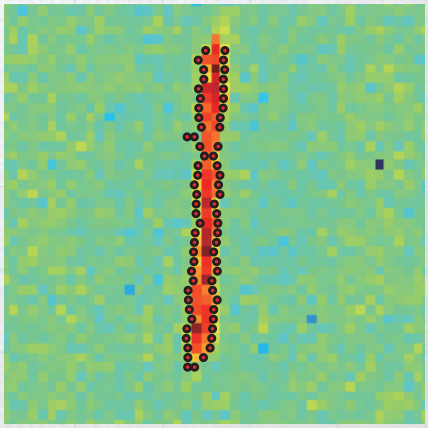


GALAXY 7
SNR: 1.91

27

Other results: fainter than 2.0 σ_{bkg} (25-cm aperture)





NAVSTAR 10
SNR: 1.95

28

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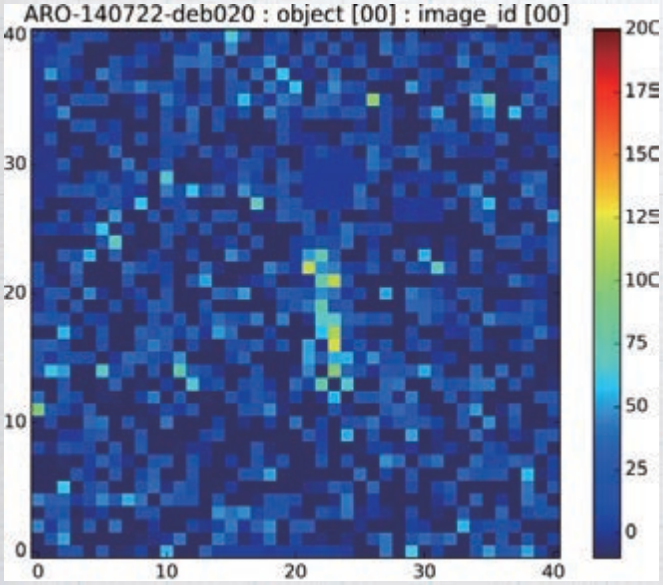
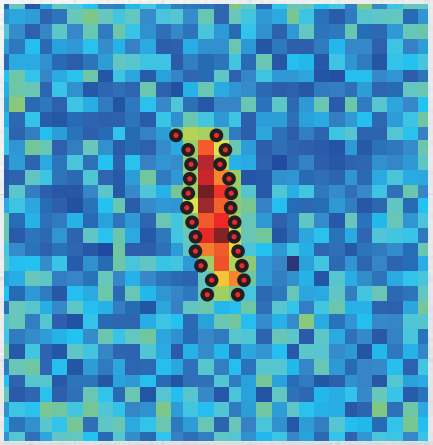
Other results: fainter than 2.0 σ_{bkg} (25-cm aperture)





Uncorrelated
SNR: 1.48

29

Summary

- We developed a new image processing algorithm to detect faint objects using streaks.
- We can detect objects even their streaks are weaker than background noise.
- The effectiveness of the algorithm is empirically confirmed.
- NOTE: The algorithm is potentially contributive to other faint objects in low Earth orbit, or unknown near Earth objects.

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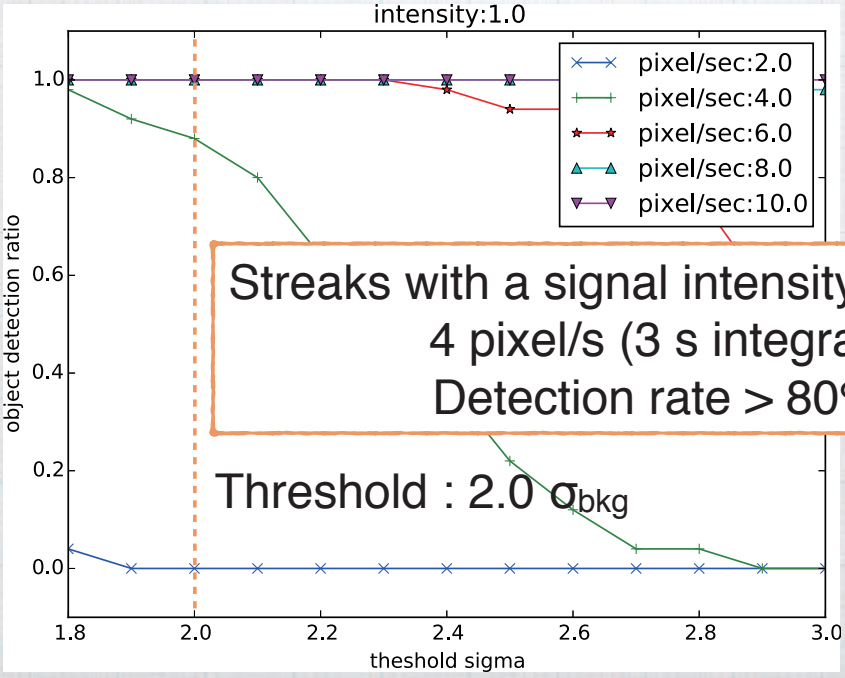
Backup slides

31

Detection rate as a function of the threshold



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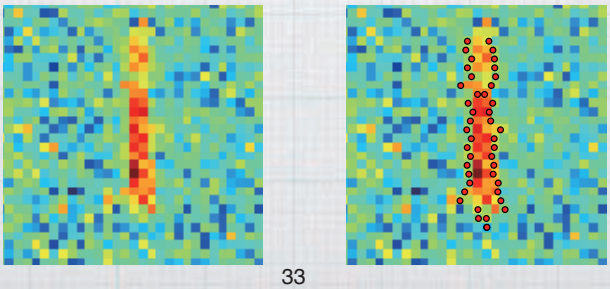
Estimation of a per-pixel-SNR

1. Integrating streaks in time-series images
2. Calculating the length of the integrated streak by using an estimated motion function
3. Estimating the width of the integrated streak by 1-D Gaussian fitting
4. Comparing the sum of the signals of the streak to background noise



33

Calculation speed enhancement

- Optimization of the algorithm
- Parallel computing using a graphics processing unit (GPU)

34

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H1

HTV-5 における微小デブリセンサ実証実験の計画

Demonstration Experiment of Space Debris Sensor on HTV-5

○奥平修、松本晴久、辻田大輔、小林裕希（JAXA）、北沢幸人（IHI）
○Osamu Okudaira, Haruhisa Matsumoto, Daisuke Tsujita, Yuki Kobayasi (JAXA),
Yukihito Kitazawa (IHI)

HTV 5 号機には宇宙環境観測装置 KASPER（Kounotori Advanced SPace Environment Research equipment）が搭載される。KASPER では HTV 電位・プラズマ電流計測とともに微小デブリセンサの軌道上実証を行なう。本センサは、JAXA で開発を進めてきたフィルム貫通型デブリ計測装置で、0.1～数 mm サイズのデブリ検出を目的としている。これまでの微小デブリセンサと比較し、有感面積が大きい割に軽量コンパクト、また回収の必要がないアクティブセンサという特長がある。これまでミリ、サブミリサイズのデブリは、宇宙機への影響が懸念されながらもほとんど観測データのない領域であった。本センサはこのような微小デブリを直接観測する手段を提供し、広く観測を進めることで宇宙機に対する適切なリスク評価・防御設計に貢献することを目標にしている。本センサの特徴および HTV-5 における実証実験について報告する。

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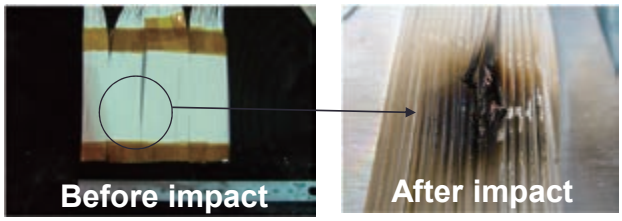
HTV-5における微小デブリセンサ実証実験の計画

DEMONSTRATION EXPERIMENT OF SPACE DEBRIS SENSOR ON HTV-5

○Osamu Okudaira, Haruhisa Matsumoto, Daisuke Tsujita,
Yuki Kobayasi (JAXA), Yukihito Kitazawa (IHI)

Background

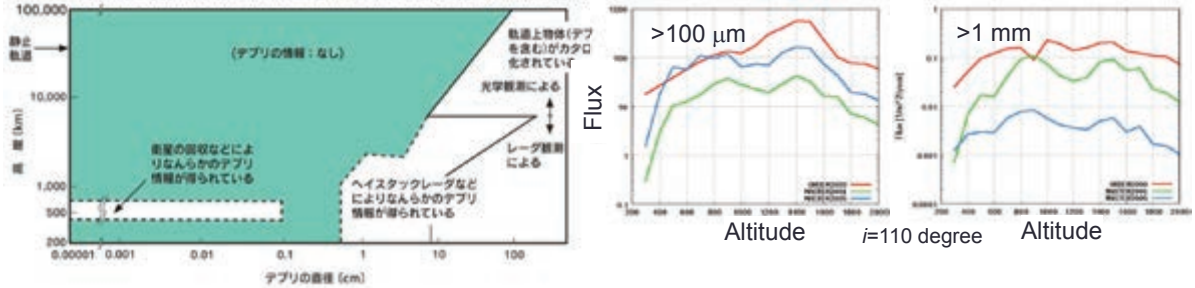
- Meteoroid and space debris of approximately 100 micro-meters to several millimeters in size
  - An impact damages the wire harness and other equipment on board.



An example of experiment results.
- Diameter of projectile : 0.3 mm
- Impact velocity : 4 km/s

(JERG-2-144-HB001 'JAXA Space Debris Protection Design Manual Appendix 2 ', 2008)

  - The debris flux in the size are not well known in LEO



➡ To measure flux of debris from 100 micrometer to several millimeters.

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Measurement Methods of Small Particles

- Target: the flux and size of debris from a hundred micrometer to several millimeters in size.

- Ground observation

It is difficult to measure the flux of the size range.

- Surface inspection of retrieved spacecraft

Only applicable to retrievable spacecraft

- Restricted orbit - Restricted flight opportunity - Not able to get real time data
- Difficult calibration

- Passive Sensor (sample return of small debris)

Only applicable to retrievable spacecraft

- Restricted orbit - Restricted flight opportunity - Not able to get real time data

- In-situ measurement by active sensors

Applicable to all spacecraft

But

- Conventional sensors are not necessarily suitable for the measurement of the size range
- Many hypervelocity impact tests are required for the calibration

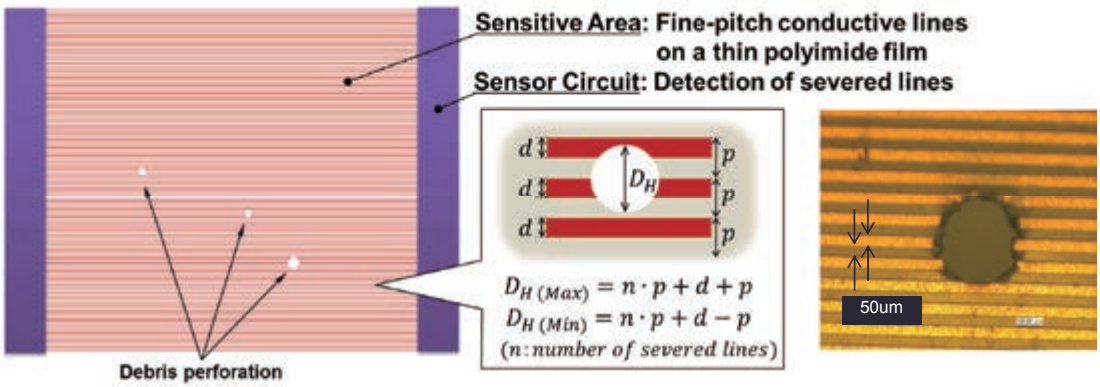
→ **Development of a sensor suitable to measure the debris in such size**

Principle of the Micro-Debris Sensor

- New type active sensor

Sensor concept (Sakurai, 2008)

  - A multitude of thin and conductive strips is formed with fine pitch on a thin nonconductive film.
  - An debris impact is detected when one or more strips are severed by the perforation.



US patent registered

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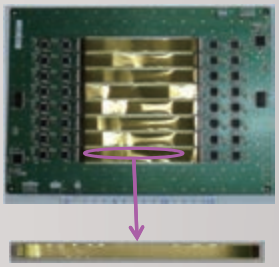
Principle of the Micro-Debris Sensor

- Features
  1. Simple mechanism and high reliability (sensing precision)
  2. Free of hypervelocity impact experiments (calibration shots)
  3. Flexible configuration (size and shape)
  4. Sensitive area is able to be monitored.
  5. Low weight, low power and low cost (ex. < 200g and < 1W per 1m^2 [sensing area])
  6. Additional parameters (velocity and incident direction) by minor expansions.

Development of Sensors

2008-2009	2010	2011-2012
Laboratory model	Breadboard model (BBM)	Engineering model (EM)
		
✓ Consists of small 8 unit. ✓ one unit size is 1.2 × 10 cm	✓ Large area unit was developed. ✓ 1 unit size is 40 × 30 cm. ✓ One large FCP board as a sensor	✓ Circuits to detect severing were equipped. ✓ No mechanical connector to the film and to reduce the number of parts

Sensitive area specification	
Thickness	< 20 um
Width of a conductive line	50 um
Gap between conductive lines	50 um

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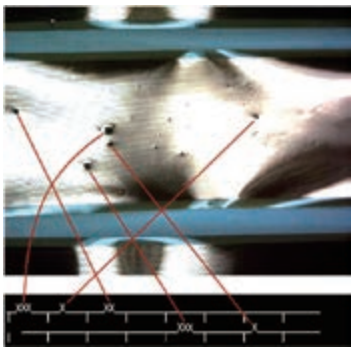
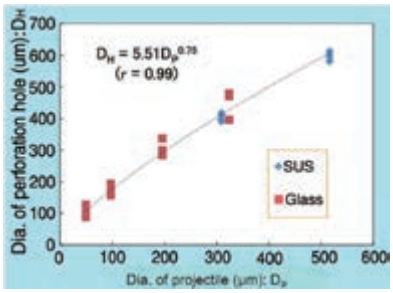
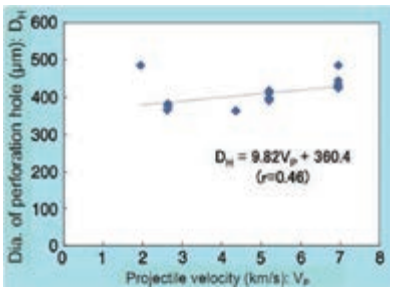
Hypervelocity Impact Experiments

Two-stage light gas gun
(JAXA/ISAS)

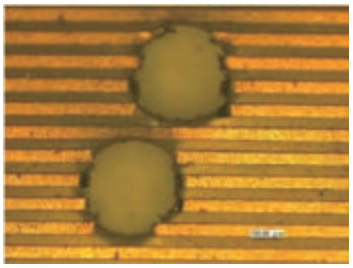
Vacuum	<5 [Pa]
Temperature	Room temperature
Projectile material	SUS304 and Glass
Projectile diameter	50 - 516 [um]
Impact velocity	1.9 - 17.0 [km/s]
Impact angle	90, 60, 30, 15 [deg]







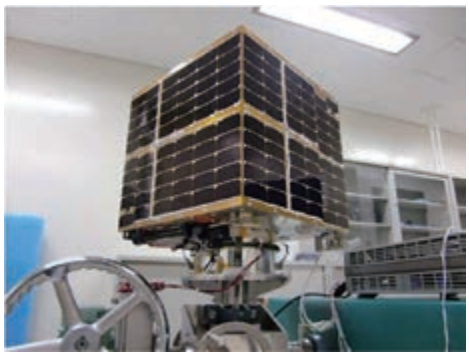
$$D_p = 1.39 \times 10^{-1} {D_H}^{1.28}, \quad D_H = n \cdot p + d \pm p$$



Example of perforation hole
- Projectile: SUS 309 μm
- Impact velocity: 4.65 km/s

Preliminary Flight Experiments

- Educational mode is onboard a small satellite Horyu-II built at KIT (Kyushu Institute of Technology) and launched on 18 May 2012
- Laboratory model on a small satellite QSAT-EOS by Kyushu Univ. was launched in 6 Nov. 2014.



Faure *et al.*, 2012

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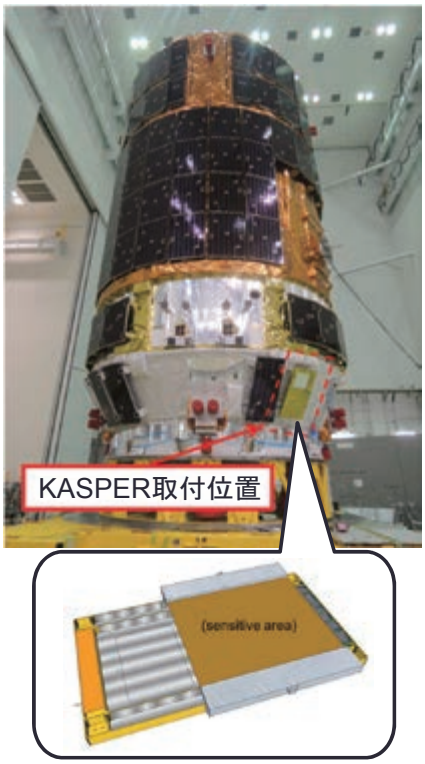
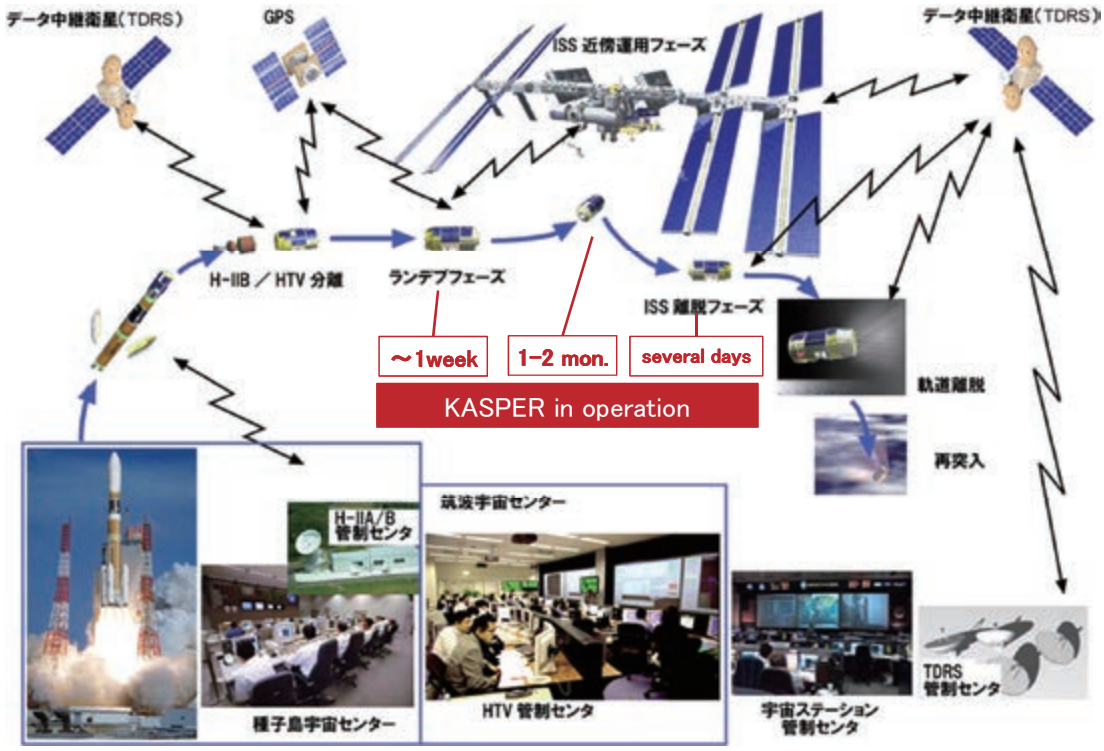
Flight Experiment on HTV

- HTV (H-II Transfer Vehicle) “KOUNOTORI”
  - JAXA’s unmanned cargo transfer spacecraft which delivers supplies to the International Space Station (ISS).
- KASPER (KOUNOTORI Advanced Space Environment Research Equipment)
  - Space Debris Monitor + Charging Monitor
  - On the propulsion module of HTV-5
  - To be launched in 2015
  - Mission duration: 1-2 months
- To demonstrate the sensor’s functional capability in space environment.



HTV Flight Plan



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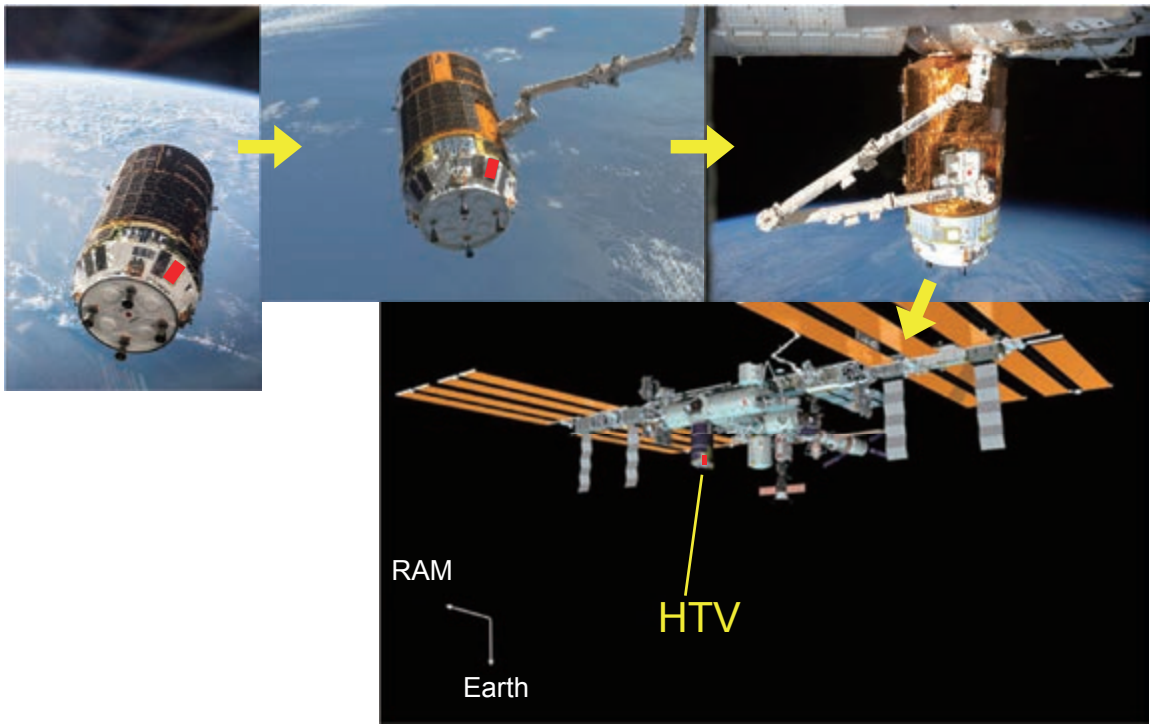
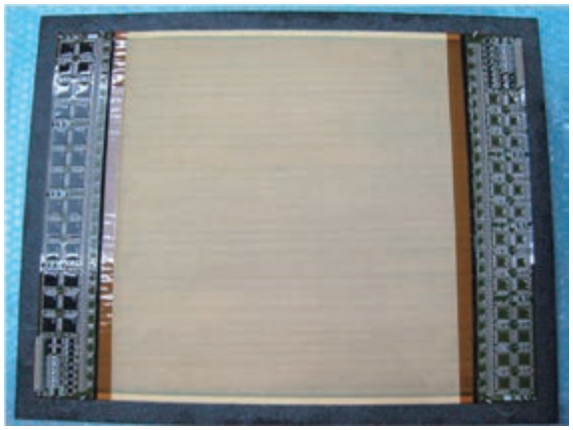
HTV Flight Plan



SDM（KASPER Model）

- A flight model sensor is reinforced mechanically with wide patterns and cover lays.
- There were less faulty wires produced in fine-structure processing
- Protective coat against atomic oxygen (AO)
  （developed by JAXA, a few micrometers in thickness）



Space debris sensor on HTV-5	
Thickness of sensitive area	< 20 um
Width of a conductive line	50 um
Gap b/w conductive lines	50 um
Sensitive area	30 x 35 cm
Number of lines	3300
Weight (incl. outer box)	1.5 kg
Size (incl. outer box)	50 x 39 x 4 cm
Power	～2W (max.)

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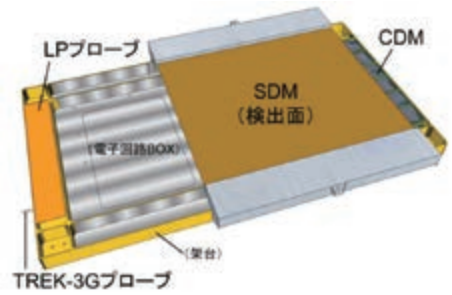
Features of KASPER

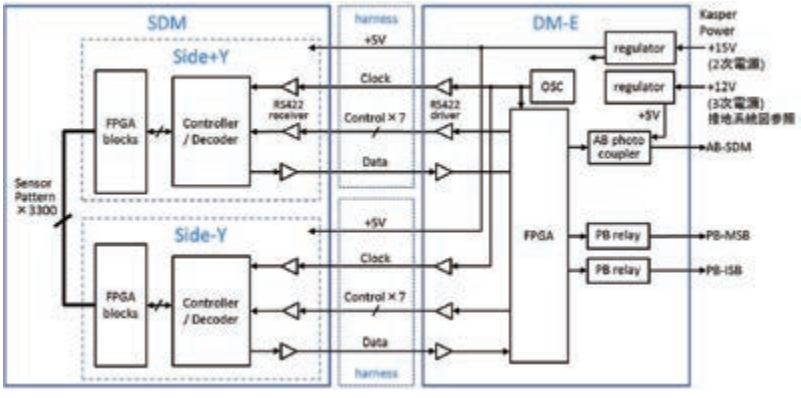
KASPER	
Sensor	2 charging sensors + 2 debris sensors
Size	75 × 50 × 12 cm
Weight	～ 8kg
Power	30W (including 16.8W for heaters)
Telemetry	PA × 2、PB × 4、AB × 2
Telecommand	6



KASPER デブリセンサ			
SDM	フィルム貫通型微小デブリ計測装置。薄膜を貫通した100μm～数mmのデブリの大きさを計測する。	測定デブリサイズ	100μm以上
		測定精度	100μm
		時間分解能	>900秒
		テレメトリレート	0.2 bps (1bit/10秒)
CDM	圧電素子型デブリ計測装置。数μm以上のマイクロデブリが衝突した際の電圧を計測する。(千葉工大)	測定範囲	100pg・km/sec以上
		時間分解能	1秒
		テレメトリレート	0.2 bps (1bit/10秒)

SDM : フィルム貫通型デブリ計測装置

- 100μm～数mmのデブリが衝突した時刻と大きさを計測
  - センサ部と回路部(DME)から構成される。
  - 回路部は900秒ごとにセンサ部を起動し、断線計測とデータ取り込みを行う。
  - センサ部は、電圧印加により1本ずつ断線を検査する。
  - 3300本の結果を回路部にて整理、パケット化し、テレメトリする。
  - 計測時刻とデブリ貫通孔をリスト化した情報がテレメトリされる。



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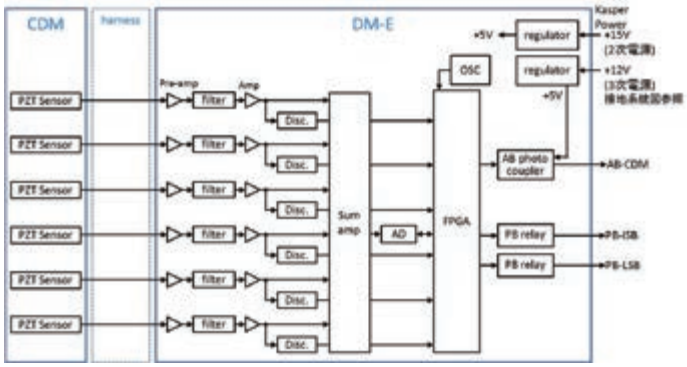
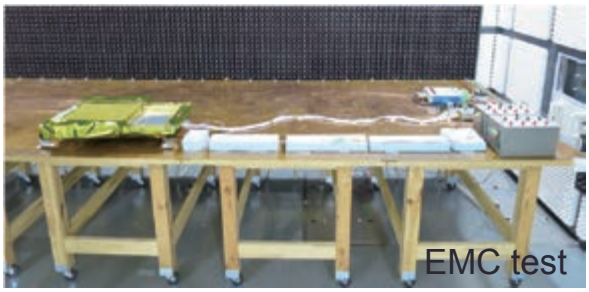
CDM : 圧電素子型デブリ計測装置

- 100μm以下のサイズのデブリ・メテオロイドのその場計測
  - 千葉工業大学　惑星探査研究センターとの共同研究
  - センサには4×4cmの圧電性素子PZT（チタン酸ジルコン酸鉛）を6枚用いており、そのいずれかにデブリが衝突した際に発生する電圧を検知する。
  - 回路部では6枚のPZTからの信号はサムされてAD変換される。
  - 設計上は10pg・km/sec以上を検出できるが、実際の下限は軌道上でのノイズレベルに依存。そのため、常時ノイズレベルをモニタし、トリガレベルを自動決定する。
  - イベントとして取り込んだAD値に時刻、トリガー条件、温度を付加してパケット化し、テレメトリする。



Development of KASPER

SDM (KASPER)	
2013	Design Review
	Initial performance test
	EMC test
2014	Shock test
	Thermal vacuum test
	Vibration test
	Final performance test
2015	PQR/PSR
	Launch & Observation



This document is provided by JAXA.

Summary

- JAXA is developing a new-type active sensor to detect particles ranging in size from a hundred micrometers to several millimeters
- This sensor has a simple mechanism and requires almost no calibration as it is essentially a digital system.
- The latest sensor model will be onboard HTV-5 and launched by H2B next year.

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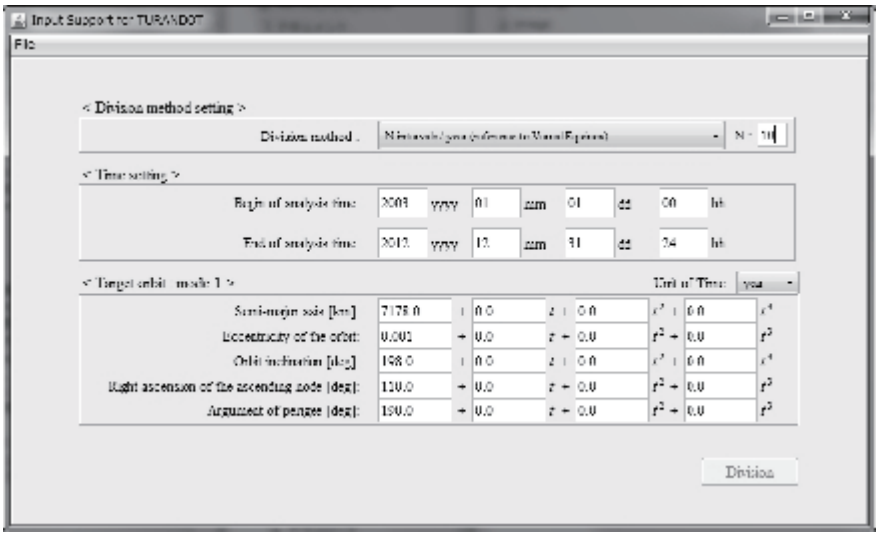
H2

デブリ衝突損傷リスク解析ツールに関する最近の機能拡充

Latest Expansion of Tactical Utilities for Rapid ANalysis of Debris on Orbit Terrestrial

○八田真児, 上田裕子, 中渡瀬竜二 (MUSCATスペース・エンジニアリング(株)),
東出真澄, 河本聡美 (JAXA)
○Shinji Hatta, Hiroko O. Ueda, Ryuji Nakawatase(MUSCAT SE),
Masumi Higashide, Satomi Kawamoto(JAXA)

デブリ衝突損傷リスク解析ツール(TURANDOT)は宇宙機設計支援ソフトウェアである。このソフトウェアを、より多くのユーザーが安心して利用できるツールとするために、過去2年間にわたって複数のベンチマークテストを実施した。また、直近ではユーザーの利便性を高めるために入力支援機能を大幅に強化中である。TURANDOT に関連する 2012 年度～2014 年度の活動状況を報告する。



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TURANDOT

デブリ衝突損傷リスク解析ツールに関する最近の機能拡充

Latest Expansion of Tactical Utilities for Rapid ANalysis of Debris on Orbit Terrestrial

○Shinji Hatta, Hiroko O. Ueda, Ryuji Nakawatase (MUSE Co., Ltd.), Masumi Higashide, Satomi Kawamoto (JAXA/ITRC)

6th Space Debris Workshop
@JAXA/Chofu, 2014/12/17~2014/12/19

Contents

- Introduction
- What is TURANDOT
- Validation
- New function
- Demonstration

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Estimated Annual Collision

- 800km Altitude

Debris Size	0.1~1mm	1~10mm	1~10cm	10cm<
Collision [1/m^2/year]	100	0.01	0.0001	0.00001
Solution	**Protection**	?	???	Manuever

  - Computation by MASTER© by ESA
  - Ref. ISSN 1349-113X Proceedings of the 5th Space Debris Workshop

Kinetic Energy @ Collision

- Is common object small enough?
- Ex. 3g/cm^3, 1mm^3, 16km/sec
  - 3g x 0.1cm x 0.1cm x 0.1cm = 0.000003kg
  - 0.5 x 0.000003kg x (16km/sec)^2 = 768 J

- 800 J concentrate on 1mm^2, in <μsec.
  - Easy to penetrate spacecraft structure

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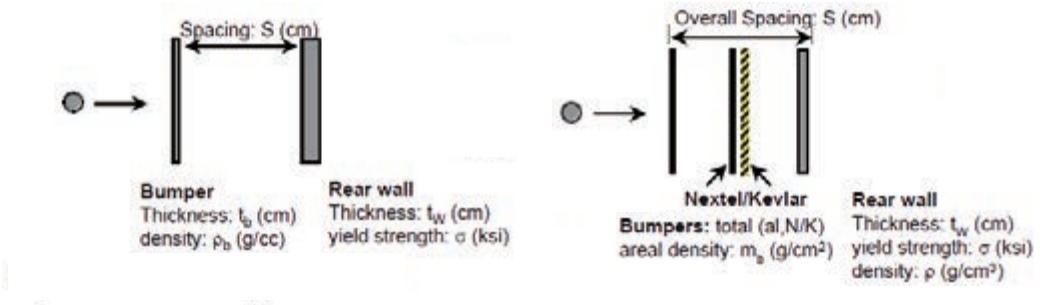
Kinetic Energy @ Collision

- Cube object, 3g/cm^3, 16km/sec, 2015/1/1~2024/12/31
- Collision Frequency is Estimated by MASTER-2009©+TURANDOT (Normal to orbit direction)

Debris Size [mm]	**0.01~0.1**	**0.1~0.316**	**0.316~0.5**	**0.5~1**
Collision Frequency [1/m^2/year]	646 (1/day)	67 (1/week)	0.6 (1/year)	0.13 (1/decade)
Kinetic Energy	<0.77J	<24J	<96J	<768J

Protection Design

- Debris Bumper : Effective & Expensive



– Ref. IADC Protection Manual v5.0

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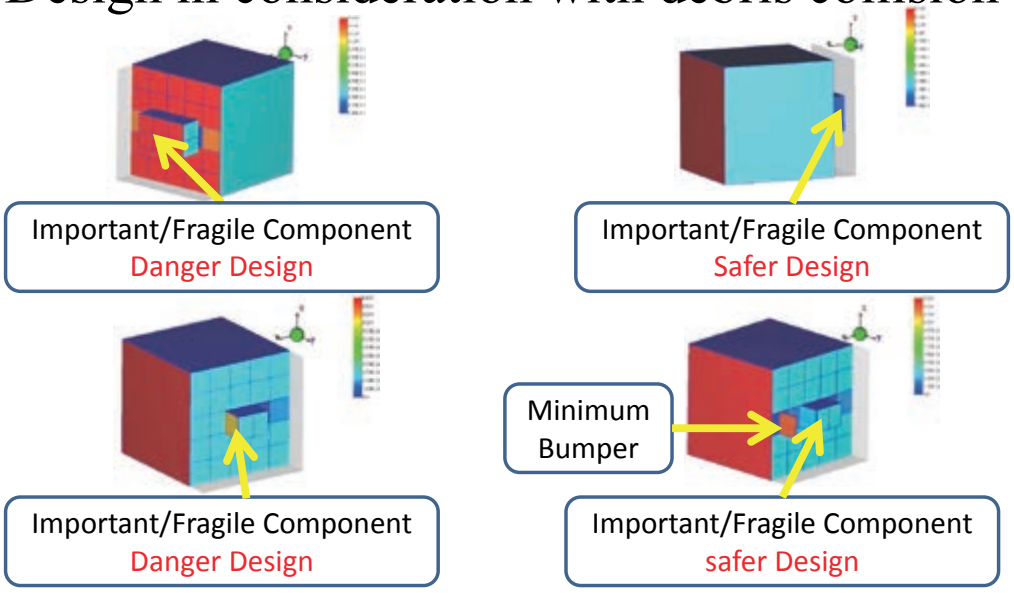
Protection Design

- Design in consideration with debris collision



History

- April, 2007~Feb., 2009
  - "Collision Probability" Analysis Tool
- April, 2009~Feb., 2011
  - "Collisional Damage" Probability Analysis Tool
- April, 2011~Feb., 2012
  - Including "MASTER-2009"
- April, 2012~
  - Detail Modifications & Validations

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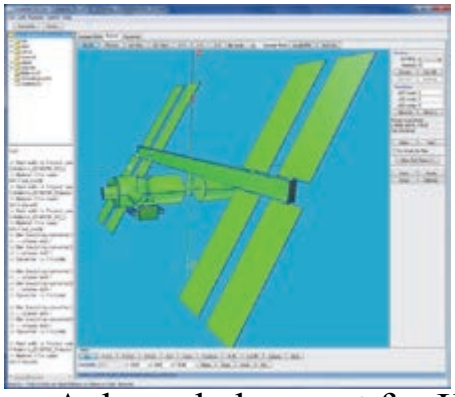
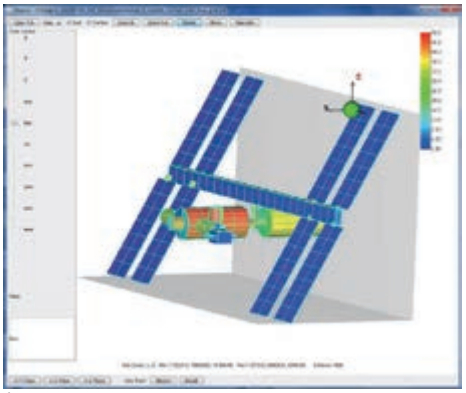
Functions I

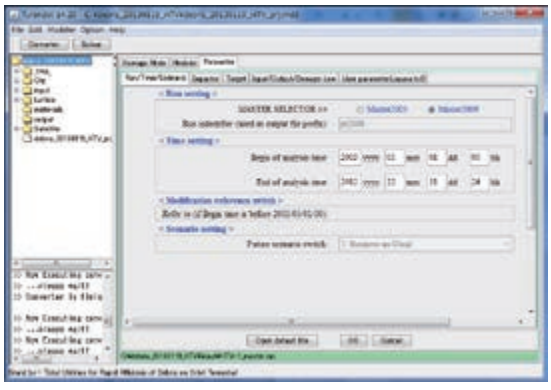
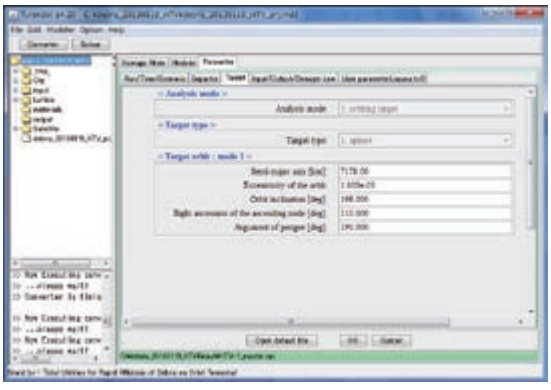
- GUI
  - Integrated Analysis Environment
  - Satellite modeling
  - Grid generation

  - Acknowledgement for Kurihara, M.

Functions I

- GUI
  - Computation condition setting
  - Requirement from Databases (MASTER & ORDEM)

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Functions II

- No Domestic Database!
  - MASTER-2005 & ORDEM2000
  - MASTER-2009 & ORDEM2000

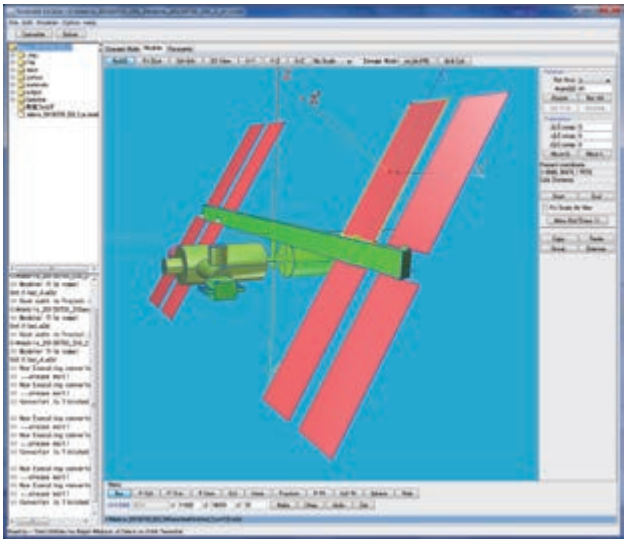
$$flux_{\mathrm{ORDEM}} = flux_{\mathrm{MASTER}} \cdot K \qquad if\ 1 < K$$

$$flux_{\mathrm{ORDEM}} = flux_{\mathrm{MASTER}} \qquad if\ K < 1$$

$$K = \frac{F_{\mathrm{ORDEM}}}{\int_{4\pi} f_{\mathrm{MASTER}} \cdot d\Omega}$$

Functions III

- Damage Probability
  - Users' Definition
  - Fortran 95 like



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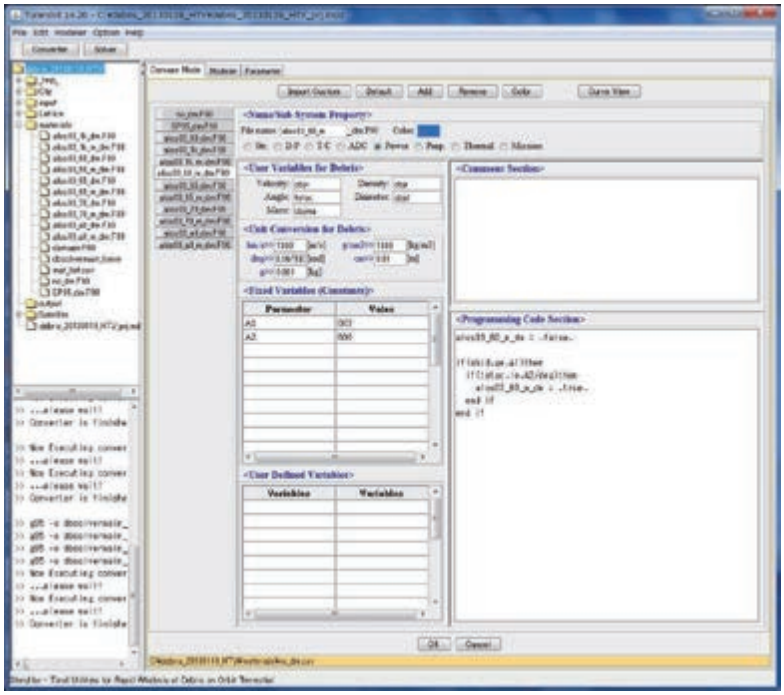
Functions III



Comparison with MASTER-2009©

- Flux computing function of MASTER-2009©
- Fluxis for 6 Faces of a cube

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Result

Condition		TURANDOT	MASTER-2009	Error
a) 0.1mm<d	Debris	6.3672	6.3678	0.0%
	Meteoroid	1.1050×10	1.1088×10	0.3%
b) 1cm<d	Debris	1.5014×10^{-5}	1.5354×10^{-5}	2.2%
	Meteoroid	8.9217×10^{-7}	8.6510×10^{-7}	3.1%

- Good agreement
- TURANDOT is reasonable

BLE Validation(1)

- MASTER-2005©
- Earth oriented attitude
- 2002/01/01~2002/12/31
- 0.001m<d<0.1m
- 85 debris flux data from “expl.cpe” as No.1001, 2001,…, 85001
  - 1 debris flux from every 1000 debris flux

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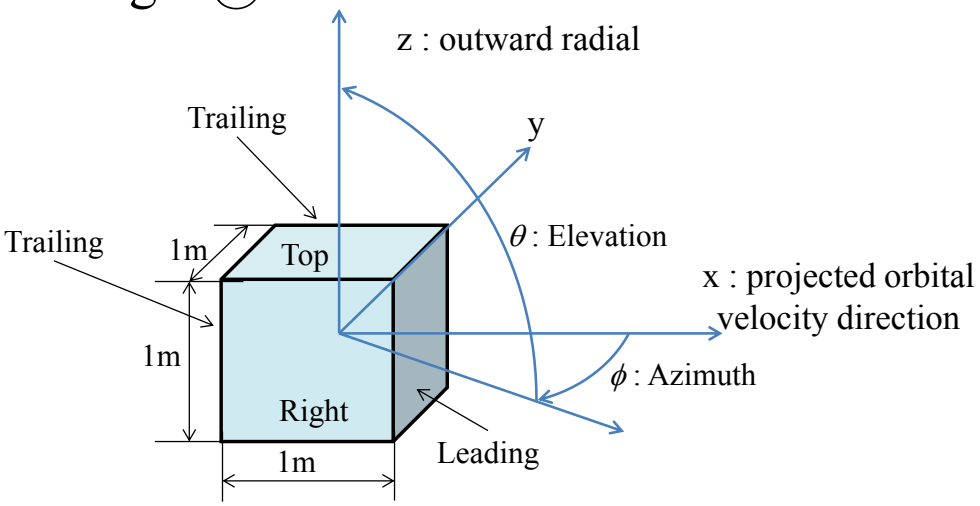
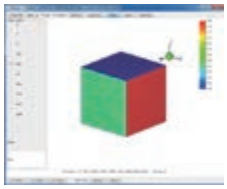
BLE Validation(2)

- Cube, $(1\text{m})^3$
- Damaged@1cm<d



BLE Validation(3)



- Direction vector of debris flux

$$\mathbf{v}_{debri} = \begin{pmatrix} \cos\theta\cos\phi \\ -\cos\theta\sin\phi \\ \sin\theta \end{pmatrix}$$

- Normal vectors of the cube surfaces

Name	Nomal Vector
Leading	(1,0,0)
Trailing	(-1,0,0)
Left	(0,1,0)
Right	(0,-1,0)
Top	(0,0,1)
Bottom	(0,0,-1)

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BLE Validation(4)

- Collision Probability for unit time

$$P_{\text{collision}} = \sum_{0<\mathbf{V}_{debri}\cdot\mathbf{V}n} \mathbf{V}_{debri}\cdot\mathbf{V}\text{n}\times flux$$

- For Damage Probabillity, including ”condition”,

$$P_{\text{damage}} = \sum_{\substack{0<\mathbf{V}_{debri}\cdot\mathbf{V}n \\ if\ contidion=true}} \mathbf{V}_{debri}\cdot\mathbf{V}\text{n}\times flux$$

BLE Validation(5)

- Result

	MASTER2009 +MS-Excel©	**TURANDOT**
Leading	9.95E-09	9.95E-09
Trailing	1.21E-12	1.21E-12
Left	1.24E-09	1.24E-09
Right	5.62E-09	5.62E-09
Top	5.49E-12	5.49E-12
Bottom	3.04E-11	3.04E-11

  - Good agreement

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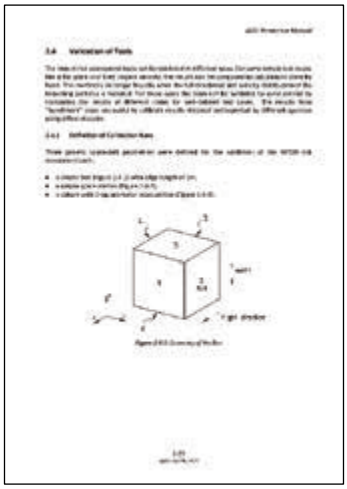
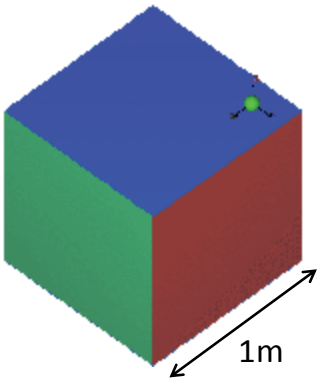
Validation

- IADC（Inter-Agency Space Debris Coordination Committee）Benchmark

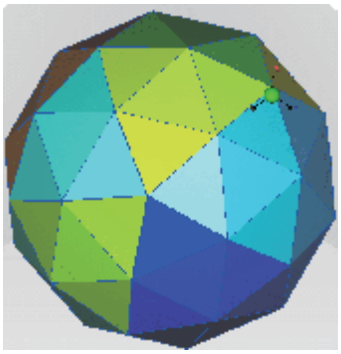


IADC Benchmark

1) Cube

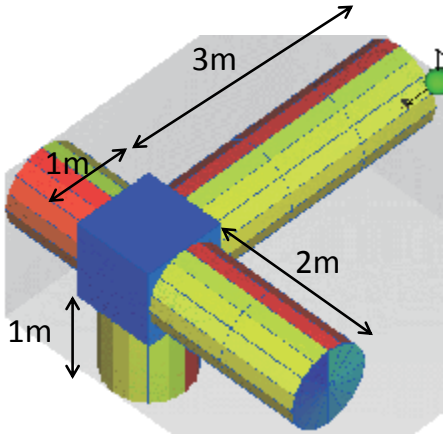


2) Sphere



Cross section 1m^2

3) Station



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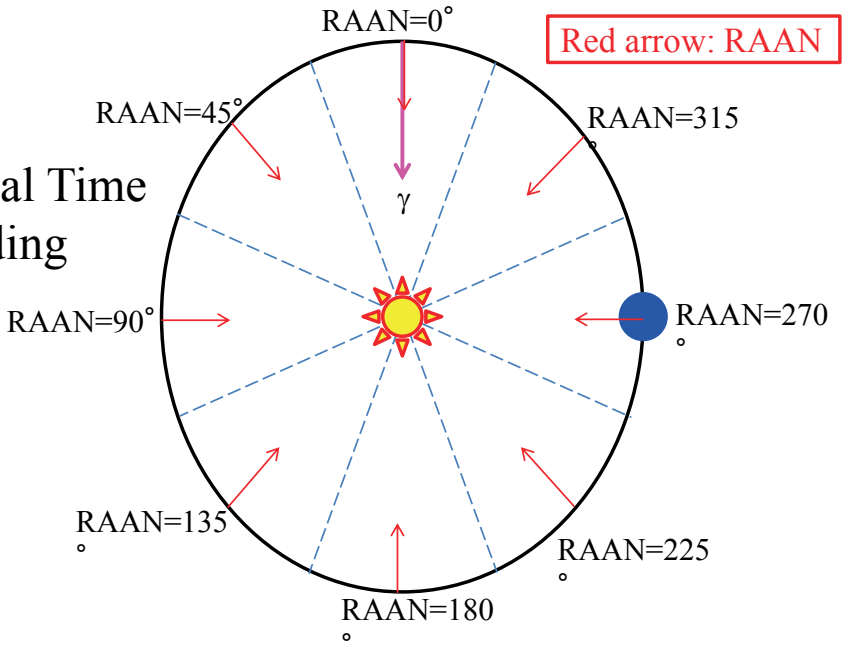
Orbit Parameter Input Support (1)

- Example:
  - SSO
  - 12:00 Local Time on Ascending



Result

- 2014/01/01~2014/12/31
- Solar Oriented, Cube of $1m^3$
- 1.E-5m < d

	W/O division	8 division	24 division
+X	108	110	105
-X	104	98	93
+Y	109	186	189
-Y	109	180	184
+Z	225	159	159
-Z	224	159	158

- Considerable difference

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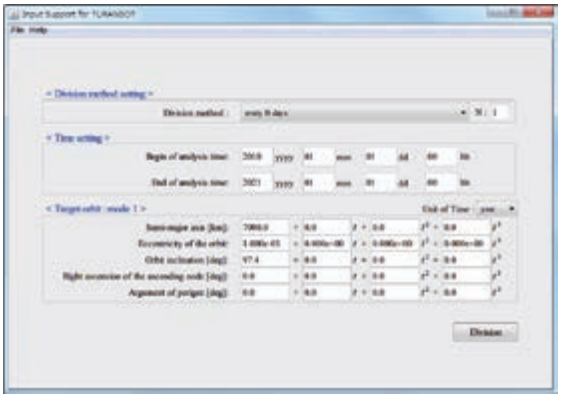
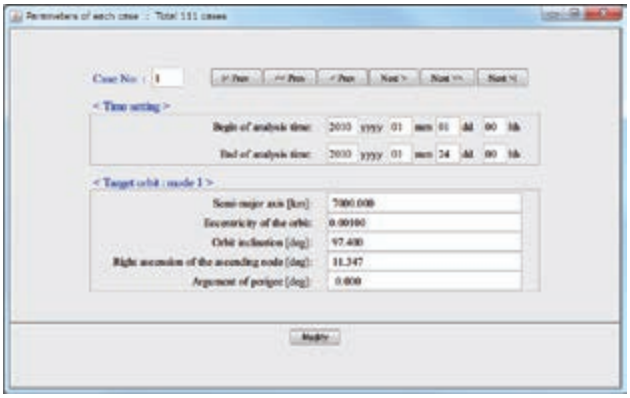
Orbit Parameter Input Support (2)

- Automatic generation of input parameter





Conclusion

- Validations and benchmarks are conducted.
- Modifications according to the results and users' opinion.
- New assistant functions.

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H3

超高速衝突耐性を持つ宇宙服積層構成の評価

Hypervelocity Impact Protective Lay-up Evaluation for Spacesuit

○川瀬 暁, 青木 伊知郎, 和田 理男, 金子 祐樹, 山口 孝夫 (JAXA)
○Satoru KAWASE, Ichiro AOKI, Yoshio WADA, Yuki KANEKO,
Takao YAMAGUCHI (JAXA)

JAXA 有人宇宙ミッション本部では、将来の有人宇宙活動に必要な要素技術の一つとして、船外活動用の宇宙服を研究している。宇宙服の重要な役割は、宇宙環境から人体を保護して安全を確保することである。特に、超高速で飛来する微小隕石やスペースデブリ(MMOD:Micro-Meteoroid and Orbital Debris)に対する防護機能は、宇宙服の安全性を決定する重要な要素である。宇宙服生地の積層構成を設定するために、複数の候補生地について超高速衝突試験を実施し、耐性を評価した。対象は、高強度繊維織布を最外層とし、宇宙服内外を断熱する蒸着フィルム等を積層した生地で、層間の一部に空隙を設けた。二段式軽ガス銃を用いて、直径 0.6mm のアルミ球を秒速 6.8km で正面衝突させ、貫通有無をマイクロスコープで観察した。その結果、宇宙服生地として有効な超高速衝突耐性を持つ積層構成を得た。

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超高速衝突耐性を持つ宇宙服積層構成の評価

JAXA有人宇宙ミッション本部
○川瀬 暁、青木 伊知郎、和田 理男、金子 祐樹、山口 孝夫

2014年12月19日
第6回　スペースデブリワークショップ

JAXA次世代先端宇宙服

- 将来の有人宇宙活動に向けてJAXAが研究する船外活動服
- スーツ本体を目的の異なる3つのASSYで構成
  （冷却下着・気密拘束層・断熱防護層）
- ジョイント部以外は繊維生地（軽量・コンパクト）

次世代先端宇宙服（スーツ本体）の構成

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試験の目的

断熱防護層の積層構成案を設定するため

― 積層候補の超高速衝突耐性を米国宇宙服（EMU）と比較

＜積層候補＞

- 防護層…芳香族ポリエステル織布
  （糸の太さ　1110dtex　または　1670dtex）
- 断熱層…アルミ蒸着ポリエステルフィルム＋ポリエステルメッシュ
- 摺動層…ナイロン織布
- 放射線遮蔽材…タングステンシート（基材：不織布）

EMU　：Extravehicular Mobility Unit
dtex　：糸の太さの単位。糸の長さ10kmあたりの質量（グラム）を示す。

試験条件

EMUの貫通限界の試験条件※にもとづき、試験条件を設定

JAXA宇宙服と米国宇宙服（EMU）の試験条件

	JAXA宇宙服	（米国宇宙服 EMU）
飛翔体	アルミ球 直径 0.6 mm	アルミ球 直径 0.6 mm
衝突速度	目標 6.8 km/s	6.71 km/s
衝突角度	正面衝突	正面衝突
貫通判断	気密層（最終層）をマイクロスコープ（50倍）で観察し、孔がある。 ⇒ 貫通と判断	①Witness plate（アクリル板）に衝突痕がある。 ②2 psiで気密層に漏洩がある。 ⇒ 貫通と判断

※Thomas D.Chase et.al. Extravehicular Mobility Unit Penetration Probability from Micrometeoroids and Orbital Debris – Revised Analytical Model and Potential Space Suit Improvements,2007,HVIS 07-138

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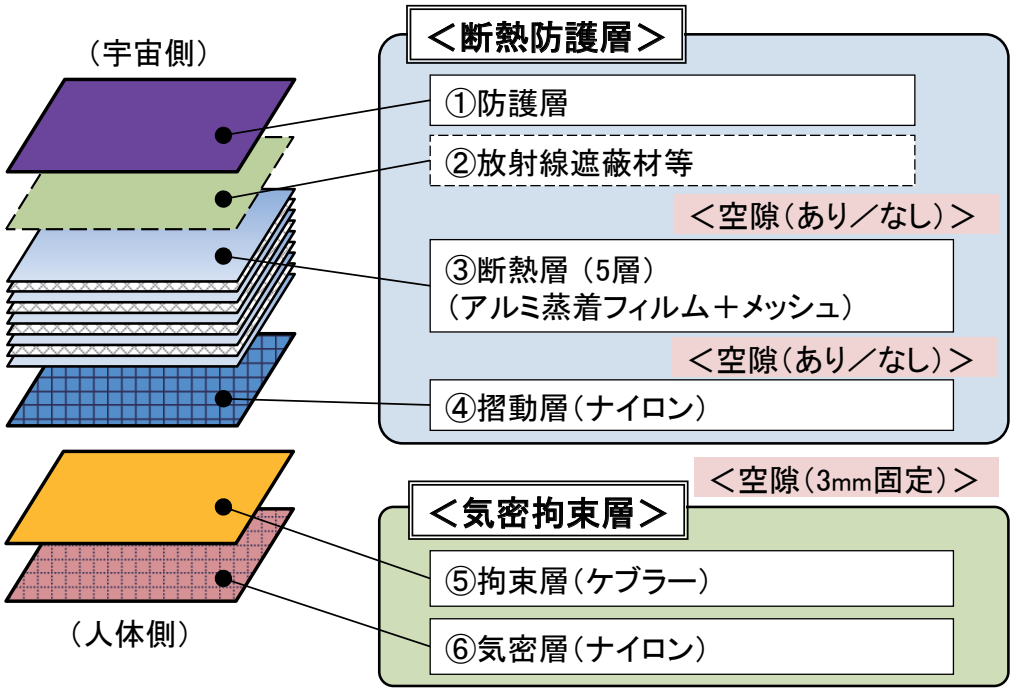
積層構成



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供試体

No	断熱防護層							気密拘束層	
	①防護層	②放射線遮蔽材等	空隙	③断熱層	空隙	④摺動層	空隙	⑤拘束層	⑥気密層
1	1110dtex	なし	なし	5層	なし	（ポリカーボネートコート付）ナイロン織布	3mm	ケブラー織布	（ポリウレタンコート付）ナイロン織布
2	1670dtex	なし	なし		なし				
3	1110dtex	なし	3mm		3mm				
4	1670dtex	なし	3mm		3mm				
5	1110dtex	防護層と同一	なし		なし				
6	1110dtex	タングステンシート	なし		なし				

防護層：芳香族ポリエステル織布

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各層の物性(1/2)

		防護層		放射線遮蔽材	断熱層	
素材		芳香族ポリエステル		タングステンシート	アルミ蒸着付ポリエステルフィルム	ポリエステルメッシュ
繊度 [dtex]		1110	1670	—	—	84
面密度 [g/m²]		276	503	867	—	56 /枚
厚さ [mm]		0.46	0.74	0.35	0.009 /枚	0.31 /枚
繊密度 [本/inch]	たて	30	37	—	—	15ﾒｯｼｭ/inch
	よこ	30	37	—	—	18ﾒｯｼｭ/inch
繊組織等		平織	平織	不織布	フィルム	ネット
引張強さ [N/3cm]	たて	7750	11300	370	—	—
	よこ	8790	14900	340	—	—
引裂強さ [N/10cm]	たて	1820	4860	3	—	—
	よこ	2200	5370	4	—	—
分解温度(融点) [℃]		450 以上		—	260 (PET) 660 (ｱﾙﾐ)	260
比熱 [J/(kg･K)]		1420 @100℃		—	1250 (PET)	1250

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各層の物性(2/2)

		摺動層	拘束層	気密層
素材		ナイロン織布 (ﾎﾟﾘｶｰﾎﾞﾈｰﾄｺｰﾄ付)	ケブラー織布	ナイロン織布 (ﾎﾟﾘｳﾚﾀﾝｺｰﾄ付)
繊度 [dtex]		56	670	460
面密度 [g/m²]		149	184	229
厚さ [mm]		0.13	—	—
繊密度 [本/inch]	たて	151	34	48
	よこ	112	33	46
繊組織等		平織	平織	平織
引張強さ [N/3cm]	たて	600	4440	3410
	よこ	400	5320	3090
引裂強さ [N/10cm]	たて	9	1290	350
	よこ	7	1070	370
分解温度(融点) [℃]		265 (ﾅｲﾛﾝ) 250 (PC)	427-482	265 (ﾅｲﾛﾝ)
比熱 [J/(kg･K)]		1675 @25℃ (ﾅｲﾛﾝ)	2010 @100℃	1675 @25℃ (ﾅｲﾛﾝ)

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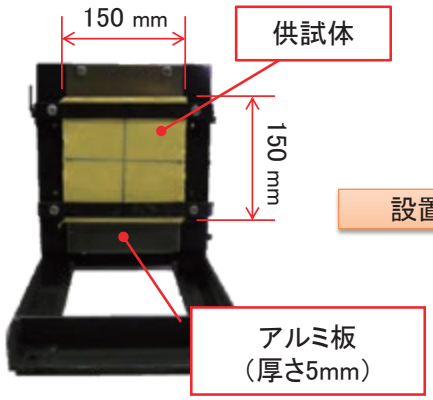
試験コンフィギュレーション

- 150mm角に裁断し積層した供試体を
  背面にアルミ板を取付けた供試体固定治具に固定
- 空隙は、層間の端面に平ゴム（厚さ3mm）を挿入



（供試体固定治具）

（JAXA二段式軽ガス銃）

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試験結果

No.	衝突速度 [km/s]	衝突エネルギー [J]	衝突エネルギー 対EMU※	貫通 非貫通	備考
1	6.89	7.24	105%	貫通	防護層：1110dtex
2	6.79	7.03	102%	貫通	防護層：1670dtex
3	6.86	7.18	104%	貫通	防護層：1110dtex 断熱層前後に空隙あり
4	6.85	7.17	104%	非貫通	防護層：1670dtex 断熱層前後に空隙あり
5	6.83	7.12	104%	貫通	防護層：1110dtex×2層
6	7.03	7.53	110%	非貫通	防護層：1110dtex 放射線遮蔽材あり

対EMU：EMUの貫通限界における衝突エネルギー6.87J（直径0.6mmアルミ球、速度6.71km/s）を100とした相対比。

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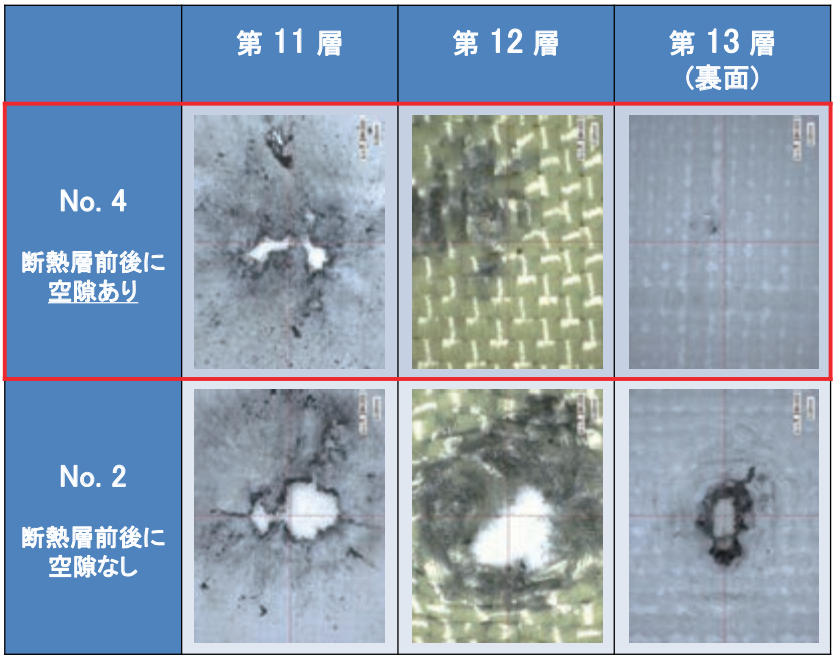
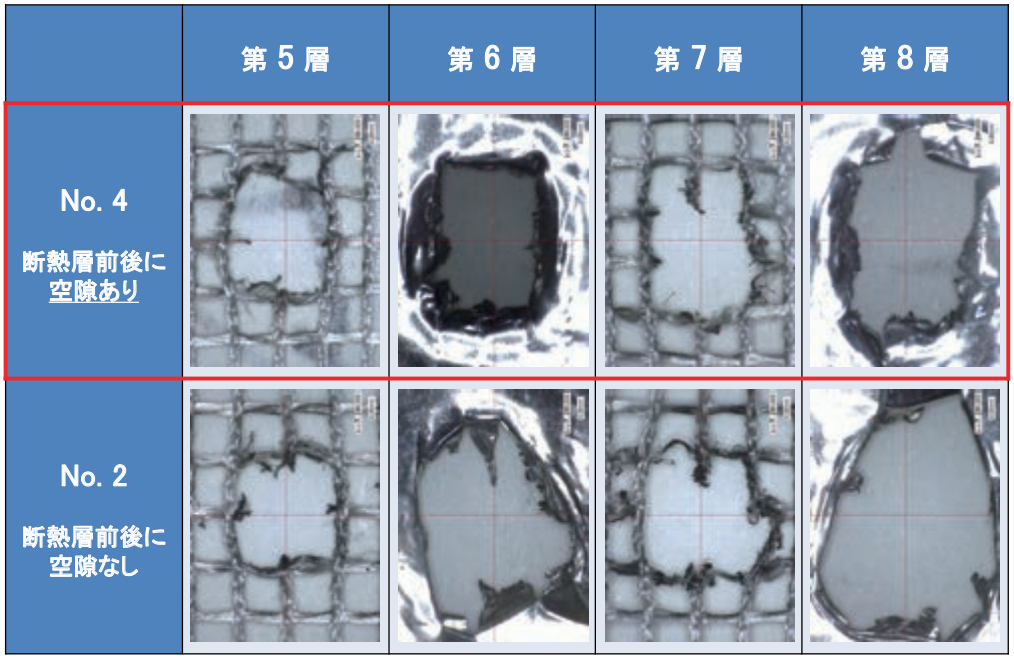
試験後の供試体（11～13層）



撮影時の倍率：50倍

10

試験後の供試体（5～8層）



撮影時の倍率：50倍

11

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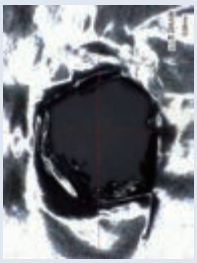
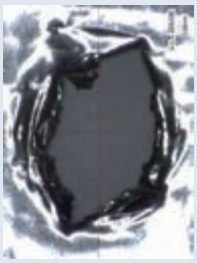
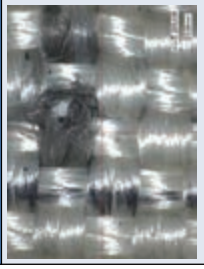
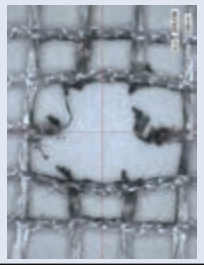
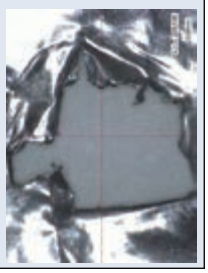
試験後の供試体（1～4層）

	第１層	第２層	第３層	第４層
No. 4 断熱層前後に 空隙あり				
No. 2 断熱層前後に 空隙なし				

撮影時の倍率：50倍

12

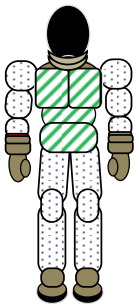
結論

米国宇宙服（EMU）と同等以上の超高速衝突耐性を有する
以下の構成を断熱防護層の積層構成案に設定する

**芳香族ポリエステル織布（1670dtex）を防護層とし、
断熱層の前後に空隙を有する積層構成**

ただし、放射線遮蔽が特に必要な胴周りや股間部等には
以下の積層構成案を設定する

芳香族ポリエステル織布（1110dtex）を防護層とし、
第2層に放射線遮蔽材を有する積層構成



防護層：芳香族ポリエステル1110dtex
第2層：放射線遮蔽材あり

防護層：芳香族ポリエステル1670dtex
放射線遮蔽材なし

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H4

微小デブリ衝突に関する研究の状況と課題

Research Status and Action of Sub-millimeter Debris Impact Damage on Spacecraft Structure

○東出真澄, 黒崎裕久, 長谷川直（JAXA）
○Masumi Higashide, Hirohisa Kurosaki, Sunao Hasegawa (JAXA)

衛星の設計時にデブリ衝突リスクを識別する必要があるが、直径 1 mm 以下の微小デブリ衝突に関する研究例は少ない。そこで JAXA では、微小デブリに対する衛星構造材料の耐デブリ衝突性能や、その防御方法について研究してきた. 本発表ではハニカムサンドイッチパネルの耐デブリ衝突性能について報告する。ハニカムサンドイッチパネルに、ISAS の所有する二段式軽ガス銃で衝突試験を実施した。直径 0.2 mm 以上のデブリはパネルを貫通することがわかった。また、斜め衝突の場合にはハニカムコアがデブリ防御の効果を持つこともわかった。

To assess debris impact risk for the satellite, submillimeter debris impact damage has not been investigated enough to conduct satellite protective designing. JAXA is researching vulnerability of satellite structure materials against submillimeter debris impact, and proposing shielding methods. This report shows summary of submillimeter impact damages of honeycomb sandwich panels. The damage of the panel was investigated by hypervelocity impact experiments with the two-stage light gas gun in ISAS. Debris larger than 0.2 mm went through the panel. In oblique impact experiments, the honeycomb core acted like multi-layer bumper.

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Research Status and Action of Sub-millimeter Debris Impact Damage on Spacecraft Structure

Masumi Higashide
Hirohisa Kurosaki, Sunao Hasegawa
Japan Aerospace Exploration Agency

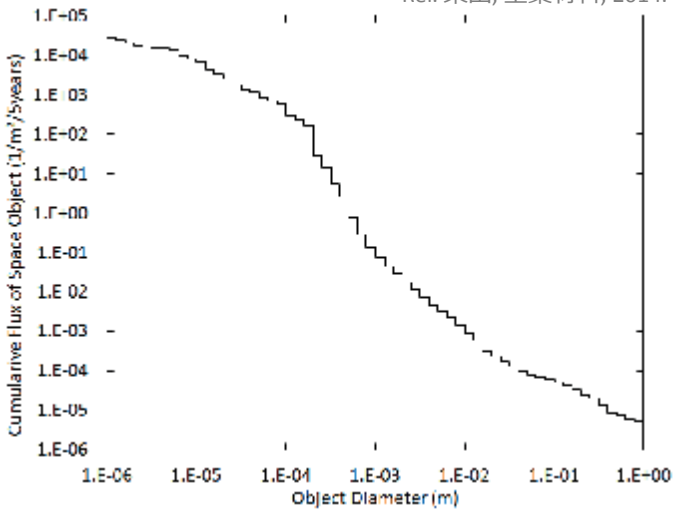
17-19 Dec 2014 第6回スペースデブリワークショップ

Submillimeter Debris

Debris smaller than 1 mm frequently impact on spacecrafts in LEO.

Risk assessment for submillimeter debris impact should be carried out before launch to protect mission-critical components.

Ref. 東出, 工業材料, 2014.



calculated by MASTER-2009 (Alt.=700km, Inc=98°)

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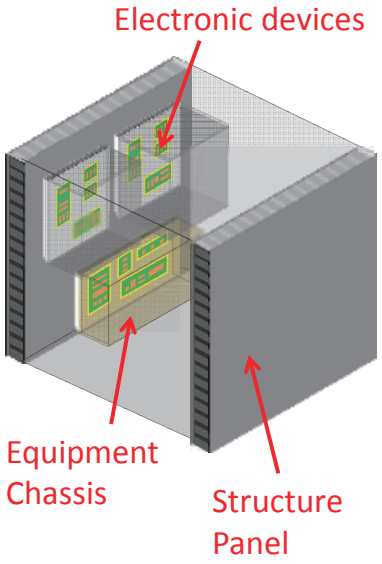
Mission Critical Components

Many important components are installed on the interior surfaces of structure panels.

Electronic devices are usually mounted in an aluminum chassis.

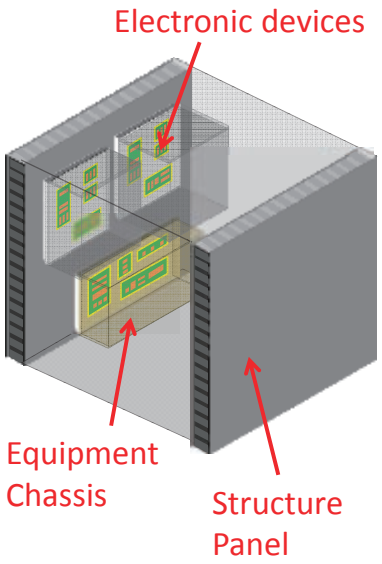
To assess the debris impact risk, it is necessary to know a damage limit of a chassis behind a structure panel.



Purpose of this study

To investigate damage of structure panel and internal equipment chassis

1. Ballistic limit of structure panel
2. Ballistic limit of equipment chassis' wall behind the structure panel
3. Detached spall of the chassis' wall behind the structure panel
4. Oblique impact effect



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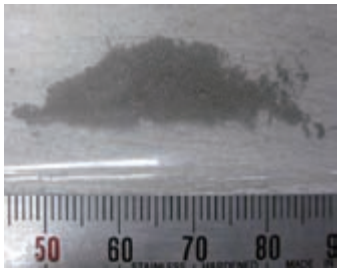
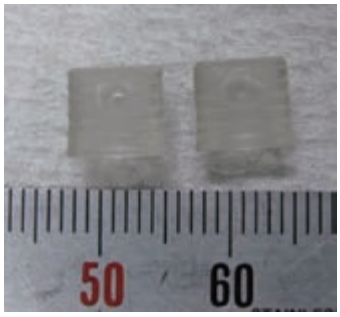
Hypervelocity Impact Experiment

two-stage light gas gun of ISAS/JAXA

projectiles (Steel, f0.3mm)



sabot



Experimental Conditions

Honeycomb Sandwich Panel
Skin: A2024, t=0.25mm
Core: A5056, h=25.4mm,
Cell Size=6.35mm,
Foil=18μm

6 km/sec

Projectile
Steel Sphere,
d_p=0.15, 0.3, 0.5, 0.8, 1.0mm

Steel was used as projectile material to simulate the impact pressure caused by alumina at 9 km/sec.

Aluminum Alloy Plate
A2024-T3

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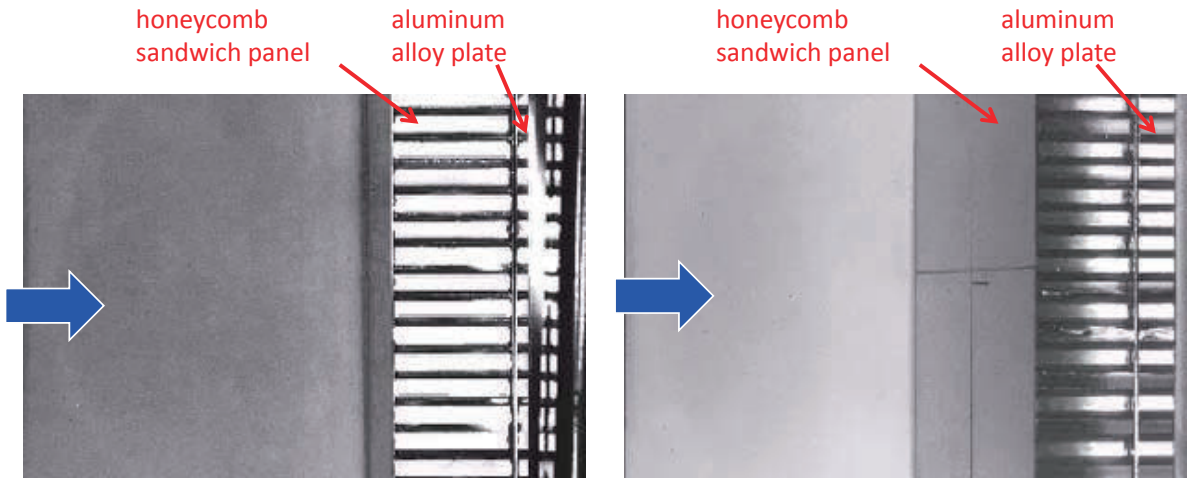
Hypervelocity Impact Experiments



d_p=0.3mm, 5.9km/sec

d_p=1.0mm, 5.9km/sec

Results (1)

Projectile: d_p=0.15mm, Impact velocity: 5.8km/sec

Front Back A2024 plate

Projectiles of 0.15mm do not perforate the honeycomb sandwich panel.

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Results (2)

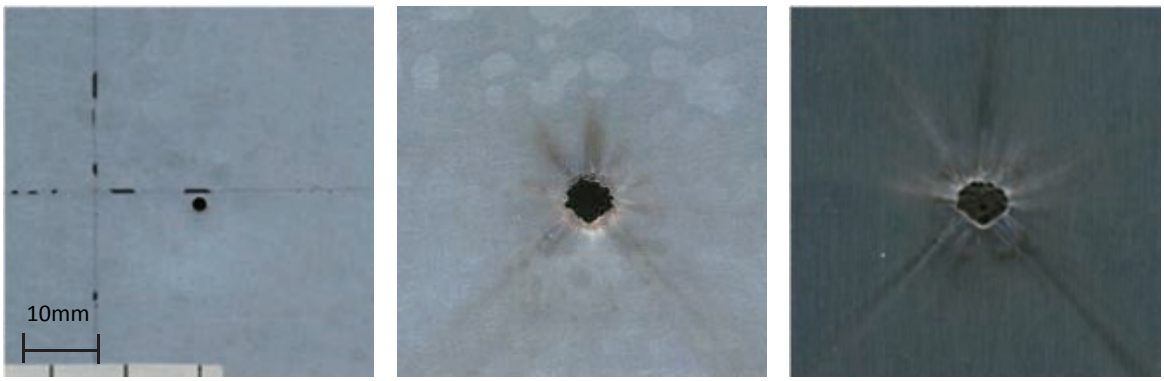
Projectile: d_p=0.3mm, Impact velocity: 5.9km/sec

Front Back A2024 plate

Projectiles changed into fragment clouds by impacts on the front face sheet.

Results (3)

Projectile: d_p=1.0mm, Impact velocity: 5.9km/sec



Front Back A2024 plate

The fragment cloud was restricted in the impacted honeycomb cell.

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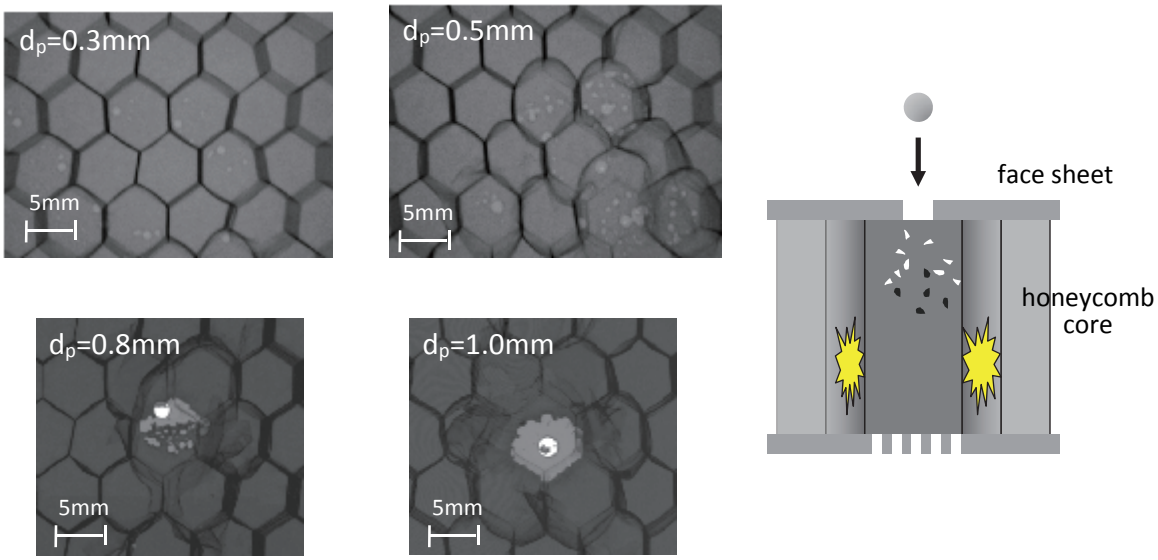
X-ray Radiographs



Honeycomb foil act as bumpers for fragment cloud.

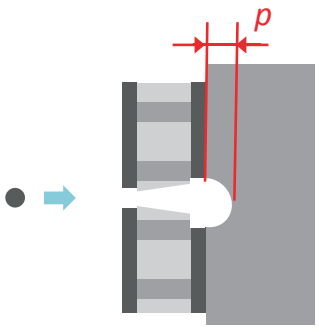
Crater Depth Equation

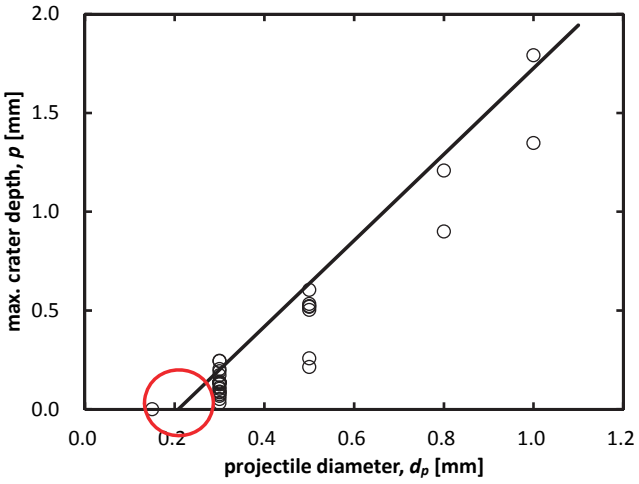
Crater depth equation

$$p \leq 2.18 d_p - 0.454$$

p : Crater depth on witness plate (mm)

d_p : Projectile diameter (mm)





d_p=0.21mm is ballistic limit of the honeycomb sandwich panel

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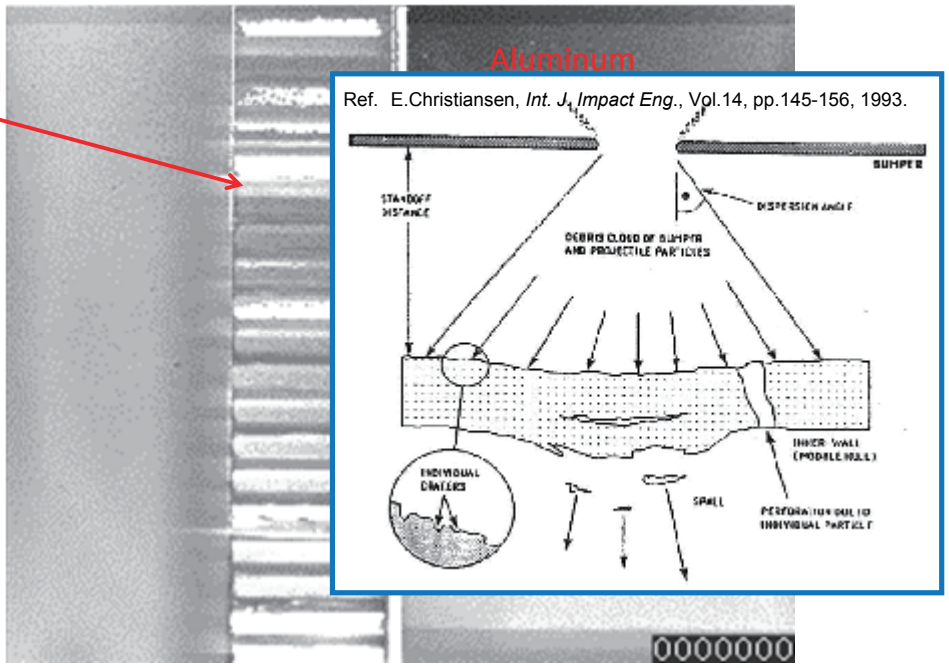
Detached Spall

Honeycomb sandwich panel

Aluminum

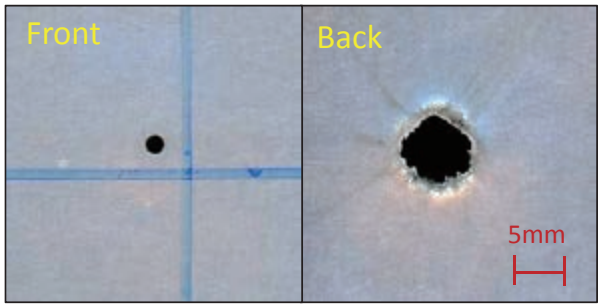


d_p=1.0mm
t_w=**2.0mm**
v_p=6.29km/s

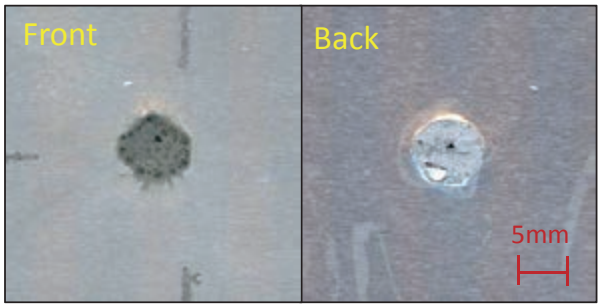
Spall Result

Projectile: d_p=1.0mm, Impact Velocity: 6.29km/sec, Plate Thickness: 2.0mm

Honeycomb Sandwich Panel



Aluminum Plate



The aluminum plate was penetrated due to cratering and spalling. This condition was considered as ballistic limit of the set of the honeycomb sandwich panel and the A2024 plate.

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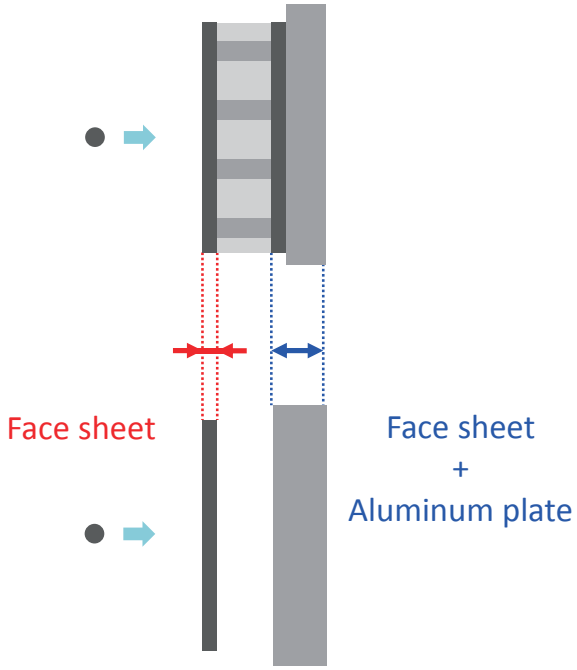
Effect of Spall Damage

The ballistic limit thickness of the second wall of double-wall structure is proportional to the crater depth on the second wall with semi-infinite thickness.

Target set can be simplified double-wall structure.

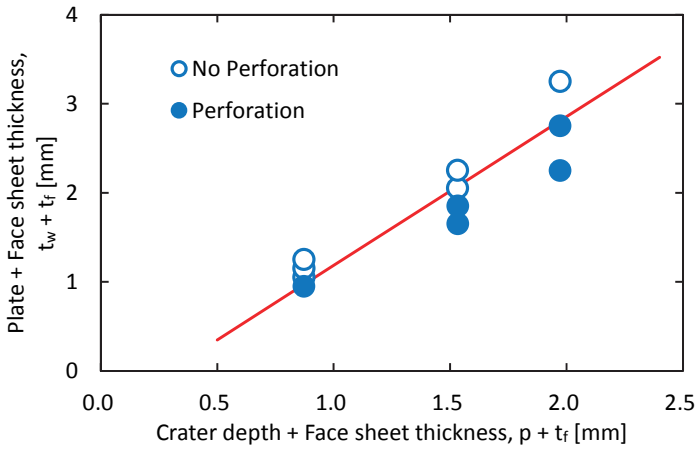


Ballistic Limit Equation

2nd wall → Face sheet + AL plate

Crater on 2nd wall
→ Face sheet
+ Crater on the AL plate

$$(t_c+t_f) = 1.67\,(p+t_f) - 0.486$$
$$\boldsymbol{t_c = 3.67d_p - 1.12}$$



d_p: Projectile diameter (mm)
t_c: Critical thickness of aluminum plate (mm)
t_f: Thickness of front face sheet (mm)
p: Crater depth on aluminum plate (mm)

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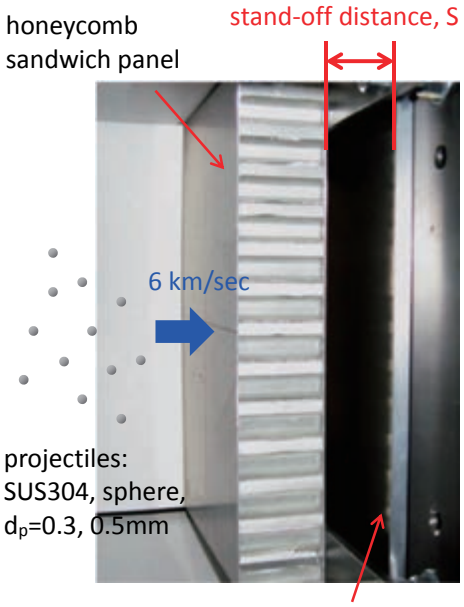
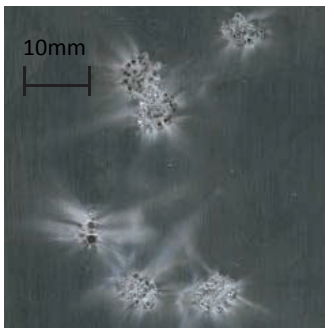
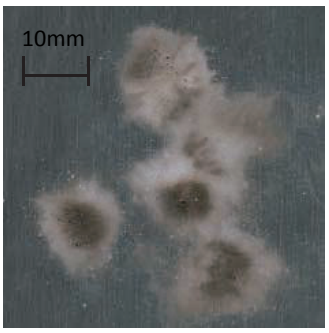
Effects of Stand-off Distance





d_p=0.5mm, S=0mm



d_p=0.5mm, S=10mm

Debris cloud generated by a honeycomb sandwich panel was dispersed in stand-off spacing.

Crater Depth

projectile diameter	maximum crater depth [mm]			
	no gap	stand-off 10mm	stand-off 50mm	stand-off 100mm
0.3mm	0.24	0.20	0.05 >	0.05 >
0.5mm	0.57	0.46	0.05 >	0.05 >

When stand-off distances were larger than 50mm, crater depths were unmeasurable because the depths were smaller than 0.05mm.

The crater depths were reduced by 15-20% by keeping the stand-off distance 10mm.

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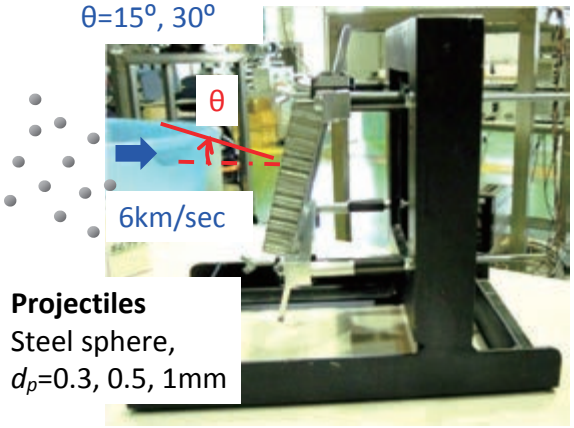
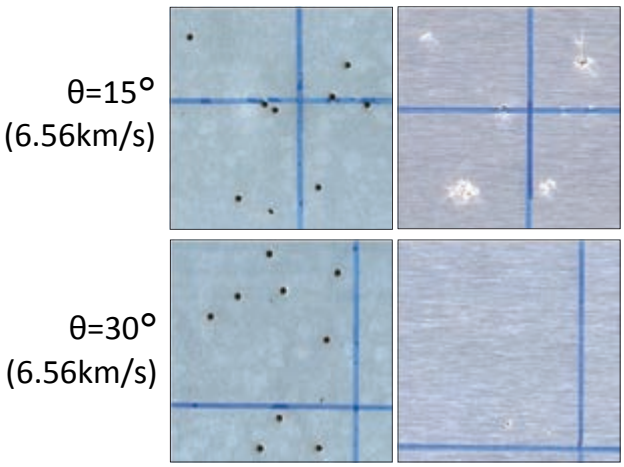
Oblique Impact Experiment

Impact angle
θ=15°, 30°



Projectiles
Steel sphere,
d_p=0.3, 0.5, 1mm

Results of d_p=0.5mm



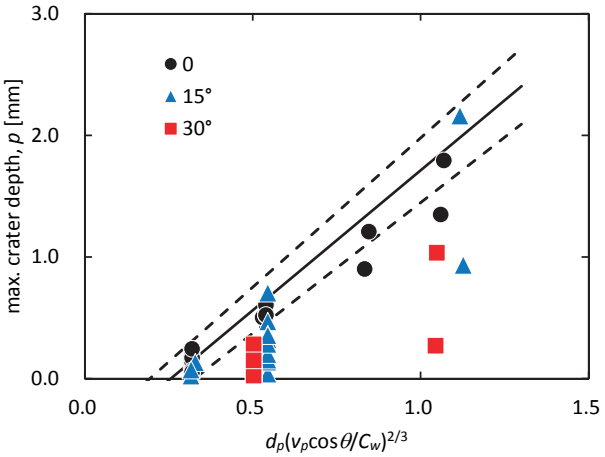
Damage to the back face sheets and witness plate became smaller at larger impact angles.

Crater Equation with Impact Angle Effect

The impact energy was assumed to be proportional to the crater volume.

$$p \geq 2.30 d_p \left(v_p \cos\theta / C_w\right)^{2/3} - 0.588$$

d_p: Projectile diameter (mm)
p: Crater depth on aluminum plate (mm)
v_p: Impact velocity (km/s)
C_w: Sound speed in witness plate (km/s)
θ: Impact angle



The results of θ=30°were much less than the upper limit

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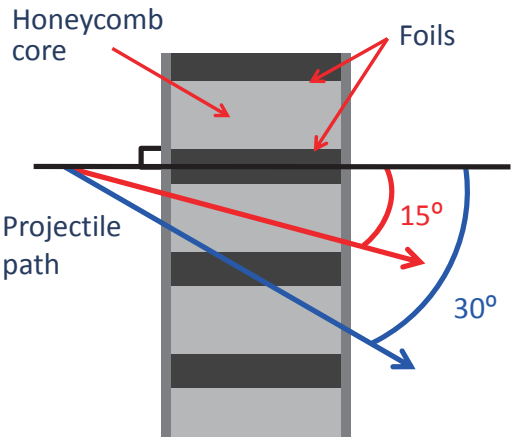
Effect of Honeycomb Foils



θ=15°: Some projectiles do NOT paths through foils.

θ=30°: Projectiles always impact on the foils.

When the impact angle is less than 16.1°, there are some paths through no foils

If θ >16.1°, the upper limit of the maximum crater depth is considered lower than the equation.

Summary

To investigate damage of structure panel and internal equipment chassis, sets of a honeycomb sandwich panel and an aluminum witness plate (chassis' wall) were tested.

Ballistic limit of the honeycomb sandwich panel was estimated by the crater depth equation of the witness plate.

The ballistic limit equation of chassis' wall was developed from crater depth equation and detached spall limit data.

The crater depth equation was considered with the assumption that the impact energy was proportional to the crater volume. The equation is applicable when the impact angle is less than 16.1°.

This document is provided by JAXA.

Acknowledgement

The work was supported by the Space Plasma Laboratory, ISAS, JAXA.

The authors acknowledge the valuable advice given by members of JAXA Spacecraft Design Standard WG3.

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1) M. Higashide, N. Onose, and S. Hasegawa, “Evaluation of Space Debris Impact on Spacecraft Structure Panels,” *Trans. Japan Society for Aeronautical and Space Sciences, Aerospace Tech. Japan*, vol. 10, no. ists28, pp. Pr_1–Pr_6, 2012.

2) 東出 真澄, 小野瀬 直美, 長谷川 直, “スペースデブリ衝突による無人宇宙機構体パネルの損傷限界評価,” 第7回構造物の安全性・信頼性に関する国内シンポジウム論文集, pp. 571–575, 2011.

3) M. Higashide, N. Onose, and S. Hasegawa, “SUBMILLIMETER DEBRIS IMPACT DAMAGE OF UNMANNED SPACECRAFT STRUCTURE WALL,” *Proc. the 13th Japan Int. SAMPE Symposium and Exhibition*, 2013.

4) M. Higashide, N. Onose, and S. Hasegawa, “Sub-millimeter Debris Impact Damage of Unmanned Spacecraft Structure Panel,” *Procedia Eng.*, vol. 58, pp. 517–525, 2013.

5) 東出 真澄, “宇宙機構造材料へのスペースデブリ衝突,” 衝撃の物理と動的材料ワークショップ2010, 2010.

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H5

太陽電池パネルの微小粒子衝突による電気的影響評価

Hypervelocity impact effects of small particles on solar arrays

○川北史朗, 艸分宏昌（JAXA 研開本部 電源 G）, 松本晴久（JAXA 研開本部 環境 G）
○Shirou Kawakita, Hiroaki Kusawake, Haruhisa Matsumoto (JAXA/ARD)

宇宙環境におけるスペースデブリの増加により, 宇宙機の大部分を占める太陽電池パネルへの衝突が懸念されている. 特に, 太陽電池パネルは人工衛星の電力源であることから, 衝突による機械的影響だけでなく電気的影響が心配される. そこで, 発電状態を模擬した太陽電池パネルへの微小粒子衝突試験を行いその影響を評価した. この結果, 衝突によって発電力に若干の低下は見られるが, 衛星グランドとの地絡故障などの大きな低下は確認されなかった. これより, 従来の太陽電池パネル設計においては, 軌道上での微小粒子の衝突は衛星システムにほとんど影響しないことが確認された.

Solar arrays are the satellite component most exposed to micrometeoroid and space debris (MM/SD) impacts. The electrical degradation by hypervelocity impacts (HVI) is characterized by considerable energy released at the impact interface leading to mechanical damage and the generation of plasma on electrical generation condition of the solar arrays. The electricity by solar array had no degradation during and after the impact tests. These results suggest the MM/SD should not effect on the generating power in space.

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第6回 スペースデブリワークショップ
平成26年12月17日～19日　JAXA 調布航空宇宙センター

太陽電池パネルの微小粒子衝突による電気的影響評価

2014/12/19

宇宙航空研究開発機構
研開本部　電源グループ
川北史朗，今泉充，艸分宏昌

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アウトライン

1. 背景と目的
   - ー太陽電池パネルへの微小粒子衝突
   - ー太陽電池の発生電力の1アレイ相当の電力劣化
2. 実験と結果
   - – 微小粒子衝突による太陽電池パネルの短絡故障モード
   - – 太陽電池パネルの微小粒子衝突試験
3. まとめ

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太陽電池パネルの微小粒子衝突

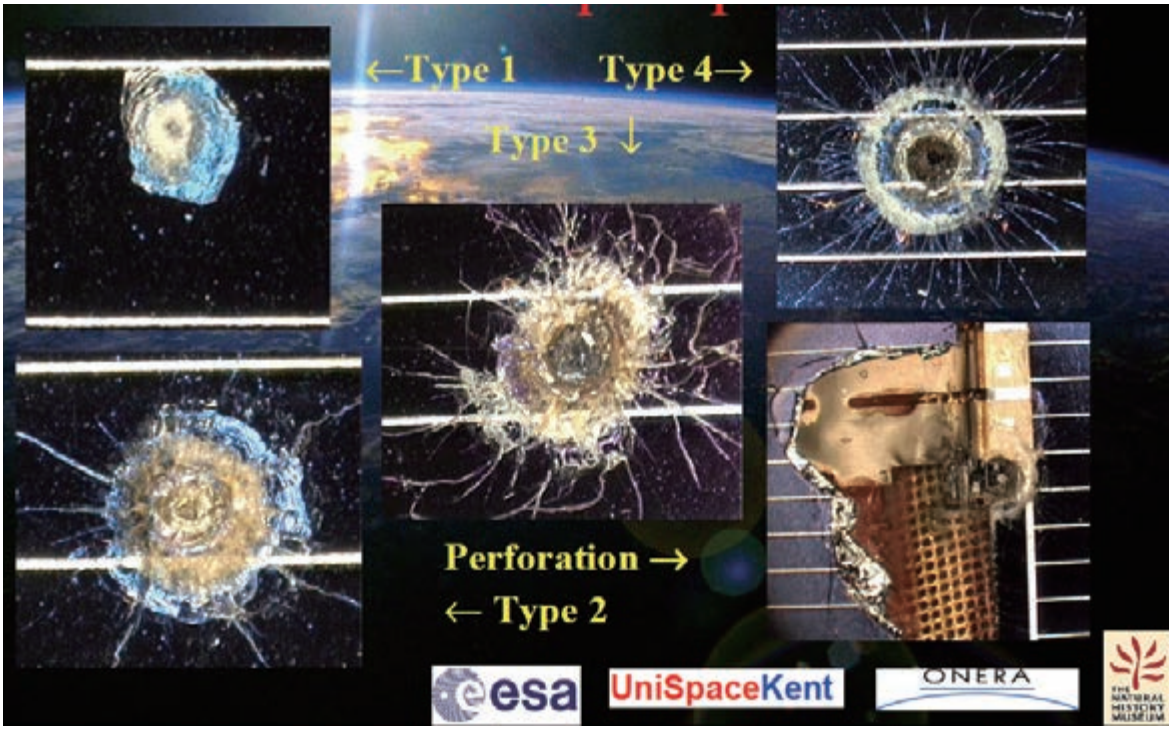
ハッブル宇宙望遠鏡
・軌道：600km，28.5°
・暴露期間：1320日
・パネル面積：42m^2
・電気出力：4.4kW(34Volts)

電気出力の異常劣化（6回）
→太陽電池アレイの地絡故障はなし.

出典：Post-Flight Impact Studies of HST Solar Arrays

4

太陽電池パネルの微小粒子衝突



出典：Post-Flight Impact Studies of HST Solar

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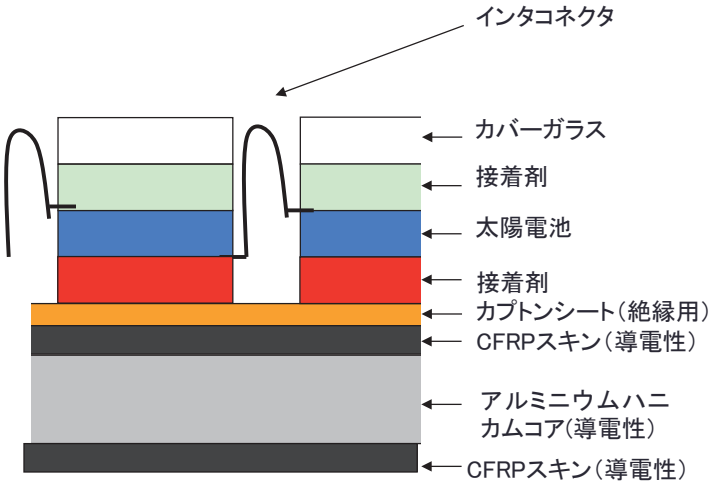
5

太陽電池パネルの微小粒子による影響



太陽電池パネルの構造

短絡/地絡故障モード

1）物理的に，太陽電池と基板とが接触

2）微小粒子衝突によって発生したプラズマを介しての持続放電による故障

3）微小粒子痕を中心とした放電による故障

4）デブリ衝突をトリガーとした雰囲気プラズマ中における放電による故障

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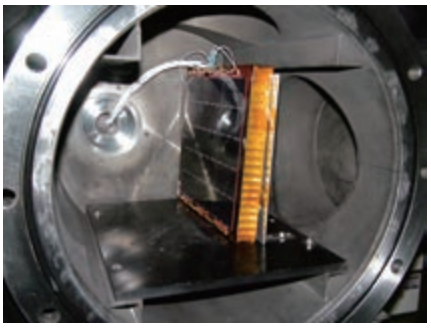
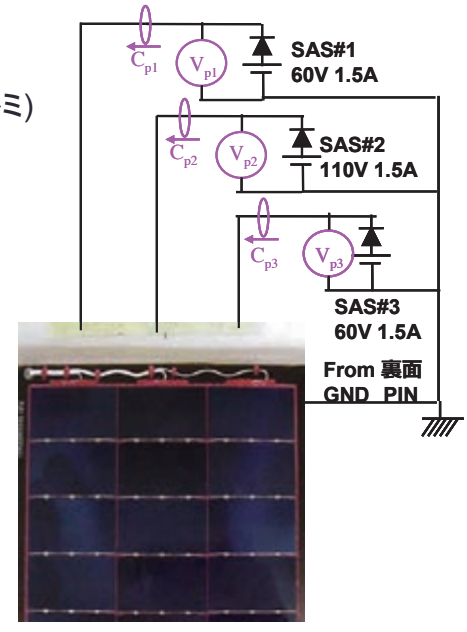
太陽電池パネルの微小粒子衝突試験

試験条件

- 使用装置：2段式軽ガス銃(JAXA/ISAS)
- プロジェクタイル：100,200,500μm（誘電体，アルミ）
- 速度：3～4km/sec
- 電圧印加：60 or 110V
- シリコン太陽電池



衝突試験チャンバー設置



試験回路

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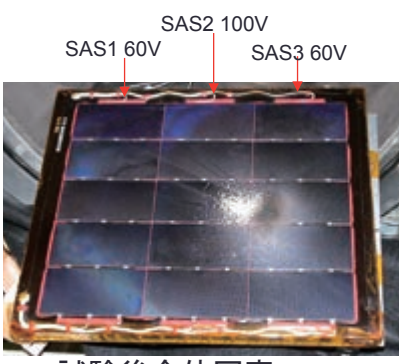
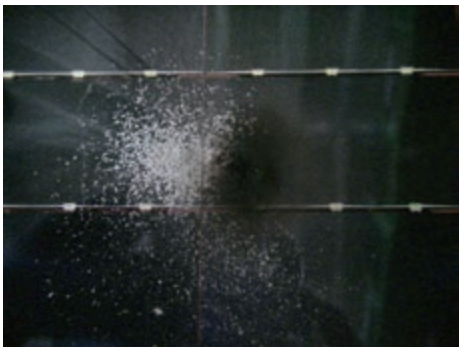
太陽電池パネルの微小粒子衝突試験　結果1

試験結果

- プロジェクタイル　100～125μm　ソーダ石灰ガラス，速度：3.3 km/s
- 多数のデブリ痕が形成される．
- 5msecの2次アーク放電を観察．
- 試験後の電気特性で大きな変化はなし．地絡故障はなし．



試験後全体写真

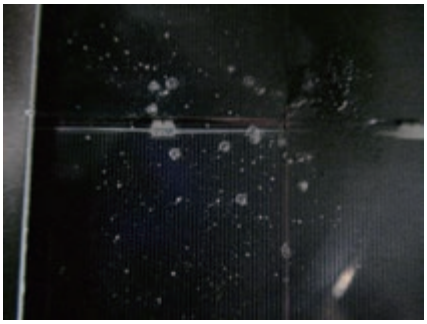

試験後拡大写真

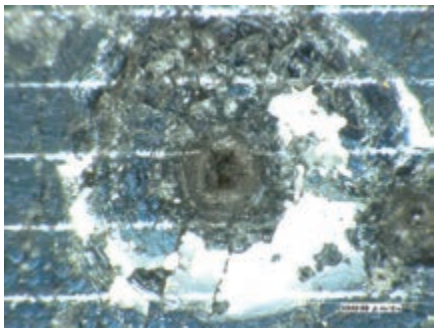
8

太陽電池パネルの微小粒子衝突試験　結果2

試験結果

- プロジェクタイル　175～250μm　ソーダ石灰ガラス，速度：3.3 km/s
- いくつかのデブリ痕が形成される．深さ約300μm．
- 2次アーク放電は観察されず．
- 試験後の電気特性で大きな変化はなし．地絡故障はなし．


試験後拡大写真


光学顕微鏡写真

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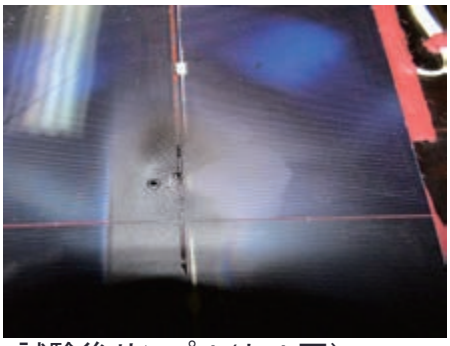
太陽電池パネルの微小粒子衝突試験 結果3

試験結果

- プロジェクタイル 450～600μm アルミナ, 速度:3.3 km/s
- 2つの貫通痕が形成される.
- 2次アーク放電は観察されず.
- 試験後の電気特性で大きな変化はなし. 地絡故障はなし.



試験後サンプル(セル面)

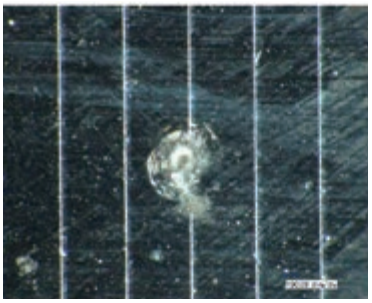
試験後サンプル(裏面)

10

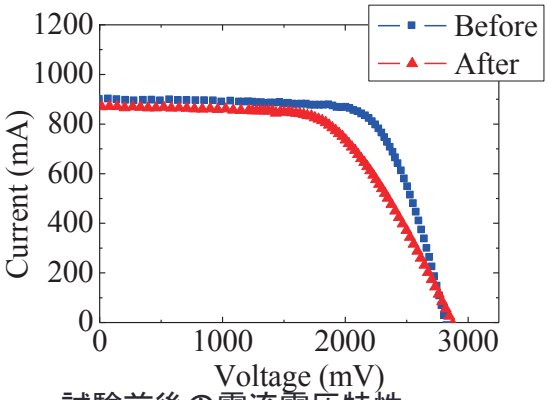
太陽電池パネルの微小粒子衝突試験 結果4

試験結果

- プロジェクタイル 125～150μm アルミ, 速度:3.8 km/s
- いくつかのデブリ痕が形成される.
- 約200msecの2次アーク放電は観察された.(すべて110V印加)
- 試験後の電気特性で大きな変化はなし. 地絡故障はなし.



試験後拡大写真



試験前後の電流電圧特性

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太陽電池パネルの微小粒子衝突試験　結果5

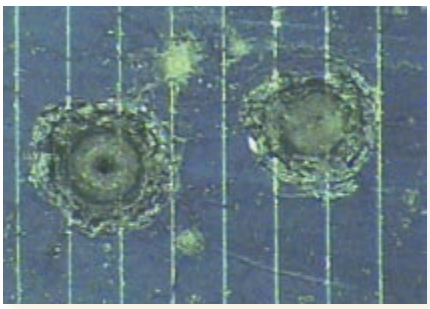
放電試験

デブリ衝突サンプルの電子ビームによる帯電放電試験

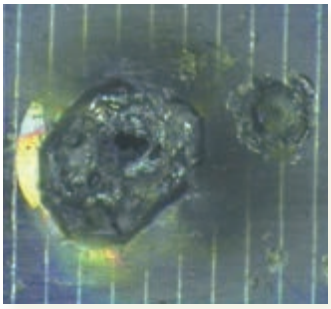
試験結果

- バス電圧110Vまで放電はするが，持続放電に至らず．
- 150V印加時に，200μm径デブリ痕にて持続放電発生．

→ 基板が露出される傷が放電に弱い？（他試験と同じ傾向）



持続放電前



持続放電後

出典：豊田他“デブリ衝突太陽電池パネルの放電試験，第2回宇宙環境シンポジウム(2005.12)

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まとめ

- **太陽電池パネルは，微小粒子衝突による物理的および衝突時の放電損傷による短絡故障には至らなかった．**
- **微小粒子衝突傷への電子線による帯放電試験の結果，150Vのバス電圧において持続放電による短絡故障が発生した．**

以上より，一般的な太陽電池パネルの設計においては，微小粒子の衝突による地絡故障は発生しないことを確認した．

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ポスターセッション

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P01

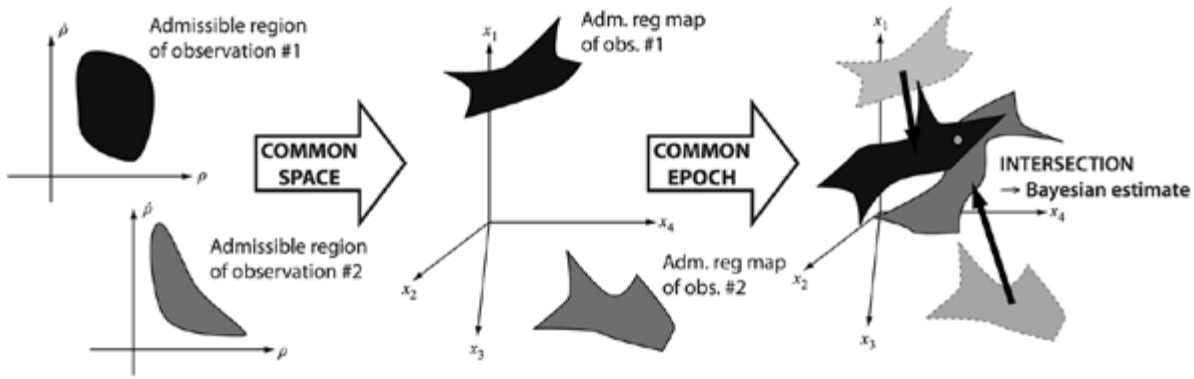
Direct Bayesian Admissible Region 手法による軌道物体追跡の改良

Improvements to Resident Space Object Tracking with the Direct Bayesian Admissible Region Approach

○藤本浩平 (テキサス A&M 大学)
○Kohei Fujimoto (Texas A&M University)

地球周辺の宇宙空間がより過密化し、多国間の競争が激化する中、宇宙状況認識 (SSA) は宇宙を利用するすべての国にとって重要な技能であり続けると考えられる。しかし、観測が希薄であるがゆえ、同定仮定を初期軌道決定の的確さによって判定する従来の方法は、しばしば失敗することが確認されてきた。Direct Bayesian admissible region 手法は、先験的な状態を必要としない、観測同定・初期軌道決定の方法である。経過時間の短い光学観測の弧を元に、観測された物体までの、もっとも可能性の高い距離・距離の変化率の値を含んだ、コンパクト空間を定義することが可能である。Admissible region とは、このコンパクト空間上に定義された連続一様分布である。本研究では、上の手法をベルン大学から提供された実データを元に検証し、新たに 2 つの物体を検出することに成功した。

As space becomes ever more congested, contested, and competitive, space situational awareness (SSA) capabilities will continue to be important for all spacefaring nations. In almost all SSA related tasks, the first step is to track, detect, and identify active satellites, space debris, and other resident space objects (RSOs). Conventional approaches of testing association hypotheses based upon IOD quality, however, can often fail since sparse measurements lead to poor, if not divergent, estimates. The direct Bayesian admissible region approach is an a priori state free measurement association and IOD technique. Given a short-arc series of optical data, or a tracklet, a compact region in the range / range-rate space is defined based on a set of physical constraints such that all likely and relevant orbits are contained within it. The admissible region (AR) is a uniform probability density function (pdf) whose support is this compact region. Multiple ARs may be propagated to a common epoch and an a posteriori pdf directly computed based on Bayes' rule. The proposed approach has been applied to tracklets from a survey of geostationary (GEO) objects taken at the Zimmerwald Observatory of the Astronomical Institute of the University of Bern. Processing a set of 212 tracklets resulted in 20 objects detected; 2 of which are newly detected by the proposed method. Furthermore, it was noted that the direct Bayesian approach would allow one to reevaluate future observational strategies in order to minimize false positive / negative association solutions. As such, this work ultimately aims to “close the loop” on the short-arc optical track association problem by enhancing the survey strategy based on the association results and vice versa.



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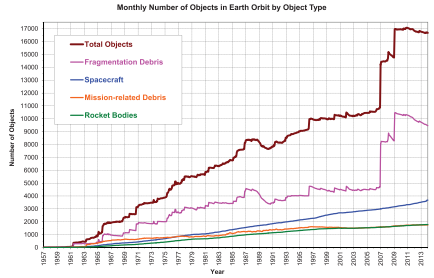
Improvements to Resident Space Object Tracking with the Direct Bayesian Admissible Region Approach

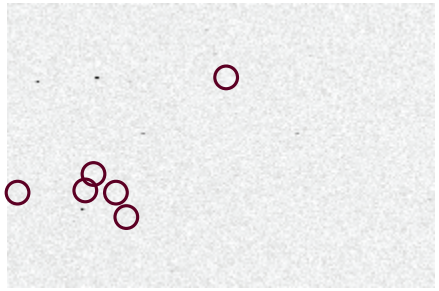
Kohei Fujimoto
Texas A&M University

Space Situational Awareness



Number of tracked objects in the Joint Space Operations Center (JSpOC) public catalog of Earth-orbiting objects [NASA, 2014].

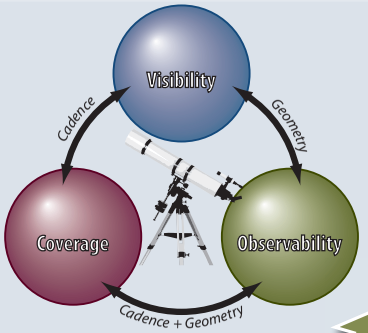
As the Earth-orbiting environment becomes ever more **congested, contested, and competitive**, capabilities to characterize resident space objects (RSOs), or space situational awareness (SSA), is now crucial for all space-faring nations in order to secure reliable access to space.



Typical telescopic negative image of geostationary objects (circled dots) [IHI Corp., Hamane, and Fujimoto, 2012].

Beyond several thousand km in altitude, optical sensors are the workhorse of SSA. Consistent tracking is difficult, however, due to short, sparse measurements and an interdependency between track association and state estimation quality.

To enable the next-generation of RSO surveys, we have been pursuing an integrative approach encompassing both hardware and software research



Current high-altitude RSO surveys are influenced heavily by observer experience and *ad hoc* rules.

*E.g. a survey targeted at objects near opposition will have excellent **visibility** and **coverage**... but poor **observability** due to repetitive geometry*

A systematic and analytic approach of optimizing leak-proofedness, lighting conditions, and orbit determination accuracy will help us better understand the RSO population.

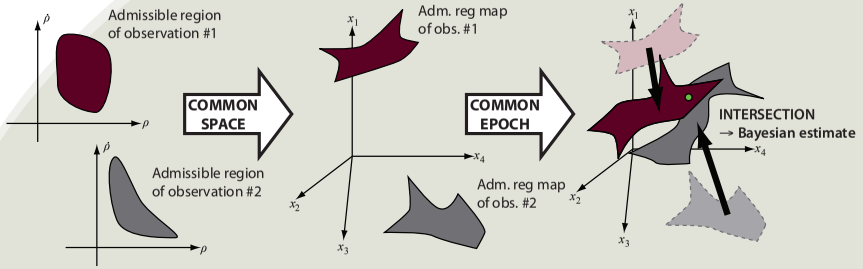
Optical Measurements

Improvement

Application

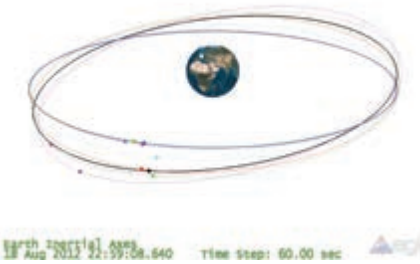
Astrodynamical Tools

Astrodynamical algorithms provide a platform for engineers to make better use of data at hand. As such, advancements in this realm may also be directly fed back into how the measurements are made.



The direct Bayesian admissible region (DBAR) approach, an *a priori* state free measurement association and IOD technique, is one such example. It employs **an exact description of the measurement uncertainty** based on physical constraints, or admissible regions, making it not only computationally efficient but also conducive to topological interpretations of the problem.

Recent Results



3-D representation of geosynchronous objects detected by the DBAR method from two nights of observations (Aug 18-20, 2012) taken at the Zimmerwald Observatory (white dot). Both previously cataloged (dotted line) and uncataloged (bold line) objects are shown.

In collaboration with the Astronomical Institute of the University of Bern (AIUB), the DBAR approach has been used to process 600+ optical tracks, **succeeding in detecting several previously uncataloged objects**. Furthermore, we revealed that their catalog accuracy would be much improved if their survey strategies were designed with explicit consideration of state observability.

Based upon these findings, we recommended a new strategy with enhanced measurement geometry diversity, which AIUB plans to implement in spring 2014.

Selected Publications

Fujimoto, K., Scheeres, D. J., Herzog, J., and Schildknecht, T. "Association of Optical Tracklets From a Geosynchronous Belt Survey via the Direct Bayesian Admissible Region Approach." *Advances in Space Research*, Vol. 53, No. 2, 295 – 398 (2014).

Fujimoto, K., Scheeres, D. J. and Alfriend, K. T. "Analytical Non-Linear Propagation of Uncertainty in the Two-Body Problem." *Journal of Guidance, Control, and Dynamics*. Vol. 35, No. 2, 497 – 509 (2012).

Fujimoto, K. and Scheeres, D. J. "Correlation of Optical Observations of Earth-Orbiting Objects and Initial Orbit Determination." *Journal of Guidance, Control, and Dynamics*. Vol. 35, No. 1, 208 – 221 (2012).

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P02

超高速衝突による飛翔体直径がイジェクタサイズ分布に与える影響

Influence of Projectile Diameter on Size Distribution of Ejecta Resulting from Hypervelocity Impacts

○平岩 泰幸, 石田 魁人, 御代川直人, 西田 政弘 (名工大),
林浩一(鳥羽商船高専), 長谷川直 (JAXA/ISAS)
○Yasuyuki Hiraiwa, Kaito Ishida, Naoto Miyokawa, Masahiro Nishida (Nagoya Institute of Technology),
Koichi Hayashi (National Institute of Technology, Toba College) and Sunao Hasegawa (JAXA/ISAS)

スペースデブリの衝突によって発生する破片(イジェクタ)は二次デブリとなる可能性が高いため, イジェクタの構成や生成メカニズムを知ることは重要である. そこで本研究グループは, アルミニウム合金球をアルミニウム合金厚板に垂直衝突させ, 実験チャンバーから回収したイジェクタについて累積個数分布により求めた結果を用いて, その相似性, 主に飛翔体直径の観点から考察した. 異なる衝突速度および飛翔体直径の結果から, 飛翔体直径が増加するにつれてイジェクタの大きさおよび個数が増加し, 衝突速度が同じ条件下において, 図1に示すように, 飛翔体の直径で規格化すると, イジェクタのサイズ分布は一致した.

Fragments (ejecta) caused by collision of the space debris have the potential to become the secondary debris. It is important to know the composition and the formation mechanism of ejecta. Scaling law of ejecta size, in particular, the effect of projectile diameters was discussed using cumulative number distributions of ejecta size collected from test chamber when aluminum alloy spheres strike perpendicularly aluminum alloy thick plates. From the results of different impact velocities and projectile diameters, the size and number of ejecta increased as projectile diameter. Under the condition of a certain impact velocity, when ejecta length was normalized by projectile diameter, the size distributions of the ejecta were consistent with each other.

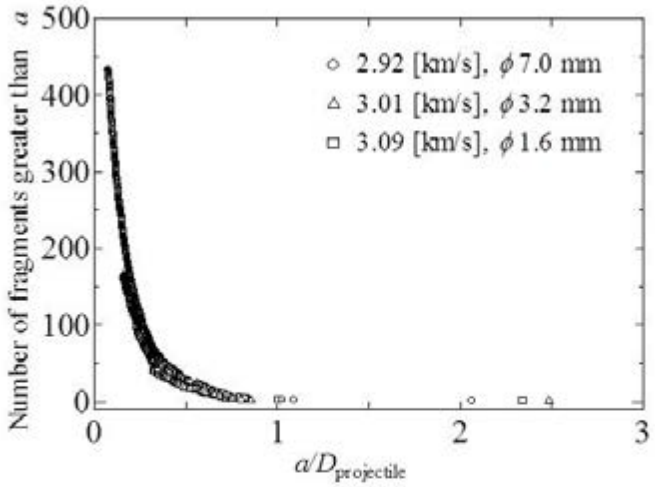

Fig. 1 Cumulative number distribution of normalized ejecta length

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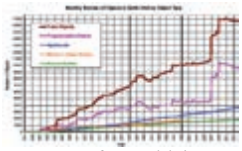
超高速衝突による飛翔体直径がイジェクタサイズ分布に与える影響

Influence of Projectile Diameter on Size Distribution of Ejecta Resulting from Hypervelocity Impacts

Yasuyuki Hiraiwa[1], Kaito Ishida[1], Naoto Miyokawa[1], Masahiro Nishida[1],
Koichi Hayashi[2], Sunao Hasegawa[3]

[1] Nagoya Institute of Technology
[2] National Institute of Technology, Toba College
[3] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency

1. Background

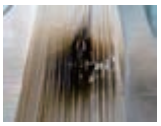


Increase of space debris

NASA Orbital Debris Program Office Orbital Debris Quarterly News, 10-1 (2016) 10.

Average velocity of space debris

: approximately 10 km/s



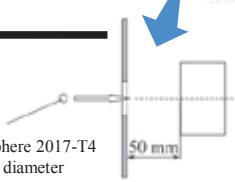
Reason for the failure of satellite ADEOS-II

Kawakita, S., Spacecraft design standard The collision experiments in debris protection design WG(in Japanese), Space Environment Symposium Proceedings, (2007), pp.131-134.

2. Experimental Methods

Schematic diagram of a two-stage light gas gun

Witness plate
C1100P-1/4H
150 mm × 150 mm

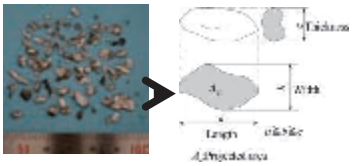


Projectile
Aluminum sphere 2017-T4
1.6 ~ 7.0 mm diameter

Aluminum alloy target
A6061-T6

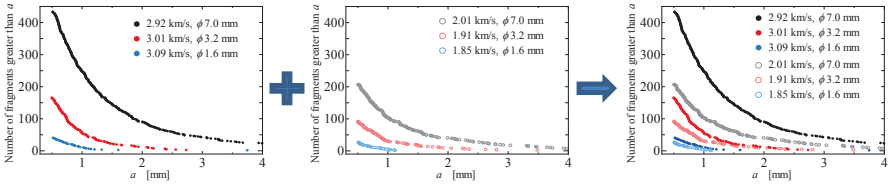
3. Results and Discussion

3.1 Definition of ejecta size

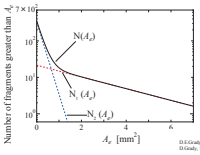


We measured only the ejecta with a length over 0.5 mm.

3.2 Cumulative number distribution of ejecta size



3.3 Bilinear distribution of ejecta size



D.E.Grady, M.E.Kipp: APPLED PHYSICS LETTERS, (2006) 89
D.Grady, Shock Wave and High Pressure Phenomena,(2006)7-32

Bilinear distribution

$N(A_e) = N_1(A_e) + N_2(A_e)$

$N_1(A_e) = a_1 (e)^{a2\ Ae}$, $N_2(A_e) = a_3 (e)^{a4\ Ae}$

3.4 Normalizing the horizontal axis in projectile diameter

Evaluation by the coefficient of determination : R^2

$R^2=1-\{\Sigma_i(y_i-f_i)^2\}/\{\Sigma_i(y_i-y)^2\}$

a/D^1.0

3.0 km/s	7.0 mm	3.2 mm	1.6 mm	Total sum
7.0 mm		0.807	0.659	1.466
3.2 mm	0.642		0.911	1.553
1.6 mm	0.124	0.877		1.001
Total sum	0.767	1.684	1.570	4.020

2.0 km/s	7.0 mm	3.2 mm	1.6 mm	Total sum
7.0 mm		0.979	0.851	1.830
3.2 mm	0.980		0.753	1.733
1.6 mm	0.778	0.618		1.397
Total sum	1.758	1.597	1.604	4.959

a/D^1.1

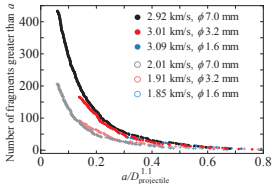
3.0 km/s	7.0 mm	3.2 mm	1.6 mm	Total sum
7.0 mm		0.928	0.944	1.873
3.2 mm	0.887		0.917	1.804
1.6 mm	0.925	0.929		1.853
Total sum	1.812	1.857	1.861	5.530

2.0 km/s	7.0 mm	3.2 mm	1.6 mm	Total sum
7.0 mm		0.822	0.997	1.819
3.2 mm	0.856		0.859	1.715
1.6 mm	0.997	0.842		1.839
Total sum	1.853	1.664	1.856	5.374

a/D^1.2

3.0 km/s	7.0 mm	3.2 mm	1.6 mm	Total sum
7.0 mm		0.967	0.828	1.795
3.2 mm	0.957		0.681	1.638
1.6 mm	0.886	0.838		1.723
Total sum	1.843	1.804	1.509	5.156

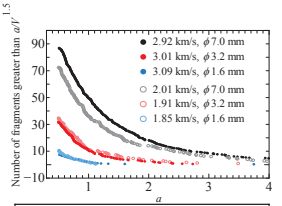
2.0 km/s	7.0 mm	3.2 mm	1.6 mm	Total sum
7.0 mm		0.349	0.651	1.000
3.2 mm	0.620		0.924	1.544
1.6 mm	0.826	0.935		1.761
Total sum	1.446	1.285	1.575	4.305



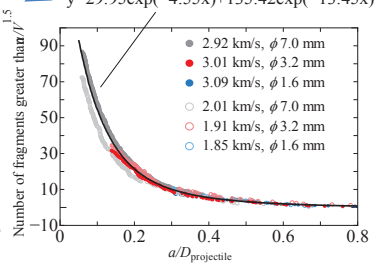
3.5 Normalizing the vertical axis in projectile diameter

Evaluation by the coefficient of determination : R^2

$R^2=1-\{\Sigma_i(y_i-f_i)^2\}/\{\Sigma_i(y_i-y)^2\}$



y=29.95exp(−4.55x)+135.42exp(−13.45x)



N(a)/V^1.4

	3 km/s	Total sum	
	2 km/s		
7.0 mm	0.741	1.337	5.089
	0.595		
3.2 mm	0.977	1.975	
	0.997		
1.6 mm	0.858	1.777	
	0.919		

N(a)/V^1.5

	3 km/s	Total sum	
	2 km/s		
7.0 mm	0.793	1.494	5.152
	0.701		
3.2 mm	0.959	1.955	
	0.996		
1.6 mm	0.804	1.704	
	0.900		

N(a)/V^1.6

	3 km/s	Total sum	
	2 km/s		
7.0 mm	0.843	1.630	5.089
	0.788		
3.2 mm	0.927	1.920	
	0.993		
1.6 mm	0.687	1.539	
	0.852		

4. Conclusions

1. The cumulative number of the size of ejecta was proportional to the projectile impact velocity to the power of 1.5 in the vertical axis.
2. The cumulative number of the size of ejecta was proportional to the projectile diameter to the power of 1.1 in the horizontal axis .
3. The cumulative number distribution the size of ejecta was fitted by a bilinear exponential distribution model.

Acknowledgments
This work was supported by the Space Plasma Laboratory, ISAS, JAXA as a collaborative program with the hypervelocity impact experiment.
This work was supported in part by a Grant-in-Aid for Scientific Research, KAKENHI (C), from the Japan Society for the Promotion of Science (JSPS).

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P03

レーザーパルス繰返し照射によるアルミニウムアブレーション積算力積特性

○鶴田久、Wang Bin、Wang Zhongyuan、佐宗章弘(名古屋大学)

レーザーアブレーションは、遠隔でデブリに運動量を与えることが可能である。そのため、デブリへの接近に必要な推進剤低減、デブリとの接触リスク回避、単一のレーザー源で複数のデブリに対応可能といったメリットがある。本研究では、波長約 1μm、パルス幅約 10ns のパルスレーザーをアルミニウムに対し繰返し照射し、アブレーションにより発生する力積の特性を調査した。発生力積は、μNs レベルの力積解像度を持つねじれ式振り子で計測した。結果として、繰返し照射に伴い積算力積は飽和すること、またレーザーパルスのエネルギー密度が大きいほど高い値に飽和することがわかった。この力積の飽和は、繰返し照射に伴う微小クレーター深化が主な原因と考えられる。このことから実用時は、特定のパルス数照射後、照射場所を切り替えることが有用と言える。

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レーザーパルス繰返し照射による アルミニウムアブレーション積算力積特性

鶴田 久, Bin Wang, Zhogyuan Wang, 佐宗 章弘
名古屋大学航空宇宙工学専攻電離気体力学研究グループ

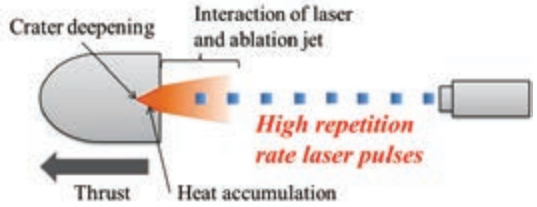
Background

レーザーアブレーションの特徴
・遠隔での運動量発生

宇宙応用
・スペースデブリ除去・回転抑制
・小規模推力のスラスタ
(developed by Phipps et al)

デブリ除去におけるメリット
・接近による衝突リスク回避および、推進剤の抑制
・単一のレーザー源で複数のデブリに対応可能

照射方式		性能
CW (Continuance Wave)		レーザー強度が弱い為基本的にアブレーションしない
パルス	1パルス	エネルギー密度に最適値が存在する 発生する力積はほとんどのミッションに対し不十分
	異なる箇所への繰返し	小型人工衛星の方向および位置変更に利用可能 (Microthruster, 100μN of normal thrust level)
	同一箇所への繰返し	ほとんど明らかになっていない

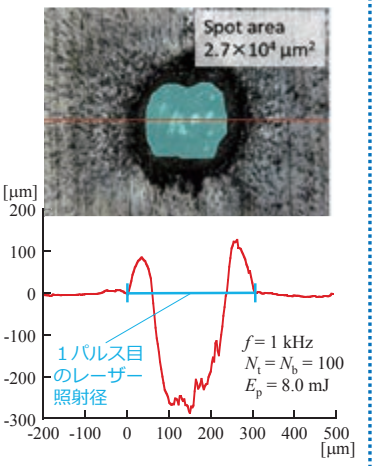


Objective

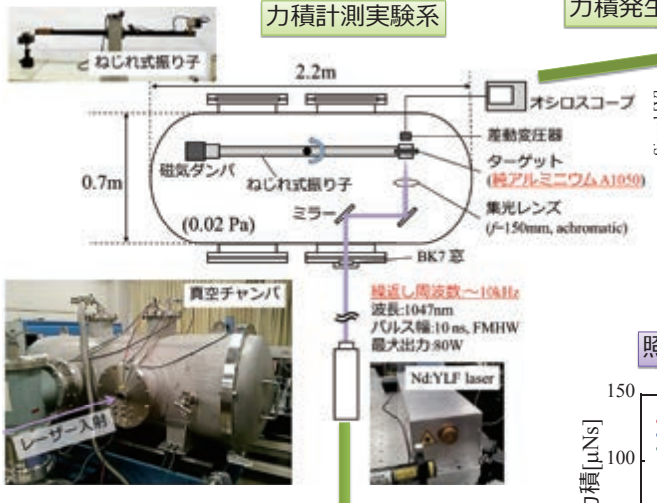
繰返しレーザーパルス照射に伴う力積の基本特性を明らかにする

Experiment and Discussion

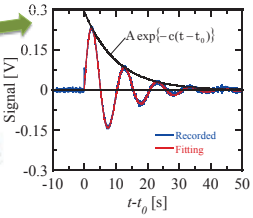
繰返し照射による微小クレータ



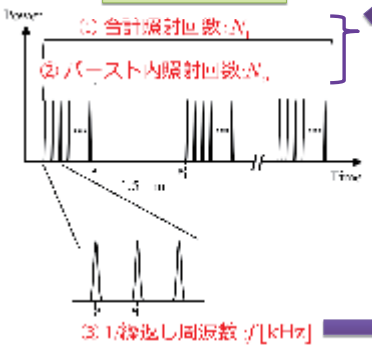
力積計測実験系



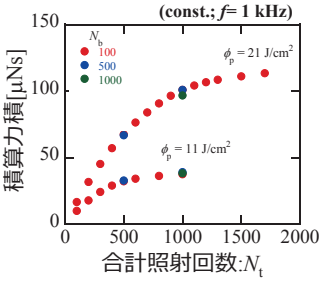
力積発生による振り子の振動



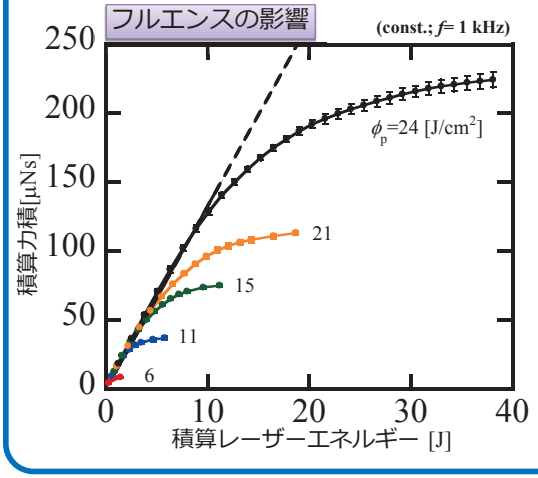
照射パターン図



照射パターンの影響

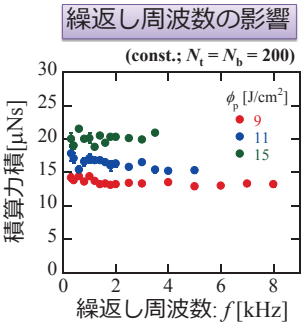


フルエンスの影響



パルスエネルギー:E_p [mJ]
*E_p:スポット面積
→④:パルスあたりのフルエンス:ϕ_p [J/cm²]

繰返し周波数の影響



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P04

ジグザグに折りたたまれた導電性テープテザーの展開力学特性解析

○松崎秀太(神奈川工科大学) , 杉本洋平(宇宙航空研究開発機構),
藤井裕矩(神奈川工科大学)

2010 年に打ち上げられた S-520-25 号機による観測ロケット実験でも実際に使用されたベア導電テープテザーは高効率な推進技術(デブリ除去技術)である ElectrodynamicTether(EDT)への応用が期待されている。同観測ロケット実験でテープテザーは 2 次元的にジグザグに折りたたまれたテザーボックスに収納された状態から展開が試みられたが、展開途中で想定外の展開抵抗が発生し全長の半分以下で展開終了となった。本研究では地上における展開実験によりジグザグに折りたたまれたベア導電テープテザーの一般的な展開力学特性を解析することを目的としている。今回の実験では、異なる展開速度とテザーボックスの開口率の条件下でのテープテザーの展開の様子を高速度カメラで観測し、その際の展開抵抗を電子天秤で計測することによって解析を試みる。現時点の実験結果から開口率が 100%である場合は安定した展開が可能で、開口率が小さくなるに従って展開力学特性が複雑になっていくことが分かった。

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2014/12/17-19

第6回スペースデブリワークショップ

ジグザグに折りたたまれた導電性テープテザーの展開力学特性解析

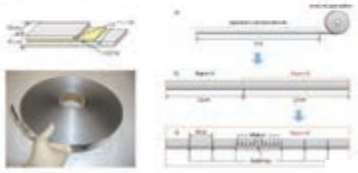
松崎秀太（神奈川工科大学、杉本洋平（宇宙航空研究開発機構）、藤井裕矩（神奈川工科大学）

テザー展開機構

- ベイトリール式展開機構：展開中、宇宙機の角運動量とテープテザーのテンションをコントロールする必要がある。
- スピニングリール放出機構：機構の特性上、テープテザーを展開することはできないが紐状と網状テザーの展開に適している。
- 折り畳み式展開機構：展開中、宇宙機の角運動量には大きな影響を与えない。テープテザーの展開特性を正しく理解する（i.e., 展開抵抗を見積もる）必要がある。

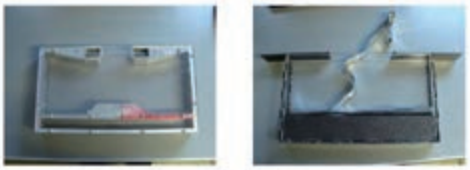
ベア導電性テープテザー

- 厚さ45μm、幅25mm、長さ3.9mの導電性テープテザーを使用
- 2.4mを30cm間隔でジグザグに折りたたみ、真ん中の一折分、60cmのテザーに展開特性解析のためのマーカーを貼付する。

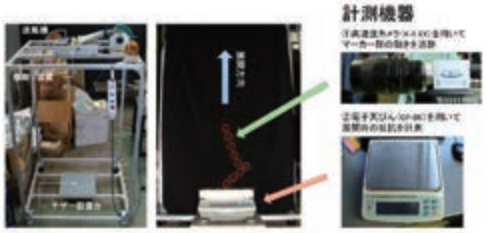


テープテザー収納ボックス

実験ではテープテザーをアクリル製のボックスに収納し展開する。左図は観測ロケットで使用された型のボックスである。今回の実験で用いるボックス（右図）は出口の開口率が可変となっている。



展開実験の構成



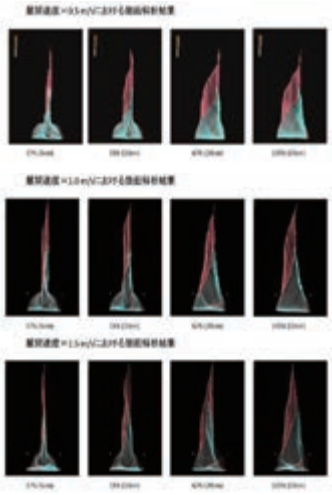
展開実験の条件

異なる条件下での展開挙動と抵抗が知りたい。

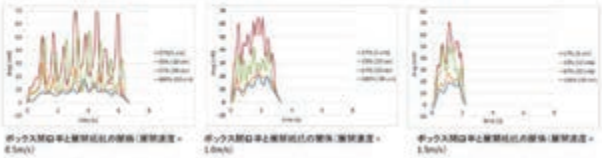
ー今回の実験条件ー
- 展開速度：0.5, 1.0, 1.5 m/s
- ボックス開口率：17% (5cm), 33% (10cm), 67% (20cm), 100% (30cm)

合計で12パターンの実験条件

解析結果：展開挙動



解析結果：展開抵抗



まとめ

過去の実験

テザー展開抵抗の見積もりを試みた。幾重にも折りたたまれたテザーが開口率20%のボックスから展開される際の抵抗の平均を取り見積もられた。

今回の実験

テザー展開挙動の解析に挑んだ。ボックス出口の開口率が高い場合、展開挙動は比較的単純だが、開口率が低い場合、展開挙動はより複雑になり、展開抵抗はきわめて非線形なものとなることがわかった。展開速度が展開挙動・抵抗に与える影響も限定的あるが確認された。

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P05

レーザーアブレーション反力による衛星回転の制御の可能性

Suppression of Satellite Rotation by the Reaction Force by Laser Ablation

○戎崎俊一、和田智之、滝澤慶之（理化学研究所）
○Toshikazu Ebisuzaki, Satoshi Wada, Yoshiyuki Takizawa (RIKEN)

宇宙デブリは宇宙開発にとって大きな課題になりつつある。運用を停止した衛星は、衛星同士の衝突による宇宙デブリの増加を抑制するために、初期軌道から外して地球に再突入させるか、衛星の存在密度が小さい軌道に再投入する必要がある。すでに運用を停止し姿勢制御を長期に起こっていない衛星は、様々な理由により回転していると考えられている。この回転を止めないと再捕獲して、新しい軌道に投入したり、新たにスラスタやテザーを取り付けることが困難である。本論文では、近距離から高輝度パルスレーザーを照射して、アブレーションプラズマの反力で回転を抑える可能性について検討する。

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Suppression of Satellite Rotation by the Reaction Force by Laser Ablation

Toshikazu Ebisuzaki, Satoshi Wada, Yoshiyuki Takizawa (RIKEN)

Space debris becomes one of the major risks for space development. Non-operating satellites have to be de-orbited to reentry to the Earth or to the orbits where the satellite density is small in order to suppress the debris creation by the collisions. The satellite, however, may have a rotation of the order of one rotation per minutes, long after the stopping its operation. This rotation prevents us to recapture them to attach a thruster or tether for the de-orbit operations. In the present paper, we seek the possibility to use intense pulsed laser to control the rotation of the satellites. The reaction force due to the plasma ablation due to the focused intense laser beam is calculated as:

$$f_L = C_m E_d R = 1.0 \times 10^{-4} \left(\frac{C_m}{10^{-4} N/W}\right)\left(\frac{E_p}{10mJ}\right)\left(\frac{R}{10^2 Hz}\right) N,$$

where C_m is the reaction force coefficient, E_p the pulse energy, R the repetition rate.

The mass of the 1 m cube satellite is calculated as:

$$M = 10^3 \left(\frac{\rho}{10^3 kg/m^3}\right)\left(\frac{a}{1m}\right)^3 kg$$

and the moment of inertia as $2/3\ Ma^2$. A significant change in the angular momentum of the satellite can be achieved within:

$$\tau = \frac{I\omega}{af_L} = 7.8 \left(\frac{a}{1m}\right)\left(\frac{M}{10^3 kg}\right)\left(\frac{f_L}{10^{-4} N}\right)^{-1}\left(\frac{\omega}{0.1Hz}\right) days,$$

when we exert the force f_L on the point separated a from the centre of mass of the satellite. Here, ω is the angular velocity of the satellite. The fluence of the laser beam on the target is as high as:

$$I = \frac{4E_p}{\pi a^2} = 1.3 \times 10^4 \left(\frac{E_p}{10mJ}\right)\left(\frac{a}{10^{-3}m}\right)^{-2} Wm^{-2},$$

which is well above the ablation threshold of 3×10^4 W m^{-2}, where n_p is the pulse duration and a the beam spot diameter on the satellite. The spot diameter of 10^{-3} m is feasible from the operation from 100 m distance, since the diffraction limited beam size is as small as 0.3×10^{-3} m for the case that the steering optics of 0.3 m and the distance of 100 m, assuming the wavelength of the laser photons to be 1 μm. A laser system with an average power of 1 W can stop the rotation of one-ton class satellite with the size of 1 m within a month.

Figure 3 shows the results of the vacuum thermal test of the laser system (Figure 4) in Photonics Control Technology Team, RIKEN in collaboration with JAXA. The power above 1 W was maintained for four days in the vacuum environment between -40°C and 60°C. The conduction cooling system shown in Figures 5 was proven to work in 1 W average power operation in vacuum.

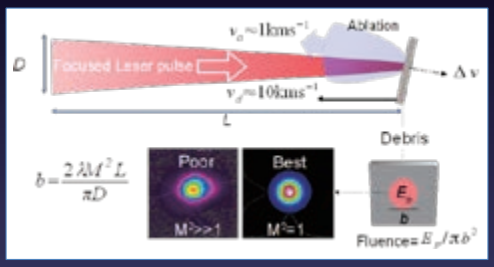

Figure 1: Concept of the propulsion by laser ablation. Ablated material is ejected as ablation plasma by the velocity of v_a.

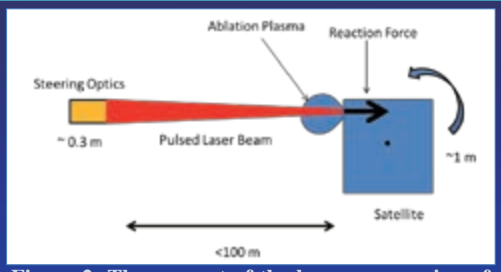

Figure 2: The concept of the laser suppression of the rotation of a satellite.

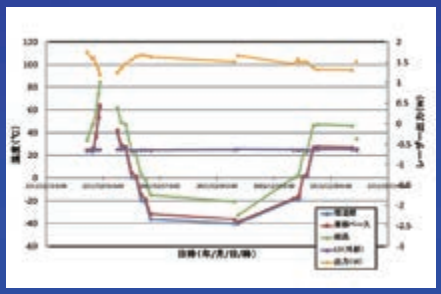

Figure 3: The result of vacuum-thermal test on the laser system. The power above 1 W was maintained for four days in the vacuum environment between -40°C and 60°C.

Figure 4: The laser system overlook and the laser system used in the vacuum thermal test.

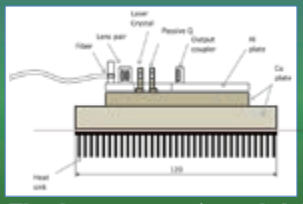

Figure 5: The laser system is cooled by only conduction by Al and Cu plate with a heat sink.

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P06

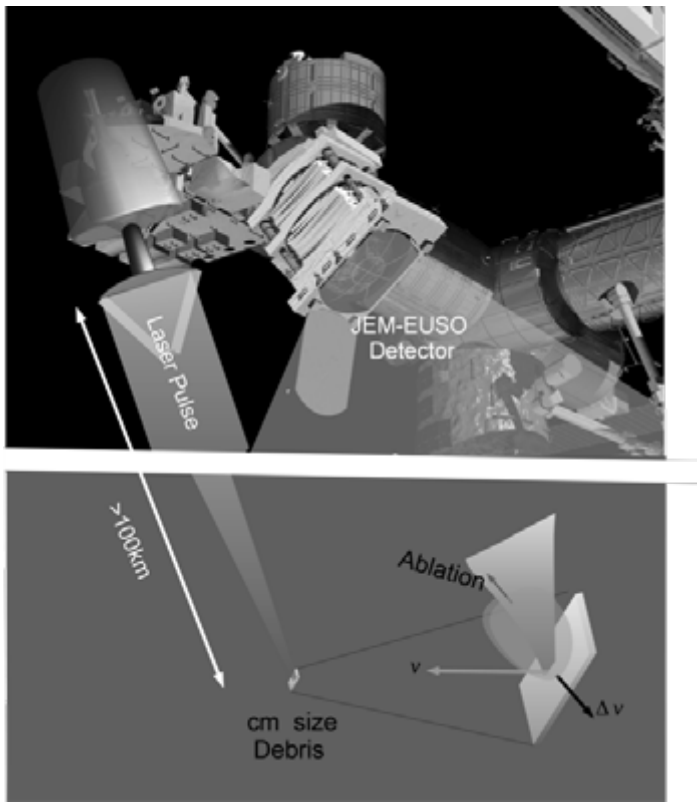
レーザーアブレーションによる宇宙デブリ除去システムの研究

Study of the removal of the space debris by the laser ablation

戎崎俊一、○滝澤慶之、大森整（理化学研究所）
Toshikazu Ebisuzaki, ○Yoshiyuki Takizawa, Hitoshi Ohomori (Riken)

宇宙デブリの除去のために、超広視野望遠鏡と超高輝度宇宙レーザーを組み合わせたシステムを構想している。最近のオプトエレクトロニクスの発展により、広範囲をもれなく走査してデブリの位置決定ができるようになってきた。超広視野望遠鏡として、宇宙から飛来する超高エネルギー宇宙線の検出用に開発しているEUSO 望遠鏡の利用を検討している。EUSO 望遠鏡は±30 度の広視野で、数マイクロ秒の時間分解能を持ち、デブリのリアルタイム検出が可能である。この望遠鏡の出力から位置を粗決定し、レーザービームを照射する。その反射信号からデブリの位置を精密決定し、高出力レーザーのエネルギーをデブリに集中させ、プラズマアブレーションを起こす。その反力で宇宙デブリを減速して地球に再突入させる。本発表では、この除去システムのコンセプトと超広視野望遠鏡の出力から位置を粗決定し、レーザービームを照射するシステムの試作プランを紹介する。

We study a design for an orbiting debris remediation system comprised of a super-wide field-of-view telescope (EUSO) and a novel fiber-based laser system (CAN) operating from the International Space Station (ISS). The EUSO telescope, has been designed for operation on-board the ISS for the detection of ultra-high energy cosmic rays. Equipped with 2.5 m optics and a field of view of ±30 degrees, the EUSO module can also be utilized for the detection of high velocity fragmentation debris in orbit near the ISS. Once detected, the CAN laser system delivers a sequence of pulses to the debris surface inducing ablation and hence momentum impulse to reduce its velocity. The range of the detection/removal operation can be as large as 100 km. We present a development plan of concept model of the detection system.



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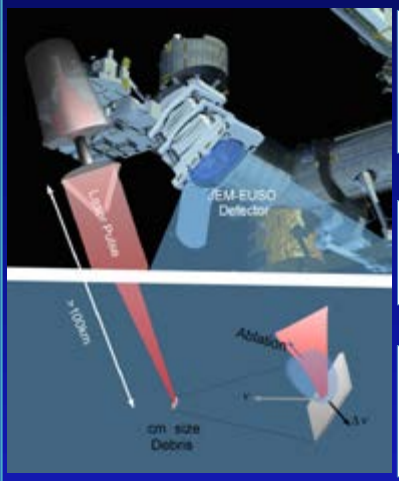
レーザーアブレーションによる宇宙デブリ除去システムの研究

戎崎俊一、滝澤慶之、大森整（理研）

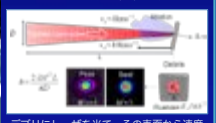
概要

宇宙デブリの除去のために、超広視野望遠鏡(EUSO)と超高輝度宇宙レーザーを組み合わせたシステムを構想している。最近のオプトエレクトロニクスの発展により、広範囲をもれなく走査してデブリの位置決定ができるようになってきた。超広視野望遠鏡として、宇宙から飛来する超高エネルギー宇宙線の検出用に開発しているEUSO望遠鏡の利用を検討している。EUSO望遠鏡は±30度の広視野で、数マイクロ秒の時間分解能を持ち、デブリのリアルタイム検出が可能である。この望遠鏡の出力から位置を粗決定し、レーザービームを照射する。その反射信号からデブリの位置を精密決定し、高出力レーザーのエネルギーをデブリに集中させ、プラズマアブレーションを起こす。その反力で宇宙デブリを減速して地球に再突入させる (Ebisuzaki,T. et al. 2014, submitted to Acta Astronautica.) 。本発表では、この除去システムのコンセプトと超広視野望遠鏡の出力から位置を粗決定し、レーザービームを照射するシステムの試作プランを紹介する。

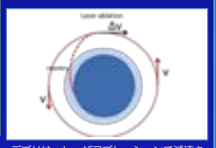
JEM-EUSOを用いたデブリ除去システム



ISSからのデブリ監視領域（水色）とデブリ除去領域（赤）の様子



デブリにレーザを当て、その表面から速度 v_eでアブレーションプラズマが射出される

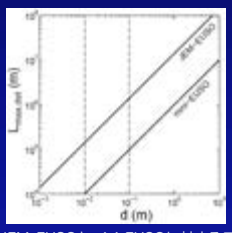


デブリは、レーザアブレーションで減速され、大気圏に突入する

ISS搭載mini-EUSOによるデブリ検出実験

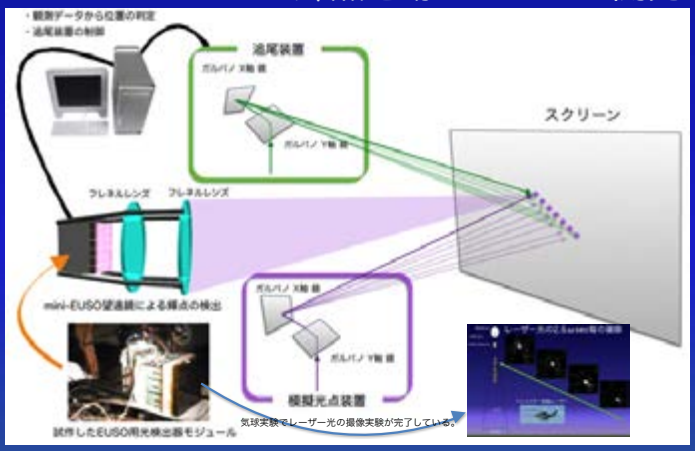
mini-EUSOは、イタリアとロシアによるEUSOの為の準備実験。地球の夜の紫外線環境を調べる。

JEM-EUSOとmini-EUSO



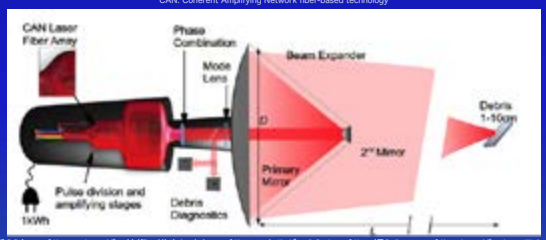
JEM-EUSOとmini-EUSOに対するデブリサイズと検出可能最大距離の関係

mini-EUSOによる輝点追跡システムの開発



宇宙CANシステム

CAN: Coherent Amplifying Network fiber-based technology



最近20年のパルス・レーザー技術の進歩により、パルスエネルギー10 J、パルス幅0.1 nsのパルスレーザーシステムを宇宙機に搭載することが可能になっている。この場合、不安定で振動に弱いモード同期レーザーの代わりに、レーザーダイオードでポンプされた固体レーザーもしくはレーザーファイバーを使う。 Soulard, R. et al. 2014, Accepted in Acta Astronautica, 105. 192-200. Mourou, G. et al. 2013, NATURE PHOTONICS, 7,258-261.

JEM-EUSO ミッションとは

JEM-EUSOは、極限エネルギー宇宙線が大気中で作る空気シャワーからの蛍光とチェレンコフ光を観測し、極限エネルギー宇宙線のの起源を探るミッションである。その他に、大気圏発光現象も観測する。

装置パラメータ

Field of View:	±30°
Aperture Diameter:	2.5m
Optical bandwidth:	330–400nm
Angular Resolution:	0.1°
Pixel Size:	3mm
Number of Pixels:	~2.0×10^5
Pixel Size at the ground:	750m
Duty Cycle:	~20%
Observational Area:	1.9×10^5 km² (nadir)

ナディアモード

チルトモード

チルトモードによる視野の増加

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P07

有機物・微生物の宇宙曝露と宇宙塵・微生物の捕集「たんぽぽ」: その概要と準備状況

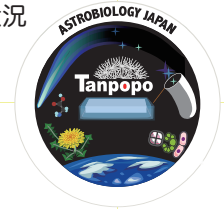
山岸明彦(東京薬大・生命科学)、○横堀伸一(東京薬大・生命科学)、矢野創(JAXA/ISAS)、橋本博文(JAXA/ISAS)、河口優子(JAXA/ISAS)、今井栄一(長岡技大・生物)、奥平恭子(会津大)、河合秀幸(千葉大・院理)、癸生川陽子(横浜国大・院工)、小林憲正(横浜国大・院工)、佐々木聰(東京工科大・応用生物)、田端誠(千葉大・院理)、中川和道(神戸大・院人間発達環境)、東出真澄(JAXA・未踏技術研究セ)、三田肇(福岡工大・工)、薮田ひかる(大阪大・院理)、たんぽぽ研究チーム

我々は、ISS-JEM(国際宇宙ステーション・日本実験棟)曝露部上での微生物と生命材料となり得る有機化合物の天体間の移動の可能性の検討と微小隕石の検出および解析実験を提案し[たんぽぽ:有機物・微生物の宇宙曝露と宇宙塵・微生物の捕集]、その準備を進めている。超低密度エアロゲルを長期間(1年以上)曝露し、惑星間塵や宇宙デブリを含む微粒子を捕集するとともに、新規に開発したエアロゲルの利用可能性を検証する。捕集された微粒子とそれが形成する衝突痕(トラック)に対して、微生物または微生物関連生体高分子(DNA 等)や有機物の検出、解析を行う。また、微生物を宇宙曝露する事により、微生物の宇宙環境での生存可能性と、生存に影響を与える環境因子について、推定を行う。また、宇宙塵に含まれて地球に飛来する有機物が宇宙空間で変成する可能性を検討する。本発表では、本計画の概要と現時点での準備状況等について報告する。

This document is provided by JAXA.

有機物・微生物の宇宙曝露と宇宙塵・微生物の捕集「たんぽぽ」：その概要と準備状況

山岸明彦[1]、○横堀伸一[1]、矢野創[2]、今井栄一[3]、奥平恭子[4]、河合秀幸[5]、河口優子[2]、癸生川陽子[6]、小林憲正[6]、佐々木聰[7]、田端誠[5]、中川和道[8]、東出真澄[9]、三田肇[10]、薮田ひかる[11]、橋本博文[2]、たんぽぽ研究チーム
[1]東京薬大・生命科学、[2]JAXA/ISAS、[3]長岡技大・生物、[4]会津大、[5]千葉大・院理、[6]横浜国大・院工、[7]東京工科大・応用生物、[8]神戸大・院人間発達環境、[9]JAXA・未踏技術研究セ、[10]福岡工大・工、[11]大阪大学 ・院理



たんぽぽ計画とは？

超低密度固体エアロゲルを１年以上の長期間曝露する事で、宇宙塵や宇宙デブリを含む微粒子を捕集する。同時に微生物の採集を試みることから、地球低軌道での地球由来微生物の存在密度の上限を推定する。また、地上で培養した微生物を宇宙空間に曝露する事によって、微生物の宇宙環境での生存時間の推定を行う。そこから、地球由来微生物の惑星間移動の可能性を検討する。さらに、宇宙塵に含まれて地球に飛来する有機物が宇宙空間で変成する可能性を検討する。同時に新規に開発したエアロゲルの利用可能性を検証する。
実験は、微生物と有機物を曝露するためのサンプル・トレイとエアロゲルを固定したエアロゲル・パネルを打上げ、国際宇宙ステーション与圧部で汎用曝露装置（ExHAM）に固定する。ExHAMをエアーロックを通して、ロボットアームで曝露部ハンドホルドに固定する。一定時間（１年以上）後、与圧部に取り込んだExHAMからサンプル・トレイとエアロゲル・パネルを取り外し、容器に収納して地球に帰還する。地上で、鉱物、有機物、微生物解析を行う。
2015年実験開始を目標として、準備を進めている。

微粒子の捕集

テーマ5：「世界最高性能エアロゲル」の宇宙実証

田畑誠（千葉大）、河合秀幸（千葉大）

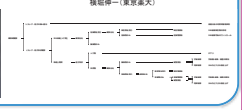
世界最高水準の超低密度エアロゲルを独自開発し、これをISSで曝露して第1, 4, 6サブテーマの採集実験を行うことにより、宇宙空間での採集能力を実証する。

主成分：シリカ（SiO_2）
上部の密度：・・・0.01 g/ml
下部の密度：・・・0.03 g/ml
超低密度であり衝突時の損傷が少ない
損傷が少ないことで微衝撃の原発を防ぐことが可能である
これまで様々な宇宙での捕集実験に使われてきた
空気中の水分の影響を防ぐため疎水性である

超低密度エアロゲル（Tabata *et al.*, 2011）

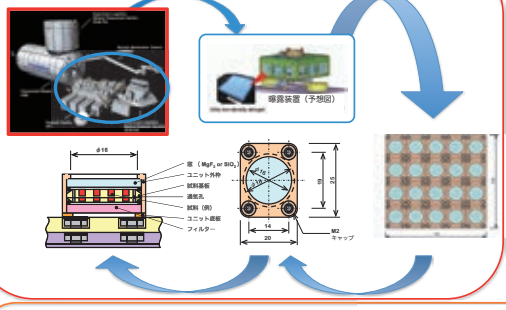
初期解析

藪田ひかる（大阪大）、三田肇（福岡工大）、奥平恭子（会津大）、矢野創（JAXA）、小林憲正（横浜国大）、山岸明彦（東京薬大）、横堀伸一（東京薬大）

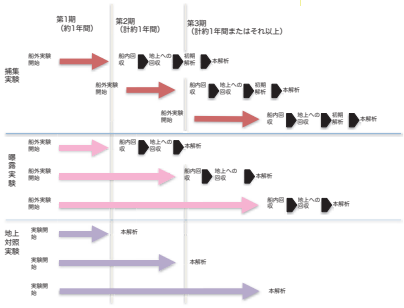


曝露ユニット

山岸明彦（東京薬大）、橋本博文（JAXA）、今井栄一（長岡科技大）、佐々木聰（東京工科大）、矢野創（JAXA）、横堀伸一（東京薬大）、他



たんぽぽ実験の運用計画

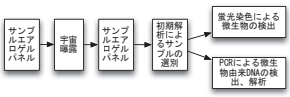


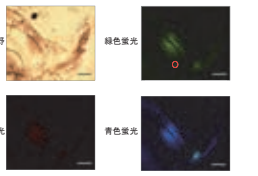
宇宙曝露

テーマ1：「地球から宇宙へ」微生物採集

山岸明彦（東京薬大）、横堀伸一（東京薬大）、河口優子（JAXA）他

地球への小天体衝突、超高層大気でのスプライトに関連する電磁的な輸送機構、火山爆発等の機構、あるいは人間の宇宙活動に随伴して地球表面を脱し、地球低軌道高度に分布している可能性のある地球起源微生物（あるいはその痕跡）をエアロゲルで採集することから、地球生命の宇宙空間への脱出可能性を検証する。





核酸特異的緑色蛍光色素による染色によるエアロゲルからの微生物の検出

テーマ2：「地球微生物の宇宙生存」微生物の曝露実験

地球から脱出した微生物、あるいは火星等地球以外の生命を育む可能性のある太陽系天体を脱出した微生物が、宇宙空間で紫外線や宇宙線を浴びた状態での生存可能時間やその条件を推定する。

横堀伸一（東京薬大）、山岸明彦（東京薬大）、鳴海一成（東洋大）、富田-横谷香織（筑波大）、林宣宏（東京工大）、他

宇宙曝露候補微生物と曝露条件（紫外光等の遮光）

種（株）名		MgF_2カバー（>110 nm）	石英ガラスカバー（>170 nm）	完全遮光	曝露微生物の特徴
Deinococcus radiodurans	R1	○	○	○	放射線・紫外線耐性菌。*D. radiodurans*のタイプ株(野生株)
	KH311	○		○	*pprA*に変異をもつ、非相同末端修復に関する*D. radiodurans*の変異株
	UV578	○		○	*mtcA*, *uvsE*に変異をもち、核酸除去修復に関する*D. radiodurans*の変異株
	rec30	○		○	*recA*に変異をもつ、相同組換えに関する*D. radiodurans*の変異株
Deinococcus aerius TR0125		○		○	高々度大気から単離された*Deinococcus*属細菌。高い放射線、紫外線耐性を示す
Deinococcus aetherius ST0316		○		○	
Nostoc sp. HK-01		○		○	陸生シアノバクテリア
Schizosaccharomyces pombe				○	分裂酵母（胞子形成）、真核生物

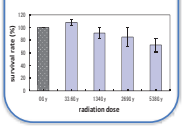
Deinococcus真正細菌の地上実験データの概要（地上実験に基づくISS上の推定一年後生存率）

	VUV (172 nm)	VUV (172 nm)厚み (mm)	UVC (254 nm)	UVC (254 nm) 厚み (mm)	γ-ray	Heavy Ion Beam	±80℃ cycle	±60℃ cycle	相乗 (80℃) (Vacuum を別にカウントしない)	相乗 (60℃) (Vacuum を別にカウントしない)
Deinococcus radiodurans R1	0.93	0.1	0.34	0.1	1	1	5.6.E-06	3.3.E-03	1.8.E-06	1.0.E-03
D. radiodurans UVS78	0.84	0.2	0.091	0.2	1	1	1.30E-30	2.90E-05	9.9.E-32	2.2.E-06
D. radiodurans KH311	0.65	0.2	8.2.E-03	0.2	1	1	8.50E-06	2.90E-03	4.5.E-06	1.6.E-05
D. radiodurans rec30	0.35	0.2	0.091	0.2	1	1	2.60E-41	2.50E-06	8.3.E-43	8.0.E-10
D. aerius TR125	0.49	0.2	0.45	0.5	1	1	1.8.E-18	9.0.E-03	4.0.E-19	2.0.E-03
D. aetherius ST0316	0.63	0.2	0.7	0.1	1	1	2.9.E-03	3.0.E-02	1.3.E-03	1.3.E-02

Nostoc sp. HK-01の顕微鏡写真

Katoh et al. (2003) Isolation and characterization of drought-tolerant cyanobacterium *Nostoc* sp. HK-01 Microbes Environ. 18, 82-88.

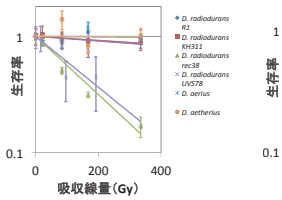
He線に対する*Nostoc* sp. の生存率



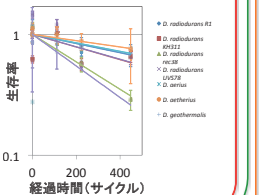
分裂酵母（*Schizosaccharomyces pombe*）のHe線に対する耐性

Sample	Colony formation Rate (%)				
Number	0 Gy	34 Gy	134 Gy	269 Gy	538 Gy
5.0E+4	100	99.8	98.1	97.6	98.0

各菌株の生存率（He線照射）



各菌株の生存率（真空、−60 ℃〜60 ℃）



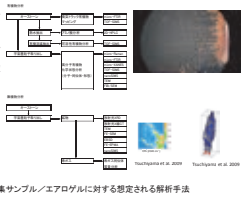
生命の天体間の移動

生命起原物質の宇宙空間での移動

テーマ4：「宇宙から地球へ」惑星間塵中有機物分析

藪田ひかる（大阪大）、野口高明（茨城大）、三田肇（福岡工大）、中嶋悟（大阪大）、奈良岡浩（九州大）、高橋健司（九州大）、丸茂克美（富山大）、奥平恭子（会津大）、土山明（京都大）、中村智樹（東北大）、伊藤元雄（IAMSTEC）、福島和彦（名古屋大）、三河内岳（東京大）、矢野創（JAXA）、他

どのような組成の地球外有機物が初期地球へ供給されたかを理解するため、地球大気圏突入前に捕集した宇宙塵、惑星間塵に含まれる有機物を、最適化されたエアロゲルによってできるだけ非破壊採集する。

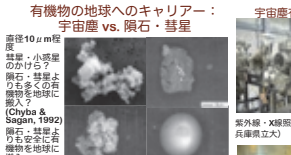


捕集サンプル／エアロゲルに対する想定される解析手法

テーマ3：「地球外有機物の宇宙変性」高分子有機物の曝露実験

小林憲正（横浜国大）、三田肇（福岡工大）、中川和道（神戸大）、薮田ひかる（大阪大）、他

宇宙環境における有機物の生成・変性・分解を調べ、恒星間での有機物の化学進化と地球生命誕生の関連を実証することと、地球と地球外天体との間での生命の移動可能性を、生体有機物の安定性の観点から検討する。

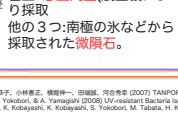


宇宙曝露候補有機化合物（MgF_2による遮光、石英ガラスによる遮光、完全遮光）

化合物名	化学式	構造式	化合物の特徴
グリシン	$C_2H_5NO_2$		生体中にも隕石中にも豊富に含まれるグリシンの安定性・変成を調べる。この化合物はα位に脱離性のプロトンがあり、プロトンをもたず光学異性体比の偏りが知られているイソバリンとの安定性を比較する。
イソバリン	$C_5H_{11}NO_2$		隕石中で光学異性体の偏りが報告されているイソバリンの安定性・変成を調べる。この化合物はα位に脱離性のプロトンがないため、通常のアミノ酸よりも安定であると予想される。またイソバリンは、炭素質隕石中に豊富に含まれ、地球上のホモキラリティーの起源を考える上で重要なアミノ酸である。
ヒダントイン	$C_3H_4N_2O_2$		グリシンの低分子前駆体。グリシン（アミノ酸vs.前駆体）、エチルメチルヒダントイン（α-プロトンの有無）との安定性の比較を行う。なお、グリシンは、炭素質隕石中に豊富に含まれる。
メチルエチルヒダントイン	$C_6H_{10}N_2O_2$		イソバリンの低分子前駆体。この化合物はα位に脱離性のプロトンがないため、通常のアミノ酸の前駆体と考えられるヒダントインよりも安定であると予想される。
模擬星間分子	CO, NH_3, H_2Oの混合物に粒子線を照射して生成する複雑有機物		アミノ酸の前駆体。星間分子雲より供給されたと考えられる複雑有機物の安定性を、低分子前駆体やアミノ酸と比較する。
アラニン	$C_3H_7NO_2$		MgF_2窓を透過する真空紫外線（VUV）照射による分解、カイラル反転を調べるとともにペプチド形成という化学進化が宇宙でおきることを実証する。SiO_2窓の試料は模分型の真空紫外線線量計として用いる。

有機物の地球へのキャリアー：宇宙塵 vs. 隕石・彗星

- 直径10 μ m程度
- 彗星・小惑星のかけら？
- 隕石・彗星よりも多くの有機物を地球に搬入？（Chyba & Sagan, 1992）
- 隕石・彗星よりも安全に有機物を地球に搬入
- 隕石・彗星よりも強く太陽紫外線、宇宙線の影響を受ける

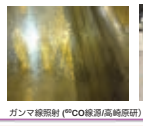


左上: 惑星間塵(航空機により採取
他の３つ:南極の氷などから採取された微隕石。

宇宙塵有機物の安定性・変成評価（地上実験）

紫外線・X線照射 (NewSUBARU/兵庫県立大)

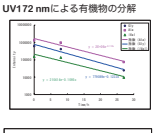
重粒子線照射 (HIMAC/放医研)

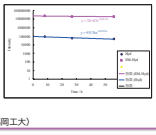


ガンマ線照射 (^{60}CO線源/高崎原研)

紫外線照射 (エキシマランプ/福岡工大)

UV172 nmによる有機物の分解





有機物曝露試料の１年後残存率（地上実験によるISS環境の推定値）

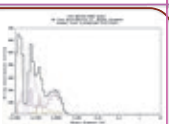
曝露試料	紫外線（エキシマランプ、ニュースバル）	γ線	重粒子線	温度	残存率（左側4条件に対する残存率を掛け合わせたもの）
グリシン	2.10×10^{-5}	99%	100%	100%	2.10×10^{-5}
イソバリン	2.90×10^{-5}	>99%	>99%	100%	2.90×10^{-5}
ヒダントイン	29%	100%	100%	100%	29%
エチルメチルヒダントイン	72%	>99%	100%	100%	72%
模擬星間分子	98%	100%	100%	100%	98%

デブリ計測

テーマ6：「微小スペースデブリフラックス評価」

東出真澄（JAXA）、矢野創（JAXA）、他

地上観測網で検出できないサブmmオーダーのスペースデブリ及び天然のメテオロイドを継続的に捕集してるフラックスを導出し、ISS軌道上の宇宙微粒子環境の危険性評価を行う。



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P08

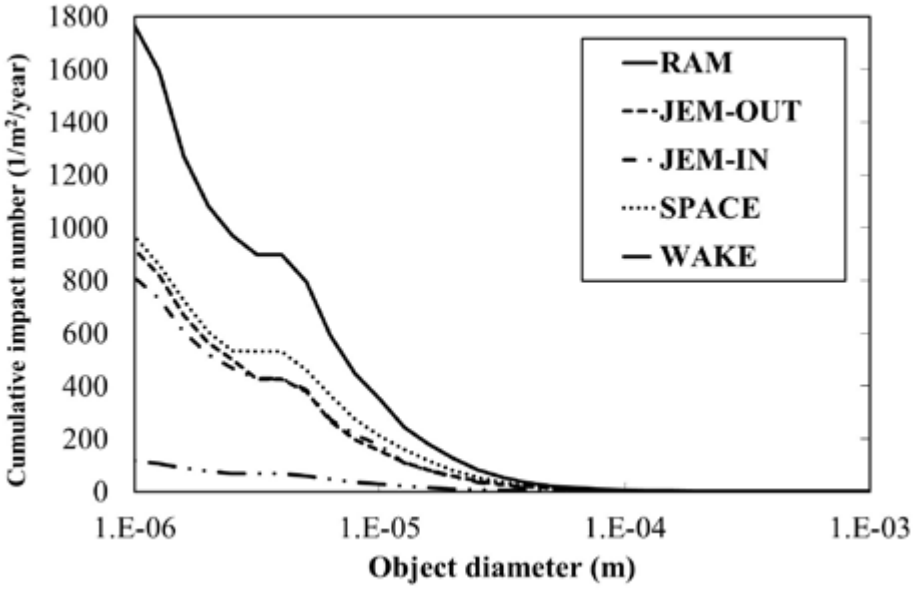
たんぽぽ捕集パネルに衝突する粒子フラックス予測

Impact Frequency Estimate of Micron-sized Meteoroids and Debris on Tanpopo Capture Panels on the ISS

○栗原愛美（法政大学大学院），東出真澄（JAXA），高柳優，新井和吉（法政大学），
矢野創（ISAS/JAXA），田端誠（千葉大学），長谷川直（ISAS/JAXA），
山岸明彦（東京薬科大学）

○Manami Kurihara (Hosei University), Masumi Higashide (JAXA), Yuu Takayanagi, Kazuyoshi Arai (Hosei University), Hajime Yano (ISAS/JAXA), Makoto Tabata (Chiba University), Sunao Hasegawa (ISAS/JAXA), Akihiko Yamagishi (University of Pharmacy and Life Sciences)

本研究は，ISS 搭載予定の「たんぽぽ」プロジェクトの一環である．きぼう曝露部に設置される捕集パネルへの衝突粒子数と，微小デブリ環境モデルとの整合性を確認することが最終目的である．たんぽぽ捕集パネルに衝突する粒子衝突頻度解析を，デブリ衝突リスク解析ツール「Turandot」を用いて行った．ISS の立体モデルをツール内に作成し，MASTER-2009 コードを環境モデルとして適用させた．2015 年初頭から 1 年間の軌道上曝露を考えた結果を下図に示した．縦軸に 1 年間あたり，1m2 あたりの累積衝突頻度を，横軸に衝突粒子の直径を示している．ここで，RAM は ISS の進行方向面，JEM-IN は与圧部側の面，JEM-OUT はその反対面，SPACE は宇宙に面しており，WAKE は RAM と反対の面である．RAM 面に設置した捕集パネルには，直径 0.01mm 以上の宇宙塵ないし微小デブリが 14 個以上衝突すると予想された．また，ISAS の2段式軽ガス銃を用いて行った，捕集パネル材のキャリブレーション試験についても報告する．



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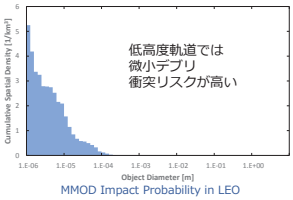
たんぽぽ捕集パネルに衝突する粒子フラックス予測

法政大学 HOSEI University　JAXA
栗原 愛美(法政大院)　東出 真澄(JAXA)　高柳 優，新井 和吉(法政大)
矢野 創(JAXA)　田端 誠(千葉大)　長谷川 直(JAXA)　山岸 明彦(東薬大)

1．研究背景・目的　Ref. [1],[3]



MMOD Impact Probability in LEO

- 低高度軌道における平均デブリ衝突速度は10km/s程度
- 人工衛星にとっては微小デブリ衝突でも致命的な損傷になり得る
- 設計時のデブリ衝突リスク評価が重要

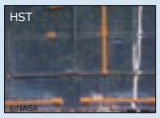
観測で軌道を決定できるのは直径10cm以上のデブリのみ

⇨ **微小デブリの衝突頻度はデブリ環境モデルを使って予測**

デブリ環境モデルは、軌道上での計測データを参考に作られている

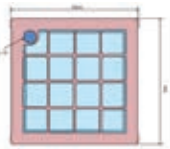
MASTER-2009で使用されたデータ
- LDEF (NASA) 1984-1989
- EuReCa (ESA) 1992-1993
- HST (NASA/ESA) 1989-1993

継続的にデータを取得し、
デブリ環境モデルの妥当性を
定期的に評価する必要がある



**たんぽぽ計画の捕集パネルを用いてデブリを計測し
デブリ環境モデルの妥当性を評価する**

捕集パネル
きぼう曝露部のExHAM各面に4個ずつ設置



Ref. Yamagishi, A., et al., *Proc. 29th ISTS*, 2013.

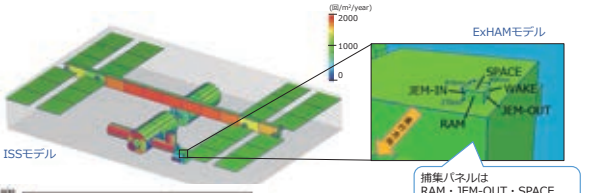
捕集パネル材への超高速衝突実験＋数値解析
↓
捕集パネルに生じたクレータと衝突物の関係式導出
↓
捕集実験による実際のクレータから衝突デブリを推定
↓
本研究の目的：**環境モデルによる予測**
↓
**低高度軌道上における捕集実験結果と
デブリ環境モデルとの差を求める**

2．捕集パネルの衝突頻度解析　Ref. [3]

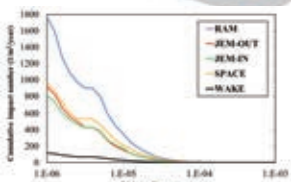
Turandotで衝突頻度解析を実施

- JAXA開発の
デブリ衝突リスク評価ツール
- 宇宙構造物の3次元モデルと
デブリ環境モデルを組み合わせて
衝突頻度を算出
- ISSモデルの作成及び評価が可能

Turandot バージョン	14.21a
デブリ環境モデル	MASTER-2009 v7.01 (ESA)
メテオロイドモデル	Seasonal met. (Jennkens)
計算期間	2015/1/1 ~ 2015/12/31
軌道長半径	6,800km (高度約400km)
離心率	1.0×10^{-3}
軌道傾斜角	51.6 deg.
近地点引数	0 deg.

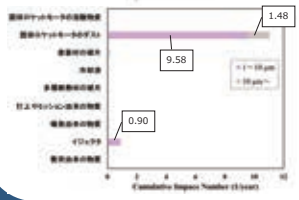


捕集パネルは
RAM・JEM-OUT・SPACE
の3面に設置



捕集パネルに対する粒子衝突頻度
※曝露面積は10,000mm²×4個で計算　(個/year)

粒子直径	RAM	JEM-OUT	SPACE
100μm～	0.18	0.11	0.093
10μm～	14.0	6.14	8.42
1μm～	70.8	36.6	38.6



環境モデルによる解析結果

直径100μm未満の粒子の衝突が期待できる
→　圧倒的にRAM面に多い

**直径1μm以上の粒子は
RAM面では70個程度
他の2面では30個以上衝突する**

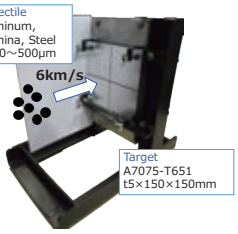
**衝突粒子の大半は固体ロケットモータ
(=アルミナ)であると予測された**

3．捕集パネルのキャリブレーション　Ref. [2]

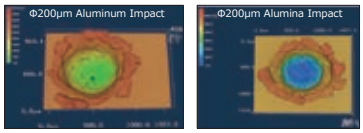
捕集パネルは
エアロゲルとエアロゲルケースで構成
（エアロゲルとエアロゲルケースの
曝露面積比はおよそ6:4）

⇩

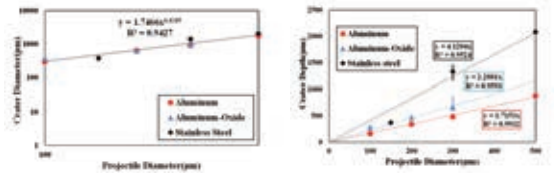
エアロゲルケース材(A7075アロジン処理)の
キャリブレーションを
模擬デブリ衝突試験を用いて実施

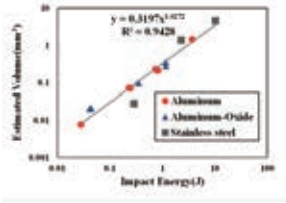


レーザ顕微鏡によるクレータ計測



**衝突クレータ底面形状による
飛翔体材質の判断はできなかった**





クレータ計測の結果

**デブリの材質に関わらず
クレータ直径とデブリ直径は比例した**
→　衝突速度はほぼ一定で試験したので
直径と衝突エネルギもしくは運動量が
比例していると考えられる

**クレータ深さはデブリの材質ごとに
関係式が異なると考えられる**

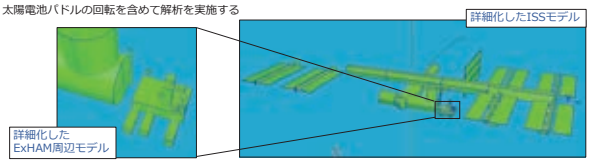
**デブリの材質に関わらずクレータ体積は
衝突エネルギに比例した**

4．今後の予定

① 構造物によるデブリ遮蔽効果を含めたデブリ衝突頻度の評価

ラジエータ・曝露部周辺を詳細にモデル化し，遮蔽の効果を含めた評価を行う

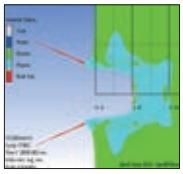
太陽電池パドルの回転を含めて解析を実施する



② 数値解析による
エアロゲルケース材のキャリブレーション

低高度軌道の平均デブリ衝突速度は10km/sだが
7km/s程度までしか実験できない

⇨　衝突解析コードAutodynを用いて
数値解析で高速度域データを補充する



Ref. [1]

③ エアロゲルのキャリブレーション

エアロゲルによってデブリの材質が特定可能

⇨　材質でデブリの発生起源が
分かる可能性がある

フライト後のエアロゲルとエアロゲルケースの
衝突データを比較しエアロゲルの感度についても
評価したい

衝突試験後のエアロゲル
Aluminum Φ100μm,
6.177km/s

Ref. [1]

謝辞

本研究は，JAXA宇宙科学研究所スペースプラズマ共同利用設備，JAXA月惑星グループの設備を用いて実施致しました．また，MUSCATスペース・エンジニアリング株式会社の八田 真児様に多大なる御助言を頂きました．更に，本研究は「たんぽぽ」の一部であり，御協力頂きました長岡技術科学大学の今井 栄一先生を始めとするたんぽぽWGの皆様に感謝の意を表します．

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[1] 東出ら，たんぽぽ計画における微小デブリ分布取得の検討，第14回宇宙科学シンポジウム，2014.
[2] Takayanagi, Y. et al, Measurement of Micro-debris Flux via Tanpopo Capture Panel Onboard ISS Kibo Exposed Facility, 65th International Astronautical Congress, 2014.
[3] 栗原ら，たんぽぽ捕集パネルに衝突する粒子フラックス予測，第58回宇宙科学技術連合講演会，2014.

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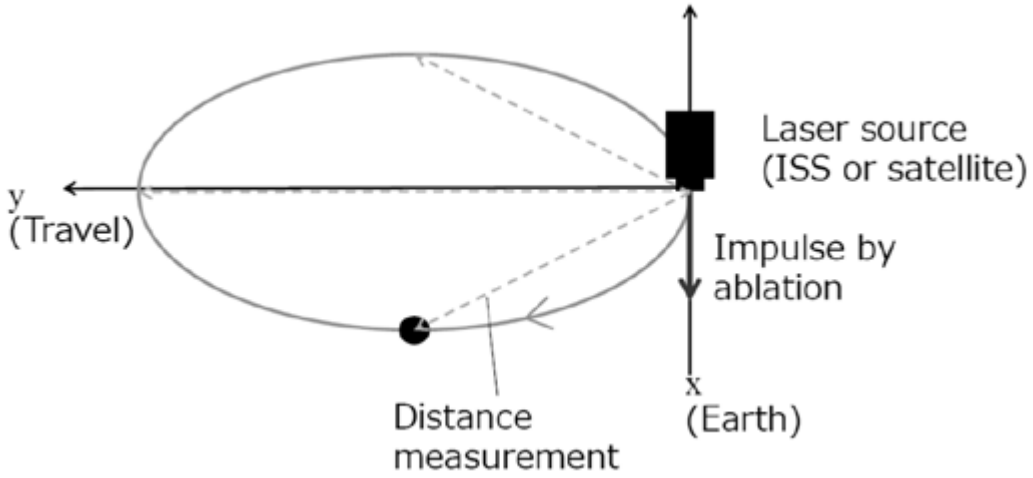
P09

レーザー照射によるデブリ制御と ISS デモ提案

Space debris control with laser irradiation and a demonstration proposal at ISS

○藤田和久, 内田成明(光大), 佐宗章弘, 鶴田久(名大), 山田克彦(阪大)
○Kazuhisa Fujita, Shigeaki Uchida (GPI), Akihiro Sasoh, Hisashi Tsuruta (Nagoya Univ.), Katsuhiko Yamada (Osaka Univ.)

金属材料に対するレーザー照射により, 材料表面を加熱して溶融・蒸散で推力を得てスペースデブリの運動を制御する可能性と, その制御性の宇宙実証として国際宇宙ステーション(ISS)を利用したデモンストレーション実験を提案する. パルスレーザー照射による推力発生として 1 dyn/W 程度のレーザー・運動量変換効率の値を想定し, 軌道上のレーザー衛星からデブリの検出・追尾・照射といった一連のシーケンスに対して位相共役光を利用したシステムを提案する. その一部のデモ実験として, 1W 程度のレーザー出力を利用し, ISS を親機, 用意する模擬デブリを子機として, 親機を原点としたときの子機の相対位置を示す Hill 方程式から模擬デブリの軌道について解析し, デモ実験の可能性を示す. 図は右側中央の ISS にレーザー光源を置き, ISS の座標で周回軌道を1周したときのレーザー照射(下向きインパルス)による放出子機(模擬デブリ, 黒丸)の予想軌道である. 加えて, 連続波レーザーの使用を想定している GEO 上のレーザー宇宙太陽光発電システム(L-SSPS)を利用した静止衛星デブリの軌道変換の可能性についても報告する.



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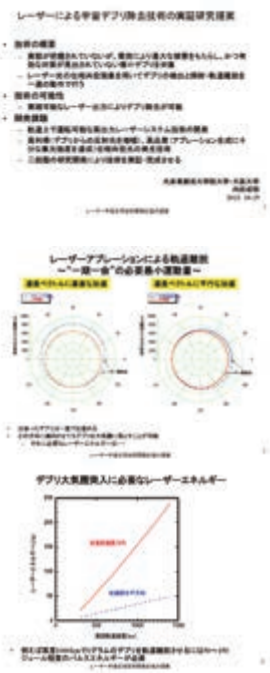
レーザー照射によるデブリ制御とISSデモ提案

Space debris control with laser irradiation and a demonstration proposal at ISS

○藤田和久，内田成明（光産業創成大学院大学），佐宗章弘，鶴田久（名大），山田克彦（阪大）

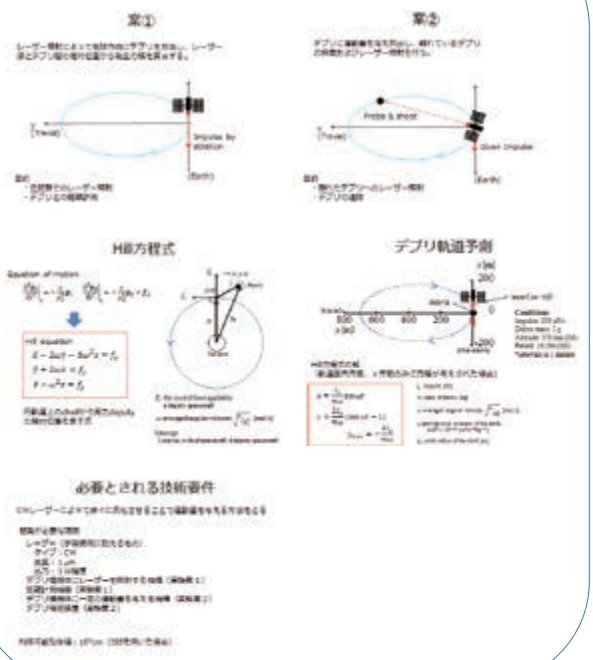
○Kazuhisa Fujita, Shigeaki Uchida (The Graduate school for the Creation of New Photonics Industries (GPI)), Akihiro Sasoh, Hisashi Tsuruta (Nagoya Univ.), Katsuhiko Yamada (Osaka Univ.)

レーザーによる宇宙デブリ除去技術の提案



ISSデモ案１（基礎的）

1Wレーザー搭載のISS親機、1g模擬デブリ子機で、
模擬デブリの運動制御実証

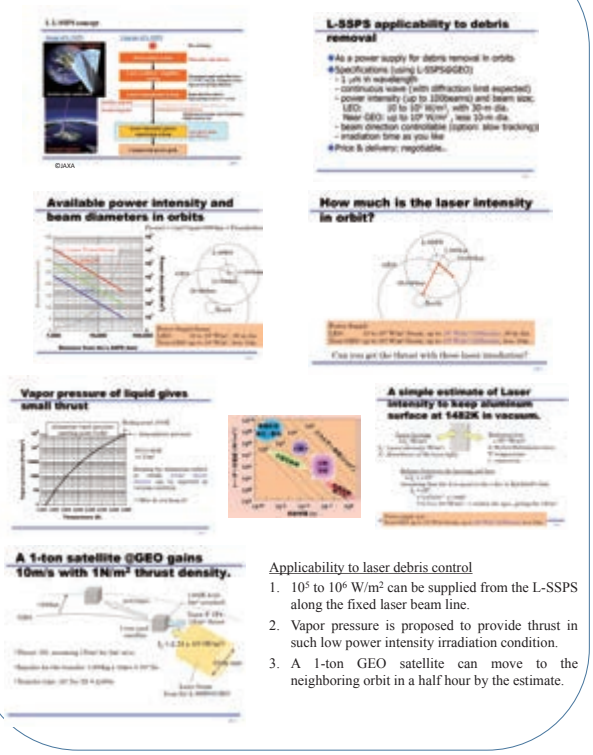


ISSデモ案2（発展的）

ISS搭載レーザー装置からの微小デブリ照射

レーザー宇宙太陽光発電システム(L-SSPS)の利用

GEO上L-SSPSを利用したGEO廃棄衛星の軌道変更



Applicability to laser debris control

1. 10^5 to 10^6 W/m² can be supplied from the L-SSPS along the fixed laser beam line.
2. Vapor pressure is proposed to provide thrust in such low power intensity irradiation condition.
3. A 1-ton GEO satellite can move to the neighboring orbit in a half hour by the estimate.

第6回 スペースデブリワークショップ、JAXA調布、2014年12月17-19日

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P10

地球天候モデルを用いた軌道物体観測計画立案

Orbital object observation strategy based on a global weather model

○田川真(九大), 柳沢俊史, 黒崎裕久, 小田寛(JAXA), 花田俊也(九大)
○Makoto Tagawa (Kyushu Univ.), Toshifumi Yanagisawa, Hirohisa Kurosaki,
Hiroshi Oda (JAXA), Toshiya Hanada (Kyushu Univ.)

地球天候モデルを用いることで, 地上観測網を効率的に運用する手法について提案する. 地表からの光学観測は主にコスト, 分解能の面で軌道上物体監視に適しているが, 天候の影響を強く受ける. 本研究は以下の二つの手法によって, 光学観測効率に対する天候の影響を低減することを図る.
1)地球全体の年間平均雲量分布を天候モデルから求めることで, 高効率な観測が期待できる地点を選定する.
2)各観測地における天候予報データおよび, 監視対象物体リストから効率的な観測計画を立案する.
また同観測計画立案・管理用ソフトウェアについても合わせて紹介する.

This study proposes a methodology to plan observations for orbital objects based on a global weather model. Optical observations from the surface has advantages in cost and resolution however their operation efficiency is strongly affected by weather condition. The methodology aims to reduce the efficiency degradation by following two steps.
1) site location selection using global cloud coverage database
2) automatic observation strategy planning using weather forecast data
An observation strategy planning and management software is also introduced.

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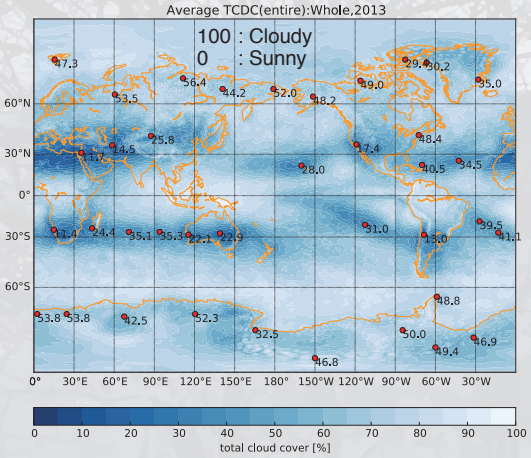
Orbital object observation strategy based on a global weather model

Makoto Tagawa (Kyushu Univ., makoto_t@aero.kyushu-u.ac.jp)
Toshifumi Yanagisawa, Hirohisa Kurosaki, Hiroshi Oda (JAXA) and Toshiya Hanada (Kyushu Univ.)

This study proposes a methodology to plan observations for orbital objects based on a global weather model. Ground-based optical observations have advantages in cost and resolution. However, their operation efficiency is strongly affected by weather condition. We aim to reduce the efficiency degradation by following two steps.
1) Site location selection using global cloud coverage database
2) Automatic observation strategy planning using weather forecast data
We also introduce an observation strategy planning and management software.

Site location selection

Average TCDC [%] (Total ClouD Cover) is calculated by using a global weather model.



The TCDC data is retrieved from the **NOAA/GFS** archive service. The TCDCs of local night time are extracted to assess an observation availability.

Left figure shows the average TCDC of 2013. Each red dot corresponds to a local minimum of the average TCDC. **An effective observatory can be designed by using the data.** The figure indicates that latitude regions around +30 or -30 degrees have an advantage in efficiency of observations.

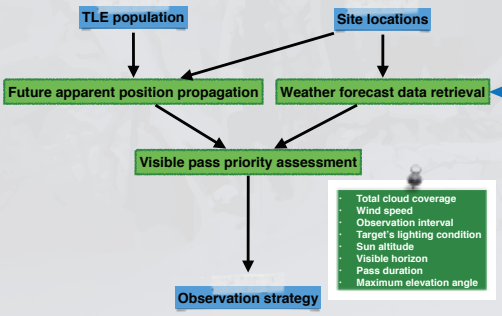
It should be noted that the TCDC distribution uses “entire” cloud layer. Therefore, the data contains overestimations for high altitude places.

National Oceanic and Atmospheric Administration

Global Forecast System

Automatic observation strategy planning

Observation strategy is planned by as follows.



Two preliminary data are required to proceed the planning, an object population file and a site location file. The method propagates each object’ s orbit and retrieves **weather forecast data** for each site. Next, **a priority of a visible pass** is calculated by using propagated and retrieved data. Finally, a observation strategy can be planned by sorting the priorities.

Using API

openweathremap.org

Using the following global forecast models,
+Global Forecast System (NOAA)
+Integrated Forecast System (ECMWF)
+The Global Multi-scale Model (RPN, MRB, CMC)
Mesoscale models, ensemble forecasts,
and weather data of the following agencies or services
+NOAA (USA), Environment Canada, ECMWF (Europe), JMA (気象庁 ,Japan)
+METAR data from airports, APRS, more than 40000 of private weather stations

$$P = W_{tcdc}S_{tcdc} \times W_{wind}S_{wind} \times W_{itvl}S_{itvl} \times B_{ilmn} \times B_{salt} \times B_{vhrz} \times B_{drtn} \times B_{elvn}$$

P : Priority $tcdc$: total cloud cover $salt$: Sun altitude
W : Weight $wind$: wind speed $vhrz$: visible horizon
S : Score $itvl$: observation interval $drtn$: pass duration
B : Boolean $ilmn$: target lighting condition $elvn$: maximum elevation

Two Line Element (TLE), European Centre for Medium-Range Weather Forecasts (ECMWF), Recherche en Prévision Numérique (RPN), Meteorological Research Branch (MRB), Canadian Meteorological Centre (CMC),Japan Meteorological Agency (JMA), Meteorological Terminal Aviation Routine Weather Report (METAR), Automatic Packet Reporting System (APRS)

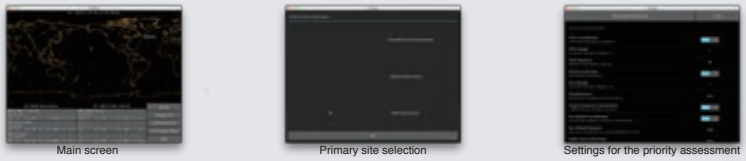
Observation strategy planning and management software

Orbital Watchdog

A software is developed to **plan and manage** the observation strategy with graphical user interface.

The **parameters** in the visible pass priority assessment can be changed in this software.

This software also enables to confirm an orbit of a target and **details of a visible pass**.



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P11

デブリ除去における帯電課題の初期検討

The Plan for Investigation of Spacecraft Charging Issue for Space Debris Removal

○奥村哲平、大川恭志、壹岐賢太郎、青山順一、河本聡美（宇宙航空研究開発機構）
○Teppei Okumura, Yasushi Ohkawa, Kentaro Iki, JunIchiro Aoyama, Satomi Kawamoto(JAXA)

導電性テザーを使用したデブリ除去方式について、宇宙機帯電の観点から衛星システム検討の実施を計画している。衛星システムへの影響について以下の二点を 課題として識別している。
1: ターゲットであるデブリの帯電電位が、除去衛星接触時に衛星システムに与える影響
2: 導電性テザー伸展後に発生する誘導起電力による衛星電位の変動が衛星システムに与える影響
上記、二つの事項につき今後取り得るアプローチと期待される結果について述べる。

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The Plan for Investigation of Spacecraft Charging Issue for Space Debris Removal

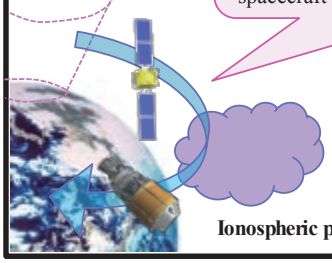
Teppei Okumura, Yasushi Ohkawa, Kentro Iki, JunIchi Aoyama, Satomi Kawamoto
Japan Aerospace Exploration Agency
6th Space Debris Workshop, Dec 17 -19, 2014, Tokyo Japan.

What is Spacecraft ChargingIntroduction

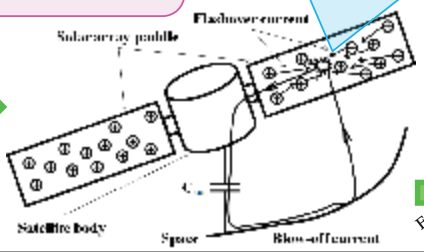
Auroral electron in auroral oval

○The spacecraft has negative potential against ambient plasma because the satellite does not have ground.○The surface has different potential against spacecraft body.

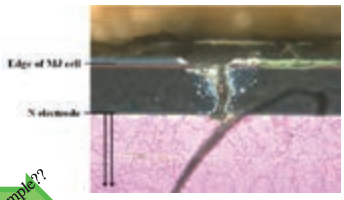
The discharge occurs on the surface of spacecraft. The discharge potentially causes anomaly of spacecraft because the discharge current flows into the electric system of spacecraft.



What happens??



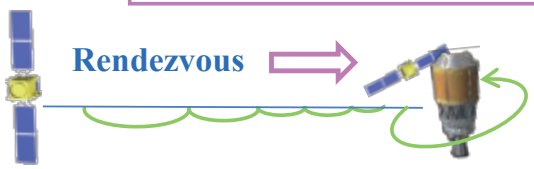
For example??



The above shows the degradation of solar cell due to discharge

Issues

Phase1: Approach to debris (Non-cooperative rendezvous)



Debris Removal Satellite

Phase2: Proximity operations

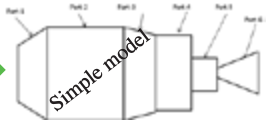
When debris removal satellite attaches the space debris, the discharge event possibly occurs if the potential difference between space debris and debris removal satellite is high. The discharge potentially causes the failure on the electrical system on debris removal satellite.

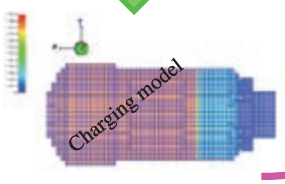
Phase3: De-orbit

If we use the electrodynamic tether system, the potential of satellite against ambient plasma easily exceeds 100V. Because the threshold voltage for the discharge in low earth orbit is 100V. It might be necessary to design the robust system against spacecraft charging.

Our Approach

Issue at proximity operation phase

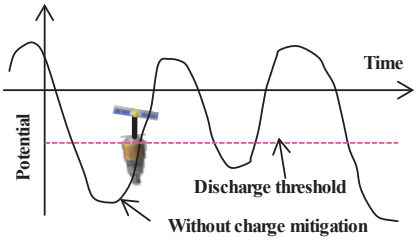




We plan to make the charging model of rocket upper stage for brief estimation of potential against space.

How much charges? Where is risky position for proximity operation?

Issue at De-orbit phase



We will investigate what kinds of charge mitigation technique is suitable for debris removal satellite.

Summary

- We plan to investigate the issues of spacecraft charging for debris removal program.
- We will propose the design of debris removal satellite based on the result of this research.

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P12

テザー牽引を用いたデブリ除去衛星の初期検討
—数値シミュレーションによる設計パラメータやモデルの影響評価—
Satellite active debris removal using tethered tug
-Evaluation of design parameters and modeling by numerical simulations-

○島野徹（早稲田大学），河本聡美，壹岐賢太郎（宇宙航空研究開発機構），
森野美樹（早稲田大学）
○Toru Shimano (Waseda Univ.), Satomi Kawamoto, Kentaro Iki (JAXA),
Yoshiki Morino (Waseda Univ.)

本研究では、ロケット上段などの大型デブリを対象としたテザー牽引を用いたデブリ除去について検討する。デブリ除去手法のひとつとして、スラスタなどの推進系を持った衛星とデブリをテザーによって連結し牽引する手法が、各国で検討されている。この際の挙動に関して、デブリ除去系を離散質点としてモデル化し数値シミュレーションによって解析する。先行研究では2質点モデルを用いたものや深宇宙を想定したものなど簡易的な解析が主である。そこで本研究では、まず離散質点モデルの質点数の影響について比較を行う。さらにスラスタ推力、テザー剛性、テザー長さの設計パラメータおよび初期姿勢が、系の挙動に対してどのように影響するかを評価する。

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テザー牽引を用いたデブリ除去衛星の初期検討
―数値シミュレーションによる設計パラメータやモデルの影響評価―

Active Debris Removal Using Tethered Tug
– Evaluation of Design Parameters and Modeling by Numerical Simulations –

○島野徹(早稲田大学), 河本聡美, 壹岐賢太郎(宇宙航空研究開発機構), 森野美樹(早稲田大学)
○Toru Shimano (Waseda Univ.) , Satomi Kawamoto, Kentaro Iki (JAXA) , Yoshiki Morino (Waseda Univ.)

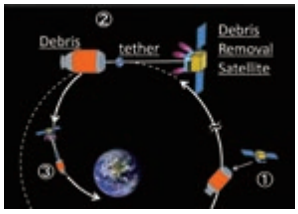
1. Introduction & Purpose

The amount of space debris has been rapidly increasing, and Active Debris Removal (ADR) is needed.

[1] NASA Orbital Debris Program Office, Orbital Debris Quarterly News volume 18January 2014.

■ **Tethered Tug**

- The removal satellite, which is connected to debris by a tether, performs de-orbit maneuver using thrusters
- Possible to perform a controlled re-entry
- Possible to use at the lower enough altitude after de-orbiting by Electrodynamic Tether
- Prior researches evaluate the system's motion by a simplified model such as 2 point masses connected by a spring



Analysis and Evaluation of Design Parameters and Modeling using Multiple Mass Model

2. Numerical Simulation

Simulation Flow

Initial State → Thruster ON (if ΔV=100 [m/s]) → Thruster OFF

■ **Tether model**

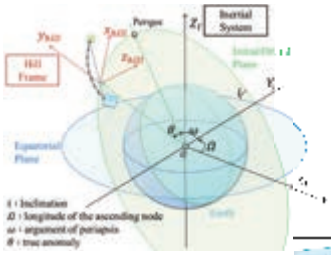
- Multiple mass point model
- Connected with spring and damper
- When compressed, restoring force = 0

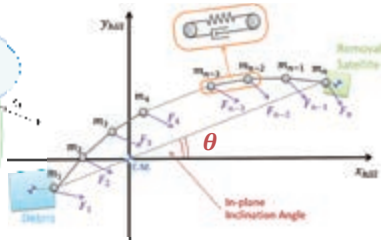
■ **Debris Removal Satellite model**

- Small satellite 1m class (360kg)
- Attitude controlled

■ **Debris model**

- H-2A rocket upper stage (mass: 3000kg, height: 800km)
- Considering attitude motion



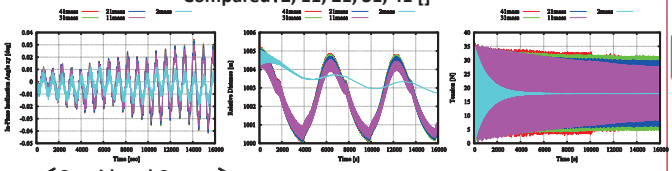


3. Design Parameters & Modeling

<Nominal value>
Number of point mass :21 , Young's modulus:14 [GPa] , Length:1.0 [km] , Thruster force:20 [N]

■ **Number of point mass**

Compared:2, 11, 21, 31, 41 []

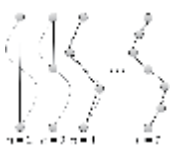


<Considered Causes>

In case of 2 mass,

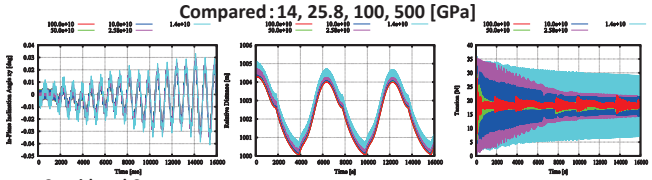
- Reconstruction of tethered structure is imperfect.
- Propagation of longitudinal vibration does not occur.

<Result>
11 to 21 point masses are appropriate considering computational cost



■ **Rigidity (Young's modulus E)**

Compared:14, 25.8, 100, 500 [GPa]



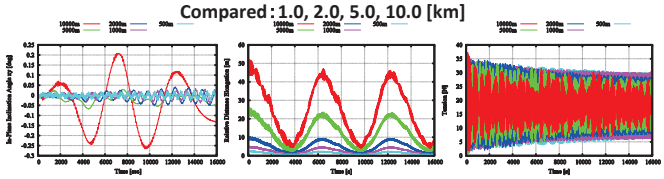
<Considered Causes>

- Higher E = larger spring constant k → faster oscillation decay
- E does not influence maximum tension

<Result>
High rigidity is preferred.

■ **Length**

Compared:1.0, 2.0, 5.0, 10.0 [km]



<Considered Causes>

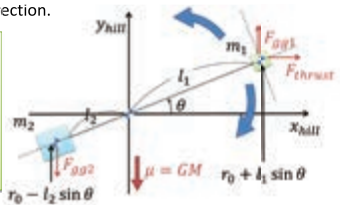
- Same E → Same elongation rate
- Lower k → gradual oscillation spread (low natural frequency)
- Longer Length produces higher gravity gradient → unstable in tangential orbital direction.

Maximum Length before θ divergence

$$l_{max} = \frac{F_{thrust} \cdot {r_0}^3}{3\mu} \cdot \frac{m_1 + m_2}{m_1(m_2 - m_1)}$$

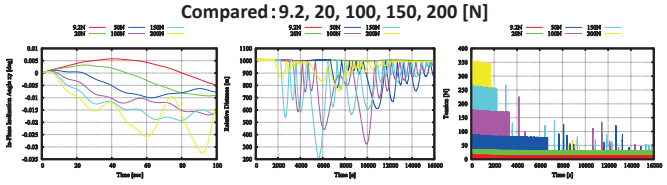
<Result>

- Tether length must be shorter than l_{max}
- Optimum length : minimum length that can keep distance for avoiding collision



■ **Thrust force**

Compared:9.2, 20, 100, 150, 200 [N]



<Result>

- Minimal thrust required by mission (such as for controlled re-entry) is preferred

4. Conclusion

The behavior of tethered tug were evaluated using design parameters of number of point mass, tether length, tether rigidity, thrust.

＜Future Research＞

- **Realistic initial conditions**
- Young's modulus is known to be nonlinear
  → modeling nonlinear spring
- Possibility of collision between debris and satellite without thrust control when the thrust is off
  → Thrust control using such as Input Shaping

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P13

石垣島(石垣島天文台 105cm むりかぶし望遠鏡)での人工衛星・地球接近天体の観測

Observations of Satellites and Near-Earth Objects with Murikabushi 105cm Telescope at the Ishigakijima Astronomical

○花山 秀和 (国立天文台), 宮地 竹史 (国立天文台)
○Hidekazu Hanayama (NAOJ), Takeshi Miyaji (NAOJ)

石垣島天文台は日本の西南端に位置する国立天文台の観測研究施設である。石垣島は日本本土より10度以上緯度が南にあり、黄道や赤道付近にある天体の観測に適したサイトである。石垣島天文台のむりかぶし望遠鏡は九州・沖縄地方では最大の口径(105cm)を持つ光学・赤外線望遠鏡で、カセグレン焦点にはMITSuME3 色同時撮像カメラが搭載されている。石垣島天文台では光・赤外線天文学大学間連携やMITSuME プロジェクトによるガンマ線バーストなどの突発天体観測が行われる一方で、サイト条件の良さを活かした太陽系天体の観測が推進されている。また、近年では人工衛星・地球接近天体に関しても積極的な観測を行っている。本発表では石垣島天文台の望遠鏡や観測装置について紹介するとともに、近年の人工衛星・地球接近天体の観測成果について報告する。

The Ishigakijima Astronomical Observatory is one of the research institutes of National Astronomical Observatory of Japan, which is located on Ishigaki Island in Okinawa Prefecture. Ishigaki Island located in the southwest corner of Japan is the appropriate site for the observation of objects near the celestial equator and the ecliptic. The Murikabushi 105-cm telescope is the largest in the Kyushu/Okinawa area. MITSuME (Multicolor Imaging Telescopes for Survey and Monstrous Explosions) tricolor simultaneous imaging system is mounted on the Cassegrain focus. Observations of transient objects such as gamma-ray burst afterglows are promoted with the domestic collaborations of OISTER (Optical and Infrared Synergetic Telescopes for Education and Research) and MITSuME project. On the other hand, the observations of comets and minor planets are also performed. In recent years, the satellites and the near-Earth objects have been actively observed. In this meeting, we talk about the observatory, and report the observational results of the satellites and the near-Earth objects.

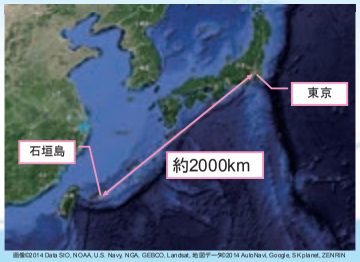
This document is provided by JAXA.

2014年12月17日(水)~19日(金)
JAXA 調布航空宇宙センター 事務棟1号館講堂
第6回 スペースデブリワークショップ

石垣島(石垣島天文台105cmむりかぶし望遠鏡)での人工衛星・地球接近天体の観測

○花山 秀和(国立天文台)
宮地 竹史(国立天文台)

石垣島



画像©2014 Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Landsat, 地図データ©2014 AutoNavi, Google, SKplanet, ZENRIN

石垣島

天文台へのアクセス：空港から車で約40分
市街地から車で約20分

石垣島天文台

- 南の空が見える日本西南端の天体研究観測施設
  - 東経124度08分21.4秒、北緯24度22分22.3秒、標高196.7m
  - 本土より緯度が10度以上南にあり、赤道・黄道付近の天体観測に適した環境
  - 88星座中84星座が見える
  - ジェット気流の影響が少なく大気が安定
  - 2006年4月にオープン
- 天文台建設の目的
  - 石垣島の大気的条件、地理的条件を生かし、太陽系天体の観測的研究を行う
  - VERA石垣島観測局(国立天文台)とともに地域と連携し、国立天文台の活動や天文学の広報普及を行い、地域の教育・振興に役立つ

©石垣島天文台

http://www.miz.nao.ac.jp/ishigaki/content/obs

2階：直径8メートルのドーム
1階：観測制御室、研究室

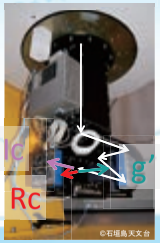
むりかぶし望遠鏡

- ■主鏡有効直径：105cm
  九州・沖縄では最大口径
  リッチー・クレチアン光学系
- ■合成口径比：F12
  カセグレン(F6.5) ナスミス(F20)
- ■焦点位置：
  カセグレン焦点（研究用）
  ナスミス焦点1（研究用）
  ナスミス焦点2（観望用）
- ■架　台：経緯台方式
- ■観測時駆動範囲：
  高度角：15－88度角
  方位角：真南±270度角
- ■ドーム直径：8m（望遠鏡に自動追随）

©石垣島天文台

MITSuME 3色同時撮像カメラ

- ガンマ線バースト即時観測のために搭載された3色(g', Rc, Ic) 同時撮像カメラ
  - MITSuME: Multi-color imaging Telescopes for Surveys and Monstrous Explosions
  - 学術創生研究「ガンマ線バーストの迅速な発見、観測による宇宙形成・進化の研究」および特定領域研究「ガンマ線バーストで探る太古の宇宙」により製作
  - 東工大、京大、国立天文台による共同研究
- 主な仕様
  - 冷却CCDカメラ：Apogee社製 Alta U6
  - フィルター：g', Rc, Ic
  - 画素数(pix)：1024 × 1024
  - 視野：12.3 × 12.3 arcmin
  - 画素スケール：0.72 arcsec/pix
  - 検出限界(mag)：g'=18.7, Rc=19.0, Ic=17.8 (S/N=10,Exp.=1min.)



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人工衛星の観測

- STARS-II (GENNAI) 地上観測天文台ネットワーク

参考資料 香川県屋STARS-II(GENNAI)の共同地上観測
竹内 伸威(STARS-II地上観測天文台ネットワーク・名誉教授立三和 自然館)、
日本公開天文台協会(JAPOS) 第9回全国大会(石垣島大会)

- 香川大学工学部が開発した小型人工衛星
  - STARS-II (Space Tethered Autonomous Robotic Satellite – II)
  - 親機と子機がテザー(ひも)で結ばれた親子衛星
  - 300mのテザーを伸ばし、電流を発生させることを目的に開発された(ローレンツ力による電気推進)
  - スペースデブリ除去の技術検証
  - H-IIAロケット23号機にGPM衛星と相乗り
    - 2014年2月28日 打ち上げ
    - 2014年3月初旬 テザー展開
    - 2014年4月26日 大気圏突入
- 衛星のテザー伸展状況の確認のため共同地上観測キャンペーンを実施
  - 全国の公開天文台等(24施設+個人)が参加

STARS-IIの実機 ©総見研究室

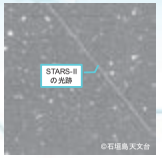
人工衛星の観測

- 観測目的
  - 地上からの光学観測により、テザーの伸展を評価
  - 複数の観測地点のデータにより挙動の解析を行う
- 観測方法
  - ターゲットは上空約400kmの低軌道、スケール~40cm、明るさ~11等
  - 衛星の追尾撮影：銀河の森天文台、富山市天文台
    - 人工衛星の追尾性能を持つ望遠鏡で観測
  - 衛星の待受撮影：他の施設(石垣島天文台を含む)
    - TLE(軌道要素、随時更新)の情報をもとに、Heavensat(軌道計算ソフト)を使って通過経路と時刻を確認
    - 衛星が通過する座標に望遠鏡を向け、通過予定時刻の前後を含む露出時間で観測
    - 写ったものがSTARS-IIか、他の人工衛星か検証

STARS-IIの イメージ ©総見研究室
胴体：16x16x25cm, 5Kg
子機：16x16x15cm, 4Kg

人工衛星の観測

- 観測結果
  - 石垣島天文台では2014年4月16日に観測に成功
    - Heavensat(軌道計算ソフト)による通過時刻と位置
      通過時刻 :05:01:56 (高度56.8583)
      通過位置(RA,DEC): 19 25 56.83, +52 35 17.2
      観測地点の緯度, 経度, 標高: 24.373617, 124.139394, 197m
    - 観測時刻：
      2014年4月16日, 5時01分56.85秒[JST](露出中央)
      [(開始)5時01分50.85秒, (終了)5時02分02.85秒]
    - 露出時間：各バンド12秒
  - 10施設で観測に成功、ただし親子機の分離は確認できず(光跡は1本のみ)
  - 今回の取り組みにより、低軌道上の数10cmスケールの小型人工衛星が地上の1mクラスの望遠鏡によって観測可能であり、衛星の挙動の解析に寄与しうることわかった



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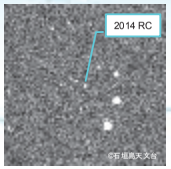
むりかぶし望遠鏡で観測したSTARS-IIの光跡
4月16日、Icバンド12秒露出, 視野: 12.3'x12.3'
(恒星映追尾)

地球接近天体の観測

- 2014 RCのキャンペーン観測
  (日本スペースガード協会)

参考資料 地球近傍小天体2014 RCの観測キャンペーン、浦川 聖太郎(日本スペースガード協会)他、第7回スペースガード研究・衝突天体・スペースガード研究会(―アジア地域観測ネットワークの構築 ― セッション1 地球天体」

- 地球近傍小天体2014 RCは、2014年9月1日にカタリナ・スカイサーベイによって発見された小惑星
- 2014年9月7日(18時02分UT)に地球中心から約4万kmまで接近、直径~20m
- 直径数十メートルクラスの小惑星の物理特性を解明する貴重な機会
- 美星天文台、西はりま天文台、石垣島天文台が観測に参加(石垣島天文台は9月5日と7日に観測を実施)
- 9月1日の発見時の明るさは20等、9月5日は18等、9月7日は13-15等



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むりかぶし望遠鏡で観測した2014 RC、2014年9月5日、Rcバンド60秒露出/枚x18枚,視野:3x3分角 (移動天体追尾)

地球接近天体の観測

- 石垣島天文台における2014 RCの観測
- 2014年9月5日
  - 時刻: 12時52分-17時46分UT(4.9時間)
  - Sky Motion:2.1-1.7['/min], 追尾: 移動天体追尾
  - 露出: 60秒/枚(各バンド)×257枚
- 2014年9月7日
  - 時刻: 13時10分-15時00分UT(1.8時間)
  - Sky Motion:175-41['/min], 追尾: 移動天体追尾
  - 露出: 20秒/枚(各バンド)×225枚
  - 時刻: 15時02分-15時44分UT(0.7時間)
  - Sky Motion:419-658 ['/min], 追尾: 移動天体追尾
  - 露出: 10秒/枚(各バンド)×109枚
  - 時刻: 15時58分-16時15分UT(0.3時間)
  - Sky Motion:781-977 ['/min], 追尾: 恒星時追尾
  - 露出: 20秒/枚(各バンド)×17枚
- 解析結果
  - 9/5のライトカーブから周期解析を行った結果、周期27秒付近に解の兆候を検出
  - 今後は9/7のデータも含めより詳細な解析を行う

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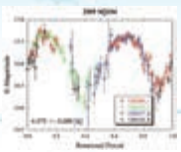
むりかぶし望遠鏡で観測した2014 RC, 2014年9月7日, 3色結合カラー合成, 20秒露出/枚x18枚, 視野:9.6x9.6分角 (恒星映追尾)

JAXAはやぶさ2に関連する連携観測

- JAXA(はやぶさ2地上観測グループ他)
  - 1999 JU3の試験観測(2011年8月 -9月)
  - 将来の探査候補小惑星の観測(2009 SQ104, 2013年5月)
    - ・北大ピリカ望遠鏡による探査候補小惑星の観測(関口朋彦 他, 日本惑星科学会2013年秋季講演会)
    - ・探査候補小惑星の観測(関口朋彦 他, 第6回 スペースガード研究会)
    - ・近地球小惑星 2009 SQ104 の可視光測光分光観測(関口朋彦 他, 日本天文学会2014年春季講演会)
  - 木星トロヤ群観測キャンペーン
    (2013年12月～2014年7月)
    - 1868 Thersites・・・L4
    - 2363 Cebriones・・・L5
    - 5028 Halaesus・・・L4



2009 SQ104の可視光ライトカーブ
赤と緑：北大ピリカ望遠鏡
青と黒：むりかぶし望遠鏡
(北大ピリカ望遠鏡による探査候補小惑星の観測、関口朋彦 他, 日本惑星科学会2013年秋季講演会)

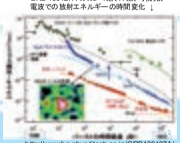
ガンマ線バースト残光観測

- 光・赤外線天文学大学間連携(OISTER: Optical and Infrared Synergetic Telescopes for Education and Research)、MITSuMEプロジェクトによる可視域での残光観測
  - ガンマ線バーストのメカニズムや初代天体の形成史を探る
- 2007年～2014年現在で63回、残光観測or検出限界をGCN(Gamma-ray Coordinates Network) Circular へ報告
  - 2007年 1回, 2008年 2回, 2009年 1回
  - 2010年12回, 2011年14回, 2012年15回
  - 2013年 8回, 2014年10回

・Maselli et al. 2013, Science, 343, 48
"GRB 130427A: a Nearby Ordinary Monster"

・Melandri et al. 2014, A&A accepted
"The nature of the late achromatic bump in GRB 120326A"

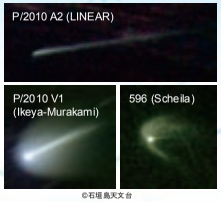
GRB 130427A のガンマ線、X 線、可視光、電波での 放射エネルギーの時間変化 ↓



http://www.whp.phys.titech.ac.jp/GRB130427A/

太陽系天体の観測 -突発現象-

- 2010/01/07　P/2010 A2
  メインベルト内で衝突起源と考えられる彗星状の天体
  - ・Kim et al., 2012, ApJ, 746, L11
    "Multiband Optical Observation of the P/2010 A2 Dust Tail"
- 2010/11/02　P/2010 V1
  ホームズ彗星と似たアウトバーストを起こして発見された彗星
  - ・Ishiguro et al., 2014, ApJ, 787, 55
    "Outbursting Comet P/2010 V1 (Ikeya-Murakami): A Miniature Comet Holmes"
- 2010/12/11　小惑星596
  メインベルト内で衝突起源の彗星状活動を起こした小惑星
  - ・Ishiguro et al., 2011, ApJ, 740, L11
    "Observational Evidence for an Impact on the Main-belt Asteroid (596) Scheila"
  - ・Ishiguro et al., 2011, ApJ, 741, L24
    "Interpretation of (596) Scheila's Triple Dust Tails"



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彗星や小惑星で起こったバースト現象の早期フォローアップ観測を行い、実験モデルや数値計算を用いた比較・分析によってその成因を探る

まとめ

- 日本西南端にある観測施設
  - 赤道・黄道付近の天体観測に有利
- むりかぶし望遠鏡 + MITSuME3色同時撮像カメラ
  - 九州・沖縄で最大の口径105cm光学・赤外線望遠鏡
  - 突発天体の即時観測等で威力を発揮
- 人工衛星・地球接近天体の観測
  - 日本スペースガード協会、JAXA(はやぶさ2関連)等
  - 待ち受け観測によるターゲットの挙動確認
  - 即時観測やモニタリング、明るさの時間変化
- 突発天体の即時観測
  - ガンマ線バーストなどの突発天体(OISTER、MITSuMEプロジェクト)
  - 彗星、小惑星などの太陽系天体における突発現象

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P14

小型光学系による低軌道物体の観測に関する研究

Investigation on the observation of LEO objects by small optical system

星野 智裕 (MHI)
Tomohiro Hoshino (MHI)

宇宙利用の拡大に伴い、スペースデブリとの衝突による損失を回避する上で、デブリの軌道情報やその運動状態を把握することが重要となっている。そのためには、年々増加するデブリの位置を速やかに把握し、その軌道を極力正確に推定出来るシステムを、極力安価に構築することが望ましい。本ワークショップにおいては、市販の小型望遠鏡を利用した低軌道物体の観測軌道決定システムの器材構成及び観測結果例を紹介する。

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小型光学系による低軌道物体の観測に関する研究

○星野 智裕(三菱重工業)、花田 俊也(九州大学)、日南川 英明(九州大学)

三菱重工

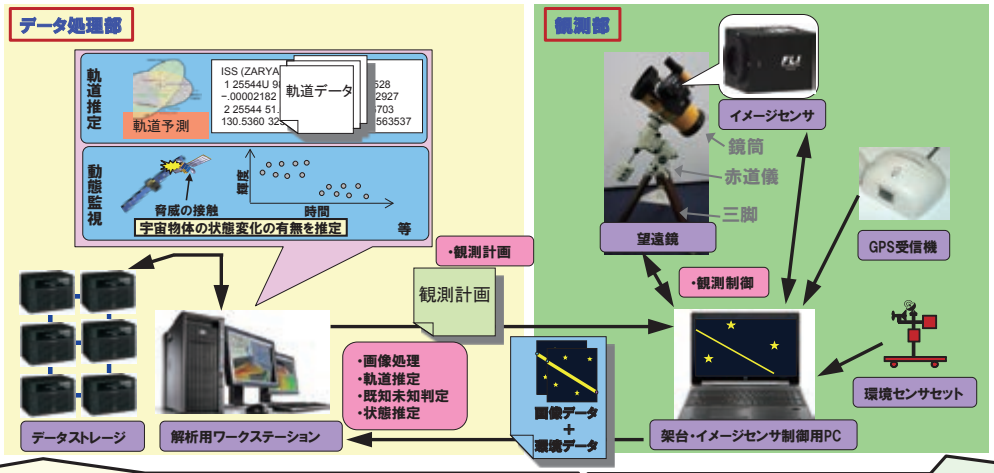
【背景】

宇宙利用の拡大に伴い、スペースデブリとの衝突による損失を回避する上で、デブリの軌道情報やその運動状態を把握することが重要となっている。そのためには、年々増加するデブリの位置を速やかに把握し、その軌道を極力正確に推定出来るシステムを、極力安価に構築することが望ましい。本ワークショップにおいては、市販の小型望遠鏡を利用した低軌道物体の観測軌道決定システムの器材構成及び観測結果例を紹介する。

【機材構成】

コンセプト:小型望遠鏡を利用した安価でコンパクトなシステム

機能:①対処デブリの軌道情報の算出(軌道推定)
②対処デブリの状態認識 (状態認識)



①軌道推定

1回の観測から次回パス時に視野内を通過するだけの精度確保できる軌道推定に関する検討を実施。

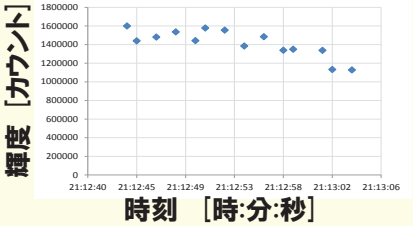
【観測条件】
対象物 :ATLAS R/B
(NORAD番号:28932)
観測場所:MHI 名誉
観測時間:01/31
18:58~19:05
露光時間:0.5s

	TLE	ODTK	楕円軌道
軌道長半径	7472.977092	7434.24	7491.49064
離心率	0.0244089	0.028993	0.0219126
軌道傾斜角	63.4695	63.3639	63.44282
近点引数	345.2183	341.457	347.77425
昇交点赤経	270.2504	250.396	250.52478
平均点離角	14.7817	164.98	145.29434

②状態認識

輝度変化を利用したライトカーブから対象物の状態把握に関する検討を実施。

【観測条件】
対象物 :H-2A R/B
(NORAD番号:28932)
観測場所:MHI 名誉
観測時間:07/01
21:12:~21:13
露光時間:0.5s



小型望遠鏡システム

使用機材		項目	諸元
光学望遠鏡	ε-180 (タカハシ社製)	有効開口径 [mm]	180
		焦点距離 [mm]	512
		F値	2.84
		架台	赤道儀
CCDカメラ	ML29050 (F.L.I社製)	視野角 [deg.]	4.05×2.70
		ピクセル数 [pixel]	6576×4384
		1画素のサイズ [μm]	5.5×5.5

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付録　講演プログラム

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第６回スペースデブリワークショップ

2014 年 12 月 17 日(水),18 日(木),19 日(金)

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

12 月 17 日(水) 13:30 ～ 17:40

13:30 **開会挨拶** 樋口清司(JAXA)

国際セッション(英語)

13:40 A1. **宇宙利用の長期持続性と宇宙空間平和利用委員会の役割**
○堀川康(宇宙空間平和利用委員会前議長、JAXA)

14:10 A2. **宇宙航空研究開発機構のスペースデブリ関連研究について**
○伊東康之(JAXA)

14:40 A3. The latest space debris related research and technology activities in the European Space Agency
○Holger Krag(ESA)

15:40 A4. **民間企業による ADR サービス実現の具体的方法**
○岡田光信(ASTROSCALE)

16:10～16:20 **休憩**

16:20 B1. **世界のデブリ関連規制の動向**
○加藤明(JAXA)

16:40 B2. **宇宙ごみのモデリングとその応用について**
○花田俊也(九大)

17:00 B3. **デブリ観測・防御技術の研究開発動向**
○柳沢俊史, 東出真澄(JAXA)

17:20 B4. **デブリ除去技術の概要と動向**
○河本聡美, 大川恭志, 壹岐賢太郎, 青山順一, 奥村哲平, 片山保宏(JAXA)

18:00～20:00 **懇親会**（JAXA 調布食堂）

12 月 18 日(木) 10:00 ～ 17:20

10:00 C1. **ロケットに対するデブリ対策の現状と取組み**
○齊藤靖博, 沖田耕一(JAXA)

10:20 C2. **地球周回近領域デブリの影響評価及びその起源イベントの識別**
○Melissa Zemoura, 花田俊也(九大), 河本聡美(JAXA)

10:40 C3. **非協力的ターゲットに対する航法誘導制御技術の研究**
○中島悠, 山元透, 村上尚美, 山中浩二(JAXA)

11:00 C4. **デブリ近傍領域における除去衛星の姿勢軌道制御について**
○田中啓太, 加藤貴昭, 桑尾文博(NEC), 山元透, 中島悠, 村上尚美, 池内正之(JAXA)

11:20 C5. **デブリ除去における画像計測と運動推定についての現状報告**
○片山保宏, 渡邊恵佑, 鈴木悟史(JAXA), 林正人(ニック), 河本聡美(JAXA)

11:40 C6. **デブリ軌道変換用の推進系取付技術について**
○青山順一, 河本聡美, 大川恭志, 奥村哲平, 壹岐賢太郎, 片山保宏, 山元透, 村上尚美, 中島悠(JAXA)

12:00～13:20 **昼休み（後半：ポスターコアタイム）**

13:20 D1. **PAF を対象としたデブリ捕獲用把持システムの概念検討**
○柴﨑浩一, 久保田伸幸, 榎本雅幸(川崎重工), 河本聡美, 大川恭志, 青山順一, 片山保宏(JAXA)

13:40 D2. **デブリ除去のための導電性テザー技術の検討**
○壹岐賢太郎, 河本聡美, 大川恭志, 奥村哲平, 青山順一(JAXA)

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14:00 D3. **HTV 搭載導電性テザー実証実験(KITE)について**
〇大川恭志, 河本聡美, 奥村哲平, 壹岐賢太郎, 堀川雄太, 川島一能, 三浦尚幸, 高井元, 鷲谷正史, 川崎治, 辻田大輔, 葛西徹, 植松洋彦, 井上浩一(JAXA)
14:20 D4. **導電性テザー実証実験に向けた HTV 開発状況**
〇辻田大輔, 葛西徹, 中野英一郎, 植松洋彦, 河本聡美, 大川恭志, 井上浩一(JAXA)
14:40 D5. **デブリ除去衛星システムサイジング検討<その 2>**
〇廣田賢治, 渡辺順一郎(TECS), 桑尾文博, 大塚聡子(NEC), 河本聡美, 池内正之(JAXA)

15:00～15:20 **休憩**

15:20 E1. **デブリ除去のための国際枠組みの検討**
〇後藤大亮, 辻田大輔, 河本聡美(JAXA), 大塚聡子, 神武直彦, 狼嘉彰(慶應大･院)
15:40 E2. **宇宙法研究所におけるデブリ研究会検討状況の報告**
青木節子(慶應大), 小塚荘一郎(学習院大), 内冨素子, 岸人弘幸, 〇川島興介(JAXA)
16:00 E3. **デオービット用膜面展開機構の開発**
〇高井元(JAXA), 古谷寛, 坂本啓(東工大), 奥泉信克, 宮崎英治, 井上浩一(JAXA)
16:20 E4. Conventional safety consideration for controlled reentry and measures for improvement
〇吉原徹(JAXA)
16:40 E5. **スペースデブリの超高速衝突解析のモデル化法の諸問題について**
〇片山雅英, 竹場敦史(伊藤忠テクノソリューションズ CTC)
17:00 E6. **イカロス探査機搭載ダスト検出器「ALADDIN」による地球・金星間の大型宇宙塵分布の直接計測**
〇矢野創, 平井隆之(JAXA), 岡本千里(神戸大), 藤井雅之(ファムサイエンス), 田中真(東海大), IKAROS-ALADDIN チーム

12 月 19 日(金) 10:00 ～ 16:50

10:00 F1. **京都大学におけるスペースデブリへの取り組み～軌道・観測・低減～**
〇山川宏(京大)
10:20 F2. **GEO デブリの画像処理及び光度変動**
〇小田寛, 黒崎裕久, 柳沢俊史(JAXA), 田川真(九大)
10:40 F3. **低軌道デブリ地上光学観測システム**
〇黒崎裕久, 柳沢俊史, 小田寛(JAXA), 田川真(九大)
11:00 F4. **スペースデブリの軌道上光学観測**
〇松本晴久(JAXA), 泉山卓(IHI)
11:20 F5. **JAXA 衛星に対するスペースデブリ接近解析の現状**
〇阿部旬也, 松田郁未, 池田人, 池田沙織, 坂本拓史, 田島徹(JAXA)

11:40～13:00 **昼休み (後半:ポスターコアタイム)**

13:00 G1. **美星スペースガードセンターにおけるスペースデブリ光学観測への取り組み**
〇奥村真一郎, 西山広太, 浅見敦夫, 浦川聖太郎, 坂本強, 橋本就安, 高橋典嗣 (JSGA)
13:20 G2. **静止軌道の宇宙状況監視技術の開発 ー小型光学望遠鏡での挑戦ー**
〇泉山卓, 樋川治, 平井健二, 北澤幸人, 橋本こずえ(IHI)
13:40 G3. **Remediation of cm-size debris from the International Space Station**
〇Toshikazu Ebisuzaki(RIKEN), Mark N. Quinn(IZEST), Satoshi Wada, Lech Wiktor Piotrowski, Yoshiyuki Takizawa(RIKEN), Marco Casolino(RIKEN, INFN), and Mario Bertaina(University of Torino), Philippe Gorodetzky, Etienne Parizot(APC-CNRS/Paris7 University), Toshiki Tajima(IZEST, Dept. of Physics and Astron. University), Remi Soulard and Gerard Mourou(IZEST)
14:00 G4. **デブリ軌道アーカイブの逆問題的解析と微光デブリの追跡に関する研究紹介**
〇上津原正彦, 樋口知之(統計数理研)
14:20 G5. **軌跡を用いた軌道上物体検出手法の提案と適用結果**
〇田川真(九大), 柳沢俊史, 黒崎裕久, 小田寛(JAXA), 花田俊也(九大)

14:40～15:00 **休憩**

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15:00 H1. **HTV-5 における微小デブリセンサ実証実験の計画**
〇奥平修, 松本晴久, 辻田大輔, 小林裕希(JAXA), 北沢幸人(IHI)
15:20 H2. **デブリ衝突損傷リスク解析ツールに関する最近の機能拡充**
〇八田真児, 上田裕子, 中渡瀬竜二(MUSCAT SE), 東出真澄, 河本聡美(JAXA)
15:40 H3. **超高速衝突耐性を持つ宇宙服積層構成の評価**
〇川瀬暁, 青木伊知郎, 和田理男, 金子祐樹, 山口孝夫(JAXA)
16:00 H4. **微小デブリ衝突に関する研究の状況と課題**
〇東出真澄, 黒崎裕久, 長谷川直(JAXA)
16:20 H5. **太陽電池パネルの微小粒子衝突による電気的影響評価**
〇川北史朗, 艸分宏昌, 松本晴久(JAXA)
16:40 **閉会挨拶** 大西充(JAXA)

ポスター発表

P01. **Direct Bayesian Admissible Region 手法による軌道物体追跡の改良**
〇藤本浩平(テキサス A&M 大)
P02. **超高速衝突による飛翔体直径がイジェクタサイズ分布に与える影響**
〇平岩泰幸, 石田魁人, 御代川直人, 西田政弘(名工大), 林浩一(鳥羽商船高専), 長谷川直 (JAXA)
P03. **レーザーパルス繰返し照射によるアルミニウムアブレーション積算力積特性**
〇鶴田久, Wang Bin, Wang Zhongyuan, 佐宗章弘(名大)
P04. **ジグザグに折りたたまれた導電性テープテザーの展開力学特性解析**
〇松崎秀太(神奈川工科大), 杉本洋平(JAXA), 藤井裕矩(神奈川工科大)
P05. **レーザーアブレーション反力による衛星回転の制御の可能性**
〇戎崎俊一, 和田智之(理研)
P06. **レーザーアブレーションによる宇宙デブリ除去システムの研究**
戎崎俊一, 〇滝澤慶之, 大森整(理研)
P07. **有機物・微生物の宇宙曝露と宇宙塵・微生物の捕集「たんぽぽ」: その概要と準備状況**
山岸明彦, 〇横堀伸一(東京薬大), 矢野創, 橋本博文, 河口優子(JAXA), 今井栄一(長岡技大),
奥平恭子(会津大), 河合秀幸(千葉大・院), 癸生川陽子, 小林憲正(横浜国大・院), 佐々木聰(東京工科大),
田端誠(千葉大・院), 中川和道(神戸大・院), 東出真澄(JAXA), 三田肇(福岡工大), 薮田ひかる(大阪大・院),
たんぽぽ研究チーム
P08. **たんぽぽ捕集パネルに衝突する粒子フラックス予測**
〇栗原愛美(法大・院), 東出真澄(JAXA), 高柳優, 新井和吉(法大), 矢野創(JAXA), 田端誠(千葉大),
長谷川直(JAXA), 山岸明彦(東京薬大)
P09. **レーザー照射によるデブリ制御と ISS デモ提案**
〇藤田和久, 内田成明(光大), 佐宗章弘, 鶴田久(名大), 山田克彦(阪大)
P10. **地球天候モデルを用いた軌道物体観測計画立案**
〇田川真(九大), 柳沢俊史, 黒崎裕久, 小田寛(JAXA), 花田俊也(九大)
P11. **デブリ除去における帯電課題の初期検討**
〇奥村哲平, 大川恭志, 壹岐賢太郎, 青山順一, 河本聡美(JAXA)
P12. **テザー牽引を用いたデブリ除去衛星の初期検討**
―数値シミュレーションによる設計パラメータやモデルの影響評価―
〇島野徹(早大), 河本聡美, 壹岐賢太郎(JAXA), 森野美樹(早大)
P13. **石垣島(石垣島天文台 105cm むりかぶし望遠鏡)での人工衛星・地球接近天体の観測**
〇花山秀和, 宮地竹史(国立天文台)
P14. **小型光学系による低軌道物体の観測に関する研究**
〇星野智裕(MHI)

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6th Space Debris Workshop

December 17-19, 2014

Administration Bldg. No1 2F Lecture-hall, JAXA Chofu Aerospace Center

Wednesday 17 December 13:30 ～ 17:40

13:30 **Opening remarks** *Kiyoshi Higuchi(JAXA)*

International Session(English)

13:40 A1. **Long Term Sustainability of Outer Space and Role of UNCOPUOS**
○Yasushi Horikawa(Chair of UNCOPUOS, JAXA)

14:10 A2. **Overview of JAXA's Space Debris related Research Activities**
○Yasuyuki ITO(JAXA)

14:40 A3. **The latest space debris related research and technology activities in the European Space Agency**
○Holger Krag(ESA)

15:40 A4. **A private company's solution to implement space debris removal service**
○Nobu Okada(ASTROSCALE)

16:10～16:20 **Break**

16:20 B1. **Current situation of the international space debris mitigation standards**
○Akira Kato(JAXA)

16:40 B2. **Orbital Debris Modeling and Applications**
○Toshiya Hanada(Kyushu Univ.)

17:00 B3. **Research and Development of Space Debris Observation and Protection Technologies**
○Toshifumi Yanagisawa, Masumi Higashide(JAXA)

17:20 B4. **Overview of studies on active debris removal**
○S. Kawamoto, Y. Ohkawa, K. Iki, J. Aoyama, T. Okumura, Y. Katayama(JAXA)

18:00～20:00 **Reception** (JAXA Chofu Cafeteria)

Thursday 18 January 10:00 ～ 17:20

10:00 C1. **Debris mitigation status for rocket upper stage in Japan**
○Yasuhiro Saito, Koichi Okita(JAXA)

10:20 C2. **Evaluation of the impacts of near-Earth-orbit debris removal & track of impactful events' origins**
○Melissa Zemoura, Toshiya Hanada(Kyushu Univ.), Satomi Kawamoto(JAXA)

10:40 C3. **A research toward guidance, navigation, and control for a Non-Cooperative Target**
○Yu Nakajima, Toru Yamamoto, Naomi Murakami, Koji Yamanaka(JAXA)

11:00 C4. **Attitude and orbit control of the active debris removal satellite**
○Keita Tanaka, Takaaki Kato, Fumihiro Kuwao(NEC), Toru Yamamoto, Yu Nakajima, Naomi Murakami, Masayuki Ikeuchi(JAXA)

11:20 C5. **Current Progress in the Application of Visual-based Perception and Motion Estimation for Space Debris Removal**
○Yasuhiro Katayama, Keisuke Watanabe, Satoshi Suzuki(JAXA), Masato Hayashi(Ltd. Nick), Satomi Kawamoto(JAXA)

11:40 C6. **Mounting Technology of the Propulsion System for De-orbiting Debris**
○Junlchi Aoyama, Satomi Kawamoto, Yasushi Ohkawa, Teppei Okumura, Kentaro Iki, Yasuhiro Katayama, Toru yamamoto, Naomi Murakami, Yu Nakajima(JAXA)

12:00～13:20 **Luncheon (latter half: Core Time for Poster Session)**

13:20 D1. **Conceptual Study of Mechanical and Sensing System for Debris Capturing for PAF**
○Kouichi Shibasaki, Nobuyuki Kubota, Masayuki Enomoto(KHI), Satomi Kawamoto, Yasushi Ohkawa, Junichi Aoyama, Yasuhiro Katayama(JAXA)

13:40 D2. **Study of Electrodynamic Tether technology for Active Debris Removal**
○Kentaro Iki, Satomi Kawamoto, Yasushi Ohkawa, Teppei Okumura, Junlchi Aoyama(JAXA)

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14:00 D3. **Current Development Status of Electrodynamic Tether Experiment on HTV**
○ Yasushi Ohkawa, Satomi Kawamoto, Teppei Okumura, Kentaro Iki, Yuuta Horikawa, Kazutaka Kawashima, Yoshiyuki Miura, Moto Takai, Masahito Washiya, Osamu Kawasaki, Daisuke Tsujita, Toru Kasai, Hirohiko Uematsu, and Koichi Inoue(JAXA)

14:20 D4. **HTV Development Status for ElectroDynamic Tether Experiments**
○Daisuke Tsujita, Toru Kasai, Eiichiro Nakano, Hirohiko Uematsu, Satomi Kawamoto, Yasushi Ohkawa and Koichi Inoue(JAXA)

14:40 D5. **Debris removal satellite system sizing examination #2**
○Kenji Hirota, Junichiro Watanabe(TECS), Fumihiro Kuwao, Akiko Otsuka(NEC), Satomi Kawamoto, Masayuki Ikeuchi(JAXA)

15:00～15:20 **Break**

15:20 E1. **Study of International Framework on space debris removal**
○Daisuke Goto, Daisuke Tsujita, Satomi Kawamoto(JAXA), Akiko Otsuka, Naohiko Kotake, Yoshihiko Ohkami(Graduate School of SDM, Keio Univ.)

15:40 E2. **Status report of Debri Study Group in the Institute of Space Law**
Setsuko Aoki(Keio Univ.), Kozuka Souichirou(Gakushuin Univ.), Motoko Uchitomi(JAXA), Kishindo Hiroyuki(JAXA), ○Kosuke Kawashima(JAXA)

16:00 E3. **Development of Membran Deployment mechanism for Deorbiting**
○Moto Takai(JAXA), Hiroshi Furuya,Hiraku Sakamoto(Tokyo Institute of Technology), Nobukatsu Okuizumi, Eiji Miyazaki, Koichi Inoue(JAXA)

16:20 E4. **Conventional safety consideration for controlled reentry and measures for improvement**
○ Toru YOSHIHARA(JAXA)

16:40 E5. **Some Problems of Modeling Method on Hypervelocity Impact Analysis of Space Debris**
○Masahide KATAYAMA, Atsushi TAKEBA(ITOCHU Techno-Solutions (CTC))

17:00 E6. **Direct Measurement of Large Meteoroid Distribution between the Earth and Venus by the ALADDIN Dust Detector onboard the IKAROS Spacecraft**
○Hajime YANO, Takayuki HIRAI(JAXA), Chisato OKAMOTO(Kobe Univ.), Masayuki FUJII(FAM Science), Makoto TANAKA(Tokai Univ.), IKAROS-ALADDIN Team

Friday 19 January 10:00 ～ 16:45

10:00 F1. **Space Debris Research at Kyoto University**
○Hiroshi Yamakawa(Kyoto Univ.)

10:20 F2. **Image-processing and light curve of orbital objects around GEO**
○Hiroshi ODA, Hirohisa KUROSAKI, Toshifumi YANAGISAWA(JAXA), Makoto TAGAWA(Kyushu Univ.)

10:40 F3. **Ground Optical Observation System for LEO Debris**
○Hirohisa Kurosaki, Toshifumi Yanagisawa, Hiroshi Oda(JAXA) and Makoto Tagawa(Kyushu Univ.)

11:00 F4. **Space Based Optical Observation of Space Debris**
○Haruhisa Mastumoto, Taku Izumiyama(IHI)

11:20 F5. **Current Status of Conjunction Assessment for JAXA satellites**
○Junya Abe, Ikumi Matsuda, Hitoshi Ikeda, Saori Ikeda, Takushi Sakamoto, Toru Tajima(JAXA)

11:40～13:00 **Luncheon (latter half: Core Time for Poster Session)**

13:00 G1. **Status of the optical observations of space debris at the Bisei Spaceguard Center**
○Shin-ichiro Okumura, Kota Nishiyama, Atsuo Asami, Seitaro Urakawa, Tsuyoshi Sakamoto, Nariyasu Hashimoto, and Noritsugu Takahashi(JSGA)

13:20 G2. **Space Situational Awareness System for Resident Space Objects in GEO Belt - Challenge of Small Optical System -**
○ Taku Izumiyama, Osamu Hikawa, Kenji Hirai, Yukihito Kitazawa, Kozue Hashimoto(IHI)

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13:40 G3. **Remediation of cm-size debris from the International Space Station**
○Toshikazu Ebisuzaki(RIKEN), Mark N. Quinn(IZEST), Satoshi Wada, Lech Wiktor Piotrowski, Yoshiyuki Takizawa(RIKEN), Marco Casolino(RIKEN, INFN), and Mario Bertaina(University of Torino), Philippe Gorodetzky, Etienne Parizot(APC-CNRS/Paris7 University), Toshiki Tajima(IZEST, Dept. of Physics and Astron. University), Remi Soulard and Gerard Mourou(IZEST)

14:00 G4. **Researches on inversion analyses of debris orbit archive and tracking of faint debris**
○Masahiko Uetsuhara, Tomoyuki Higuchi(The Institute of Statistical Mathematics)

14:20 G5. **Orbital object detection algorithm using streaks**
○Makoto Tagawa(Kyushu Univ.), Toshifumi Yanagisawa, Hirohisa Kurosaki, Hiroshi Oda(JAXA), Toshiya Hanada(Kyushu Univ.)

14:40～15:00 **Break**

15:00 H1. **Demonstration Experiment of Space Debris Sensor on HTV-5**
○Osamu Okudaira, Haruhisa Matsumoto, Daisuke Tsujita, Yuki Kobayasi(JAXA), Yukihito Kitazawa(IHI)

15:20 H2. **Latest Expansion of Tactical Utilities for Rapid ANalysis of Debris on Orbit Terrestrial**
○Shinji Hatta, Hiroko O. Ueda, Ryuji Nakawatase(MUSCAT SE), Masumi Higashide, Satomi Kawamoto(JAXA)

15:40 H3. **Hypervelocity Impact Protective Lay-up Evaluation for Spacesuit**
○Satoru KAWASE, Ichiro AOKI, Yoshio WADA, Yuki KANEKO, Takao YAMAGUCHI(JAXA)

16:00 H4. **Research Status and Action of Sub-millimeter Debris Impact Damage on Spacecraft Structure**
○Masumi Higashide, Hirohisa Kurosaki, Sunao Hasegawa(JAXA)

16:20 H5. **Hypervelocity impact effects of small particles on solar arrays**
○Shirou Kawakita, Hiroaki Kusawake, Haruhisa Matsumoto(JAXA)

16:40 **Closing address** *Mitsuru Ohnishi(JAXA)*

Poster Session

P01. **Improvements to Resident Space Object Tracking with the Direct Bayesian Admissible Region Approach**
○Kohei Fujimoto(Texas A&M Univ.)

P02. **Influence of Projectile Diameter on Size Distribution of Ejecta Resulting from Hypervelocity Impacts**
○Yasuyuki Hiraiwa, Kaito Ishida, Naoto Miyokawa, Masahiro Nishida(Nagoya Institute of Technology), Koichi Hayashi(National Institute of Technology, Toba College) and Sunao Hasegawa(JAXA)

P03. **レーザーパルス繰返し照射によるアルミニウムアブレーション積算力積特性**
○鶴田久, Wang Bin, Wang Zhongyuan, 佐宗章弘(名大)

P04. **ジグザグに折りたたまれた導電性テープテザーの展開力学特性解析**
○松崎秀太(神奈川工科大), 杉本洋平(JAXA), 藤井裕矩(神奈川工科大)

P05. **Suppression of Satellite Rotation by the Reaction Force by Laser Ablation**
○Toshikazu Ebisuzaki, Satoshi Wada, Yoshiyuki Takizawa (RIKEN)

P06. **Study of the removal of the space debris by the laser ablation**
Toshikazu Ebisuzaki, ○Yoshiyuki Takizawa, Hitoshi Ohomori(RIKEN)

P07. **有機物・微生物の宇宙曝露と宇宙塵・微生物の捕集「たんぽぽ」:その概要と準備状況**
山岸明彦, ○横堀伸一(東京薬大), 矢野創, 橋本博文, 河口優子(JAXA), 今井栄一(長岡技大), 奥平恭子(会津大), 河合秀幸(千葉大・院), 癸生川陽子, 小林憲正(横浜国大・院), 佐々木聰(東京工科大), 田端誠(千葉大・院), 中川和道(神戸大・院), 東出真澄(JAXA), 三田肇(福岡工大), 薮田ひかる(大阪大・院), たんぽぽ研究チーム

P08. **Impact Frequency Estimate of Micron-sized Meteoroids and Debris on Tanpopo Capture Panels on the ISS**
○Manami Kurihara(Hosei Univ.), Masumi Higashide(JAXA), Yuu Takayanagi, Kazuyoshi Arai(Hosei Univ.), Hajime Yano(JAXA), Makoto Tabata(Chiba Univ.), Sunao Hasegawa(JAXA), Akihiko Yamagishi(University of Pharmacy and Life Sciences)

P09. **Space debris control with laser irradiation and a demonstration proposal at ISS**
○Kazuhisa Fujita, Shigeaki Uchida(GPI), Akihiro Sasoh, Hisashi Tsuruta(Nagoya Univ.), Katsuhiko Yamada(Osaka Univ.)

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P10. **Orbital object observation strategy based on a global weather model**
○Makoto Tagawa(Kyushu Univ.), Toshifumi Yanagisawa, Hirohisa Kurosaki, Hiroshi Oda(JAXA), Toshiya Hanada(Kyushu Univ.)

P11. **The Plan for Investigation of Spacecraft Charging Issue for Space Debris Removal**
○Teppei Okumura, Yasushi Ohkawa, Kentaro Iki, Junlchiro Aoyama, Satomi Kawamoto(JAXA)

P12. **Active debris removal using tethered tug**
-Evaluation of design parameters and modeling by numerical simulations-
○Toru Shimano(Waseda Univ.), Satomi Kawamoto, Kentaro Iki(JAXA),Yoshiki Morino(Waseda Univ.)

P13. **Observations of Satellites and Near-Earth Objects with Murikabushi 105cm Telescope at the Ishigakijima Astronomical**
○Hidekazu Hanayama, Takeshi Miyaji(NAOJ)

P14. **Investigation on the observation of LEO objects by small optical system**
○Tomohiro Hoshino(MHI)

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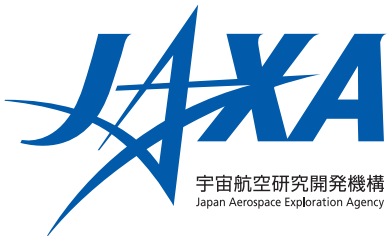

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