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宇宙航空研究開発機構特別資料
JAXA Special Publication

第5回「スペースデブリワークショップ」講演資料集
Proceedings of the 5th Space Debris Workshop

デブリ除去に向けたHTV搭載導電性テザー実証実験のイメージ図

2014年3月

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

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宇宙航空研究開発機構特別資料
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第５回「スペースデブリワークショップ」講演資料集
Proceedings of the 5th Space Debris Workshop

研究開発本部
未踏技術研究センター

Aerospace Research and Development Directorate
Innovative Technology Research Center

2013 年 1 月 22 日，23 日
宇宙航空研究開発機構
調布航空宇宙センター

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

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巻頭の言葉

平子 敬一
宇宙航空研究開発機構 研究開発本部 未踏技術研究センター長

Keiichi Hirako
Director, Innovative Technology Research Center,
Aerospace Research and Development Directorate, JAXA

日本の高度経済成長期に、環境汚染や地球温暖化のリスクをどの程度予見したであろうか、まして、日本初の人工衛星「おおすみ」の 1970 年の打上げで代表される日本の宇宙開発の黎明期に、宇宙開発活動の活性化によって将来宇宙飛翔体が増加する結果、宇宙機同士の衝突が生じることをどのくらいの人が予測したであろうか。

経済活動に伴い河川水が汚染されて魚が生息しなくなり、スモッグのために青空が少なくなったような環境汚染に対して国として対策した結果、魚が棲めるようになり、青空を見上げることができるようになってきた。これは、日本の企業や国民の意識改革による環境回復活動の成果であると考える。また、地球温暖化問題は日本のみでなく、世界中の国の危機意識と連携して、世界的な対応を講じている。

宇宙デブリ問題も上記と類似したプロセスを経てきている。宇宙開発の黎明期には予想できなかった国際的課題として年々認識が高まっていること、また、その対策に多くの技術課題や法的考慮などの研究開発課題を有しており、デブリを議論するコミュニティーが拡大してきている。

宇宙航空研究開発機構（JAXA）では、古くから少数のメンバでデブリ問題の研究を開始し、その後問題認識が高まるにつれて関係する人員も増加してきている。そしてデブリ対策を世界的に議論し研究するようになって、世界との協働も活性化してきている。

JAXA は、世界との情報交換を考慮して海外からの招待講演を含めてデブリワークショップを隔年で開催している。今回は日本航空宇宙学会の後援を得て開催して登壇者も含め 165 名が参加した。この参加人数は指数的に増加しており、デブリが宇宙開発と利用において重要な課題として認識されていることが分かる。

デブリ対策が宇宙開発に携わる世界中の人々に十分認識されて、全員が問題解決に積極的に取り組む風土が醸成され、今後の宇宙開発活動が安定的に維持されることを願っている。

国際セッション

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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 and Role of UNCOPUOS

堀川 康 （宇宙空間平和利用委員会 議長）

Yasushi Horikawa (Chair of UNCOPUOS)

Space science and technology and their applications, such as satellite communications, Earth observation systems and satellite navigation technologies, provide indispensable tools for achieving viable long-term solutions for sustainable development and can contribute more effectively to efforts to promote the development of all countries and regions of the world, to improving people's lives.

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 mishaps, misperceptions 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 status of discussions among the related states will be presented.

Biography - - - - -

Yasushi HORIKAWA (Japan)

He is a technical counselor of Japan Aerospace Exploration Agency (JAXA), Tokyo Japan. He graduated at Tokyo University and he received PhD from Tokyo University on Electrical Engineering. He worked in the field of spacecraft design. He contributed to the implementation of Japanese meteorological satellite programs and the Earth observation programs. He also contributed to the achievement of the Japanese space station program as the Program Manager. After that, he was responsible for the application satellite programs as an executive director of JAXA, including Earth observations, communications and broadcasting, and global positioning satellites and those operation and utilization as well. At the present time, he is advising to the activities of the Japanese application satellite development and utilization programs in JAXA. He is a president of Japan society of cost estimate and analysis since 2011. He is a professor of Tokai University and he is a chairman of UN COPUOS for 2012-2013.

He is a member of IEICE, JAAS, AIAA, IAA, JRS, JSCEA and SCEA.

Operational Satellite in Space

Categories:

- Communication
- Broadcasting
- Weather Forecast
- Earth Observation
- Positioning, Navigation and Timing
- Engineering Experiment
- Science
- Exploration
- Manned
- Security
- Military

Orbit	Operational Satellites
LEO	~ 450
MEO	~ 55
GEO	~ 400

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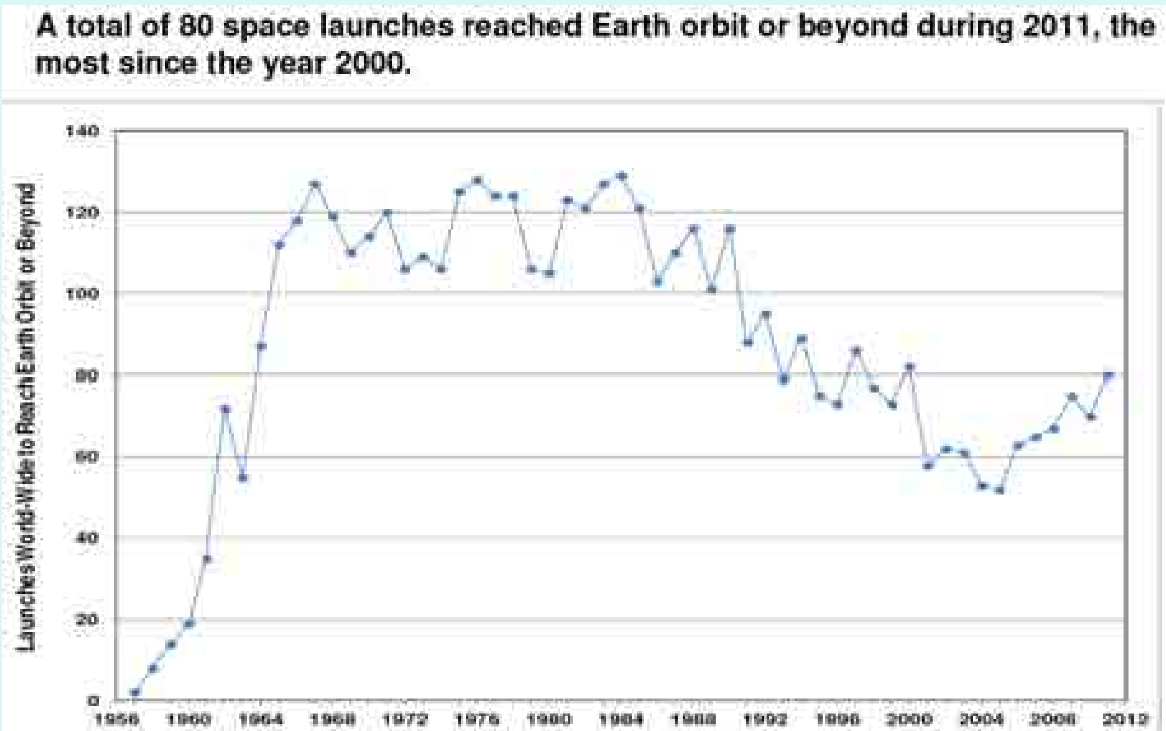
“ Space is helping us to address some of today’s most urgent problems. Space technology has produced tools that are transforming weather forecasting, environmental protection, humanitarian assistance, education, medicine, agriculture and a wide range of other activities.”

Former United Nations Secretary-General Kofi Annan, on the occasion of the World Space Week, 2001

Launch Activity 1957 - 2012



Nicholas Johnson, NASA

Coordination Mechanisms for the Use of Outer Space

CEOS-GEOSS------------------Earth Observation
UN-ICG----------------------------Global Positioning
WMO: CGMS--------------------Meteorological
Space Station Partners------Space Station
Science Community----------Science
Amateur Community---------Amateur
ITU Frequency allocation----Most Satellites with Exception

No Coordination Mechanisms
- Small Satellites
- Commercially procured
- Security
- Military

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Objectives of the COPUOS

UNCOPUOS to facilitate;

- the activities and resources of the United Nations, the specialized agencies and other international bodies relating to the peaceful uses of outer space;
- international cooperation and programmes in the field that could appropriately be undertaken under United Nations auspices;
- organizational arrangements to facilitate international cooperation in the field within the framework of the United Nations; and
- legal problems which might arise in programmes to explore outer space.

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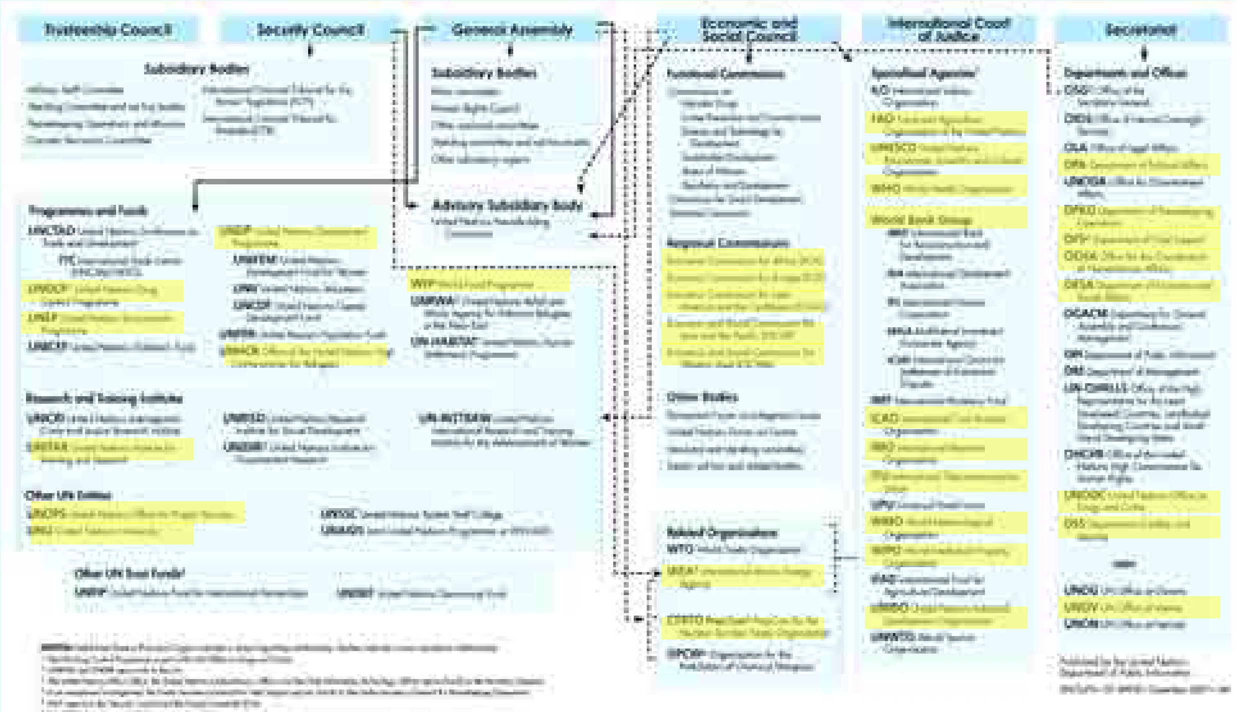
Space and the United Nations System



Member States: 193

Personnel: 44000

UN and Outer Space: Early Years

- 1959: UN General Assembly resolution 1472 (XIV) reaffirmed the role of COPUOS and mandated the Committee to:
  - Review international co-operation
  - Study space-related activities that could be undertaken under United Nations auspices
  - Encourage and assist with national space research programmes
  - Study legal problems which may arise from the exploration of outer space;

Committee on the Peaceful Uses of Outer Space

- 1961: Establishment of two Subcommittees
  - Scientific and Technical Subcommittee (STSC)
  - Legal Subcommittee (LSC)
- Membership to date:74 member States and 32 organizations with permanent observer status
- Reports to the Fourth Committee of the General Assembly
- Adopts an annual resolution on "International Cooperation in the Peaceful Uses of Outer Space"

United Nations Office for Outer Space Affairs

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United Nations Committee on the Peaceful Uses of Outer Space

Albania, Algeria, Argentina, Australia, Austria, Azerbaijan, Belgium, Benin, Bolivia, Brazil, Bulgaria, Burkina Faso, Cameroon, Canada, Chad, Chile, China, Colombia, Cuba, Czech Republic, Ecuador, Egypt, France, Hungary, Germany, Greece, India, Indonesia, Iran, Iraq, Italy, Japan, Kazakhstan, Kenya, Lebanon, Libya, 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, Costa rica, Jordan, Armenia

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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
1968	Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space
1972	Convention on International Liability for Damage Caused by Space Objects
1976	Convention on Registration of Objects Launched into Outer Space
1984	Agreement Governing the Activities of States on the Moon and Other Celestial Bodies
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
Framework	
2009	Safety Framework for Nuclear Power Source Application in Outer Space

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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

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SPACE AGENDA TODAY

- GREENING SPACE:

Mitigating Space Debris

‣Space debris includes defunct satellites, discarded sections of rockets and parts of satellites that have exploded. Most numerous of all are tiny particles such as paint chips and liquid droplets.

‣ Space debris orbits the Earth at incredibly high speeds, normally several kilometres per second, making even small particles a hazard to active satellites and space missions.

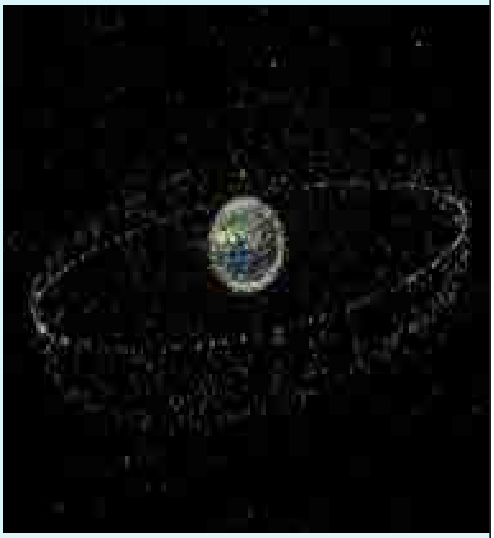

Image: Artist's impression ©ESA

‣In 2007, COPUOS achieved a major result by adopting its own **Space Debris Mitigation Guidelines.** There is general agreement among States that the implementation of these voluntary guidelines for the mitigation of space debris at the national level would increase mutual understanding on acceptable activities in space, thus enhancing stability in space and decreasing the likelihood of friction and conflict.

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SPACE AGENDA TODAY

- THREATS FROM ASTEROIDS:

Near-Earth Objects

‣Near-Earth objects (NEOs) are asteroids, comets and large meteoroids whose orbit intersects the Earth's orbit and may therefore pose a danger of collision.

‣ NEOs with a diameter of over 1 km hit the Earth a few times in a million years.

‣COPUOS works on establishing international procedures and decision-making mechanisms for dealing with a potential NEO threat.

Photo: Japan's Hayabusa space probe travelled to the Itokawa asteroid and in 2010 returned the first samples of an asteroid to Earth. Photo ©JAXA

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SPACE AGENDA TODAY

Long-term sustainability of outer space activities:
SUSTAINABLE SPACE = SUSTAINABLE DEVELOPMENT ON EARTH

- **Sustainable development on Earth is not possible without sustainable space.**

- **Space applications such as earth observation, communications, navigation, timing and positioning provide strong support for the implementation of the actions called for in the United Nations development agenda.**

- **COPUOS works on issues such as:**
"Space and sustainable development"
-the use of space technology and its applications climate change, food security, monitoring of natural resources, agriculture....

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United Nations Register of Objects Launched into Outer Space

- Established in 1962, the Register is the central repository of official information provided by States on space objects in accordance with the Registration Convention and on a voluntary basis.
- The Register contains information received from the Member States and also complementary information collected from external sources on all functional objects launched into outer space since 1957.
- Space debris and non-functional objects are not included.
- Search could be performed using different parameters (name, international designator, launching State, date of launch, orbital status, etc.)
- The links between space objects and their relevant registration documents are provided. This way, every user can download and print any registration document.
- All information contained in the Register is publicly available via the UNOOSA website:

www.unoosa.org

- Since 1957, about 38.300 space objects have been tracked in Earth orbit or beyond. Approximately 6.400 are "functional" (i.e. satellites, probes, manned spacecraft and/or space station components). The rest are spent rocket boosters, shrouds and detached components or other residual nonfunctional components resulting from the launch, operation or termination of the space object, collectively known as "non-functional")

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Domestic legislation

- National legislation domesticates international treaty obligations
- National register of space objects
- Licensing and other regulatory practices allows States to implement non-binding international norms into national practices
- Non-binding does not mean non-legal

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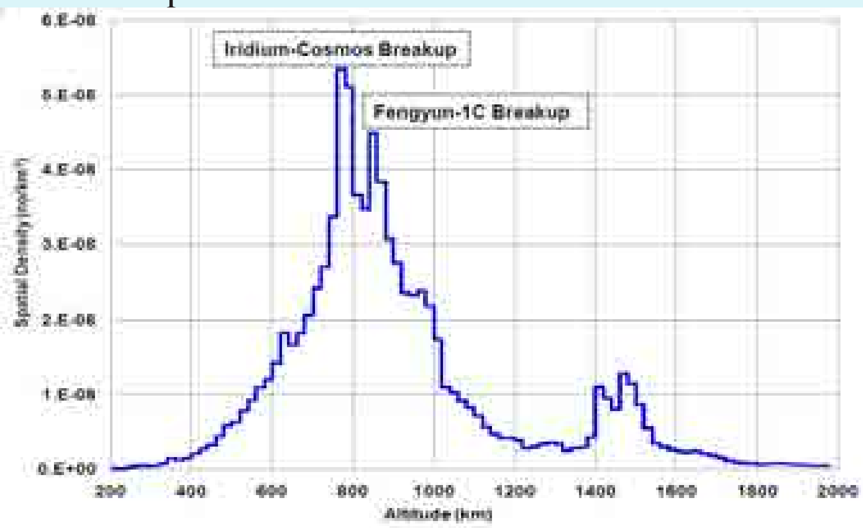
The concern

- The growing population of space objects in orbit may in time make activities in regions of near-Earth space hazardous and extremely expensive
- U.S. now tracks about 17,000 objects in Earth orbit
  - ~ 1,000 working satellites
  - ~ 21,000 debris pieces > 10 cm



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But that’s not all…

consistentlyでなければトラックできている？

- Objects smaller than 10 cm are not consistently trackable
  - There may be as many as 500,000 objects of 1-10 cm size
  - Perhaps as many as 10s to 100s of millions < 1 cm
- No active collision avoidance is possible for such objects
- These objects can cripple or destroy spacecraft and endanger astronauts
- Total mass ~ 6300 tons

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Sources of debris

- Defunct spacecraft
- Mission debris
- Rocket bodies
- Fragmentation debris
  - Explosions
  - Degradation
- Collisions
- Deliberate debris creation
  - ASAT tests

Images: ESA

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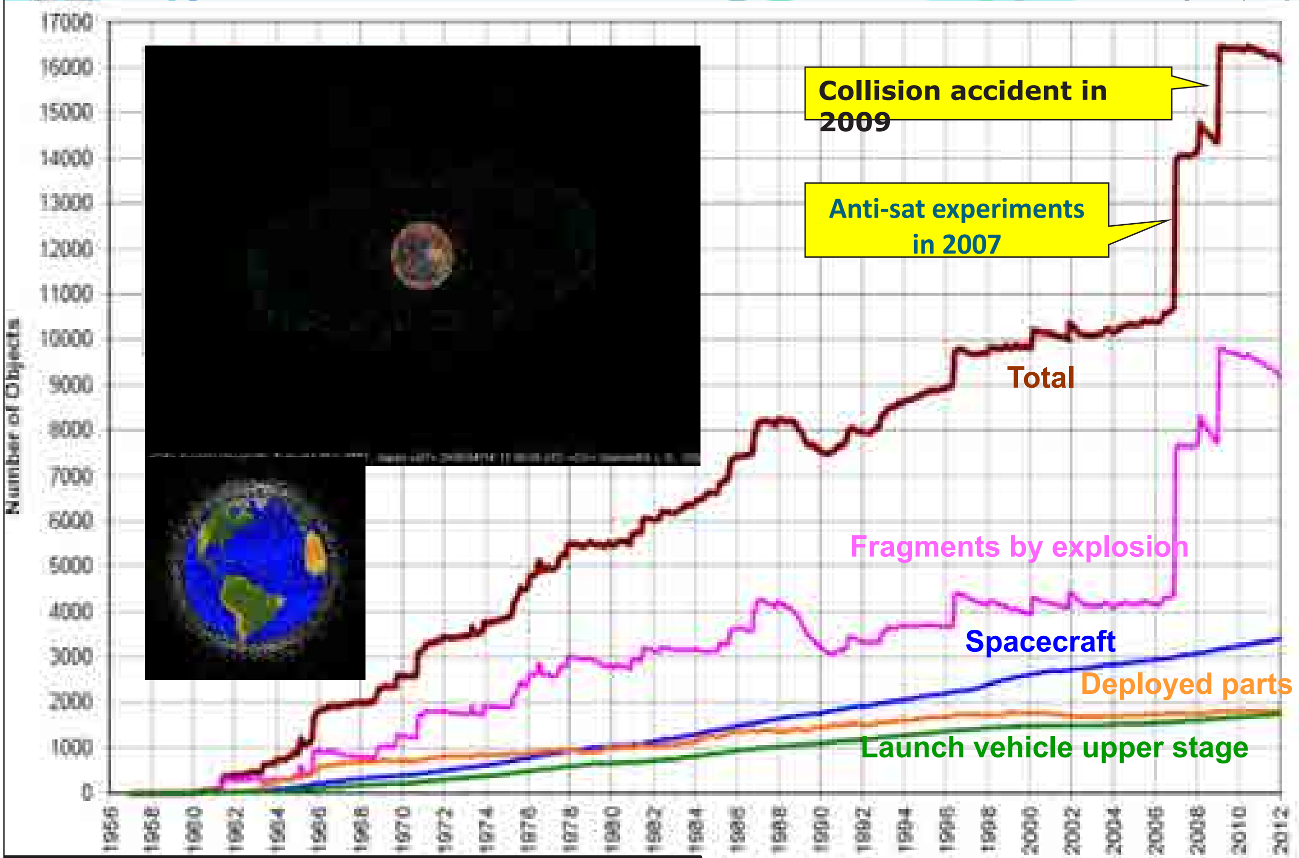
Number of Objects in Earth Orbit by Object Type



(Low Earth orbit: over 10cm, geostationary orbit: over 1m)

Catalog data of Space Surveillance Network, NASA 20

Working Group on Long-term Sustainability of Outer Space

Objectives of the Working Group

- To identify and examine a wide range of issues and concerns to the long-term sustainability of space activities
- To prepare a consolidated set of practices and operating procedures and guidelines.

a. sustainable space utilization;
b. space debris mitigation;
c. safe space operations and collision avoidance;
d. space situational awareness;
e. impact of space weather phenomena on operational space systems;
f. national regulatory frameworks, including guidance for actors in the space arena and technical standards,
g. technical and legal capacity-building

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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 Anthony Wicht (Australia)

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Space Situational Awareness (SSA)

- Aims towards a full knowledge of the dynamic near-Earth space environment
- Three main pillars of SSA
  - Space weather
  - Space debris
  - NEOs
- Makes use of a variety of optical and radar techniques
- Requires coordinated, multisite networks of sensors
  - On Earth (& in space)

http://globalssasensors.org/

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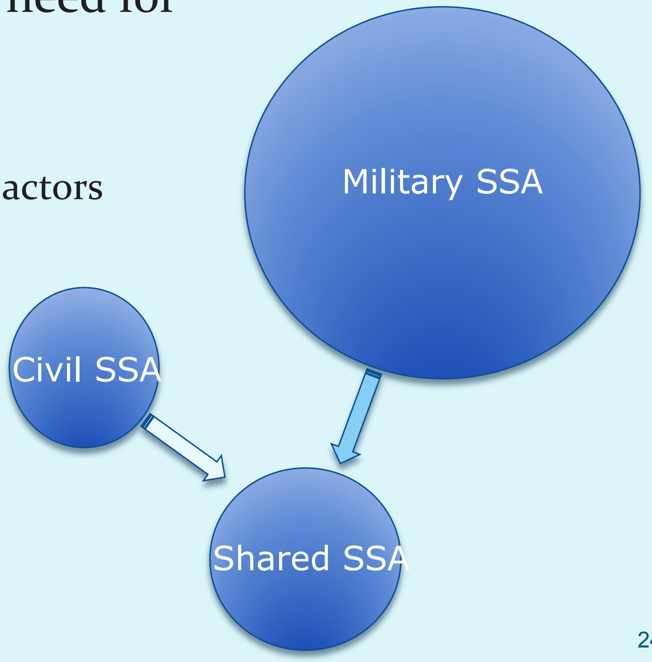
SSA – Broadening the SSA base

- Currently, almost all SSA is done for ***military purposes***
- Emerging recognition of the need for
  - Civil SSA to support safety
  - Sharing of SSA between
    - Government and commercial actors
    - With other governments
    - With the public



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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

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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

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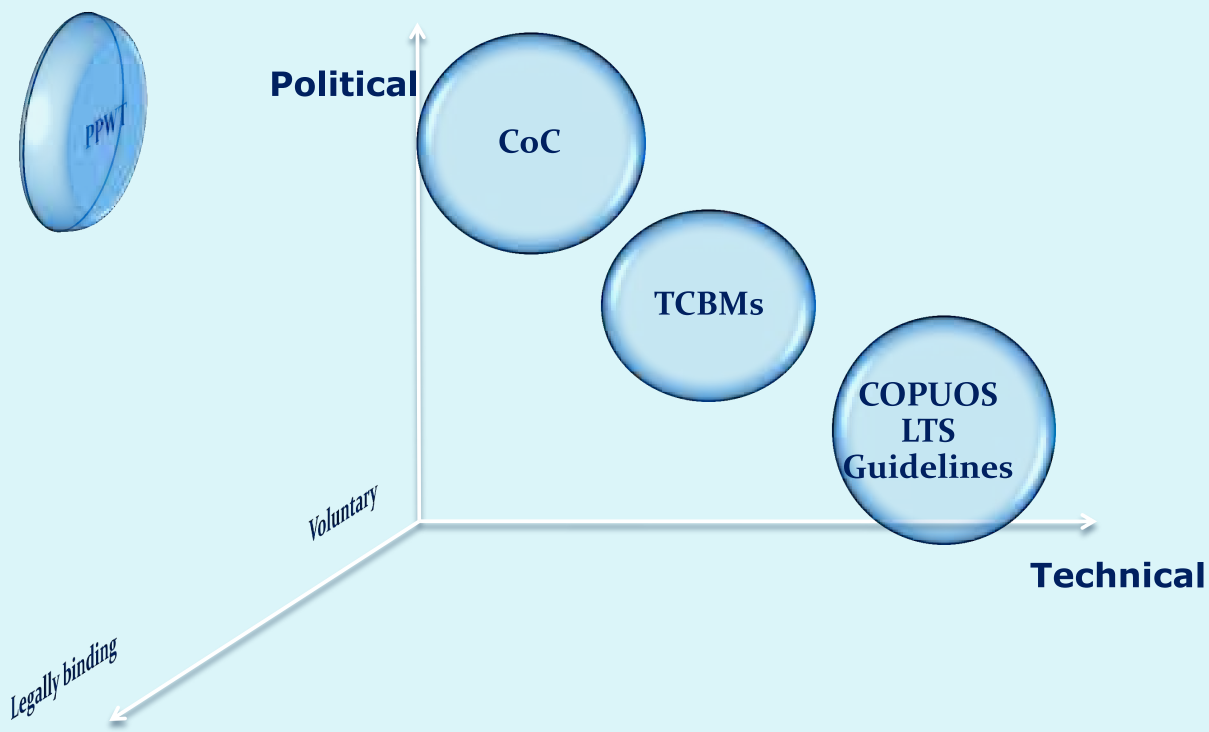
How do these initiatives relate to each other?



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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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Thank you for your attention!

Visit to UNOOSA　Website :

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

"Bringing the benefits of space to humankind"

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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活動について

Overview of JAXA's Space Debris related Activities

伊東康之（宇宙航空研究開発機構 研究開発本部）

Yasuyuki ITO (JAXA/ARD)

Space debris is a risk factor for all the countries and organizations who perform space activities. For example, multiple collision damages are possible for satellites with projected areas exceeding 10 m^2. 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 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 1mm φ 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活動を概観する。

Biography - - - - -

ITO, Yasuyuki
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 Directrate: Synthetic Aperture Radar, Microwave Radiometer
Conseptual 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 Resorces Dept., Audit & Evaluation Office, Earth Obs. Science Team Management

Overview of JAXA's Space Debris related Activities

January 2013
5th Space Debris Workshop
at Chofu, Tokyo

Yasuyuki ITO, JAXA/ARD

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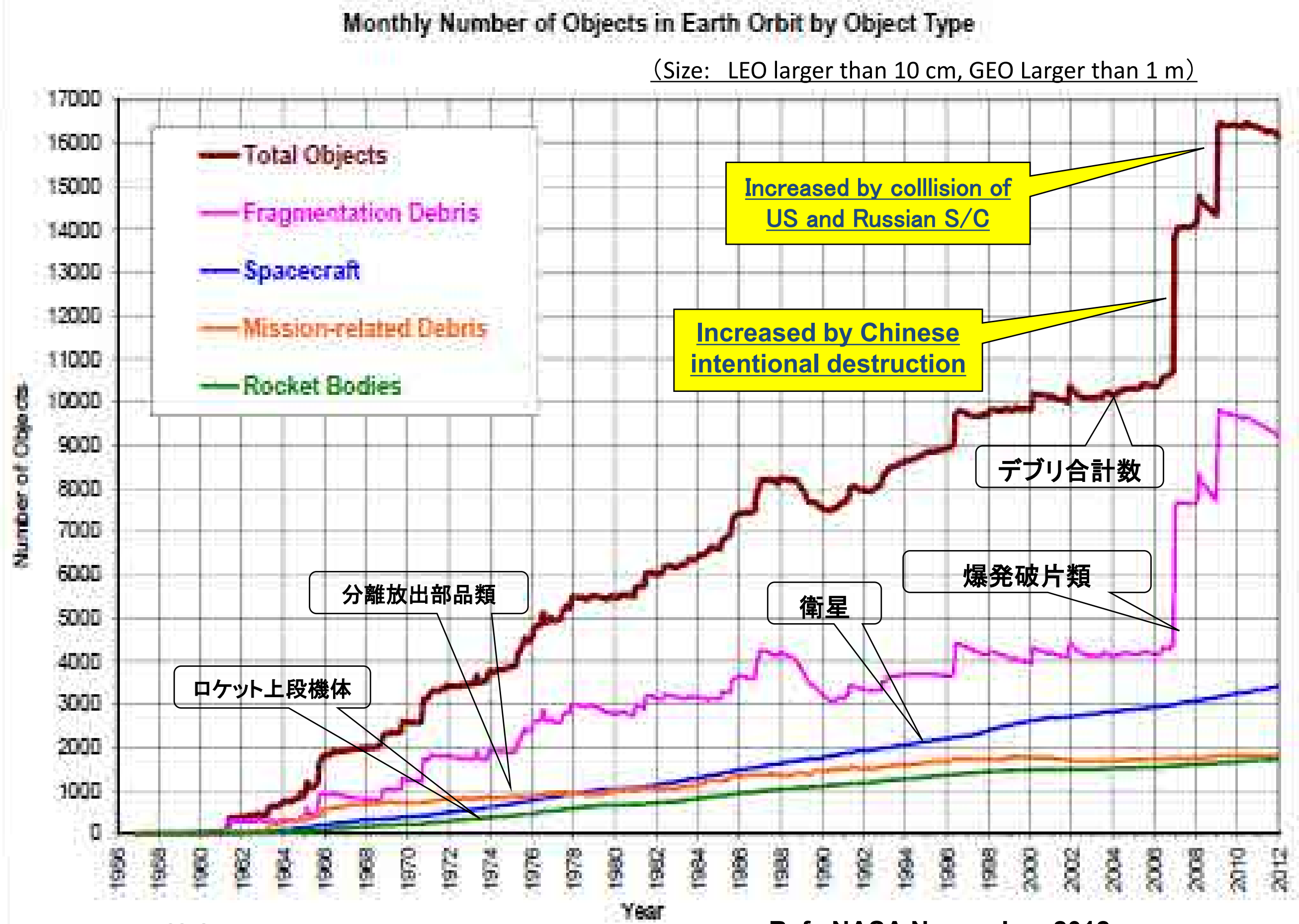
– Basics updates
– “ Clear and present danger”

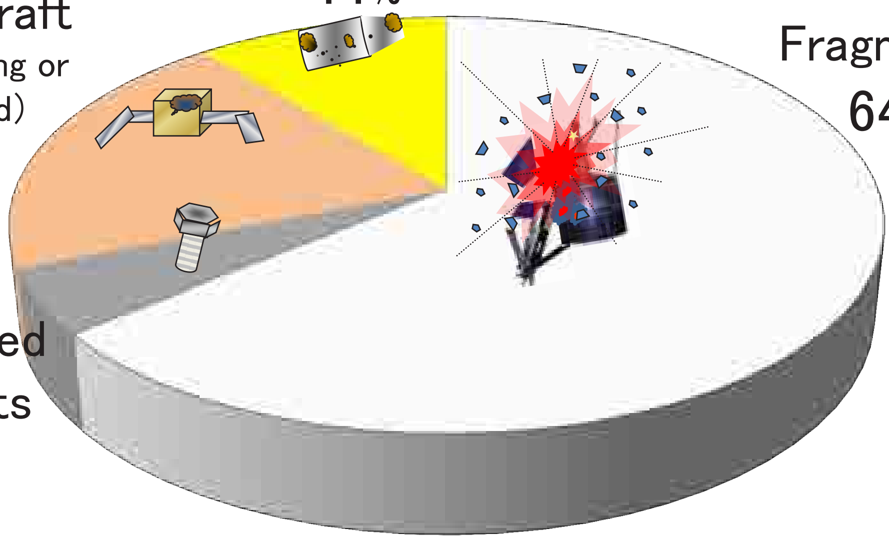
Y.Ito : Jan. 2013 3



Y.Ito : Jan. 2013 Ref. NASA News Jan. 2012 4

Causes of Generation of Debris

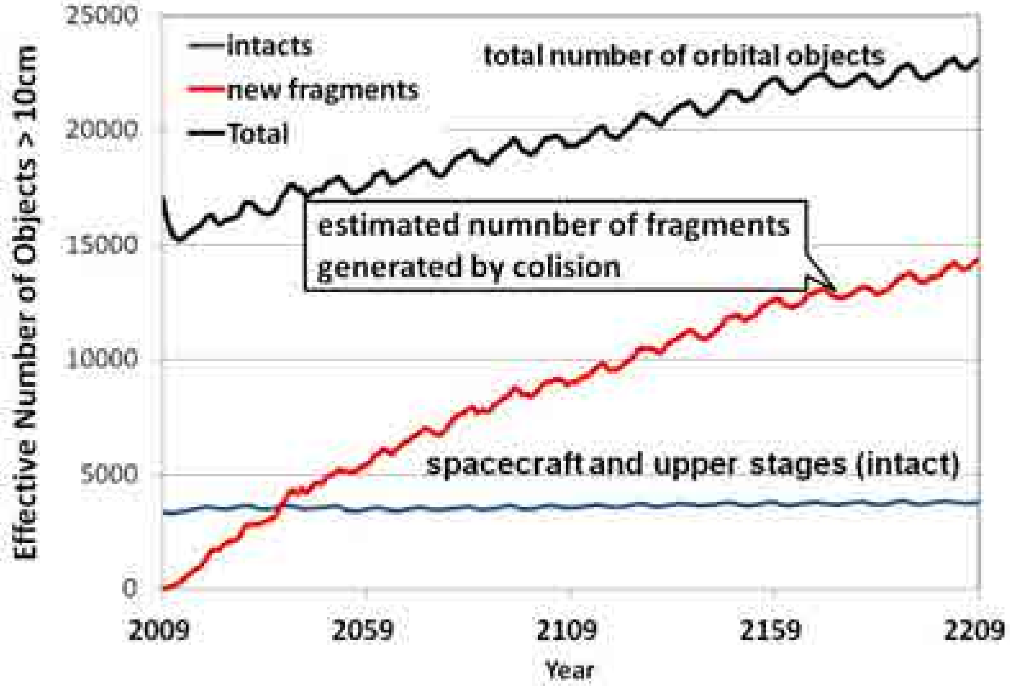
（地上観測可能な物体について）



Ref. ESA Report to UN/COPUOS／STSC Feb. 2011

Y.Ito : Jan. 2013 5

Prediction of Number of Orbital Objects Increased by Collision



Average number of objects analyzed by Monte-Carlo simulation 60 cycles by the following condition;
(1) number of explosion : no after 2009,
(2) number of launching operation : number of launch events from 2001 to 2008 will be repeated.
(3) compliance with 25-year-rule: 90% **【Ref; Article by JAXA and Kyushu Univ.】**

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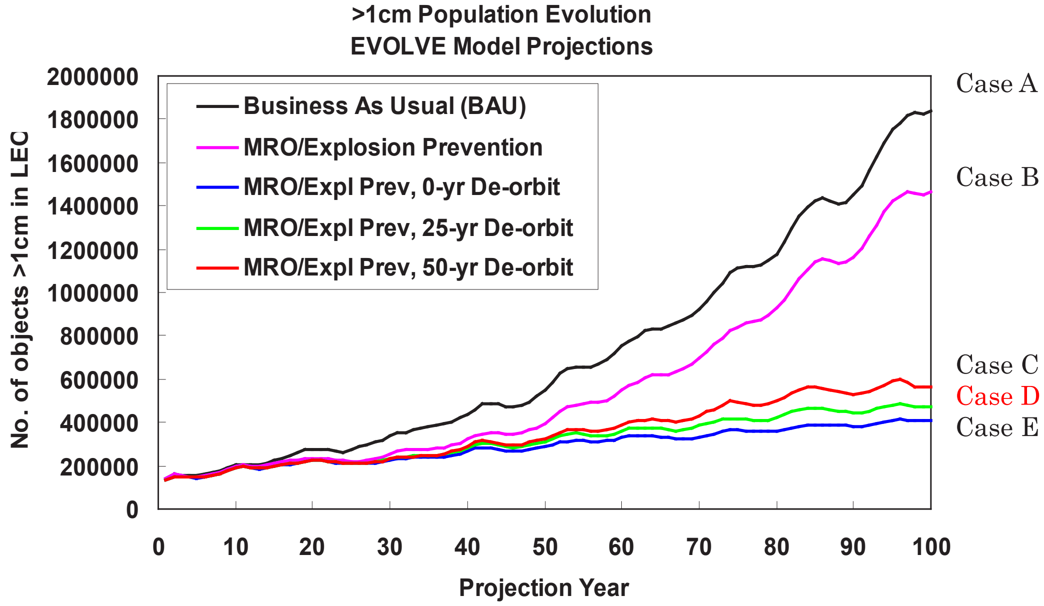
Mitigation Measures and their effects

[Ref. End-of-life Disposal of Space Systems in the Low Earth Orbit Region, IADC/WG 2, 1 March 2002,]

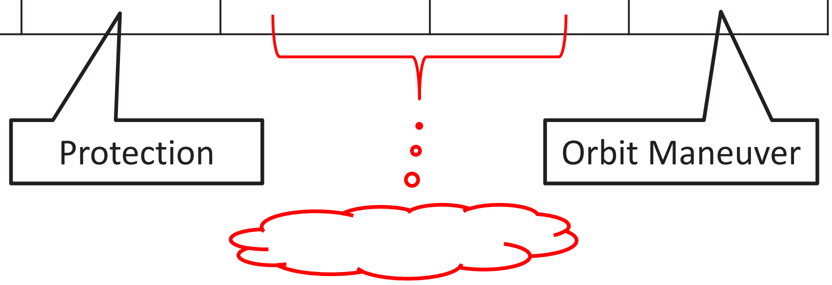


Case A: Any mitigation measures will not be applied.
Case B: Any mission related objects (MRO) will not be released, and on orbital break-ups will be prevented.
Case C: Adding to case B, every objects will be removed within 50 years.
Case D: Adding to case B, every objects will be removed within 25 years.
Case E: Adding to case B, every objects will be removed at the mission termination.

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"

2. about JAXA

1. Japan’s government organizational change
2. 9 years and half, next 5 years
3. Debris comittee

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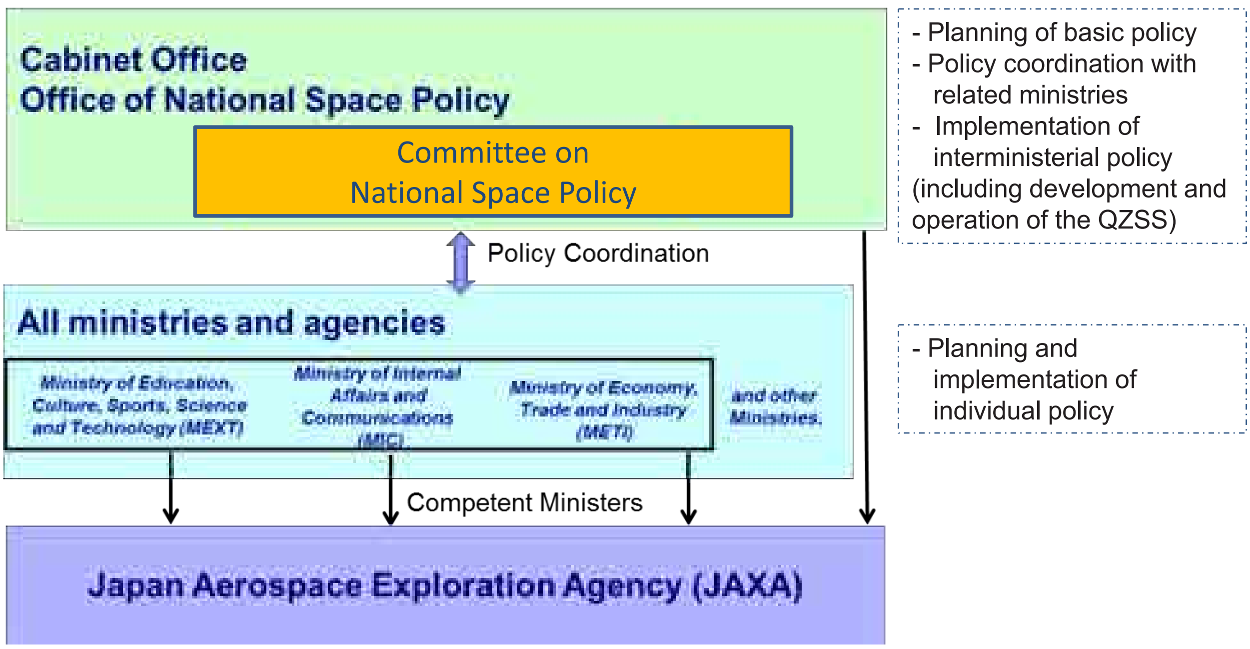
Organization chart

（Space related ministries in Japan）



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

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Office of National Space Policy, Cabinet Office ---The Headquarter for Japanese Space Policy---

The Office of National Space Policy shall

- Assist the Strategic Headquarters for Space Policy (Chaired by the Prime Minister / Constituted by all ministers of the Cabinet)
- Deal with the following issues by using the function of the Committee on National Space Policy
  - Formulate budget request policy and make follow-ups on each ministry's budget request to confirm their budget request is consistent with the policy
  - Revise the Basic Plan for Space Policy
- Develop and operate satellite systems for inter-ministerial use, including QZSS

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

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Japan Aerospace Exploration Agency (JAXA) ---The core implementing agency to support the development and use of space by the entire government with technology---

The amendment of the law concerning Japan Aerospace Exploration Agency (JAXA law)

- Aligns description of the "peaceful purpose" in JAXA law with the Basic Space Law which is consistent with the Constitution
- Adds to JAXA's authority to assist and advise matters related to development, launch and operation of satellites in response to request from industry
- Any ministry could become competent ministers for individual projects when added by cabinet order. JAXA will develop satellites based on the needs of each ministry.

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

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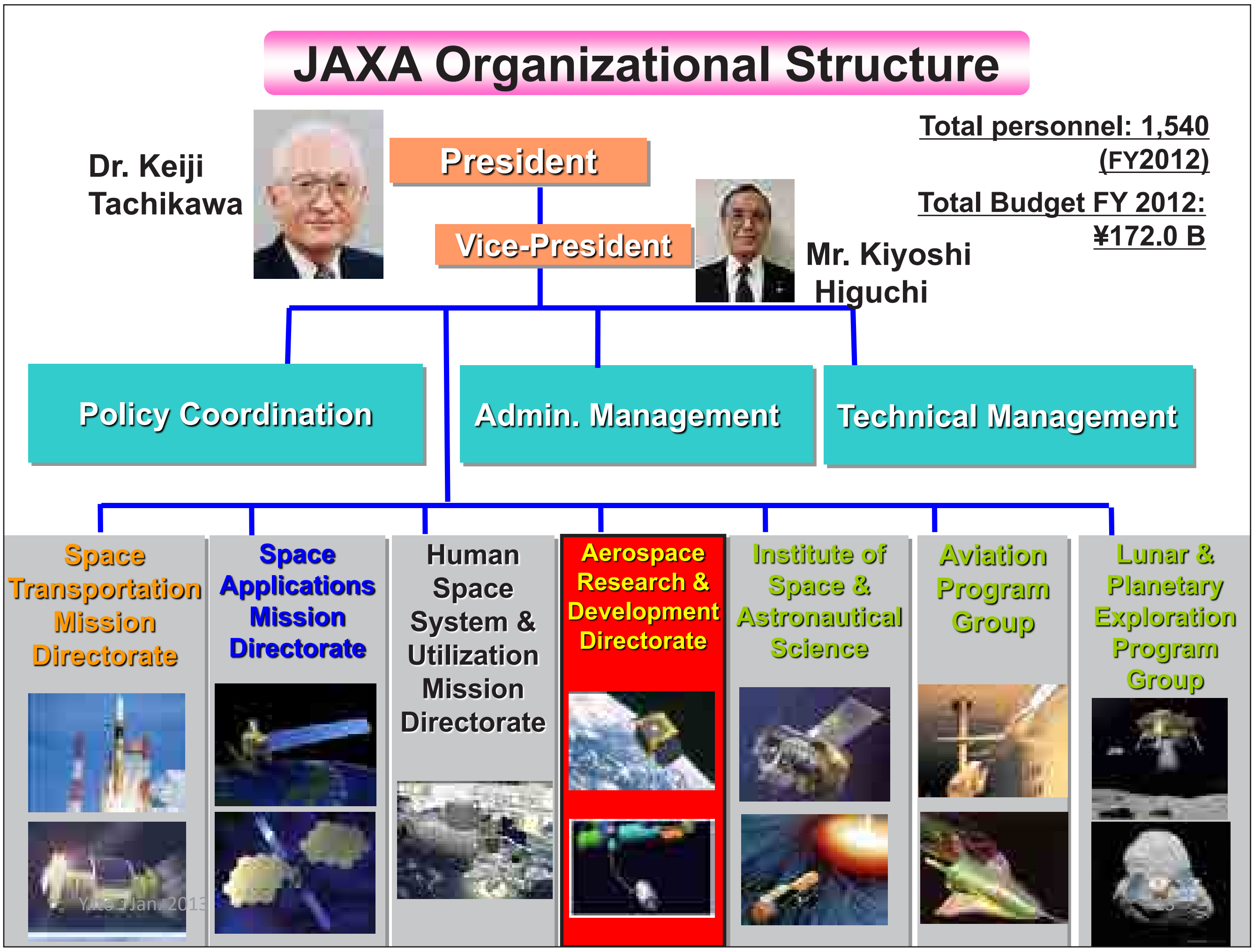

ISAS / NAL / NASDA		1996 : NASDA first Debris Standard 1999 : Japan proposed a specific committee to UNCOPUOS for debris issue	1995 : NASA first Debris Standard 1999 ~ 2007 : CNES first Debris Standard European Code of Conduct 2002 : IADC released the IADC Debris Mitigation Guidelines
JAXA First Mid-Term	2003	2006 : JAXA Debris Committee	2007 : UN adopted the COPUOS Debris Mitigation Guidelines
JAXA Secnd Mid-Term	2008	2012 : (Japan's New Law) < 5th Debris Workshop >	2011 : ISO released "Debris Mitigation Requirements"
JAXA Third Mid-Term	2013		

History of JAXA and World Debris Activities

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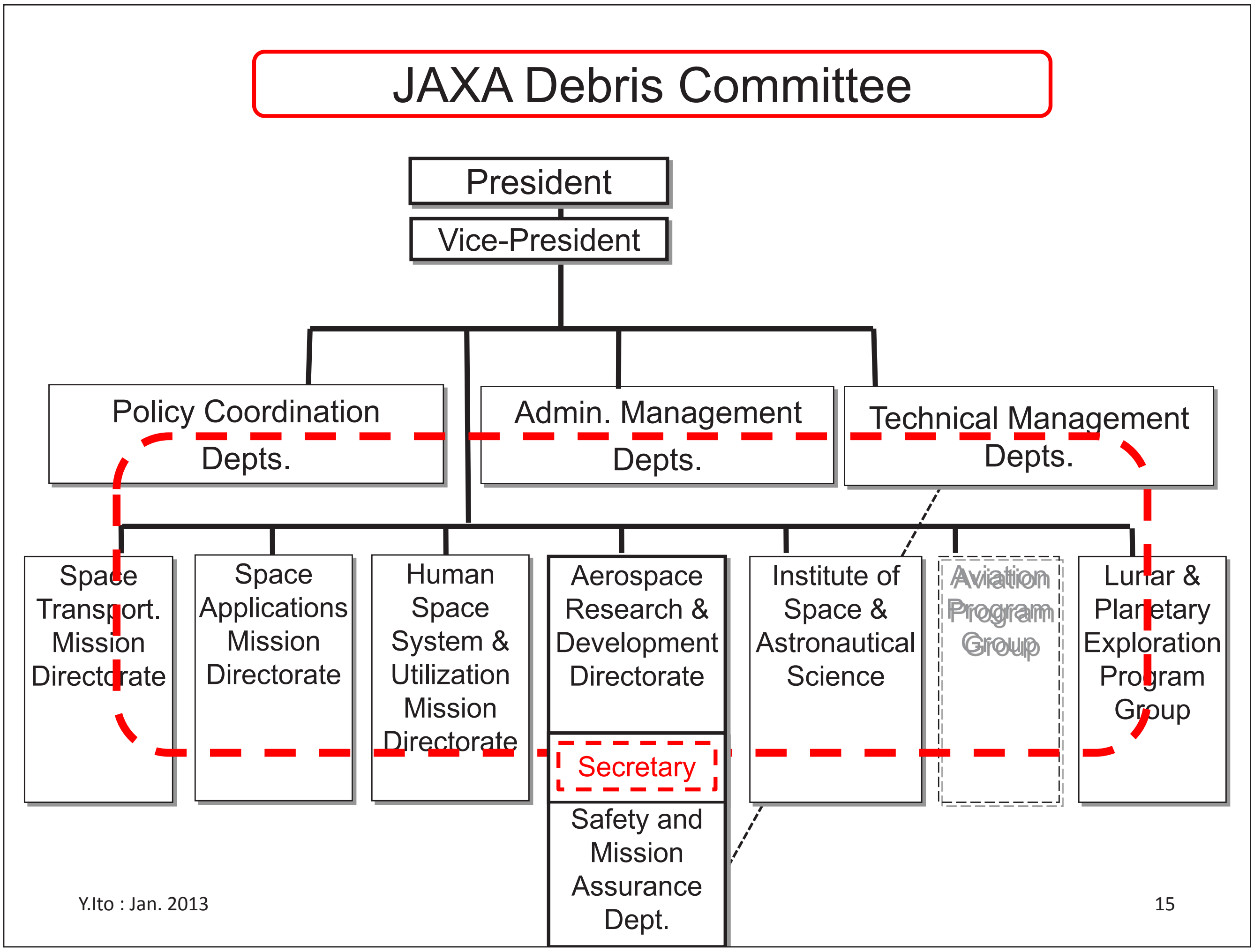
JAXA Debris Committee
President
Vice-President
Policy Coordination Depts.
Admin. Management Depts.
Technical Management Depts.
Space Transport. Mission Directorate
Space Applications Mission Directorate
Human Space System & Utilization Mission Directorate
Aerospace Research & Development Directorate
Secretary
Safety and Mission Assurance Dept.
Institute of Space & Astronautical Science
Aviation Program Group
Lunar & Planetary Exploration Program Group
Y.Ito : Jan. 2013
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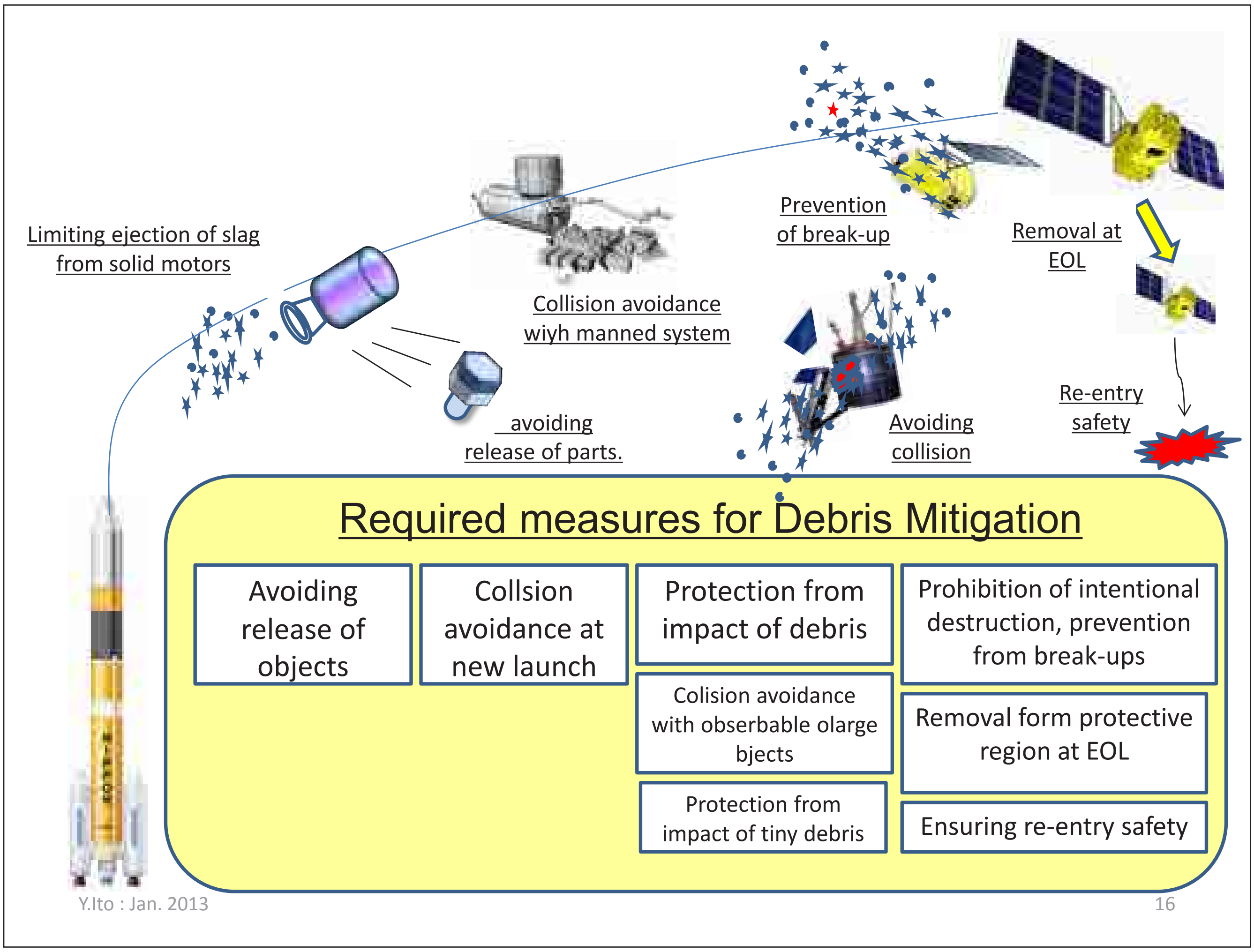
Limiting ejection of slag from solid motors
Collision avoidance wiyh manned system
Prevention of break-up
Removal at EOL
avoiding release of parts.
Avoiding collision
Re-entry safety
Required measures for Debris Mitigation
Avoiding release of objects
Collsion avoidance at new launch
Protection from impact of debris
Prohibition of intentional destruction, prevention from break-ups
Colision avoidance with obserbable olarge bjects
Removal form protective region at EOL
Protection from impact of tiny debris
Ensuring re-entry safety
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Major Elements of Strategy

Mission Assurance

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.

↓

Sustainable Development

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.

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3. Research and Development activities

1. Observation technology
2. Modeling
3. Protection design
4. Ground safety
5. Active removal

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Mission Assurance: Ground Observation

Goals in next 5-year-plan

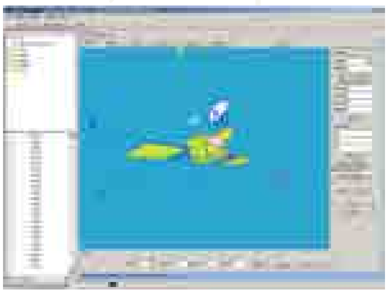
1. Objects smaller than 10 – 20 cm in GEO can be observed.
2. Conjunction with debris can be assessed by domestic facilities in sufficient precisions to support avoidance maneuver.

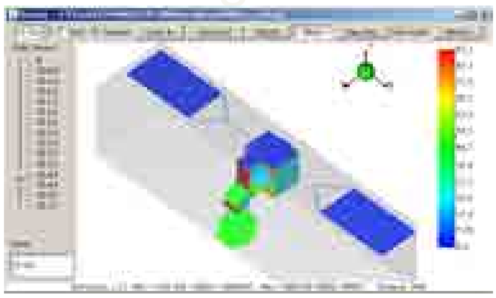
Image of the automatic debris detection tool

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

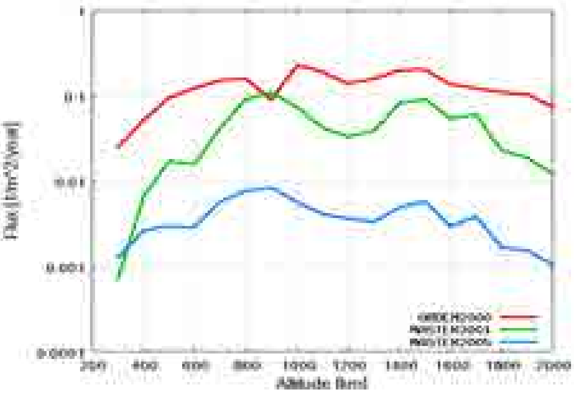
Goals in next 5-year-plan

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

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

<u>Goals in Ground Safety after deorbit</u>

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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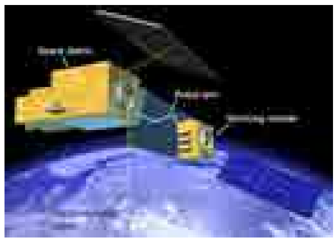
Preservation and improvement of the environment

<u>Goals in Active Debris Removal</u>



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

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Summary

- “Clear and present danger”
- Japan’s organization change
- JAXA Debris Committee
- R & D for the future
  - Mission Assurance
    - Debris detector in orbit
  - Preservation of environment and Ground safety
  - Improvement of environment
    - Active debris removal mission study

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A3

The Long-Term Stability of the LEO Debris Population and the Challenges for Environment Remediation

J.-C. Liou (NASA)

The near-Earth space environment has been gradually polluted with orbital debris (OD) since the beginning of human space activities in 1957. The OD problem was highlighted by the collision between Cosmos 2251 and the operational Iridium 33 in 2009. This accidental collision underlined the potential of an ongoing collision cascade effect (also known as the "Kessler Syndrome") in low Earth orbit (LEO, the region below 2000 km altitude). Recent modeling studies conducted by major space agencies around the world indicated that the current LEO environment had already reached the level of instability. Mitigation measures commonly adopted by the international space community, such as the 25-year decay rule, will be insufficient to stabilize the LEO debris population. To better limit the OD population growth, more aggressive actions must be considered.

There are three options for OD environment remediation: (1) removal of massive intact objects with high collision probabilities to address the root cause of the long-term OD population growth problem, (2) removal of the ~5-mm-to-1 cm debris to mitigate the main mission-ending threats for the majority of operational spacecraft, and (3) prevention of major debris-generating collisions as a temporary means to slow down the OD population increase. The technology, engineering, and cost challenges to carry out any of these three options are monumental. It will require innovative ideas, game-changing technologies, and major collaborations at the international level to address the OD problem and preserve the near-Earth environment for future generations.

Biography - - - - -

Dr. **J.-C. Liou** is a member of the NASA Orbital Debris Program Office. He is the Lead Scientist for long-term environment modeling, and for MMOD in-situ measurements. He also serves as the Chief Technologist for the Astromaterials Research and Exploration Science (ARES) Directorate at the NASA Johnson Space Center.

Dr. Liou led the development of the NASA Orbital Debris Engineering Model, ORDEM2000, and NASA's long-term debris evolutionary model, LEGEND. He has authored more than 80 technical publications, including 40 papers in peer-reviewed journals, and is the Technical Editor for the NASA Orbital Debris Quarterly News. Dr. Liou was the recipient of NASA Exceptional Engineering Achievement Medal in 2012.

Dr. Liou earned his B.S. degree in Physics from the National Central University in Taiwan, and his M.S. (1991) and Ph.D. (1993) degrees in Astronomy from the University of Florida.

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Long-Term Stability of the LEO Debris Population and the Challenges for Environment Remediation

J.-C. Liou, PhD
NASA Orbital Debris Program Office
Johnson Space Center, Houston, Texas
jer-chyi.liou-1@nasa.gov

JAXA Space Debris Workshop
JAXA HQ, Chofu Aerospace Center, Tokyo, 22-23 January 2013

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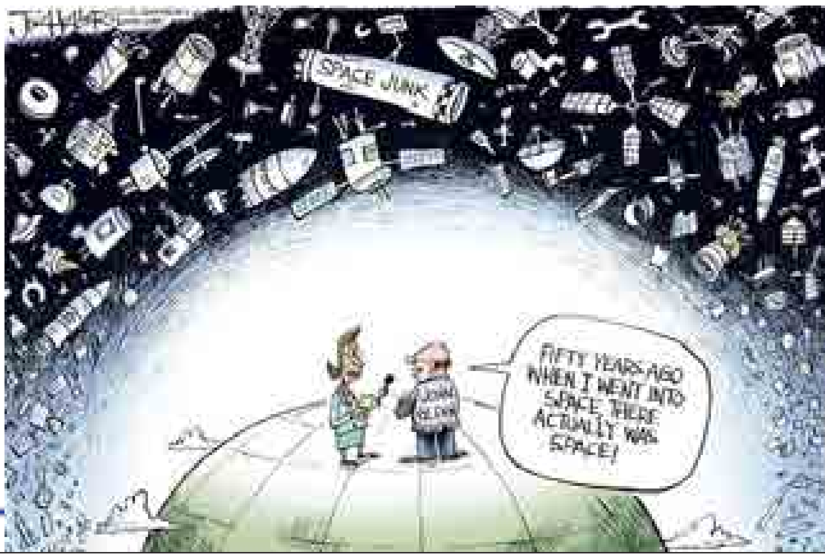
Outline

- **Buildup of the Orbital Debris (OD) Population**
- **Projected Growth of the OD Population**
- **Options for Environment Remediation**
- **Challenges Ahead**



JCL

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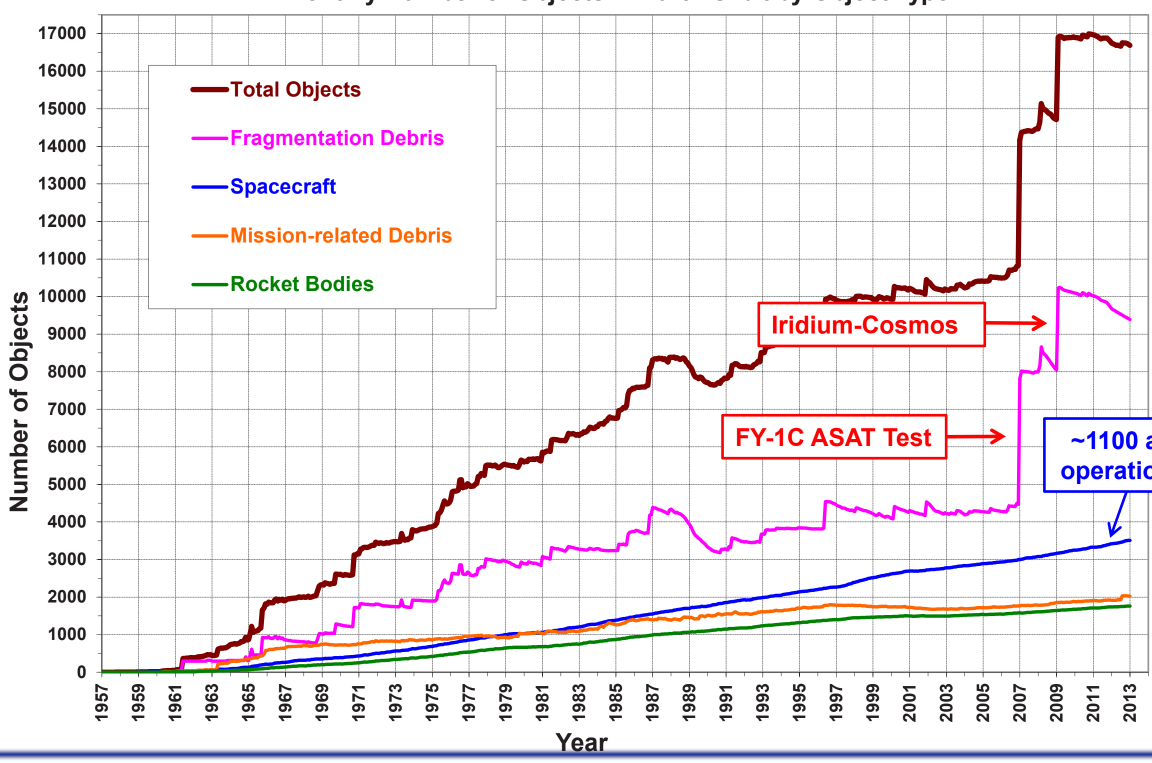
Growth of the Cataloged Populations



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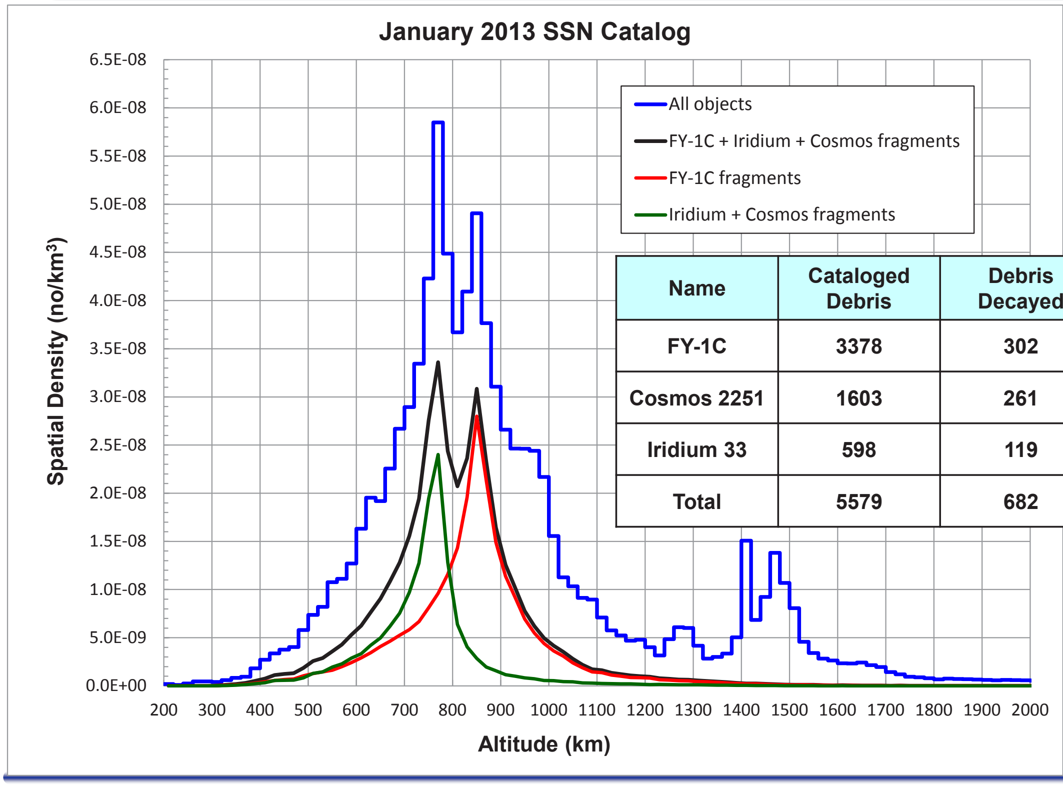
The LEO Environment



Name	Cataloged Debris	Debris Decayed	Debris in Orbit
FY-1C	3378	302	3076
Cosmos 2251	1603	261	1342
Iridium 33	598	119	479
Total	5579	682	4897

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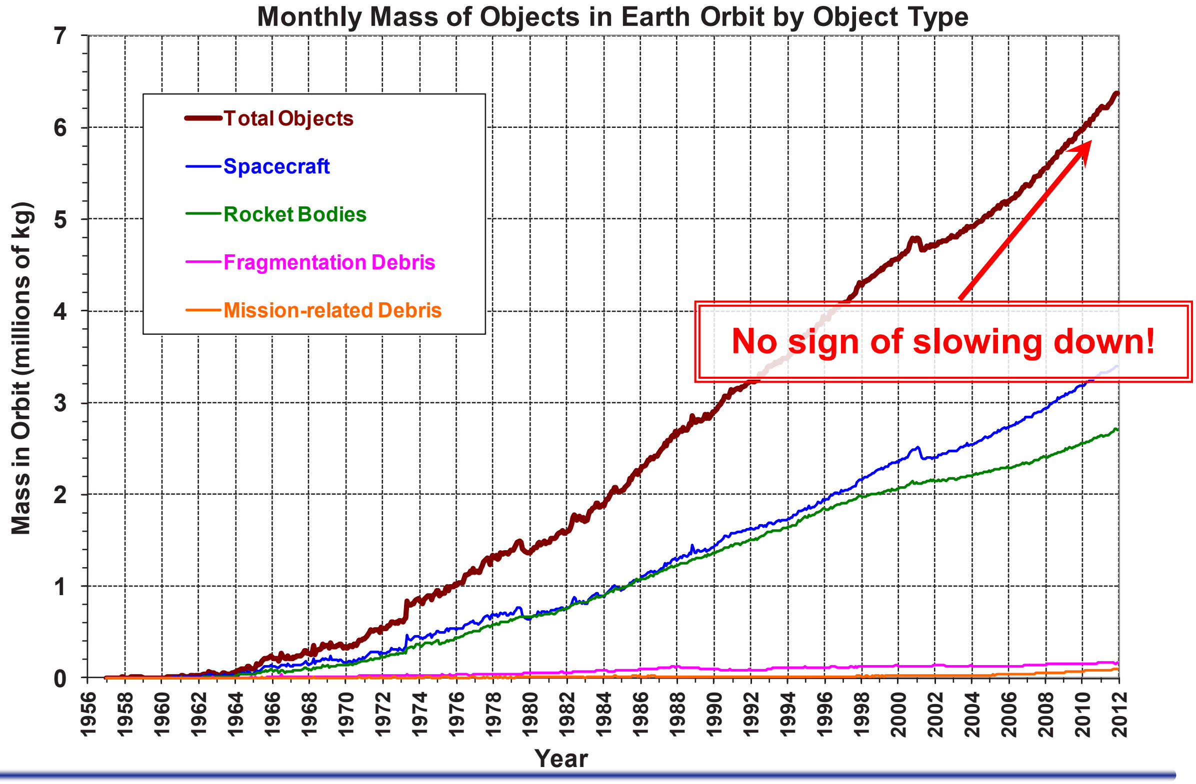
Mass in Orbit



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The Big Sky Is Getting Crowded

- **Four accidental collisions between cataloged objects have been identified**
  - The collision between Cosmos 2251 and the operational Iridium 33 in 2009 underlined the potential of the Kessler Syndrome
- **The US Joint Space Operations Center (JSpOC) is currently providing conjunction assessments for all operational spacecraft (S/C)**
  - JSpOC issues ~10 to 30 conjunction warnings on a daily basis, and more than 100 collision avoidance maneuvers were carried out by satellite operators in 2010
- **The International Space Station has conducted 16 debris avoidance maneuvers (DAMs) since 1999**
  - 3 DAMs and 1 shelter-in-Soyuz in 2012

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Projected Growth of the Debris Population

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Uncertainties In Environment Projection

- **Future launches**
  - Orbits, masses, materials, mission lifetimes, etc
- **Solar activity projection**
  - Orbit propagation
- **Breakup frequency and outcome**
  - Explosions
  - Collisions
- **Postmission disposal implementation**

Two general approaches for future projection:
- Examine extreme cases to bound the problem
- Analyze nominal cases based on reasonable assumptions

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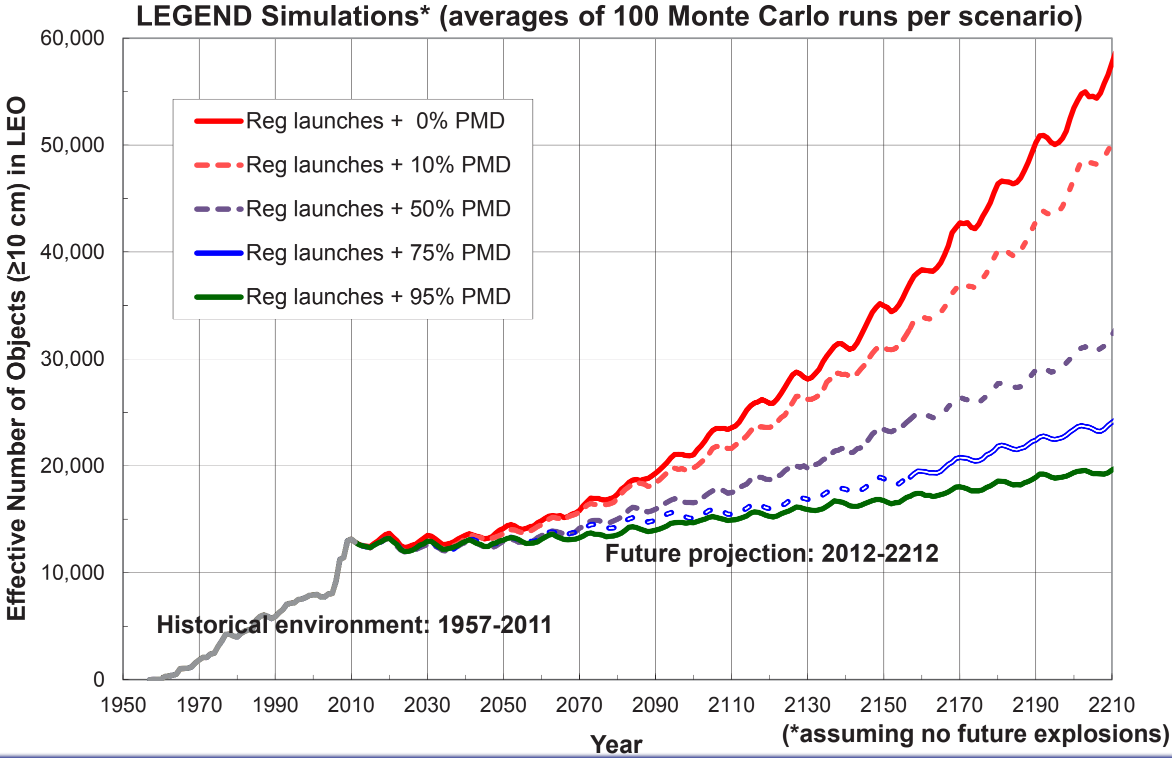
Effectiveness of Postmission Disposal (PMD)



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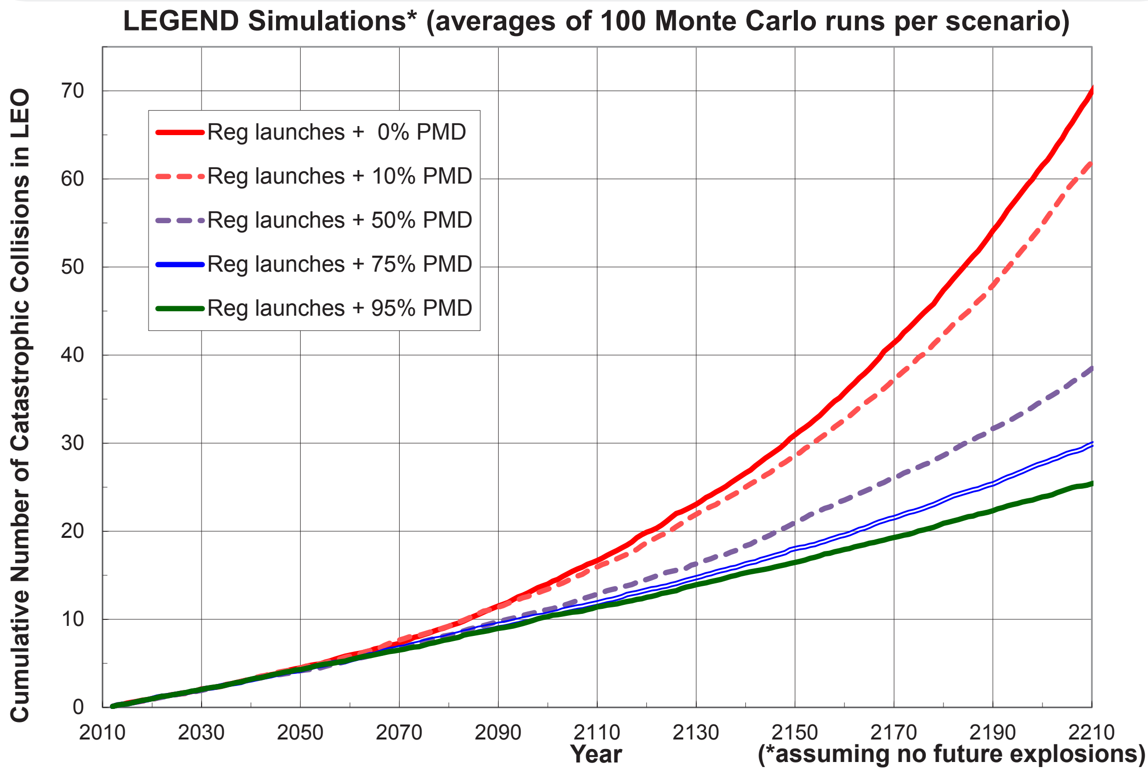
Projected Catastrophic Collisions in LEO



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Assessments of the Future Projections

- **Postmission disposal (PMD), including passivation and the 25-year decay rule, can significantly limit the future population growth, but PMD will be insufficient to stabilize the LEO environment**
- **To preserve the near-Earth space for future generations, more aggressive measures, such as active debris removal (ADR), should be considered**

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Options for Environment Remediation*

***Remediation = Removal of pollution or contaminants (*i.e.*, old and new debris) to protect the environment**

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Problems and Solutions

- **LEO debris population will continue to increase even with a good implementation of the commonly-adopted mitigation measures**
  - The root-cause of the increase is catastrophic collisions involving large/massive intact objects (R/Bs and S/C)
  - The major mission-ending risks for most operational S/C, however, come from impacts with debris just above the threshold of the protection shields (~5-mm to 1-cm)
- **A solution-driven approach is to seek**
  - Concepts for removal of massive intacts with high $P_{collision}$
  - Concepts capable of preventing collisions involving intacts
  - Concepts for removal of 5-mm to 1-cm debris

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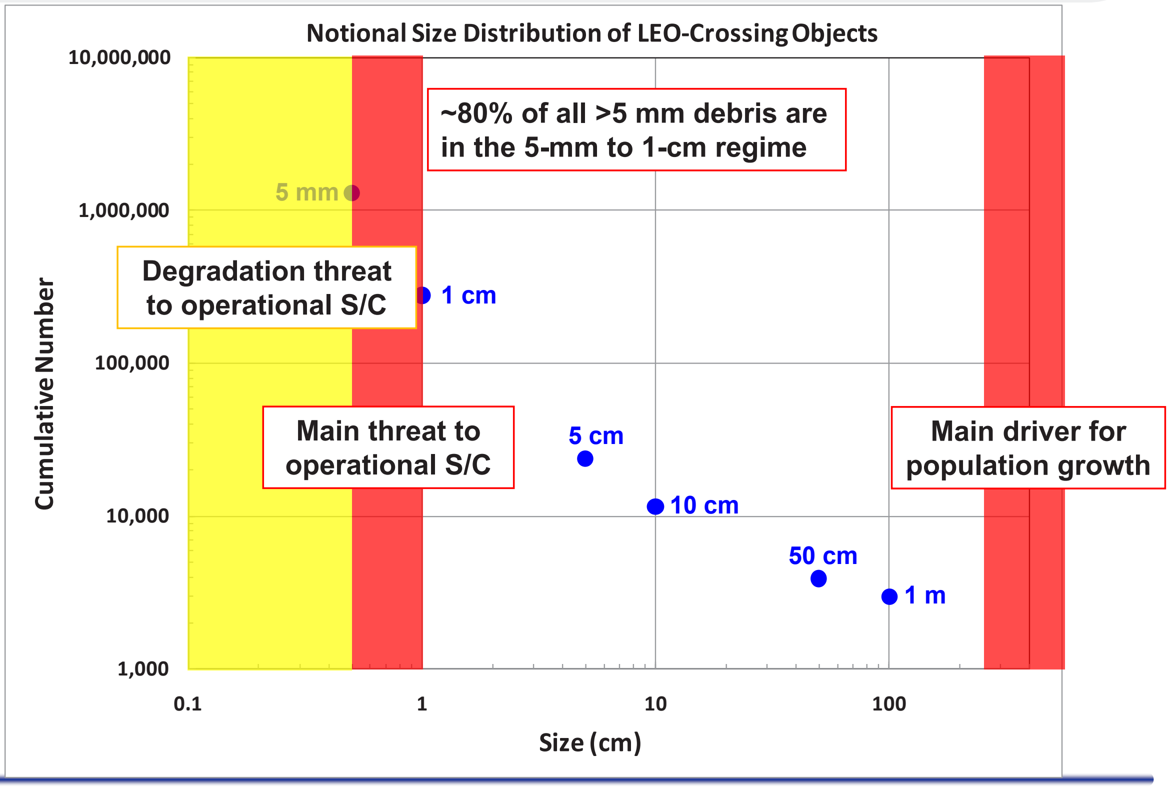
Targets for Environment Remediation



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Options for LEO Environment Remediation

- **Removal of massive intact objects with high collision probabilities to address the root cause of the future debris population growth problem**
- **Removal of 5-mm to 1-cm debris to mitigate the main threat for operational spacecraft**
- **Prevention of major debris-generating collisions involving massive intact objects as a potential short-term solution**

These three options
- have different objectives, benefits, and timeframes
- are not mutually exclusive

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Challenges for Environment Remediation

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Challenges for Small Debris Removal

- **Targets are small**
  - Approximately 5-mm to 1-cm
- **Targets are numerous (>500,000)**
  - For any meaningful risk reduction, removal of a significant number of targets is needed
- **Targets are not tracked by the U.S. SSN or other space surveillance systems**
- **Targets are highly dynamic**
  - Long-term operations are needed
- **Concepts proposed by various groups: large-area collectors, laser removal, tungsten dust, *etc.***

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Challenges for Collision Prevention

- **To allow for actionable prevention operations involving uncontrolled objects**
  - Conjunction assessments should include R/Bs and retired S/C
  - Improvements to assessment accuracy would be beneficial
- **To be an effective means to reduce debris growth**
  - Prevention operations should be applied to most predicted events with probabilities exceeding acceptable threshold
- **Targets are limited in number, but many are massive R/Bs or S/C (up to 9 metric tons dry mass)**
- **Concepts proposed by various groups: ballistic intercept, frozen mist, laser-nudging, *etc.***

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Targeting the Root Cause of the Problem

- **A 2008-2009 NASA study shows that the two key elements to stabilize the future LEO environment (in the next 200 years) are**
  – A good implementation of the commonly-adopted mitigation measures (passivation, 25-year rule, avoid intentional destruction which produces long-lived debris, *etc.)*
  – An active debris removal of about five objects per year
    - **These are objects with the highest [M × P_{coll}]**
    - **Many (but not all) of the potential targets in the current environment are spent Russian SL upper stages**
      - **Masses: 1.4 to 8.9 tons**
      - **Dimensions: 2 to 4 m in diameter, 6 to 12 m in length**
      - **Altitudes: ~600 to ~1000 km regions**
      - **Inclinations: ~7 well-defined bands**

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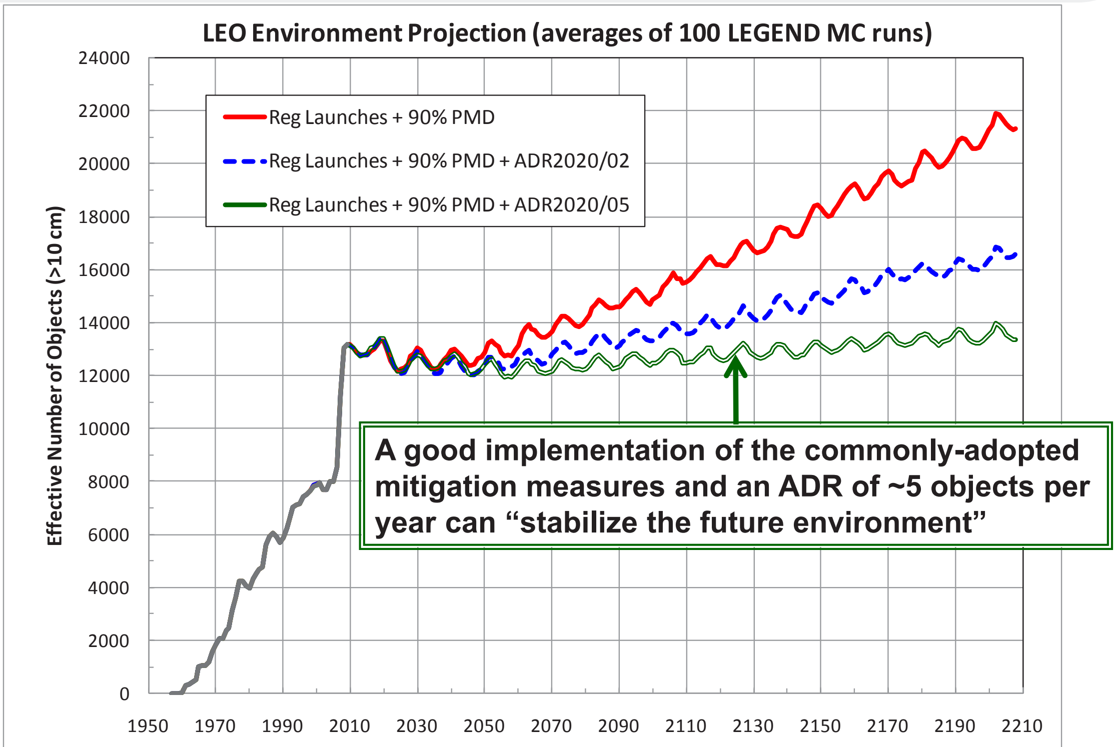
Controlling Debris Growth with ADR



(Liou, *Adv. Space Res*, 2011)

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About the "Five Objects Per Year"

- **The "removing five objects per year can stabilize the LEO environment" conclusion is somewhat notional. It is intended to serve as a guidance for ADR planning.**
- **Assumptions in the LEGEND ADR simulations**
  - Nominal launches during the projection period
  - 90% compliance of the commonly-adopted mitigation measures
  - ADR operations starts in 2020
  - Target selection is based on each object's mass and P_{coll}
  - No operational constraints on target selection
  - Immediate removal of objects from the environment
  - Average solar activity cycle

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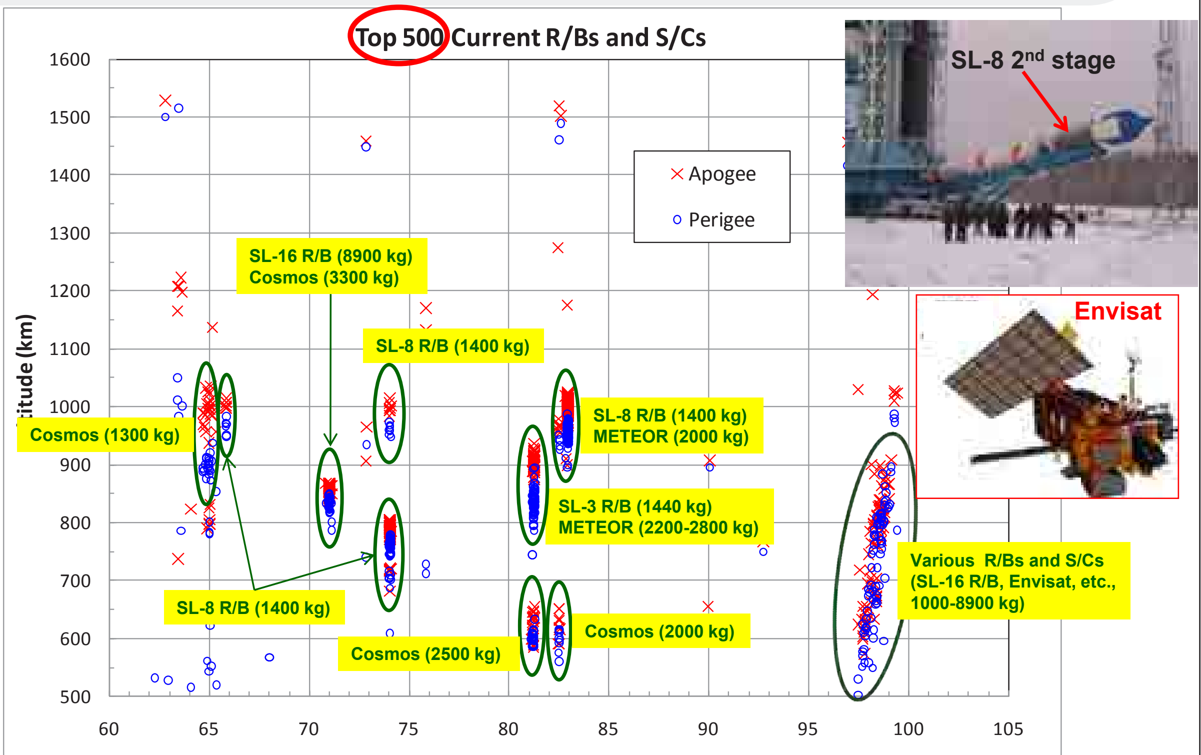
Potential Active Debris Removal Targets



(Liou, *Adv. Space Res*, 2011)

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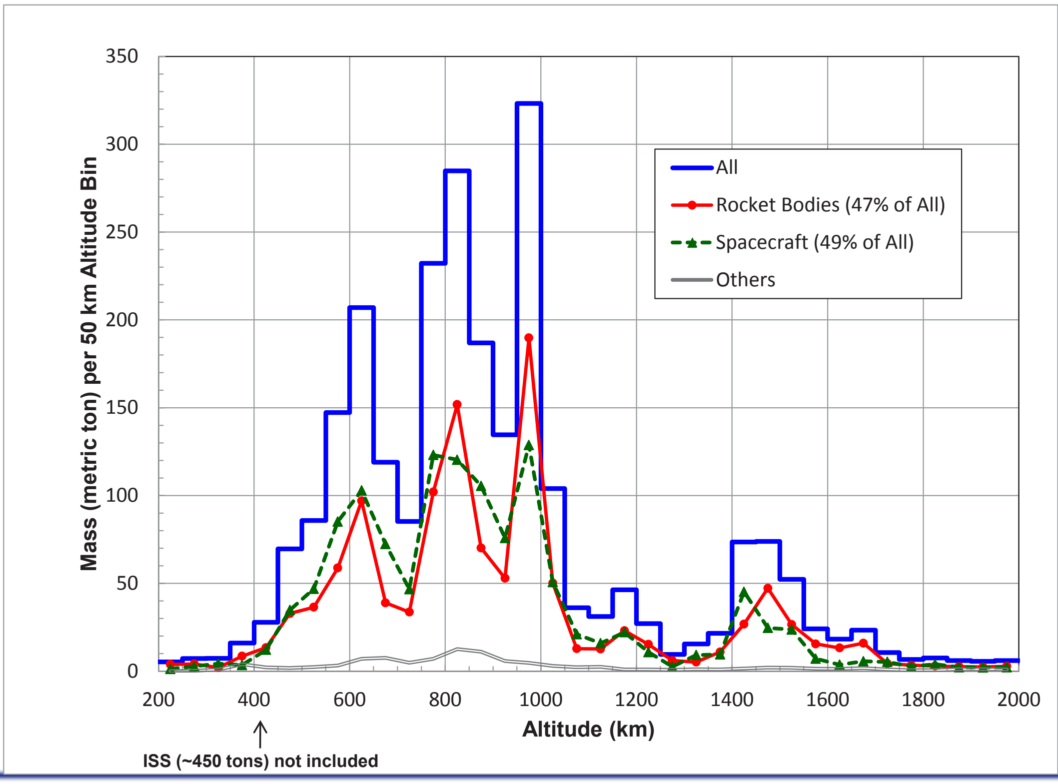
Mass Distribution in LEO (1/2)



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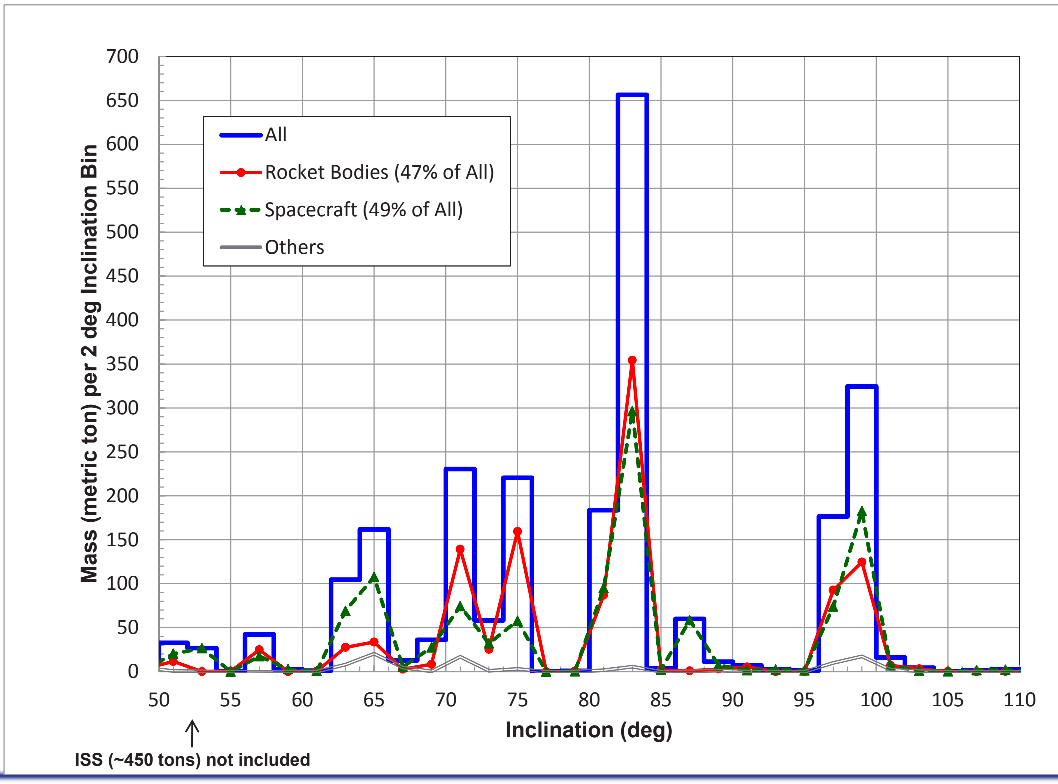
Mass Distribution in LEO (2/2)



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Challenges for Large Debris ADR Operations

Operations	Technology Challenges
Launch	Single-object removal per launch may not be feasible from cost perspective
Propulsion	Solid, liquid, tether, plasma, laser, drag-enhancement devices, others?
Precision Tracking	Ground or space-based
GN&C and Rendezvous	Autonomous, non-cooperative targets
Stabilization (of the tumbling targets)	Contact or non-contact (how)
Capture or Attachment	Physical (where, how) or non-physical (how), do no harm
Deorbit or Graveyard Orbit	When, where, reentry ground risks

- **Other requirements:**
  - Affordable cost
  - Repeatability of the removal system (in space)?
  - Target R/Bs first?

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Forward Path

- **There is a need for a top-level, long-term strategic plan for environment remediation**
  - Define "what is the acceptable threat level"
  - Define the mission objectives
  - Establish a roadmap/timeframe to move forward
- **The community should commit the necessary resources to support the development of innovative, low-cost, and viable removal technologies**
  - Encourage multi-purpose technologies
- **Address non-technical issues, such as policy, coordination, ownership, legal, and liability at the national and international levels**

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Preserving the Environment for Future Generations

- **Innovative concepts and technologies are key to solve the environment remediation challenges**
- **International consensus, cooperation, collaboration, and contributions are needed to move forward**

27/27 JCL

A4

Active Debris Removal activities in CNES

Christophe Bonnal (CNES)

A vast majority of studies led at international level, mainly in the frame of IADC, has shown that the future stabilization of the orbital density in Low Earth Orbits (LEO) imposes the active retrieval each year of some 5 to 10 large debris. This Active Debris Removal (ADR) activity, theorized since more than 30 years, appears now as a must since 2007 and the Fengyun 1C destruction, then the Iridium 33 – Cosmos 2251 collision.

CNES has published on ADR since 1998 and has been pro-active on the subject ever since, mainly through internal studies jointly led by the Toulouse Space Centre and the Launcher Directorate, through industrial studies financed since 2009 and through numerous smaller actions at laboratory or academic studies performed on the most sensitive technological hurdles.

The first part of the paper is devoted to the elaboration of the high level requirements, mainly devoted to the number, type, and frequency of objects to be retrieved, together with the influence of the date of operational availability of an ADR system. This activity is fundamentally led at international level, mainly through cooperation with JAXA, NASA and Russian entities. Some questions are of paramount importance, such as the acceptability of a random re-entry, potentially non compliant with applicable safety rules.

The second part deals with the various potential schemes at system level, trading between small chasers devoted to a single debris up to huge ones dealing with some 25 to 30 debris, with numerous variants using de-orbiting kits, or medium sized Orbital Transfer Vehicles OTV dealing each with some 4 or 5 debris.

The third part aims at identifying the criticality of the technologies required for ADR operations. Five functions are identified: long-range rendezvous; short-range rendezvous up to contact; mechanical interfacing; control of the chaser-debris assembly; de-orbiting. For each of these functions, associated sub-systems and equipment are identified together with their degree of maturity. The specificities of ADR compared to "conventional" rendezvous missions are identified, mainly the fact that rendezvous is performed with non-cooperative, un-prepared, potentially tumbling, potentially optically undetermined object. The fact that a debris may be dangerous in some cases, prone to explosion at contact, is addressed.

The fourth part of the study gives a status on some of the "smaller" studies led in the frame of ADR, such as the control of the "chaser-tether-debris" assembly required for a towing de-orbiting solution, as well as most recent results concerning the potential random movement of debris in orbit.

As a conclusion, the paper deals rapidly with the non-technical issues of ADR, and proposes potential ways to be explored.

Biography - - - - -

Christophe Bonnal is Senior Expert in charge of Systems in the Technical Directorate of the CNES Launcher Directorate in Paris.
Since 1984 he has been in charge of numerous technical and project activities dealing with all current and future European launchers.
Christophe Bonnal is in charge of Space Debris aspects since 1987, French delegate to the IADC, member of the ECSS-ISO Working Group on Space Debris Mitigation, Chairman of the Space Debris Committee of the International Academy of Astronautics, coordinator of the IAC Space Debris Symposium and Editor of the IAA Position Paper on Space Debris Mitigation.

ACTIVE DEBRIS REMOVAL:
CURRENT STATUS OF ACTIVITIES IN CNES

Christophe BONNAL

CNES – Paris - Launcher Directorate

christophe.bonnal@cnes.fr

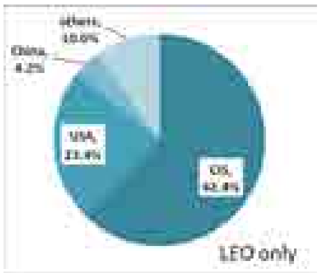
Content

Introduction
1. High Level Requirements
2. System Architectures Options
3. ADR High Level Functions
4. Support studies
5. Conclusions

Introduction

■ Kessler syndrome

- Identified theoretically by Don Kessler and Burt Cour-Palais in 1978 [1]
- Four sources of space debris:
  - Mission Related Objects, Break-up, Aging, Collisions
  - When the “collision” source becomes larger than the “atmospheric cleaning”, natural increase of orbital population
  - Critical density varies strongly with the orbit altitudes:
    ↳ Most critical zones in LEO, between 700 and 1100 km, highly inclined (including SSO)
- Potential need for Active Debris Removal (ADR)
- International problem
  - Sources of debris from every space-faring nations
  - No nation shall nor can solve the problem alone



[1] *D.J. Kessler, B.G. Cour-Palais, Collision frequency of artificial satellites: the creation of a debris belt, JGR 83 (A6) (1978) pp. 2637–2646.*

Introduction

■ Logic of the activities

- Consolidate the need, if any, to perform ADR in addition to the proper application of mitigation rules,
- Identify the corresponding system solutions,
- Identify the required technologies and clarify the corresponding development constraints,
- Identify some reference scenarios, with solutions precise enough to evaluate the programmatic consequences,
- Propose a scheme at international level to initiate such operations if, once again, they appear compulsory.

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1. High Level Requirements

- **Number of debris to remove**
  - **Studied at worldwide level since more than a decade**
  - **Reference studies from NASA Orbital Debris Office [1]**
    - **Need to remove 5 large debris per year to stabilize the environment**
    - **Numerous robustness and sensitivity studies**
  - **Cross-check led by 6 other IADC delegations**
    - **Same hypotheses, model and mitigation**
      - 100% explosion suppression
      - 90% success of end of life measures
    - **Different tools**
    - **IADC Action Item 27.1**
    - **Coherent results, and confirmation of the need to remove 5 large objects, at least, per year**

    ↳ ***"new mitigation measures, such as Active Debris Removal, should be considered".***
- **Highest level priority for CNES:**
  - **Development by Toulouse Space Center of a predictive tool, with different modeling, enabling robustness studies**

  ↳ **Tool MEDEE is now available and will be presented in Darmstadt**

[1] *J.-C. Liou, N.L.Johnson, N.M.Hill, Controlling the growth of future LEO debris populations with active debris removal, Acta Astronautica 66 (2010) pp. 648 - 653*

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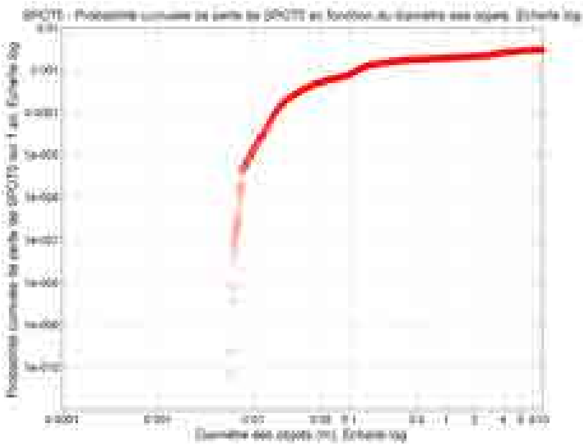
1. High Level Requirements

- **Size of Debris**
  - **Removing large debris enables a long term stabilization of orbital environment**
  - **Operators' main concern is short term risk induced by small debris**
  - **Examples:**
    - **Risk on Spot 5 (CNES) [1]**
    - **Mission loss 0.3% per year**
    - **Main influence of < 5 cm**
    - **Risk on Sentinel 1 (TAS-I draft) [2]**
    - **Mission loss 3.2% over lifetime**

  ↳ **Large integer objects may not be the only ones to remove:**
    - **Different concerns**
    - **Very different solutions**



[1] *P. Brudieu, B. Lazare, French Policy for Space Sustainability and Perspectives, 16th ISU Symposium, Feb. 21st, 2012*
[2] *R. Destefanis, L. Grassi, Space Debris Vulnerability Assessment of the Sentinel 1LEO S/C, PROTECT Workshop, Mar. 21st, 2012*

1. High Level Requirements

■ Stabilization of environment

- **Current recommendations aim at stabilizing the orbital environment**

↳ But do we really want a stabilization ?

- Is the current risk considered acceptable by operators ?
- Could it be increased ? To which level ?
- Should it be decreased ?
- When should we act ? Now ? In 20 years time ?

■ Acceptability of random reentry

- Can ADR operations lead to random reentry of large dangerous objects ?
  - ⇨ Casualty threshold = 10^{-4} per operation
  - ⇨ By definition, ADR shall be done on large objects ≡ Dangerous
  - Random reentry would be illegal according to French Law on Space Operations
  - However, it improves both debris situation and casualty risk
  - Action on-going at CNES Inspector General level
  - Action to be led within IADC WG4

1. High Level Requirements

■ JAXA-NASA-CNES Coordination Working Group in the area of Orbital Debris Removal

- NASA, JAXA and CNES shall use reasonable efforts to carry out the following responsibilities:

1. Provide information regarding the orbital debris removal inputs and requirements;
2. Participate and contribute to the technical discussions on orbital debris removal requirements
3. Participate and contribute to the discussion of possible common approaches to orbital debris removal requirements
4. Participate and contribute to the discussion on the advantages and disadvantages of possible concepts and technologies in the area of orbital debris removal

- Priority shall be given to:
  - Need for stabilization criteria for environment
  - Size of debris

    ↳Probability of mission loss
  - Acceptability of random reentry
  - Date of operations

2. System architecture options

- **Debris playground**
  - **Definition of an "interesting target":**
    - **Function of size – mass – orbit density**
    - **Function of the debris population in one given zone in case of multiple debris chasing**
      - Minimization of the mission ΔV
      - Minimization of global mission duration
    - **Could be function of criticality of random reentry:**
      - Random reentry not acceptable if casualty > 10^{-4}
      - To be confirmed at national level, then at IADC level
      - Typical threshold in size: 500 to 1000 kg
      - Could be antagonist with finality of ADR
      - ➯ Only solution with Direct Controlled Reentry are studied today
    - **Could be function of nature of debris**
      - Launcher stages pose potentially less problems than Satellites (definition of a debris, confidentiality, mechanical robusteness…)
    - **Not function of country**
      - Deliberate choice to consider for the operational phase all debris
      - ➯ International problem, tackled at international level
  - **Identification of the most interesting zones:**
    - **Initial sorting identified 10 critical zones**
    - **Refined subdivision into coherent sub-regions [2]**

[1] *JC. Liou, The top 10 Questions for Active Debris Removal, #S1.3, 1st European Workshop on ADR, Paris, June 2010*
[2] *P. Couzin, X. Rozer, L. Stripolli, Comparison of Active Debris Removal Mission Architecture, IAC-12-A6.5.5, Naples 2012*

2. System architecture options

- **Strategy for successive debris removal**
  - **Numerous possible schemes:**
    - **Single shot: one chaser, one debris**
    - **Multiple debris: one chaser, several debris**
    - **Multiple debris: one carrier + multiple deorbiting kits, one debris per kit**
    - **Multiple debris: multiple chasers in one launch, several debris each**
  - **No obvious solution:**
    - **Cost of the launch → Dedicated or Piggy-back**
    - **Size of the launcher**
    - **Cost of the chaser "functions" → Effect of mission rate**
    - **Sizing of the multiple debris chasers → Global mission ΔV**
  - **Analyses performed by Astrium, TAS-F and Bertin under CNES contract**
    - **Results are still differing !**

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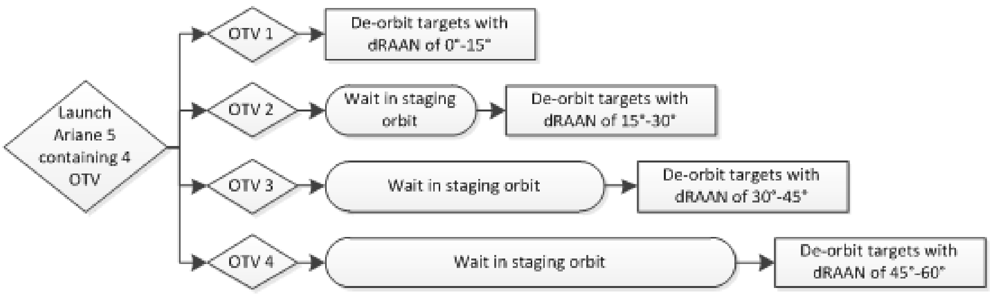
2. System architecture options

■ Among the most promising solutions:

- **Considered for the Operational phase**
  - First Generation may show different optimum
- **Large launcher with multiple chasers, each delivering multiple kits [1]**

◆ **Big launcher (e.g. Ariane 5) launching N different multi-debris OTV's**

- Group is divided into N RAAN regions
- Each OTV targets a certain part of the group
- Lower launch staging orbit generates a shorter wait



[1] *P. Couzin, X. Rozer, L. Stripolli, Comparison of Active Debris Removal Mission Architecture, IAC-12-A6.5.5, Naples 2012*

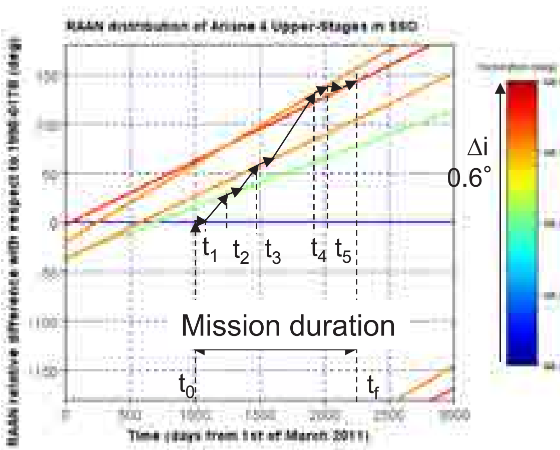
2. System architecture options

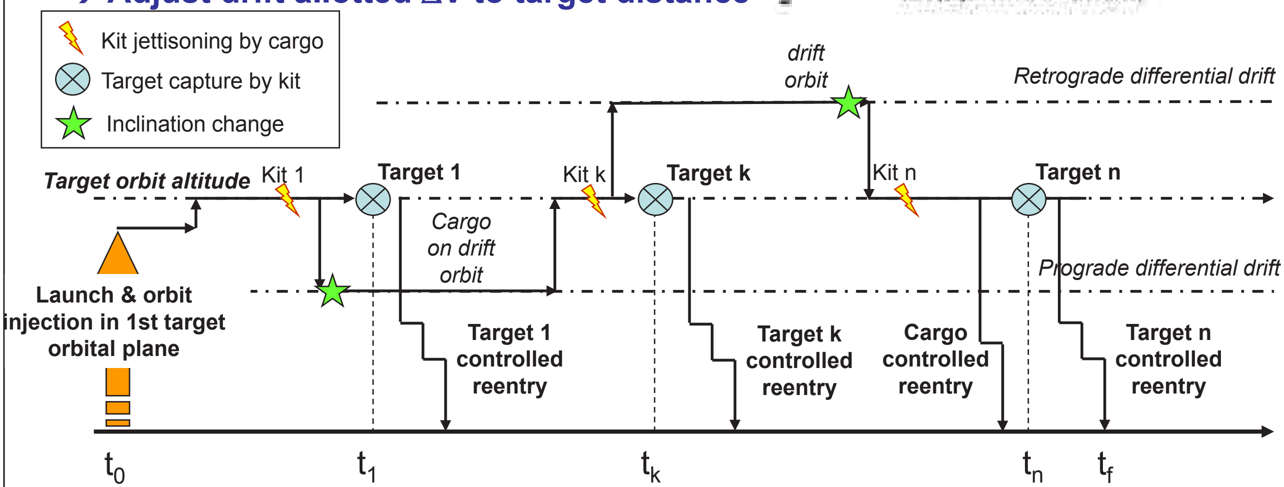
■ From CNES Internal Study OTV [1]

- ◆ **Removal of 5 Ariane upper stages**
- ◆ **Autonomous kit achieves capture**
- ◆ **Similar targets**
- ◆ **+/-200 km Δa → +/-36° /yr drift capacity**
- ◆ **Targets visited in increasing order of inclination → cumulated 0.6° Δi**

→ Mission duration depends on launch date

→ Adjust drift allotted ΔV to target distance





[1] *E. Pérot, Active Debris Removal Mission Design for LEO, #479, 4th EUCASS, St Petersbourg July 2011*

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3. ADR High Level Functions

■ Active De-orbiting of a debris requires 5 functions:

- **F1: Far Range rendezvous between Chaser and Debris:**
  - **Up to 10 to 1 km from target**
  - **Can be done through absolute navigation**
  - **Already demonstrated and space qualified**
- **F2: Short Range rendezvous, up to contact**
  - **Never demonstrated (published) yet for objects which are:**
    - Non cooperative
    - Non prepared
    - Potentially tumbling
    - Potentially physically and optically different from expected
- **F3: Mechanical Interfacing between Chaser and Debris**
  - **Never demonstrated (published) yet for a non prepared object**
- **F4: Control, De-tumbling and Orientation of the debris**
  - **Partially demonstrated in orbit, but Human operations**
- **F5: De-orbitation**
  - **Low thrust or drag augmentation solutions are discarded here**
  - ↳ **Lead to uncontrolled reentry**
  - ↳ **Or too high complexity if coupled with high thrust for final boost**

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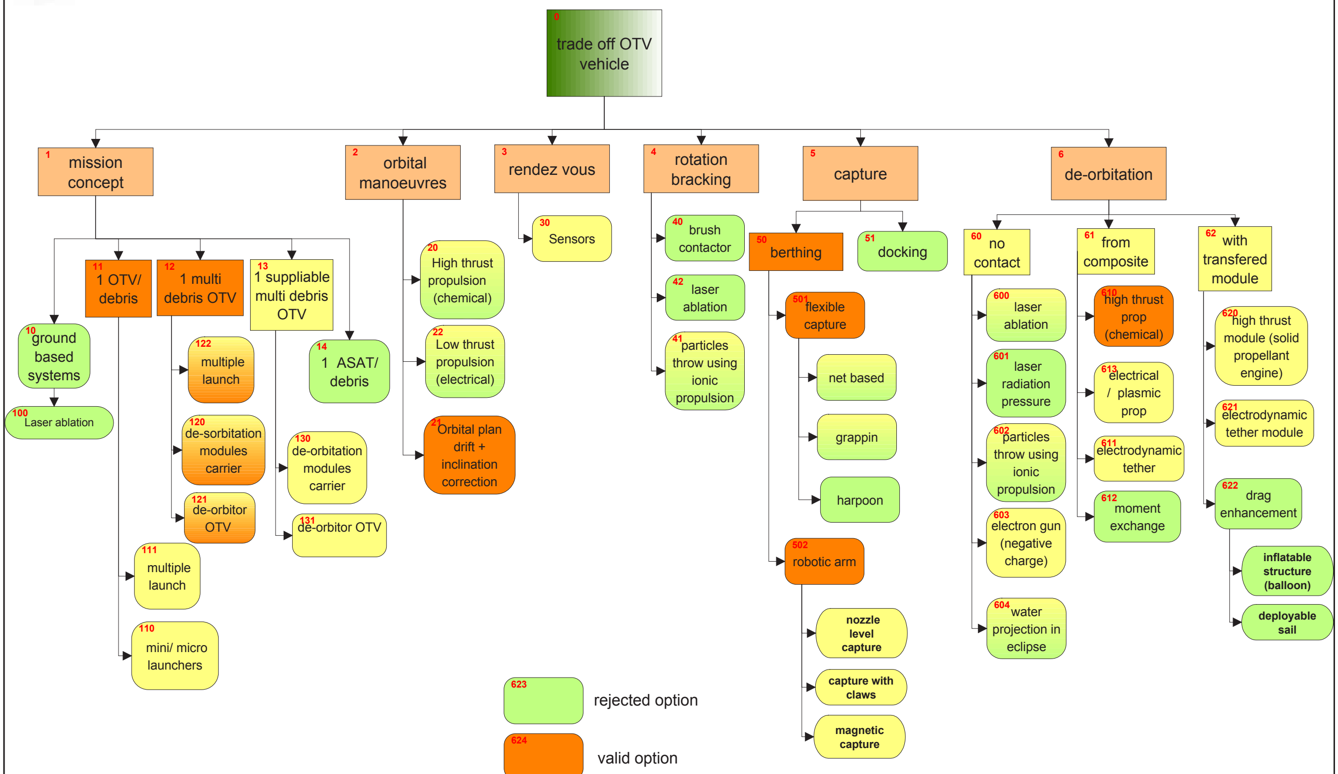
3. ADR High Level Functions

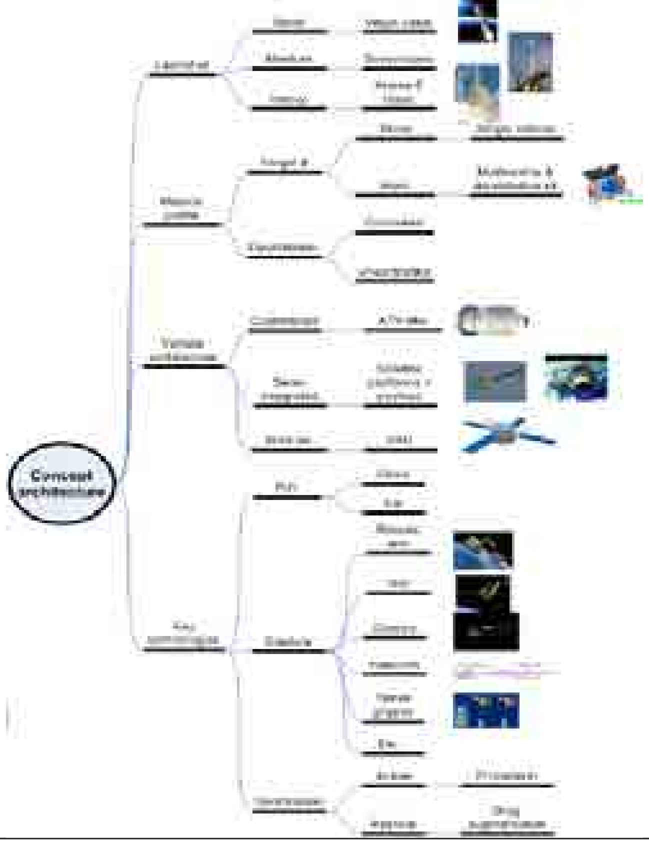
■ General approach and trade-off (example from TAS-F [1]):



[1] *TAS-F – MDA – GMV, CNES OTV-1 Study*

3. ADR High Level Functions

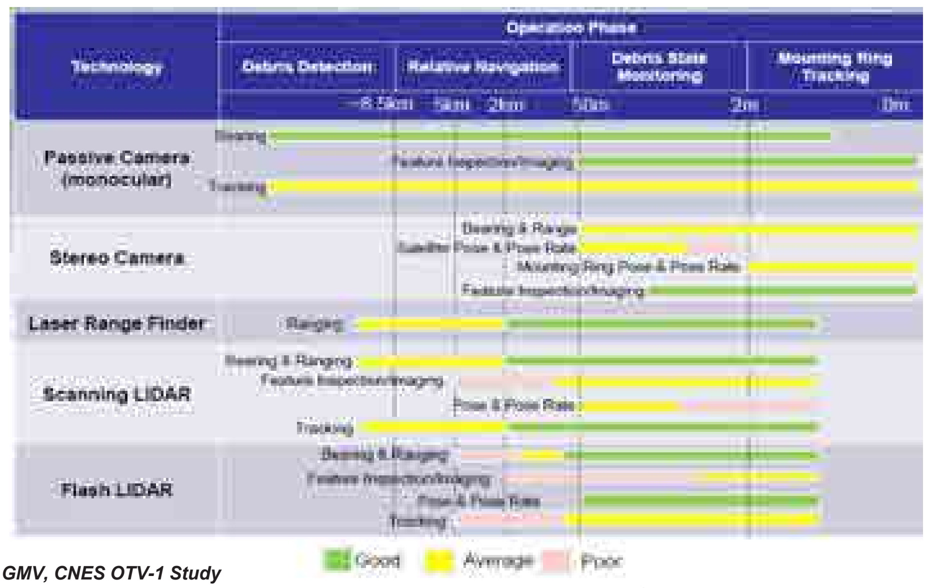
- General approach and system breakdown (example from Astrium):



[1] *Astrium, CNES OTV-1 Study*

3. ADR High Level Functions

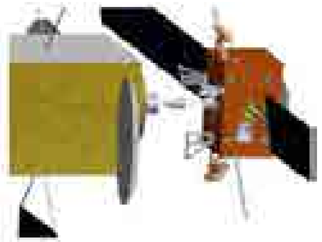
- F2: Short Range rendezvous, up to contact
  - Numerous sensors can be considered
    - Optical, Mono or Binocular, Lidar / Radar…
    - Example from MDA-TASF [1]
  - No single technology can cover the complete function



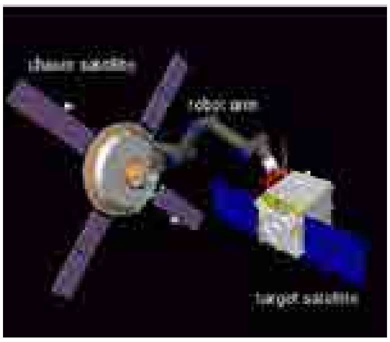
[1] *TAS-F – MDA – GMV, CNES OTV-1 Study*

3. ADR High Level Functions

■ F3: Mechanical interfacing, some examples:



OSS: clamp inside the target nozzle

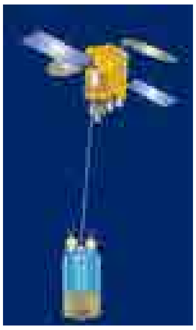


DLR: robotic arm DEOS

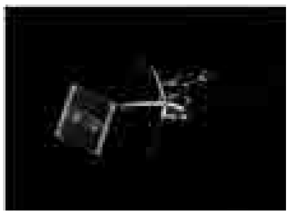
Astrium UK: harpoon

Uni. Roma: foam gluing

CNES: deorbiting kit with robotic operations



ESA-Astrium: hook ROGER



EPFL: claw

Astrium: net capture

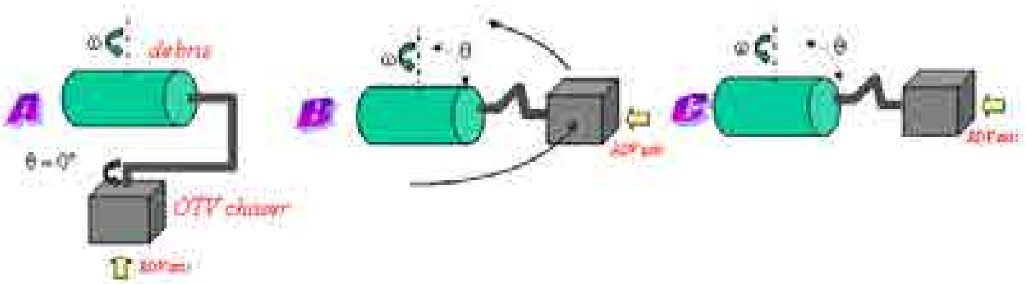
3. ADR High Level Functions

■ F3: Capture – Mechanical Interfacing

- **No reference solution yet**
- **Solutions without mechanical interface are discarded here:**
  - Electrical engine beam pressure
  - Electrostatic tractor
  - ➾ **Lead to uncontrolled reentry**
- **Solutions may impose different modes of deorbiting**
  - Net, hook… will impose “pulling” the debris
  - Some allow the control of the debris, other don’t
- **Among the preferred:**
  - Net capture
  - Harpoon or hook
  - Robotic arms
  - ➾ Trade-off ongoing during the OTV-2 study (AST and TAS)

3. ADR High Level Functions

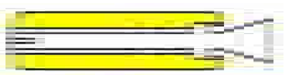
- **F4: Control-Detumbling of the debris:**
  - **Example from MDA [1]**
  - **Rendezvous analyses demonstrate:**
    - **A dramatic dependency of the rendezvous sizing to the tumbling rate**
    - **The importance of the rendezvous axis**
  - **Results suggest to assess different rendezvous scenarios, associated to different robotic solutions:**
    - **A – RDV along the debris tumbling axis**
    - **B – RDV along the robotic capture axis**
    - **C – Approach perpendicular to the tumbling axis**

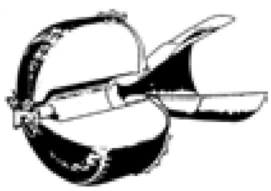


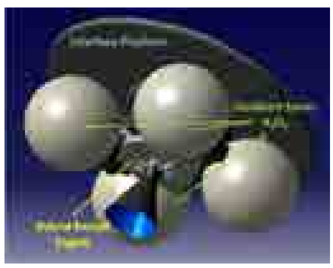
[1] TAS-F – MDA – GMV, CNES OTV-1 Study

3. ADR High Level Functions

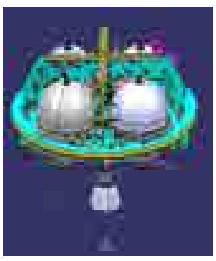
- **F5: Deorbitation:**
  - **High thrust deorbitation, Controlled reentry**
  - **Rendezvous analyses demonstrate:**
    - **Conventional chemical propulsion**
      - Solid, Hybrid, Monopropellant, Bi propellant
      - Each have drawbacks and advantages
    - **Potentially most promising: Hybrid propulsion**

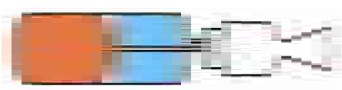




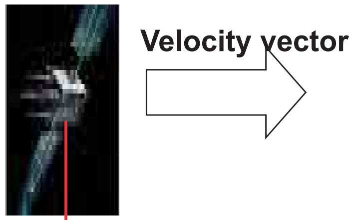


DeLuca et al. IAC-12-A6.5.8

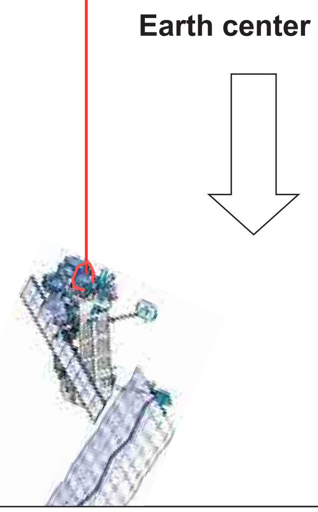




4. Support studies



- **Envisat:**
  - **One of the highest priorities debris**
  - **Proposal to reorbit above 2000 km:**
    - **First generation**
      - Would allow a full scale demonstration of most of the functions
      - Need to find the cheapest solution possible
    - **Electrical propulsion**
      - Derived from Smart 1 (x 4)
      - Compatible with a Vega launch
      - Long tether (500 to 1000 m)
    - **Mechanical interfacing with hook on one of the "zenit" instruments**
    - **Global mass budget ≅ 820 kg**
  - **Presented in Ref [1]**



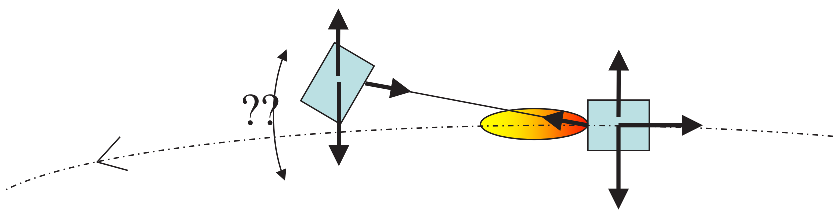
[1] C. Bonnal, C. Koppel, 2nd European workshop on ADR, Paris, June 2012

4. Support studies

- **Stability of the Chaser-Tether-Debris assembly:**
  - **Towing = Preferred solution today, but very low TRL**
  - **Control laws of the chaser during de-orbiting boost:**
    - Parameters of tether: length, elasticity, damping
    - Initial conditions of Debris: 6 DOF = orientation = angular motion
    - Parameters of Chaser: MOI, thrust and variation, initial orientation
    - Parameters of tether-debris interface: unbalance
    - Acceptance criteria: ΔV amplitude, orientation, dispersions
    - Control laws
  - **Three teams working on the topic in France**
    - Mines Paris-Tech
    - Supelec
    - Thales Alenia Space

  - **Numerous other teams worldwide (ESA, Russia, USA…)**
  - **Results not yet available**

  ↳ **Dedicated session during upcoming EUCASS in July 2013**



5. Conclusions

- First priority is to consolidate high level requirements:
  - Question today is not yet How, but What and When
  - Study of technical solutions:
    - Necessary for programmatic evaluations
    - Necessary for R&T programs for TRL increase
  - Numerous questions have very high priority:
    - Legal and insurance framework, ownership, launching state
    - Political hurdles: Parallel with military activities
    - Financing schemes
    - International cooperation framework
- Recommendation to work on a reference test case
  - Cosmos 3M upper stage could be a good example
  - Benchmarking of solutions over same hypotheses
  - Initial steps of international cooperation
    - Ad-hoc framework: JAXA-NASA-CNES Working Group

一般セッション

B1

世界のデブリ管理状況と JAXA の対応

Global Debris Mitigation Control and Corresponding Activities in JAXA

加藤 明（宇宙航空研究開発機構）
Akira Kato (JAXA)

デブリの発生防止管理は、国連や IADC が推奨するガイドライン、国際標準化機構が進めている一連の規格類、並びに宇宙先進国政府あるいは公的機関が発行する標準書等にて進められている。 これらで規制されているデブリ対策の主要項目は、①破壊行為や爆発事故の防止、②部品などの放出の抑制、③衛星やロケットの運用終了後の有用な軌道からの排除、④排除した物体が再突入する場合の地上安全の確保、⑤衝突被害の防止などである。 JAXA は昨年、従来から適用してきたデブリ発生防止標準を ISO の最新規格と同等の規制となるように改訂した。これで国内衛星開発企業が JAXA の標準へ適合した製品を開発する努力は、そのまま世界の規制に合致した製品の供給が可能になる体制を保証するものとなる。今後、衛星国際調達市場や打上げサービス市場では軌道環境への配慮が入札条件に含まれることが考えられる。JAXA では規制面のみでなく、種々の解析ツールなどを整備して産業界のデブリ対策技術の確立を支援している。

Debris mitigation effort is being progressed by the guidelines registered by the United Nations, and IADC, standards by the International Standardizing Organization (ISO), and other standards registered by the national governments and space agencies. The primary objectives of these rules are “Prevention of Break-ups”, “Limitation of Releasing Objects during Operations”, “Disposal of Mission Terminated Spacecraft and Launch Vehicle Orbital Stages from the Useful Orbital Regions (with considering ground safety from the re-entering objects)”, “Avoiding damage caused by on-orbital collisions or impact”. Last February JAXA revised its Space Debris Mitigation Standards to be equivalent with “ISO-24113 Space Debris Mitigation Requirements”. It will enable that the space system manufacturers deliver the merchandizes which comply with global debris mitigation guidelines through the process that they try to develop the technology to comply with the JAXA standard. In near future, the international trade market for spacecraft and launch services may add a requirement to consider the orbital environment as a coessential condition to apply the contract. JAXA is providing not only regulations but also various kinds of analysis tools and support documents to support industry.

Global Debris Mitigation Control and Corresponding Activities in JAXA
世界のデブリ管理状況とJAXAの対応

Akira KATO, Dr.ENG.
22 January 2013
5th Space Debris Workshop,
JAXA/HQ
Tokyo, Japan

Contents

1. Debris Mitigation Rules and Their Background
2. Global Situation and JAXA Standard
3. Support Documents and Analysis Tools
4. Further Subjects

1. Debris Mitigation Rules and Their Background

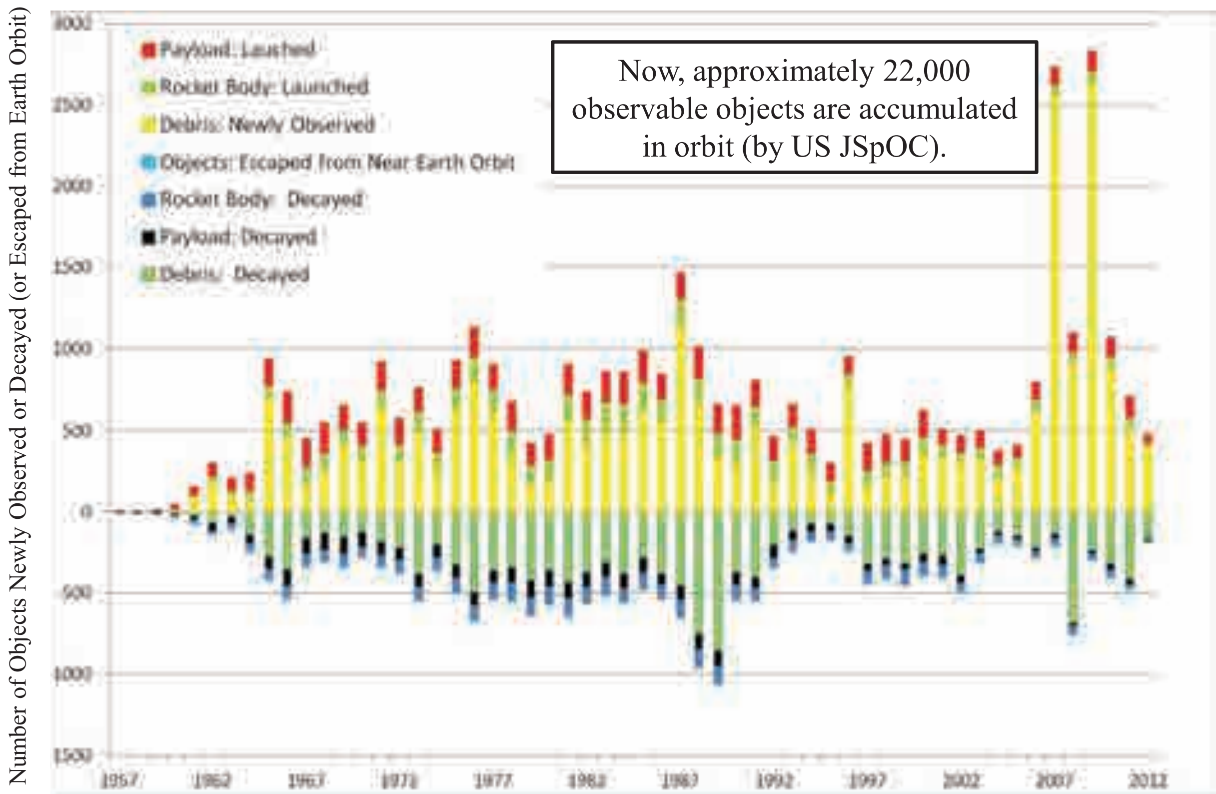


Figure 1 Number of Objects Newly Observed or Decayed (or Escaped from Near Earth Orbit)
(Ref. Data from Satellite Situation Report / Space-Track / USSTRATCOM, @June 25, 2012) (processed by A. Kato)

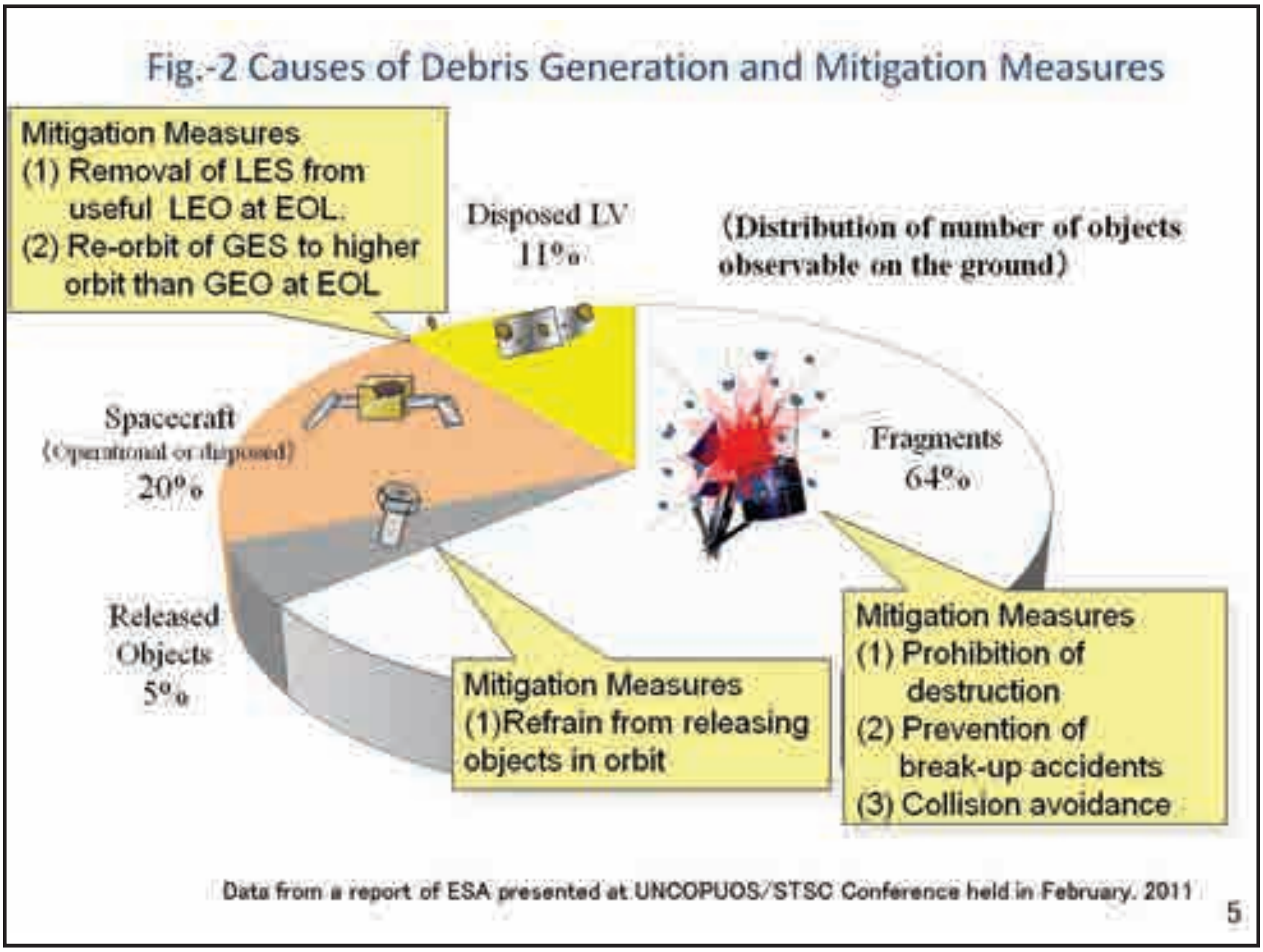


Fig.-2 Causes of Debris Generation and Mitigation Measures

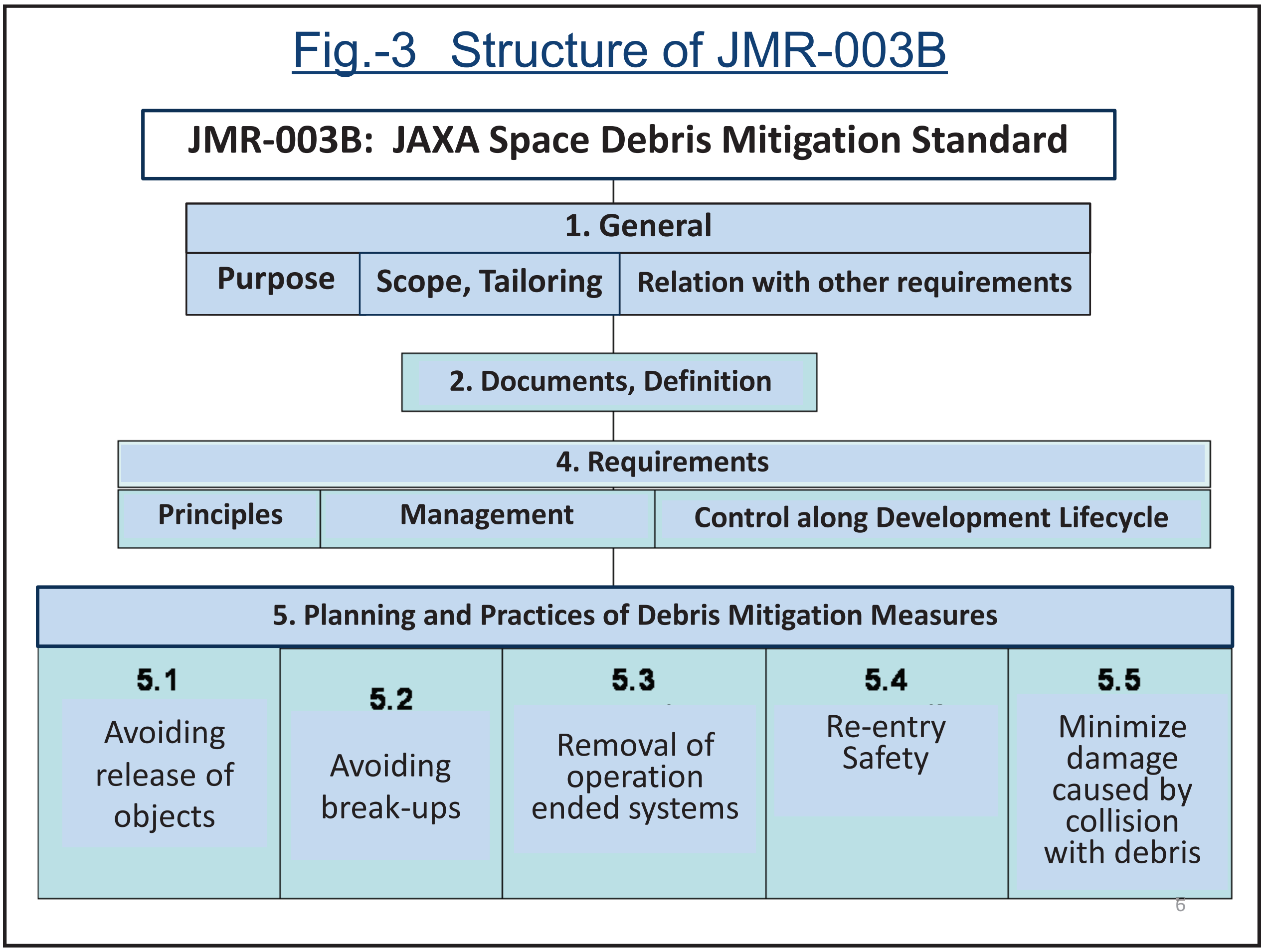


Fig.-3 Structure of JMR-003B

2. Global Situation and JAXA Standard

Fig.-4 International Framework for Debris Control

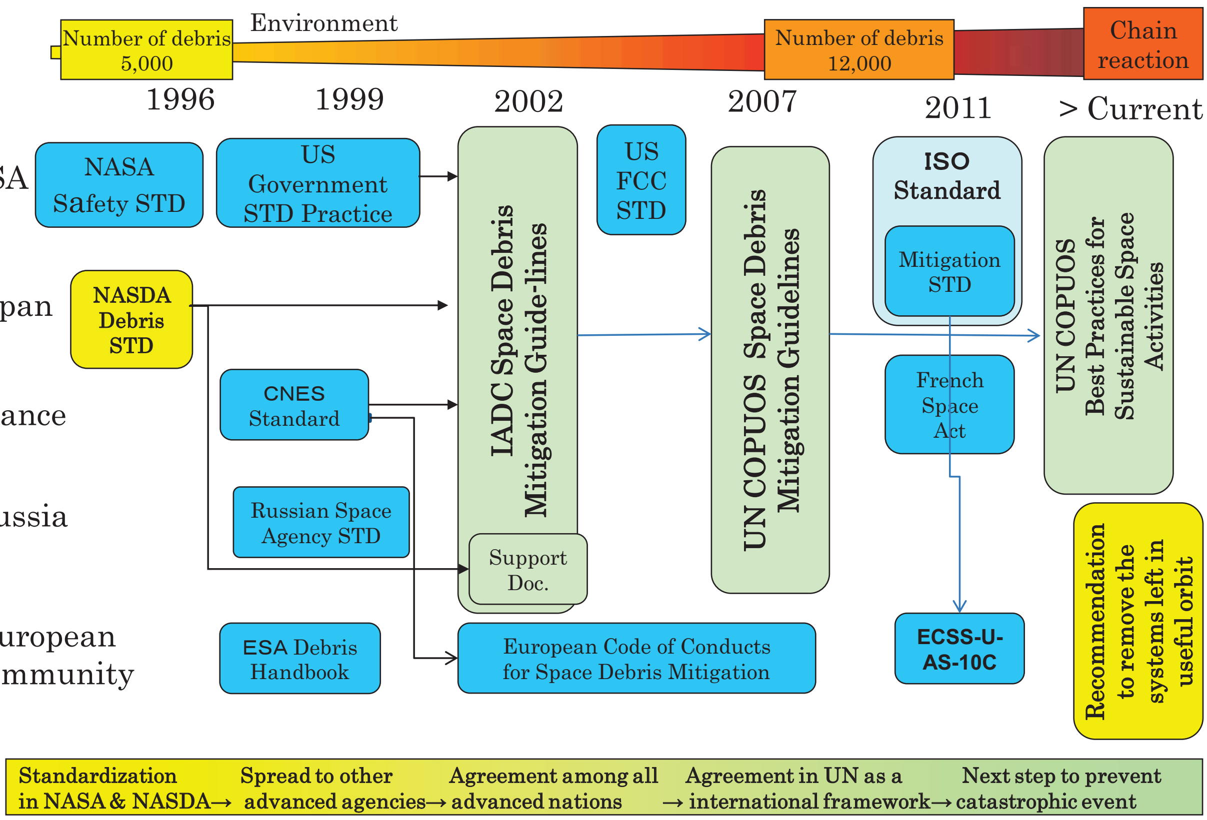
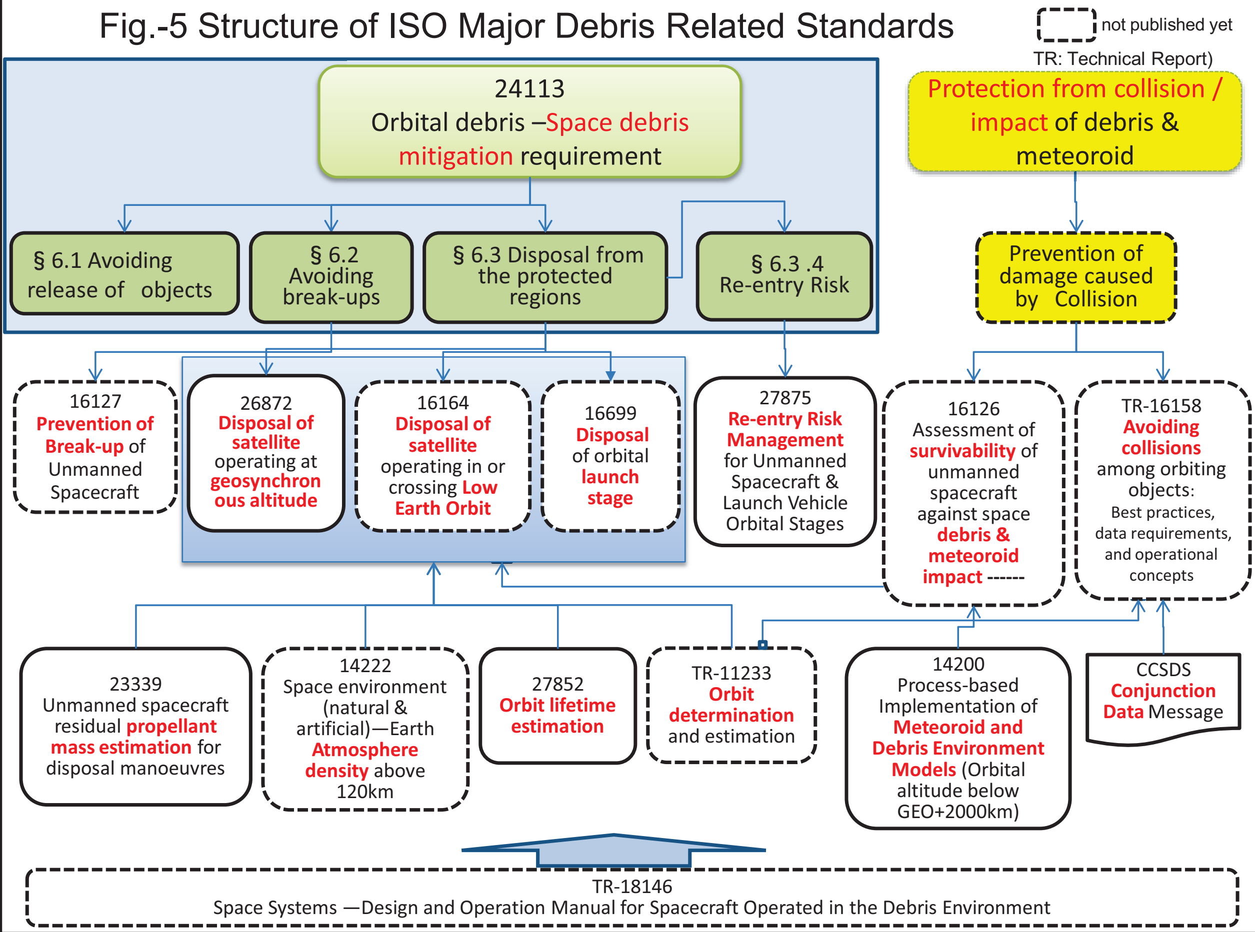


Table-1 global debris mitigation rules and JAXA standard

JAXA-003 was revised in the following yellow-colored parts

		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)**	Ec < 10^{-4}	§ 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

Fig.-5 Structure of ISO Major Debris Related Standards



Current Status of JAXA Debris Mitigation Standard

- Last February JAXA revised its Space Debris Mitigation Standards to be equivalent to “ISO-24113 Space Debris Mitigation Requirements”.
- Then the effort of the Japanese spacecraft manufacturers to comply with the JAXA standard will ensure that their merchandizes would be accepted in the global market.
- In near future, the international trade market for spacecraft and launch services may require to consider the preservation of the orbital environment as an essential condition.

- JAXAは昨年、従来から適用してきたデブリ発生防止標準をISOの最新規格と同等の規制となるように改訂した。
- これで国内衛星製造企業のJAXA標準への適合努力は、そのまま世界の規制に合致した製品の供給が可能になる体制を保証するものとなる。
- 今後、衛星国際調達市場や打上げサービス市場では軌道環境への配慮が入札条件に含まれることが考えられる。

3. Support Documents and Analysis Tools

JAXAでは支援文書、解析ツールなどを提供し、産業界のデブリ対策を支援している。
JAXA is providing various documents and analysis tools to support industry.

Table-2 Tools and Documents to Support Debris Mitigation Design and Operation

	Subjects	Support Tools and Documents
1	General Mitigation Tec. -Collision probability - Orbital Lifetime - Required Fuel for disposal -Re-entry survivability	(1) JERG-0-0-002A: JMR-003B Support Handbook (2) JAXA/DEMIST (Debris Mitigation Assessment Tool) (3) NASA/Debris Assessment Software (DAS) (4) JAXA-CAA- 111003: L/V Debris Mitigation Design & Operation Technique (5) JAXA-CAA- TBD : S/C Debris Mitigation Design & Operation Manual (to be released in 2013)
2	Debris Population Model	(1) ESA/MASTER-2009, NASA/ORDEM
3	Orbital Lifetime	(1) JAXA Orbital Lifetime Analysis Tool (追跡管制設備付属)
4	Protection Design	(1) JERG -2-144 Debris Impact Survivability Assessment STD (2) JERG-2-144-HB001 : Debris Protection Design Manual (3) JAXA/TURANDOT (tool for debris impact probability and damage analysis)
5	Re-entry Survivability	(1) ORSAT-J (being revised every year) (2) CAA-109029: Re-entry analysis Manual

Fig.-6 Support system for protection design

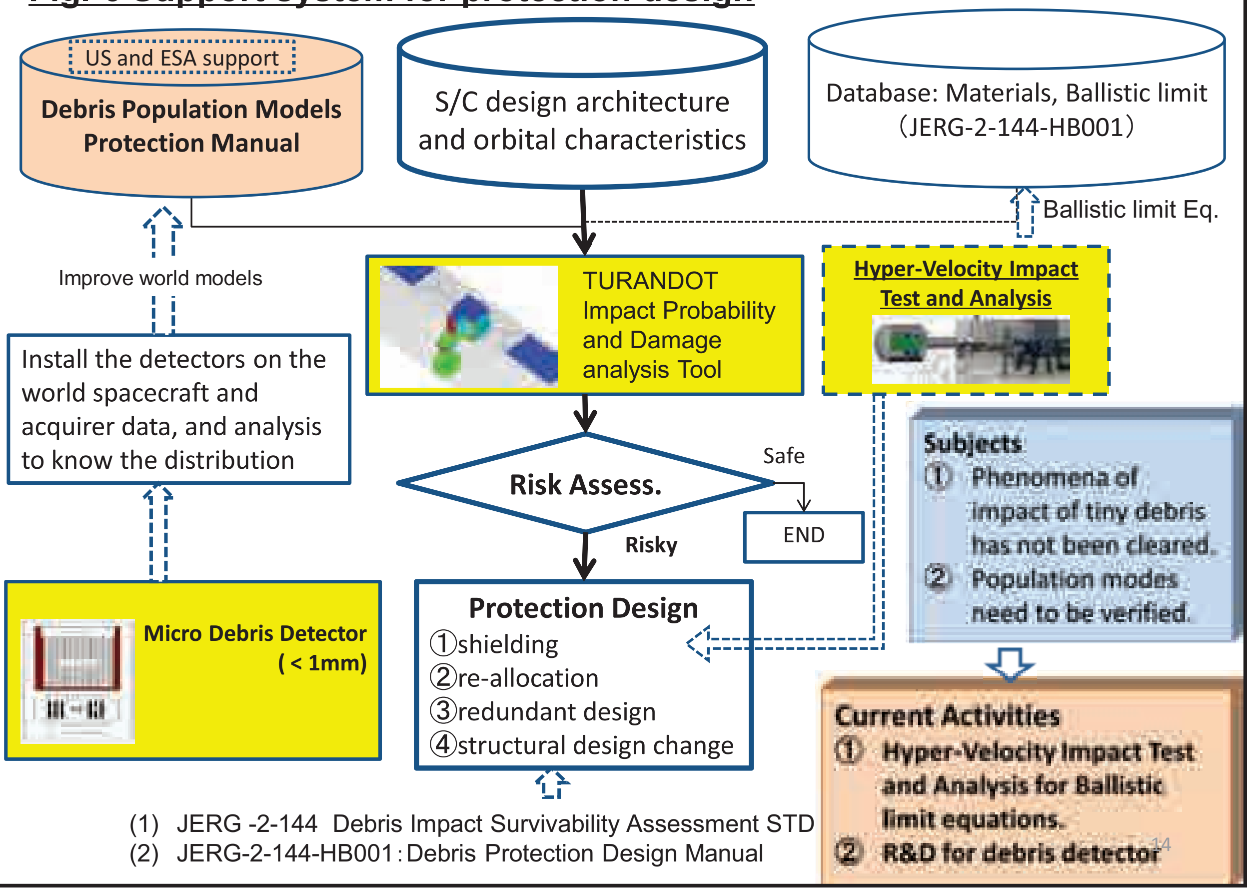
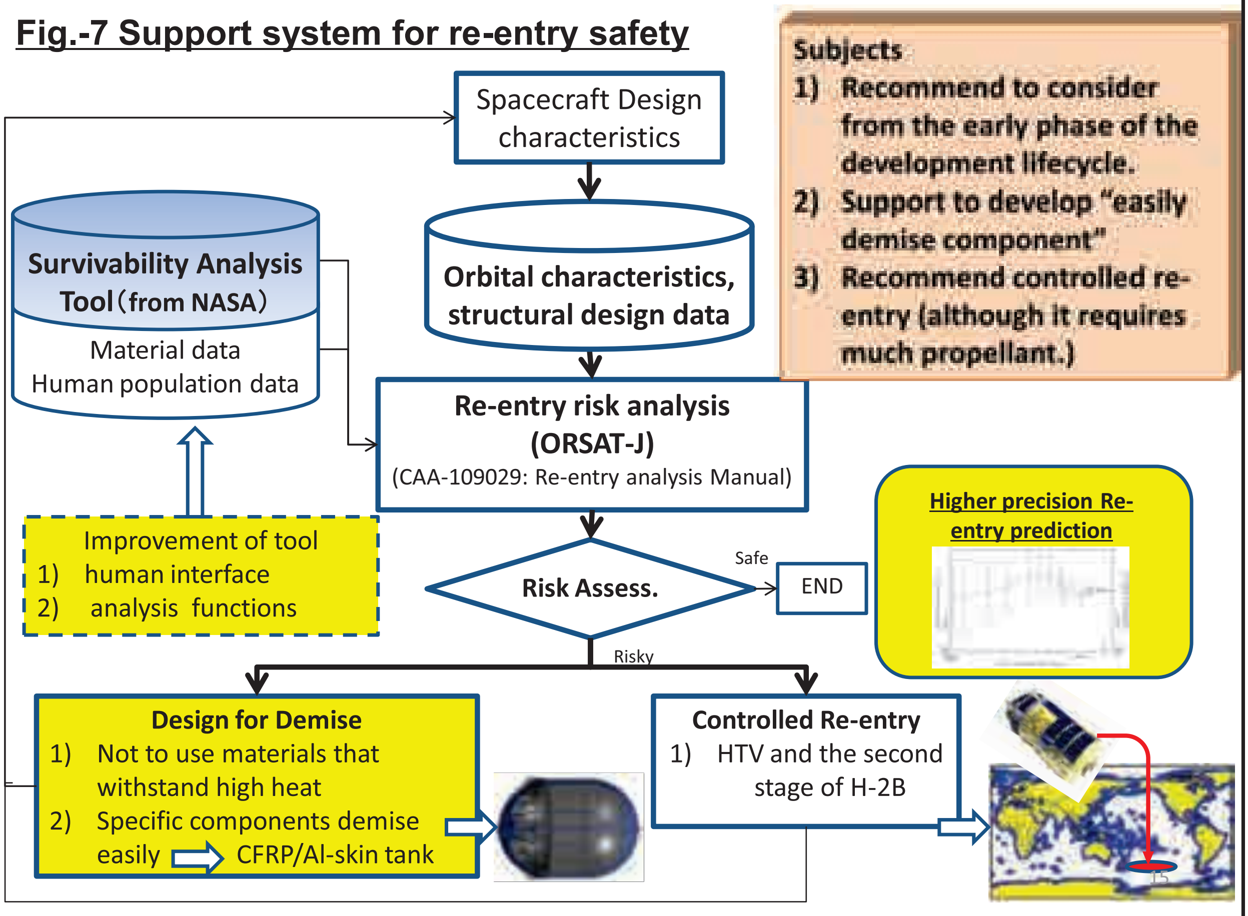


Fig.-7 Support system for re-entry safety



4. Further Subjects

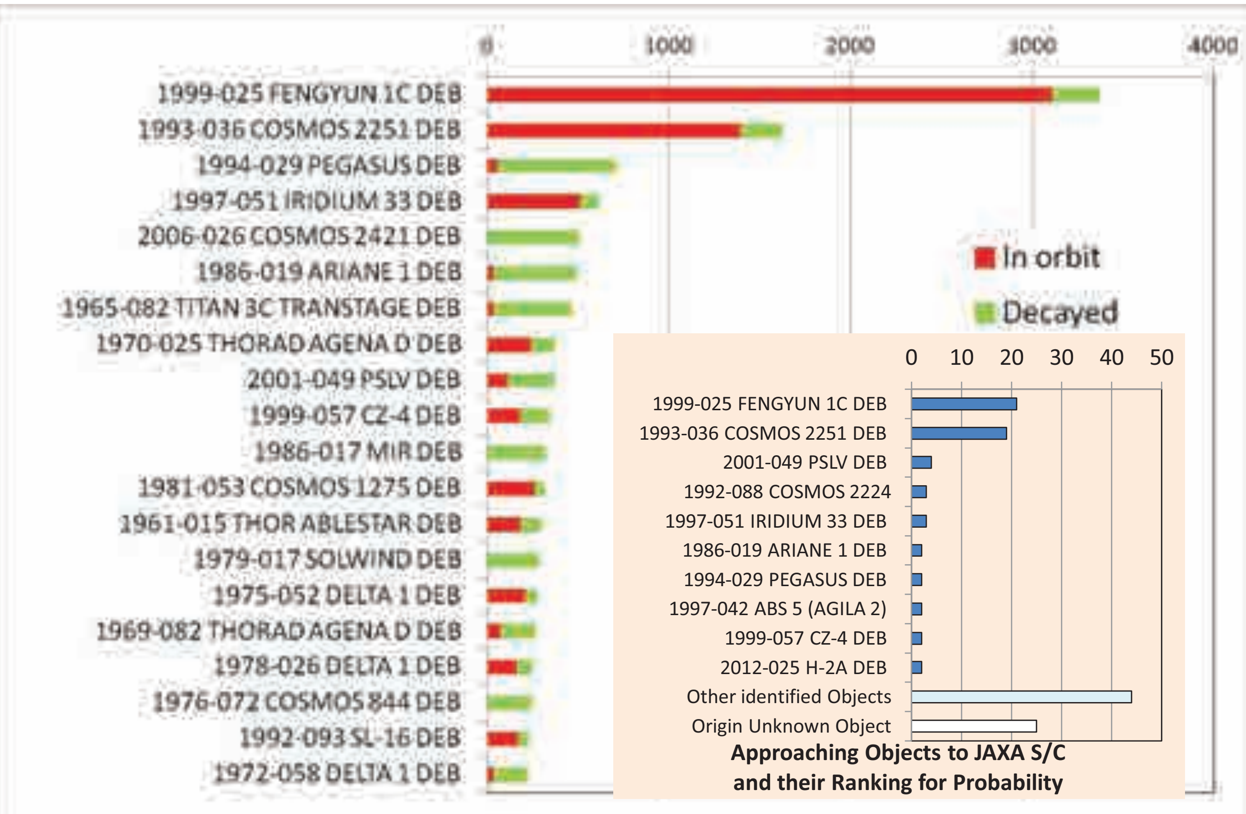


Fig.-8: Top 20 space objects which generated many debris
(data from the Space Situation Record of USSTRATCOM, dated June 2012)

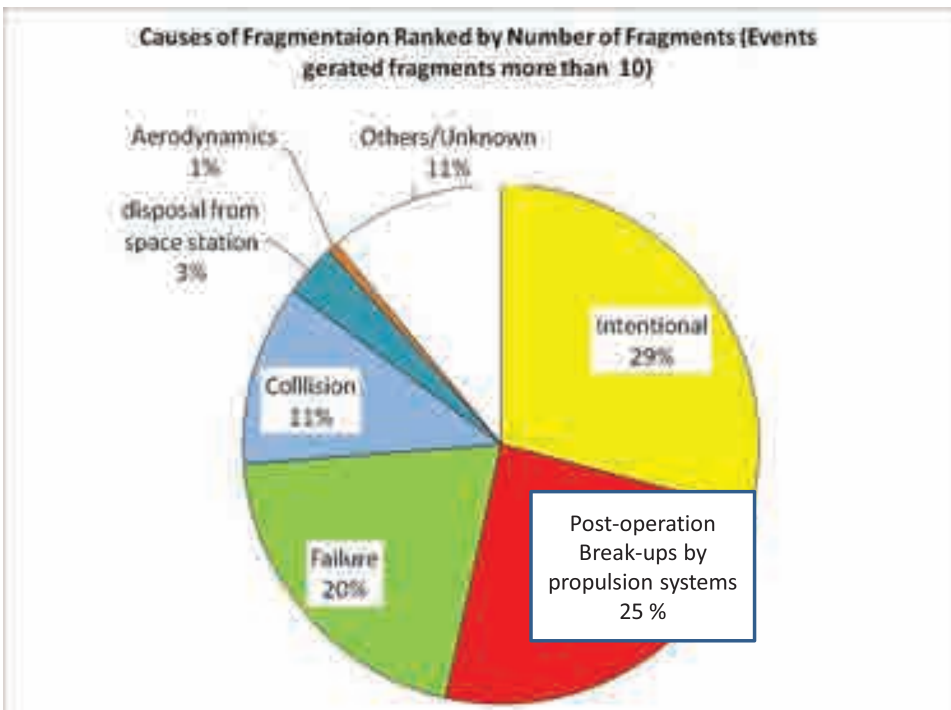


Fig.9: Distribution of Causes of Debris According to the Number of Fragments

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.

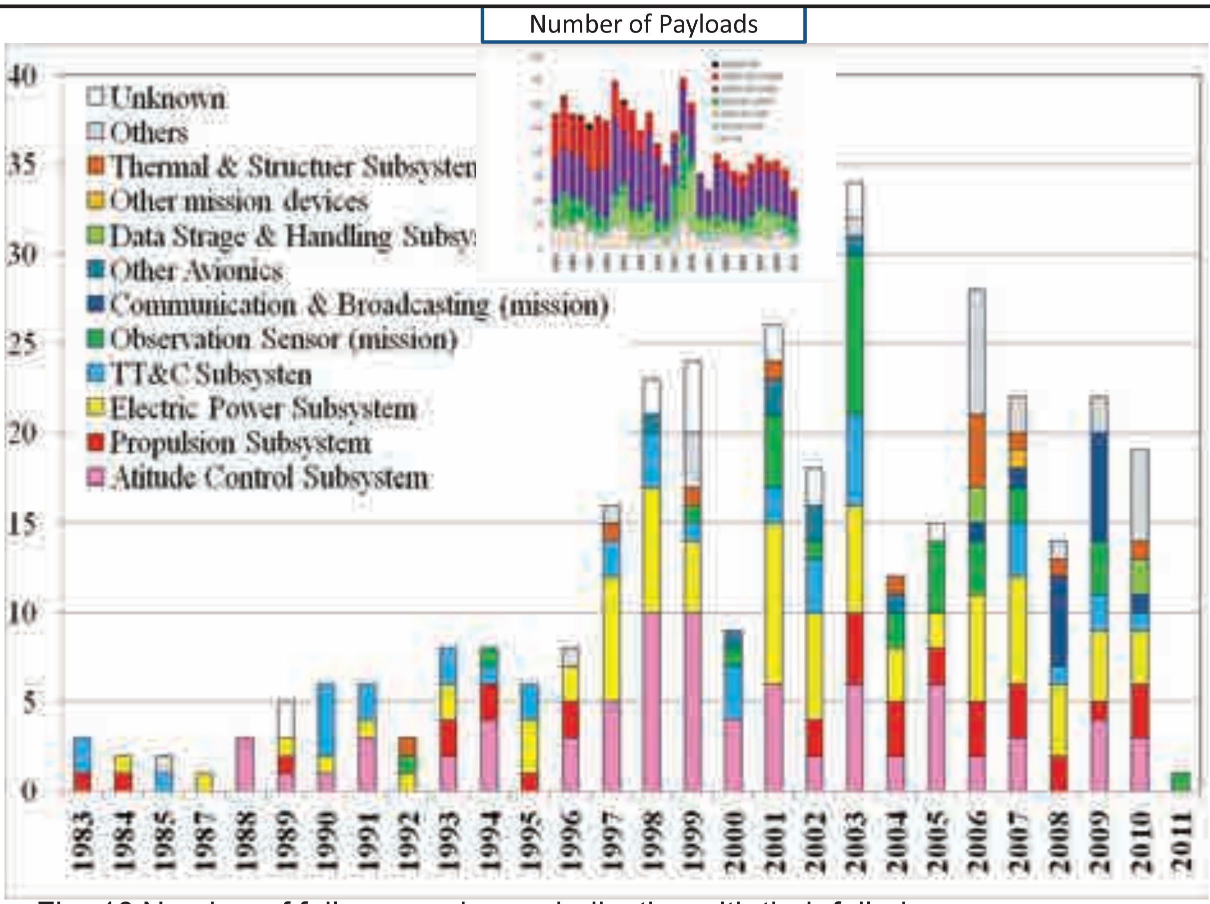


Fig.-10 Number of failures each year indicating with their failed year

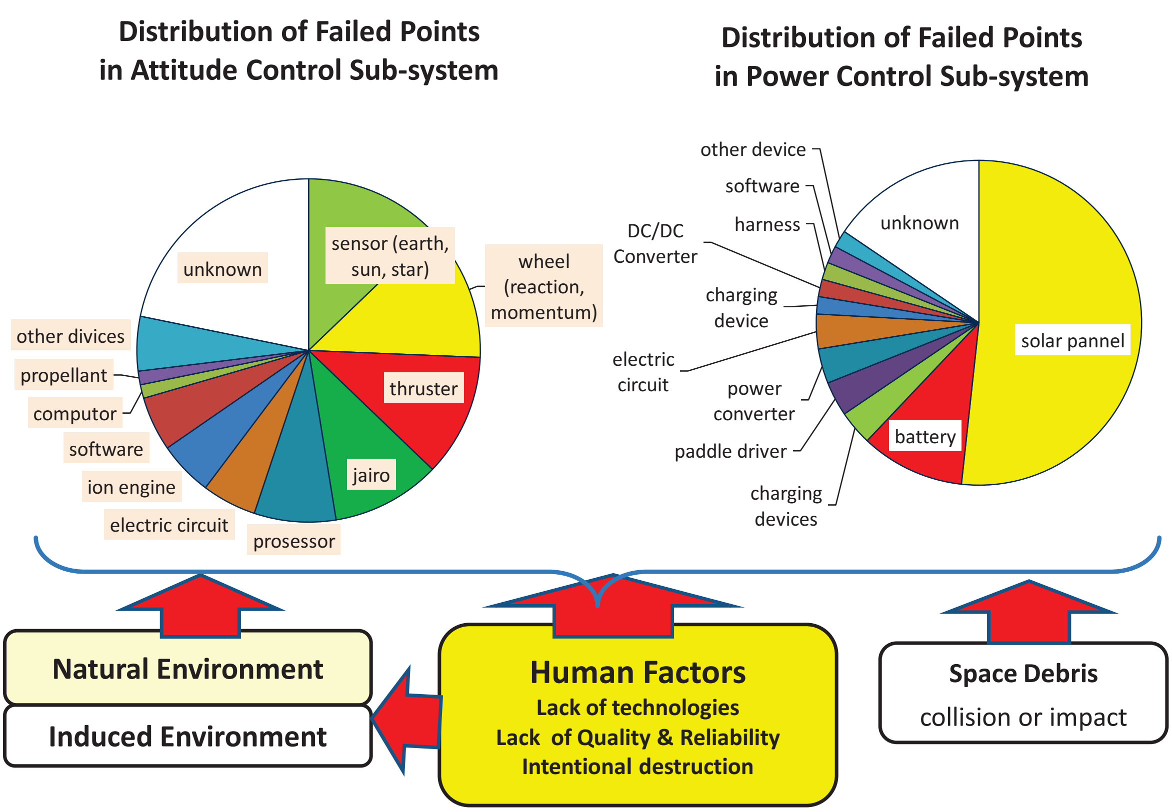
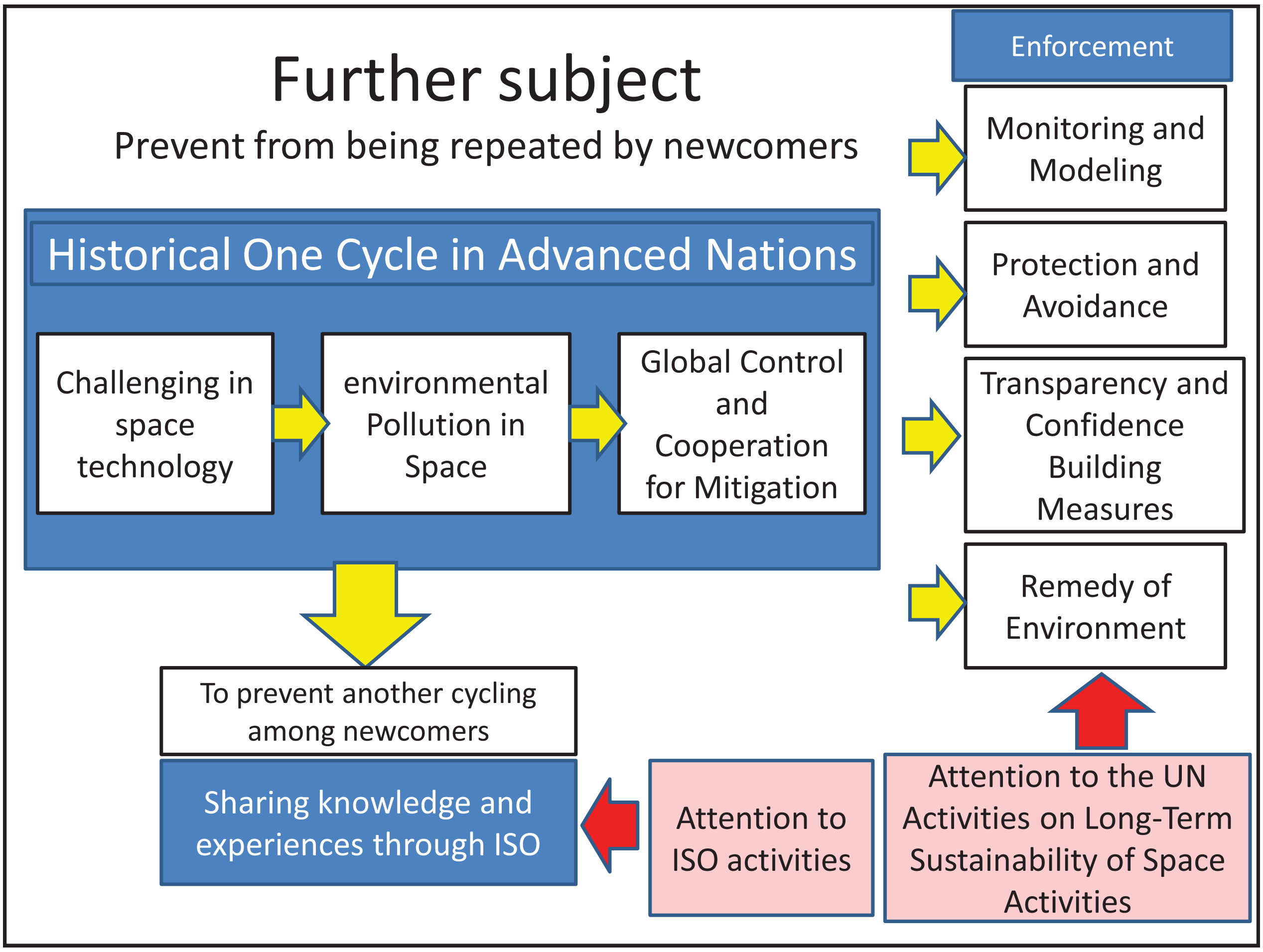


Fig.-11 Failed components in the “attitude control” and “power control” sub-system


Further subject
Prevent from being repeated by newcomers
Enforcement
Historical One Cycle in Advanced Nations
Challenging in space technology
environmental Pollution in Space
Global Control and Cooperation for Mitigation
Monitoring and Modeling
Protection and Avoidance
Transparency and Confidence Building Measures
Remedy of Environment
To prevent another cycling among newcomers
Sharing knowledge and experiences through ISO
Attention to ISO activities
Attention to the UN Activities on Long-Term Sustainability of Space Activities

B2

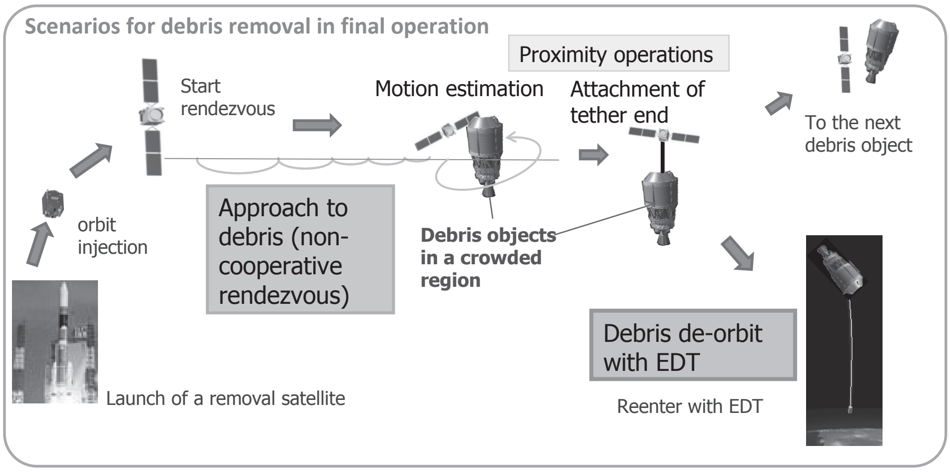
JAXAにおけるデブリ除去の研究状況

Current status of studies on active debris removal at JAXA

○河本聡美，大川恭志，片山保宏，上村平八郎，中西洋喜，井村信義，
北村正治，木部勢至朗，平子敬一（宇宙航空研究開発機構）
○S. Kawamoto, Y. Ohkawa, Y. Katayama, H. Kamimura, H. Nakanishi, N. Imura,
S. Kitamura, S. Kibe, K. Hirako (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自己増殖が開始していると考えられている。その場合、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り難易度が高いが、JAXA では安価なコストで実現できるデブリ除去技術の開発を目指して研究を実施している。本発表では、JAXA 研究開発本部未踏技術研究センターで行われているデブリ除去の研究について報告する。

The amount of space debris has been increasing, and many evolutionary models predict that it would increase even if new satellite launches were stopped because of mutual collisions between existing objects. In such a case, debris mitigation measures such as explosion prevention and end-of-mission de-orbit will be inadequate and an active debris removal will be needed to preserve the space environment. The Japan Aerospace Exploration Agency (JAXA) has been studying a cost-effective active debris removal system. This presentation introduces the current status of studies on active debris removal at JAXA.



JAXAにおけるデブリ除去の研究状況

Current status of studies on active debris removal at JAXA

河本聡美、大川恭志、片山保宏、上村平八郎、中西洋喜、
井村信義、北村正治、木部勢至朗、平子敬一(JAXA)
S. Kawamoto, Y. Ohkawa, Y. Katayama, H. Kamimura, H. Nakanishi, N. Imura, S. Kitamura, S. Kibe, K. Hirako (JAXA)

5th Space Debris Workshop, 2013

Introduction

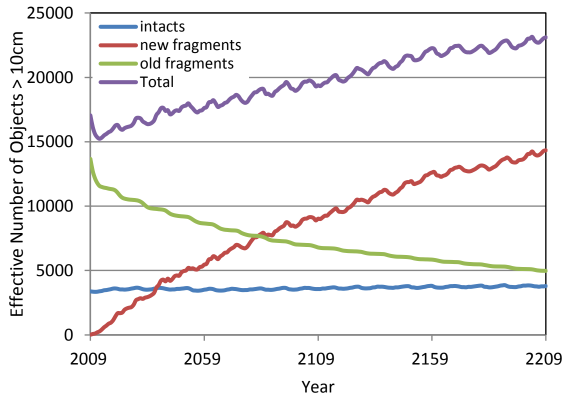
- JAXA has been studying cost-effective removal of large intact objects in crowded regions for many years
- Contents
  - Target of removal
  - Removal scenario and required technologies
  - Current status of each technology
  - Roadmap for developing debris removal system

2

Introduction : Necessity of Active Debris removal (ADR)

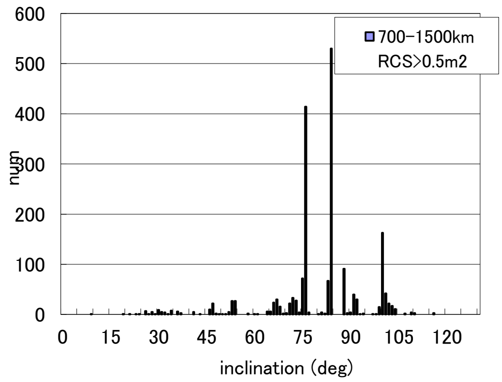
- Evolutionary models predict the amount of debris will continue to increase due to mutual collisions
- Active debris removal is necessary to reduce
  - Burden of Collision Avoidance Maneuvers (CAM)
  - Burden of debris protection design
  - Risks of unavoidable debris collisions
- To realize a practical debris removal
  - Technological feasibility
  - Reasonable cost
  - International cooperation

  will be needed

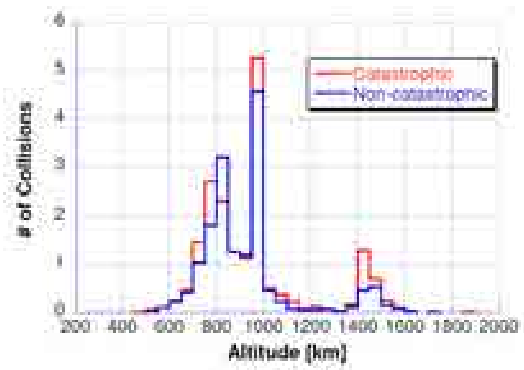


Targets of removal

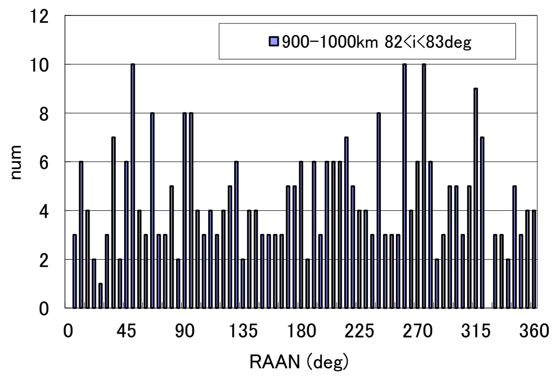
- Removal of large intact objects from crowded regions such as
  - SSO (98-100deg)
  - 900-1000km, 82-83deg
- Because they are the potential source of numerous small debris that pose direct risks and burdens
  - Removal of small debris is not efficient
- Numerous debris objects in the narrow orbital plane



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



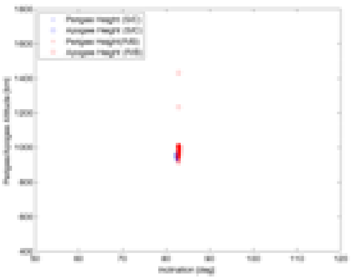
Number of collisions at each altitude predicted by LEODEEM, debris evolutionary model developed by Kyushu Univ. and JAXA



The number of objects in alt. of 900-1000 km and inc. 82-83 degree with RCS > 0.5 m^2 in each 5 deg RAAN bin.

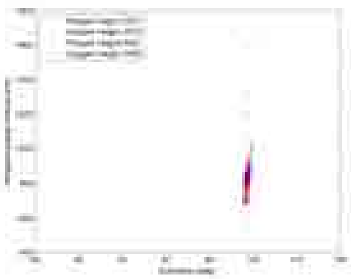
Which debris should be removed?

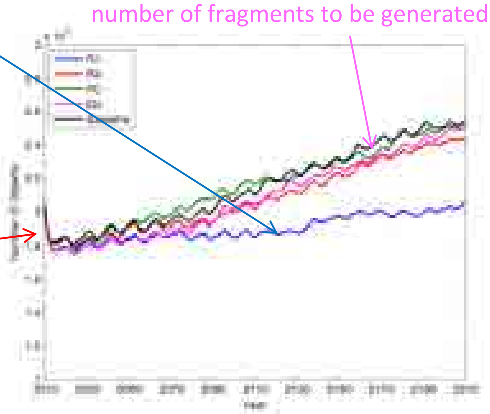
- The effect of removal was studied using debris evolutionary model developed by Kyushu Univ. and JAXA
- We must consider the effect of removal, technological aspects, legal aspects, etc



100 removal targets considering expected number of fragments to be generated in 25 years

100 removal targets in alt. of 900-1000 km and inc. 83 deg





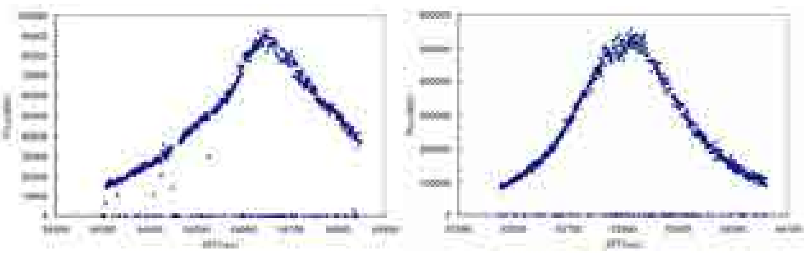
100 removal targets in SSO, 0.5ton<mass<4ton

5

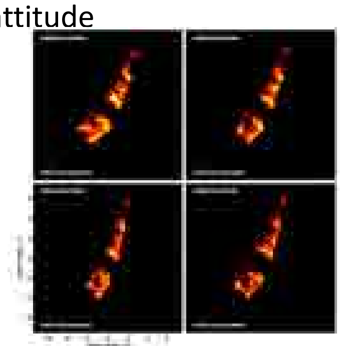
Rocket stages

- Rocket stages can be removal targets
  - Their design details are less confidential than satellites. ← non-technological
  - There is less variation in the shapes compared with satellites
  - Rocket stages are cylindrical and the reflections of light, lasers or other signals can be more easily predicted than 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.
  - Some studies indicate that any rotational motions will almost have been stopped due to interaction between their metal bodies and the geomagnetic field → there are some R/Bs with stable attitude

← technological



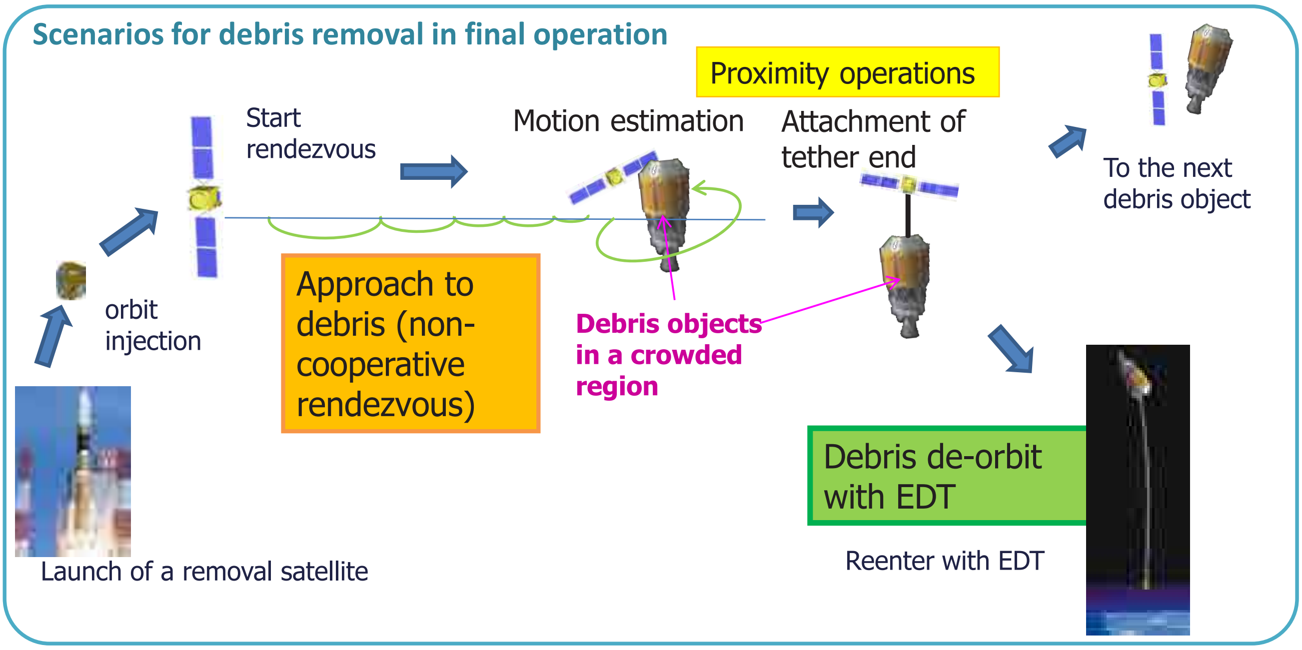
Light curve of SL-8 rocket upper stage.
There exists no tumbling objects.



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

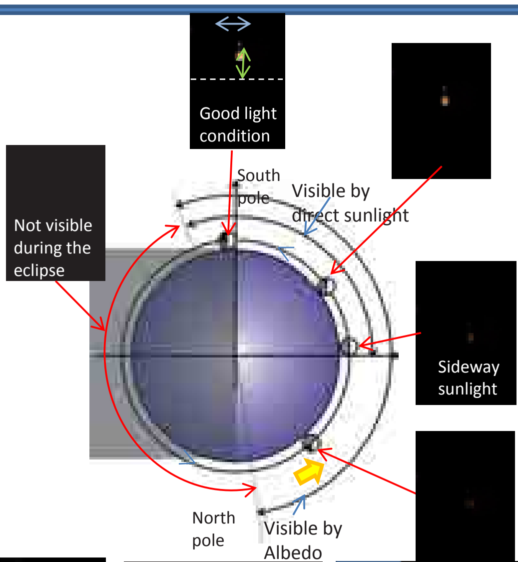
Scenarios for debris removal

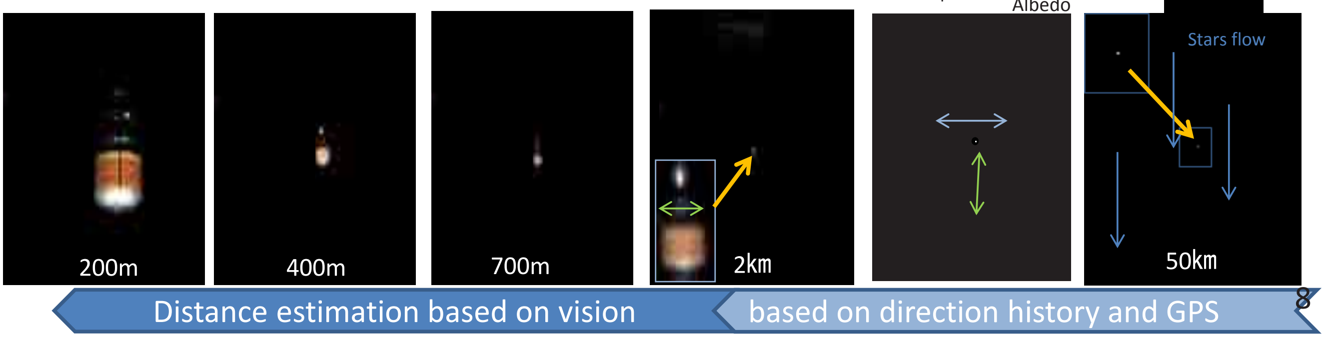
- Technologies to realize ADR have been studied and key technologies to be demonstrated identified



Non-cooperative rendezvous

- Estimation of relative distance and attitude motion of debris that has no markers nor reflectors is difficult
- Orbital motion effects much compared with rendesvous with asteroids such as optical environment changes so
- Status:
  - Non-cooperative rendezvous using simple, low cost sensors such as GPS receiver, optical cameras have been studied
  - Cameras have been evaluated using “optical simulator”

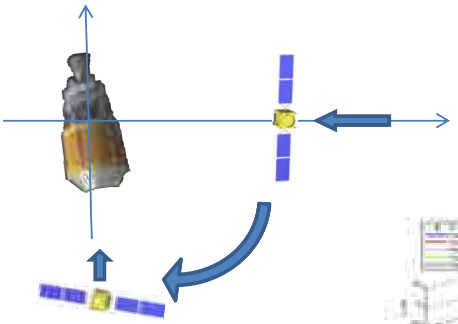


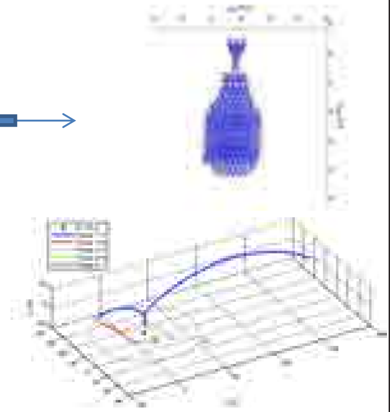


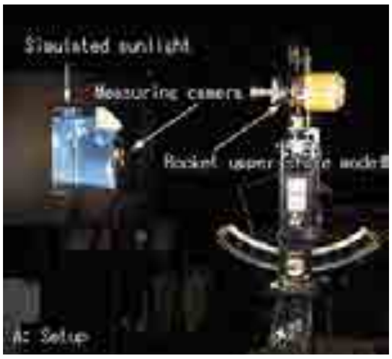
8

Proximity operations (1)

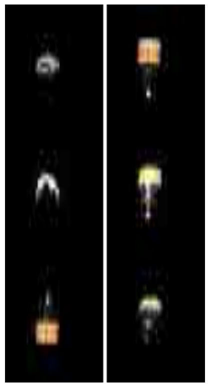
- Attitude of debris is unknown as their attitude is no longer controlled
- Status:
  - Final approach using have been studied using
    - Image processing using stereo vision
    - Model matching to identify its attitude/position and motion
  - Numerical simulations and on-ground experiments using a model of H-IIA rocket upper stage and optical simulator have been performed







Optical simulator

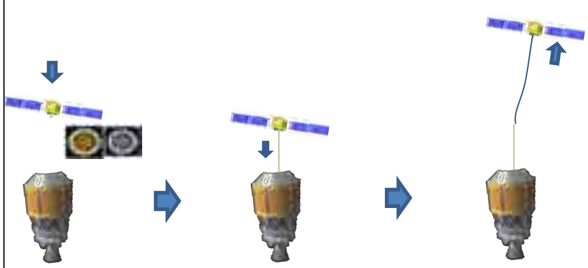


Rocket upper stage model images taken using optical simulator

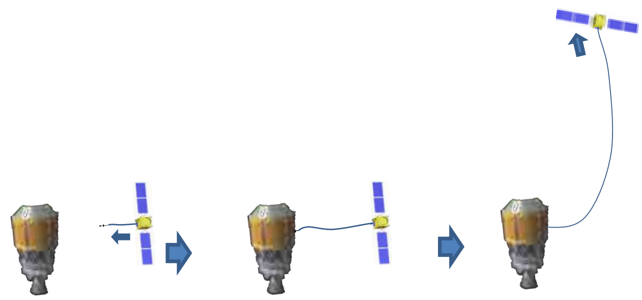
9

Proximity operations (2)

- Attachment of propulsion is required to give dV > 100 m/s to debris with > some tons
  - Control of C.G. when removal satellite pushes debris, or stable pulling is required
- Status:
- Attachment of the tether end without need for precise position control
  - Attachment to the payload attachment fitting of the rocket upper stage using an extensible boom mechanism
  - Harpoon
  - Extensible robot arms
- Preliminary studies including numerical simulations have been performed and challenges to be studied were identified



Attachment to the PAF using an extensible boom mechanism. Image processing of PAF structure to estimate relative position and attitude is studied

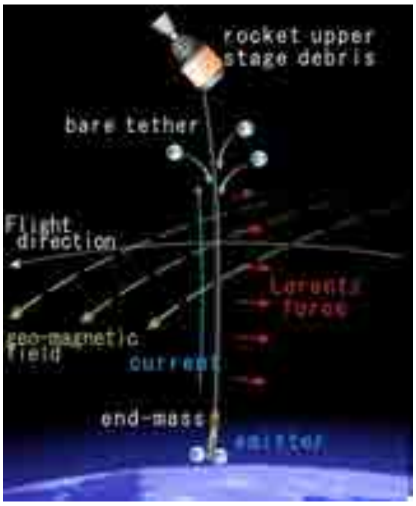


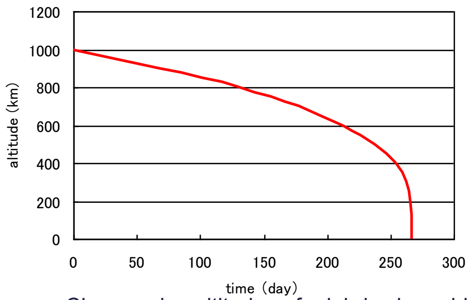
Attachment using a harpoon. Impact analysis showed that fragment will not be generated when harpoon penetrates the propellant tank of R/B

10

Deorbit (Efficient Orbital Transfer)

- Large amount of fuel required for de-orbit prohibiting removal by small satellite and multiple removal by one satellite
- Electrodynamic tether (EDT) is promising for LEO removal
  - No need for propellant or high electrical power
  - Its thrust is so small and attaching operation will be less challenging
- Status: Numerical simulations have been conducted and some key components are developed and tested



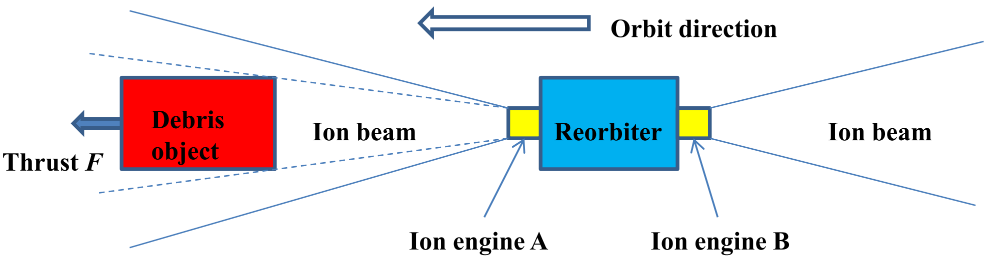


Change in altitude of debris in orbit altitude 1000 km, inclination 83 deg (1400kg) with EDT of 10 km.

11

GEO Debris Reorbiter using Ion Beam Irradiation

- GEO remediation is also necessary because no air drag to clean up debris is expected in the precious GEO
- Ion Beam Irradiation to put large debris to grave yard orbit
  - Non-contacting with non-cooperative debris
- Status
  - A preliminary system study has been conducted. Numerical simulations and some experiments in progress.



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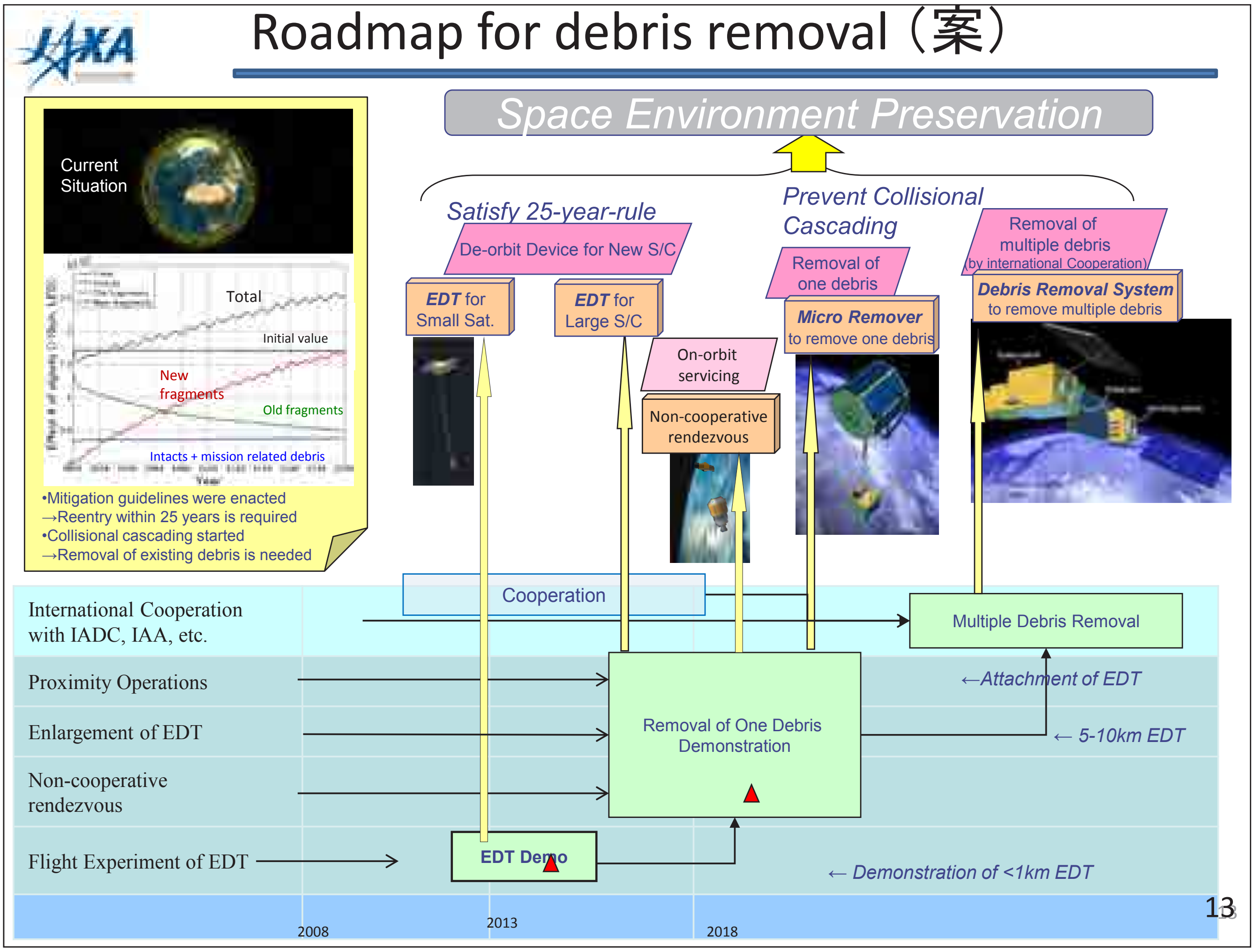
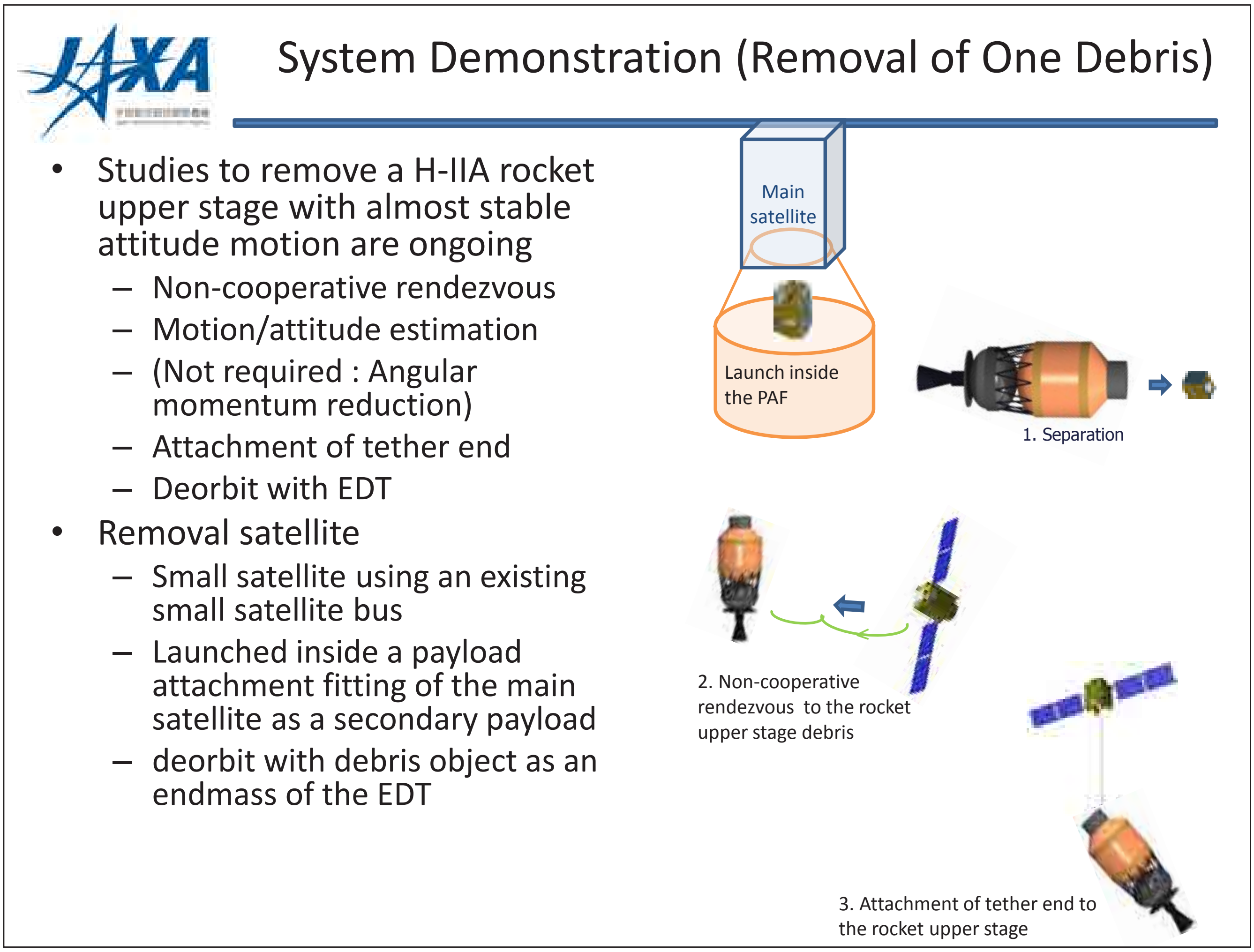

Roadmap for debris removal（案）
Space Environment Preservation
Current Situation
Total
Initial value
New fragments
Old fragments
Intacts + mission related debris
•Mitigation guidelines were enacted
→Reentry within 25 years is required
•Collisional cascading started
→Removal of existing debris is needed
Satisfy 25-year-rule
De-orbit Device for New S/C
EDT for Small Sat.
EDT for Large S/C
On-orbit servicing
Non-cooperative rendezvous
Prevent Collisional Cascading
Removal of one debris
Micro Remover to remove one debris
Removal of multiple debris (by international Cooperation)
Debris Removal System to remove multiple debris
Cooperation
International Cooperation with IADC, IAA, etc.
Multiple Debris Removal
Proximity Operations
Enlargement of EDT
Non-cooperative rendezvous
Flight Experiment of EDT
Removal of One Debris Demonstration
←Attachment of EDT
← 5-10km EDT
EDT Demo
← Demonstration of <1km EDT
2008
2013
2018
13


System Demonstration (Removal of One Debris)
• Studies to remove a H-IIA rocket upper stage with almost stable attitude motion are ongoing
– Non-cooperative rendezvous
– Motion/attitude estimation
– (Not required : Angular momentum reduction)
– Attachment of tether end
– Deorbit with EDT
• Removal satellite
– Small satellite using an existing small satellite bus
– Launched inside a payload attachment fitting of the main satellite as a secondary payload
– deorbit with debris object as an endmass of the EDT
Main satellite
Launch inside the PAF
1. Separation
2. Non-cooperative rendezvous to the rocket upper stage debris
3. Attachment of tether end to the rocket upper stage

Conclusions

- JAXA's studies for cost-effective active debris removal
  - Targets of removal are 100-150 large debris in some crowded regions such as SSO, 900–1000 km alt. and 83 deg inc.
  - Rocket bodies with stable attitude
- Technologies for realizing ADR
  - Non-cooperative Rendezvous
  - Proximity operations (motion estimation and attachment of tether end)
  - De-orbit by EDT for LEO and ion beam irradiation for GEO
  - Cost effective small satellite for debris removal
- Roadmap towards realizing the debris removal system was shown

B3

スペースデブリ除去を実施する上での宇宙諸条約上の制約と解決策のための予備的検討

Some constraints of international space law on the conduct of active debris removal and preliminary studies to searching for a solution

岸人弘幸（宇宙航空研究開発機構）
Hiroyuki Kishindo (JAXA)

宇宙空間におけるデブリの増加に伴い、デブリ発生の低減だけでなく除去の必要性が国際的に議論され始めている。JAXA においても、伝導性テザーを利用したデブリ除去の軌道上実証を検討している。そこで、まず初めにデブリの国際法上の位置付けを明らかにするために、宇宙諸条約における関連規定について検討する。続いて、伝導性テザーを用いてデブリ除去を実際に行う状況を題材とし、除去対象の決定から除去作業の実行までに至る各プロセスにおいて、国際法上および国内法上いかなる問題があるのか、法的観点から検討する。最後に、これまでの検討を踏まえ、今後各国がスペースデブリ除去を実施するにあたっては、どのようにしてこれらの課題を解決し得るのかについて提言し結びとしたい。

第5回　スペースデブリワークショップ

スペースデブリ除去を実施する上での宇宙諸条約上の制約と解決策のための予備的検討

2013年1月22日
@調布航空宇宙センター
事務棟1号館2階講堂

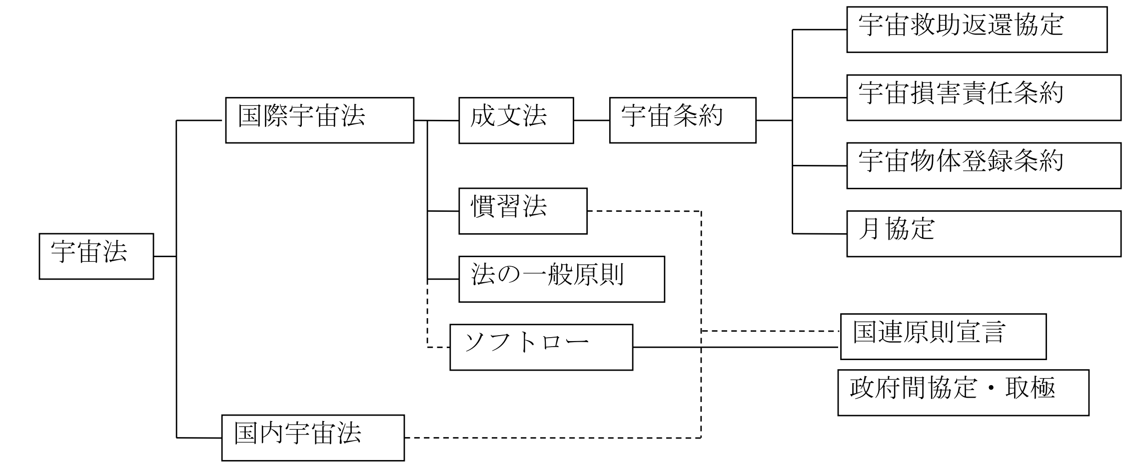
Some constraints of international space law on the conduct of active space debris removal and preliminary studies to searching for a slution

Hiroyuki Kishindo
Legal Affairs Division, General Affairs Department, JAXA

宇宙法のフレームワーク

○宇宙法とは何か

- ✓ 国際公域である「宇宙」の活動を規律する法
- ✓ 狭義では「国際宇宙法」を指し、広義では「国内宇宙法」を含む。

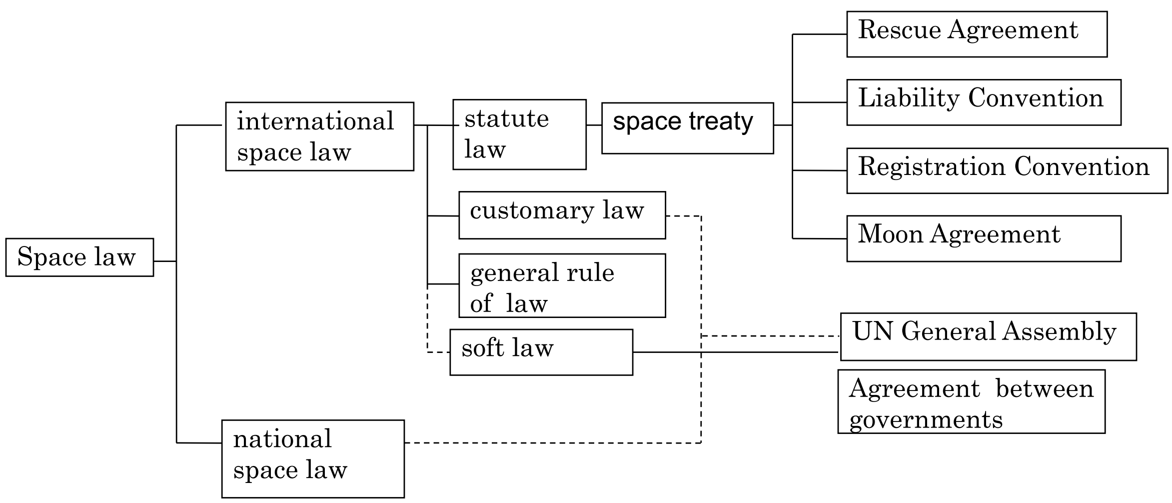


2

Framework on the Space Law

○What is “Space law”?

- ✓ the law to regulate the space activities
- ✓ in a narrow sence, the international space law
  in a broad sence, the space law including the national space law



3

宇宙法の主要規定・論点

- 宇宙活動自由の原則(OST1条)
- 宇宙空間領有禁止(OST2条)
- 平和利用原則(OST4条／月3条)
- 関係当事国への責任集中(OST6条)
- 打上げ国による損害賠償責任(OST7条→LC)
- 登録国による管轄権・管理権(OST8条→RC)
- 有害な汚染の禁止(OST9条)

※ 管轄権とは、国家がその国内法を一定範囲の人、財産または事実に対して適用し行使する国際法上の権能をいい、国家主権の具体的な発現形態。(立法管轄権、司法管轄権、執行管轄権)

※管理の権限とは、宇宙物体の活動に対する指令・追跡・管制など、関係国内法令に基づいて行われる事実上の規制行為 。

4

Main Provision in Space Treaties

- Freedom of the space activities(OST Art.1)
- Prohibition against national appropriation(OST Art.2)
- Peaceful purposes(OST Art.4)
- State's responsibility for the activities by non-governmental entities(OST Art.6)
- International Liability for Launching State(OST Art.7)
- Jurisdiction and control over space object by the Registration State(OST8条)
- Prohibition of contemination(OST Art.9)

5

デブリ除去事業の法的論点

	国際的平面での問題	国内的平面での問題
【フェーズ1】除去対象の決定	登録国(管理・管轄権を有する国)の同意が必要。	非政府団体の衛星の場合、衛星所有者の同意が必要。
	論点①:デブリの定義、同意を得る相手	
【フェーズ2】除去のための契約締結	所有者が不明、倒産等の場合の契約相手先はどこか。	所有者が不明、倒産等の場合の契約相手先はどこか。
	論点②:除去の費用	

6

Legal points to implement ADR

	International Level	National Level
【Phase 1】Identify the object for ADR	Necessary to get Registration State's consent	Necessary to get owner's consent, if satellite is owned by non-governmental entity
	Point①:Definition of "space debris"、Contracting Party to get consent	
【Phase2】Make a contract to implement ADR	If the satellite's owner isn't clear or go out of buisiness, is there any appropriate contracting party to implement ADR?	If the satellite's owner isn't clear or go out of buisiness, is there any appropriate contracting party to implement ADR?
	Point②:Cost for ADR	

7

デブリ除去事業の法的論点（続き）

	国際的平面での問題	国内的平面での問題
【フェーズ3】除去作業に必要な情報取得や国内手続		宇宙物体に関する機微情報を除去作業者に開示することになり得る。
	論点③：各国の国内法制（国内宇宙法を含む）	
【フェーズ4】除去作業の実行	デブリの落下や再突入に対する許可の必要性。 デブリ除去によって他の宇宙物体や地表に損害を与える可能性	
	論点④：損害賠償責任	

8

Legal points to implement ADR

	International Level	National Level
【Phase3】Get nessary information to implement ADR and Take appropriate procedure		Necessary to get some information which is a kind of sensitive information
	Point③：Legal system in each State	
【Phase4】To implement ADR	Necessary to get permission for landing or reentry Possible to cause damage aganst other space object or on the surface of the Earth	
	Point④：Liability	

9

論点①:デブリの定義、同意を得る相手

〇スペースデブリの定義

✓ 条約上の定義はない。

✓ 除去候補であることを決定するため、宇宙物体の価値や有用さをどのようなプロセスで決定するか。

⇔IADCや国連でのデブリの定義は技術的な機能面に注目。しかし、非機能物体はなお法的価値を有しており、法的には所有者による廃棄の意思表示が必要。（登録国が管理・管轄権を行使できなくなれば、放棄されたとみなせることができるか？）

〇同意を得る相手

✓ 衛星所有者である非政府団体が同意しているにも関わらず、登録国が同意していない場合

✓ 軌道上売買され所有者の国籍国と登録国が異なる場合

⇒ ①宇宙物体を運用する登録国から許可が得られない場合に宇宙物体を除去することが認められるか、②除去が認められる場合、何を根拠に決定されるか、③登録国からの許可が得られない場合、デブリ除去を行うことに対する国家安全保障上の懸念はないか、等の問題がある。

10

Point①

〇Definition of “space debris”、

✓ There is no definition of “space debris” in the space treaties.

✓ How identify the object for ADR? How evaluate the value and/or useful of space objects?

〇 Contracting Party to get consent

✓ If the satellite’s owner doesn’t consent , or if the satellite’s owner is changed in orbit, what is the contracting party to get consent?

11

論点②：除去の費用

○費用効果の観点では、短期的には能動的デブリ除去は小さな利益しかなく、太陽電池パネルのデザインを改善することで容易に同じ効果を得られる。

⇒長期的にはコントロールできないデブリ増加や将来の宇宙活動の規制といった可能性を低減できる。

○費用負担の観点では、国際的な経済ファンドを立上げ、政府や民間が打上げや衛星運用といった活動の現在のシェアに応じて支出するなどの検討が必要。

⇒①国際的に許可された団体に必要な技術の開発を競争させ、②これらの団体が必要な技術の開発やデブリ除去に成功した場合に報酬を支払い、③ミッション終了時にファンドも終了する、スキームの検討

12

論点③：各国の国内法制（国内宇宙法を含む）

○米国：武器国際取引に関する規則（ITAR:International Traffic in Arms Regulations）

⇒米国衛星または米国のコンポーネントや技術を搭載した衛星を除去することは、ITAR上の「輸出」に該当する。

○英国：宇宙活動法第5条2項(1986年)

⇒国務大臣は宇宙活動を許可し特定の条件を命ずる権限があり、条件に違反した場合、宇宙物体の放棄を命ずることができる。

○カナダ：リモートセンシング法第9条1項（2007年）

⇒外務国際貿易省大臣が、ライセンスを発給するための要件として、(a)ライセンス対象システムに関するシステム廃棄計画で、とりわけ、環境、公衆衛生並びに人及び財産の安全の保護を規定するもの、(b)当該システム処分計画に基づくライセンス取得者の義務履行を保証する取極め、が掲げられている。

○日本：外為法　第25条1項

⇒安全性の観点から他国からデブリ除去機の情報を求められた場合、開示する技術内容によっては本条項の規制がかかると考えられる。

13

Point②:Cost for ADR

〇Cost effective to implement ADR

〇To establish international funds to implement ADR, we have to study how sharing cost

Point③: Legal system in each State

〇United State:ITAR:International Traffic in Arms Regulations

⇒It is regarded as "export" in ITAR to implement ADR.

〇United Kingdom:Space Activities Law Art.5(2)

〇Canada:Remotesensing Law Art.9(1)

〇JApan:Foreign exchange Law Art.25(1)

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論点④:損害賠償責任

〇損害賠償責任は、所有権と関係なく、打上げ国※が連帯責任を負う。

⇒ ・「宇宙物体」にデブリが含まれるか。

・地上:無過失 ←→ 宇宙空間:過失(立証が困難)

・「損害」には生命身体財産のみを想定(間接損害が含まれず)

・賠償責任を負うのは民間ではなく、国

・締約国間にのみ適用

・強制力のない紛争解決制度

⇒ 高度な技術、高いリスク、低い発生確率の他の分野での賠償レジームを参考に新たな損害賠償責任制度の検討が必要。

※LC1条(d)
「宇宙物体」には、宇宙物体の構成部分 並びに宇宙物体の打上げ機及びその部品を含む。

※LC2条
打上げ国とは、
① 宇宙物体を打上げる国、
② 打上げを行わせる国、
③ 宇宙物体が、その領域から打上げられる国
④ 宇宙物体が、その施設から打上げられる国

15

今後の課題

○　COPUOSでの新たな条約の作成は困難（コンセンサス方式の課題）

⇒　宇宙活動国間でのデブリ除去のモデルとなるような実行が必要

⇒　日本の国際競争力確保のためにどのようなルール作りが有利かを検討
（政府や宇宙活動事業者とともに、デブリ除去の必要性やそのための課題を発信していくことで、デファクトスタンダードを構築していくことが重要。）

ex）デブリ除去にあたっての国際的枠組み作り、損害賠償レジームや保険の検討

16

Point④：Liability

○Launching state laible to damage caused by space object.

⇒　・"space object" include Space debris?

・on the surface of the Earth ←→ in space：need to proove fault

・"damege" is not include indirect damage

・Liability owe State、not non-governmental entity

・Apply only to ContractingState

Challenges in the future

○Challenge to the consensus system in COPUOS

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B4

デブリ除去プロジェクト立上げとビジネスへの展開

Promoting the Active Debris Removal Project on Business

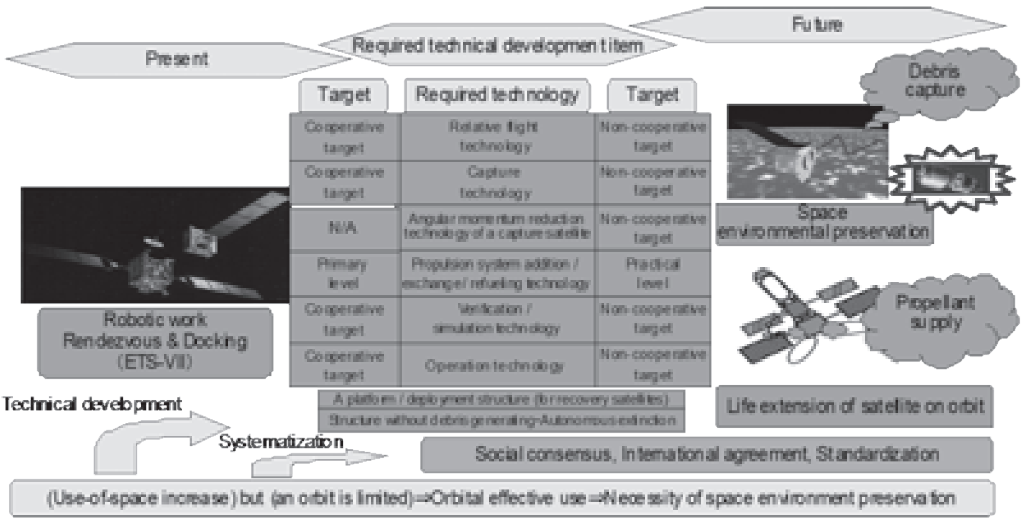
SJAC 次世代プロジェクト推進委員会
副委員長　峰　正弥（NEC）
Committee for Next-generation Space Project Promotion,
The Society of Japanese Aerospace Companies (SJAC)
co-chairman　Masaya Mine (NEC)

現在、宇宙環境は、新たに衛星を打上げなくても、軌道上に存在するデブリのみでデブリ増殖される状態となっている。一方、人類は、宇宙からの観測、通信、測位等々、宇宙環境を利用することで豊かな生活を送ることに慣れてしまっている。従って、未来永劫、宇宙環境を利用出来るという状態は、維持さねばならない。

このことから、少なくとも、現有の軌道上デブリを除去することが必須となる。

SJAC では、2006 年から、この軌道上デブリをアクティブに除去するプロジェクト立上げの検討を行って来た。当然の事ながら、このプロジェクトは一過性ではない実用プロジェクトであることから、ここには、誰がどう言う形で行い、実施するためのお金をどの様に導出していくかの検討をも含んでいる。

実現のために設定した 7 つのアクションの実施状況をチェックするとともに、これを加速する必要があることを述べる。



Road Map for the Active Debris Removal System

Promoting the Active Debris Removal Project on Business

January 22nd , 2013

Committee for Next-generation Space Project Promotion,
The Society of Japanese Aerospace Companies (SJAC)
Co-chairman Masaya Mine (NEC)

Propositions

■ Facts about space environment

① Even if we don't perform new launches, debris that have already been on the orbit will grow to bring about an unusable condition of the space (the results of analysis coincide in many countries and regions such as Japan, the USA, Europe and Russia).

② Human beings want to keep using the space environment because of convenience and usefulness of using the space for earth observation, communication, global positioning, etc. (trivial)

⇒ We need to eliminate debris located on the orbit.

■ Implementation status of debris removal analysis

① Many countries analyzed the relationship between the state of on-orbit debris and the active debris removal which will have removed five ,ten, or more life-ended satellites per year in early 2020s.

Start up a debris removal business in early 2020s!

2

What we must do to achieve our goal

① Building of international consensus at legislative level, if possible

Authorize a business to remove debris on a global basis by 2020 (Is it positioned as a global public project?)

② Having an ability as project promoter

Work to ensure the preferable position of Japan at the time of launch of the debris removal project

Japan should play the role in above 2 actions.

①⇒ Implementation at the initiative of Japan (Bilateral negotiation to multilateral negotiation)

②⇒ Verification of technological/business (cost) appropriateness of the project through demonstration

3

Summary of necessary actions

- In the investigation report on space debris for FY 2006/2007, SJAC explained the necessity of the following actions.
  - ① Spread into general ideas
  - ② Recommendation of Japan to United Nations/Committee of the Peaceful Uses of Outer Space
  - ③ Adoption of appropriate ISO standards and business model which is advocated by Japan
  - ④ Setup of a space environment preservation body by Japan
  - ⑤ Validation of debris removal satellite by Japan
  - ⑥ Japan's idea of debris observation
  - ⑦ Establishment of backup think tank and materialization of the above ① to ⑥.
- By *realizing these as a national strategy*, we would like to achieve *the global industrialization launched by Japan* that leads the world.

4

Consideration status of the current state

① Spread into general ideas (△)

- In 2008, Yomiuri Shimbun wrote the article about the necessity of active removal of debris and its business model (industrialization model). However, the boost was within the level of impulse at that time. The boost of the A-SAT coverage of China after that was also within the level of impulse.
- In 2009, IRIDIUM-33 and Russian satellite COSMOS-2251 collided against each other on the orbit. Mass media reported that there was an actual possibility of collision of satellites and debris rapidly increased as a result of such an accident.
- Within the theme of global environment, a TV program (NTV: Sho Sakurai appeared) covered that not only the earth but also the outer space had been contaminated (a remark by Mr. Mohri).
- Although there were some coverage by media on robot/debris removal after that, they mainly focused on technical appeal. Understanding of Japanese people about the necessity and the appropriateness of debris removal has not been obtained yet.
- To spread this issue into the general public, not a impulsive coverage but a continuous one is required. We should promote it as part of the (global) environment problem.

5

Consideration status of the current state

② Recommendation of Japan to United Nations/Committee of the Peaceful Uses of Outer Space (COPUOS) (△)

- At a subcommittee meeting within IADC held in 2009, the necessity of ODR (orbital debris removal) was discussed. The sub-committee decided to formally discuss the theme as IADC starting from the next meeting.
- Although it was at the initiative of the USA, the first international conference related to the issue was held in December, 2009. Japan also participated in the conference to make three reports. They reported that not technological feasibility but also a business model (an industrialization model) had been considered in Japan.
- The report on discussion at the meeting hosted by McGill University in Canada was submitted to the United Nations Scientific and Technical Subcommittee and registered as a United Nations Document (see next page: McGill Declaration).
- Since 2011, the international best practices/guidelines have been reviewed at the UN COPUOS/Scientific and Technical Subcommittee/Space Activity Long-term Continuity Workshop/Specialist Meeting “B” (space debris, space operation and space state recognition) and the description has been drawn up to the necessity of ODR. Specific consideration of ODR will be done in the future, including the decision about whether the description of ODR is drawn up or not.
- We will not be able to achieve our initial goal unless we play at least a central role in advancing the above UN-related activities.

6

Consideration status of the current state

■ McGill Declaration on active space debris removal and on-orbit satellite servicing (November 2011)

・・・Discussion on the following subjects had been made at the meetings hosted by McGill University in Canada over three years: the current state and the problem of debris in the first year, reduction of debris in the second year and removal of debris and its implementation structure in the third year. The results were complied in the report, which was submitted to the United Nations Scientific and Technical Subcommittee. After being published at the meeting, it was registered as a united nations document. Details of the report are as shown below.

- To promote the removal of debris and on-orbit services, United Nations and international organizations should work to improve not only the responsibility for space activities but also international treaties to address especially control right and control over objects in the outer space.
- National governments and international organizations should consider the legislative and regulatory mechanism and process to promote debris removal.
- They should also consider establishing an international fund to support debris removal.
- We should promote the international obligations of registering space objects and international recognition of the control right about them.

7

Consideration status of the current state

③ Adoption of appropriate ISO standards and business model which is advocated by Japan (△)

- Except for on-orbit debris removal (ODR), the work to create ISO standards for debris mitigation have advanced.
- As to the debris treatment including ODR, a business model considered by SJAC (and published at ISTS in 2008) was introduced at ISO Conference in 2008 but there has been no progress on this issue.
- About consideration of business model and how to raise fund ・・・

(Plan 1) Collect money depending on the level of responsibility for generating debris in the past

(Plan 2.1) Collect money in the form of something like space environment utilization tax (Allocation simply depending on the volume)

See Slide No.9

(Plan 2.2) Collect money in the form of something like space environment utilization tax (Allocation based on debris index)

See Slide No.10

- As an implementation body, “Collect money as an international public work company” or ”Only perform coordination in the form of international coordination body” (See Slide No.11)

8

Consideration status of the current state

Tradeoff of fund raising methods

Proposed plan (Note 1) (Note 3)	Overall judgment	Fairness	Transparency/ Verifiability	Comment
Uniform rate across all countries	×? (Note 4)	×? (Note 4)	○	This plan is in favor of advanced countries and those that highly utilize the space. Developing countries may be opposed to it. Also to be considered from the viewpoint of (Note 4)?
Rate in proportion to price	○	○	△	Is it difficult to ensure transparency of price?
Rate in proportion to the number of launched rockets	○	△	○ (Note 2)	We can check it with the ground debris observation network.
Rate in proportion to weight/size	○	○	△ (Note 2)	We can check the size, etc. with the ground debris observation network.

(Note 1) The above ratios are those taking into account of carrier rocket and satellite.
(Note 2) Although these values are based on notifications, we can validate those for objects with shape as we can observe them from the ground.
(Note 3) The space environment is the common resource given to all nations. Collect money from a viewpoint of utilization tax (cf: Land use)
(Note 4) The USA and European countries provided data from the debris observation net. Is it possible to make a balance with the facilities maintenance expense?

9

Consideration status of the current state

Numerical example of debris index (Yasaka, 2009, 2011)

If one Collision Avoidance (CA) maneuver is performed.

$$I_{DEB}=\alpha M\cdot A\cdot F(h)\cdot \varepsilon_{AVOI}\cdot T_{orb}$$

If multiple CA maneuvers are performed.

$$I_{DEB}=\alpha M\cdot A\Sigma_i F(hi)\cdot \varepsilon_{AVOI,i}\cdot T_{orb,i}$$

Where,
αM: Number of fragments created by mass M of object (ex. spacecraft, rocket body, etc.)
A: Cross sectional area of the object
$F(h)$: M&D flux at altitude h
T_{orb}: Orbital life of the object

Satellite Type	α 1/kg	Altitude km	Flux 1/year/m²	Orbital Life year	Mass kg	Area m²	Debris Index w/o CA	Debris Index CA
Typical SSO Sat	30	800	10^{-4}	25	800	4	269	27
Typical GEO Sat	3	36000	10^{-6}	10	2000	10	0.6	0.1
Object in SSO	30	800	10^{-4}	100	2000	10	6000	N/A
Small Sat	30	800	10^{-4}	25	50	0.25	0.9	N/A
Cube Sat	30	800	10^{-4}	25	1	0.01	0.001	N/A

Fragments/Flux considered >1cm
Tentaive Assumptions
$\alpha = 30$(LEO), 3(GOE) $\varepsilon_{AVOI} = 0.1$
$F(800) = 10^{-4}$(1year/m²) $F(36000) = 10^{-6}$(1year/m²)

W/O CA: No CA maneuvers
CA:10 CA maneuvers

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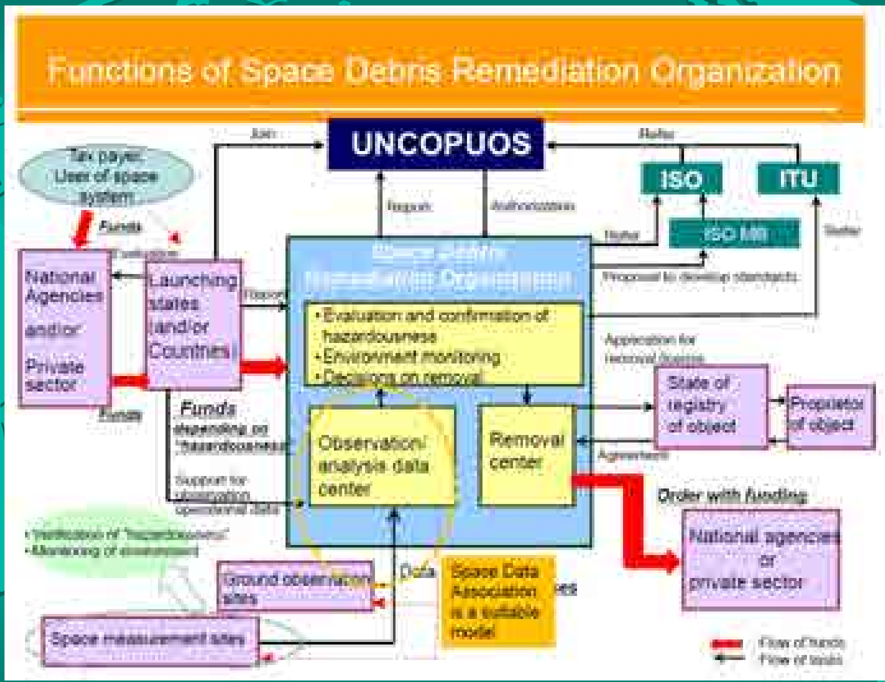
Consideration status of the current state



Kitazawa, "Organizational and Operational Requirements for Space Debris Remediation", International Interdisciplinary Congress on Space Debris Remediation, 2011, McGill University

11

Consideration status of the current state

④ Setup of a space environment preservation body by Japan (×)

- We have not got into action yet.

⑤ Verification of debris collection/recovery satellite by Japan. (△)

- JAXA has started the feasibility study for realizing this project to support SJAC.
- They created the roadmap including on-orbit verification for debris removal. (See next slide)

⑥ Japan's idea of debris observation (△)

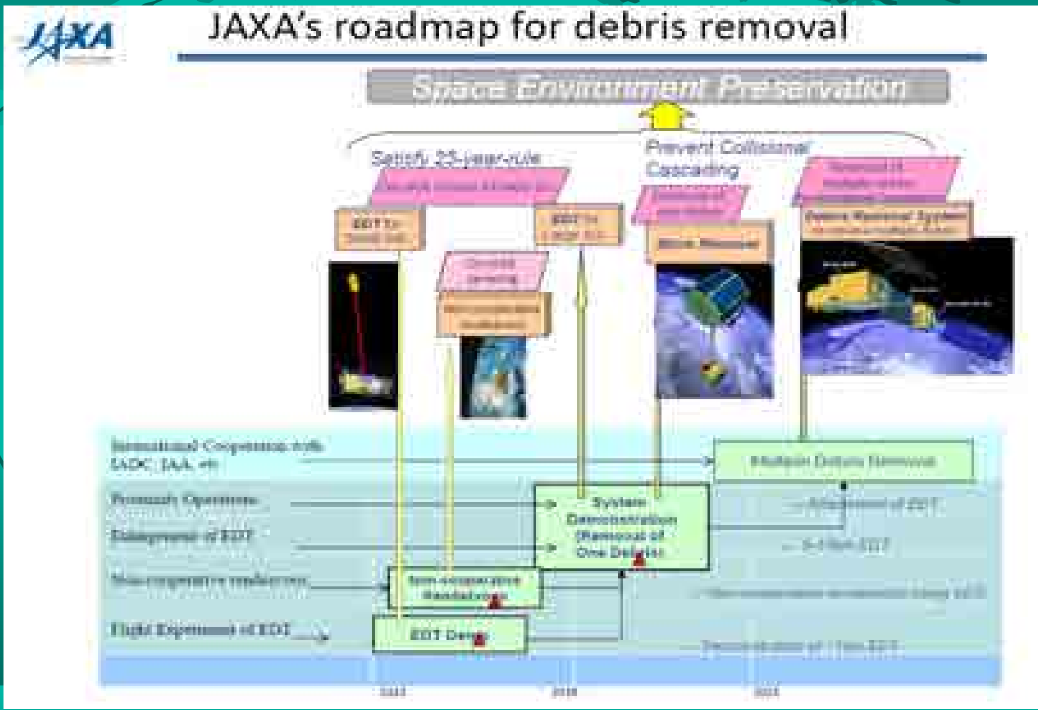
- We are considering various issues including its positioning such as to what extent we have to make observations. We also study how far we can go using existing facilities of JAXA only.

⑦ Establishment of backup think tank and materialization of the above ① to ⑥ (×)

- We have not achieved yet.

12

Consideration status of the current state



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Development status of the World and Japan related to this issue

■ What has the world done?

・・・・ Has started to take actions proactively since around 2007

DARPA／ Orbital Express Mission
DLR／ DEOS
NASA／ GEO Supersync
NASA／ Robot and Humans in HEO
MDA／ Space Infrastructure Servicing

■ What has Japan done?

・・・・ No study has been made since Japan succeeded in making an on-orbit verification with ETS-VII in 1997.

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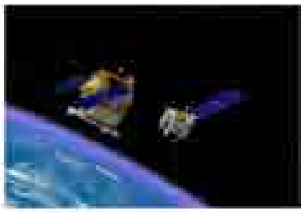
Development status of the World and Japan related to this issue

Orbital Express Mission of DARPA

- Orbital Express is a technical verification satellite aiming to provide unattended services including fuel supply/parts replacement to an on-orbit satellite that DARPA have worked on development. It was launched in March 2007 and succeeded in the verification experiment.
- It is composed of ASTRO (Autonomous Space Transport Robotic Operations), a parent satellite which provides unattended services, with mass of 700 kg, an NEXTSat/CSC, a client satellite which receives services, with mass of 226 kg. Although they were coupled at the time of launch, they were separated after having been placed on the orbit.
- We conducted a rendez-vous docking to NEXTSat, fuel supply, a device replacement experiment and a capture experiment.

  - All of the above were conducted with ETS-VII more than ten years ago.



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Development status of the World and Japan related to this issue

DEOS project of DLR

- DEOS project of DLR is a technology verification project to control on-orbit disposals of nonfunctioning satellite. It also aims to acquire technologies to successfully conduct on-orbit maintenance (especially fuel supply).
  - ➢ Conducted Phase-0 study in 2007, Phase-A study in 2008 and Phase-B study in 2010.
- DEOS is a system composed of two satellites, “Client” and “Servicer.” The two satellites are launched at the same time to be placed on an orbit at the height of 550 km. According to the current plan, it is scheduled to be launched in 2018.
- On September 13, 2012, DLR awarded Astrium GmbH the management contract for the entire system in the DEOS definition phase (the final design phase before the hardware creation stage). The contract is the value of approximately 13 million Euros for one year.

Credit: Astrium

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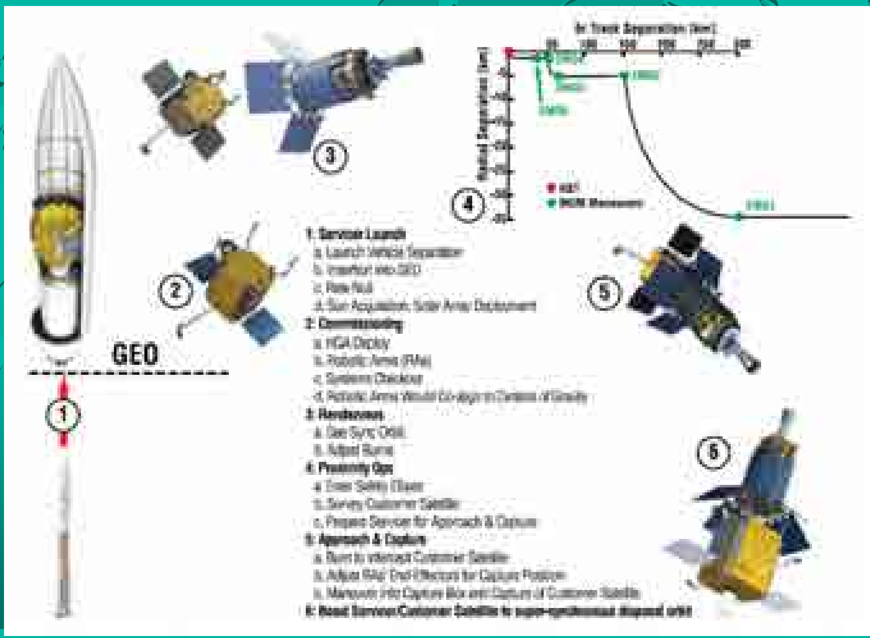
Development status of the World and Japan related to this issue

NASA: GEO Supersync



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Development status of the World and Japan related to this issue

NASA: Robot and Humans in HEO

18

Development status of the World and Japan related to this issue

SIS (Space Infrastructure Servicing) of MDA Corp.

- MDA Corporation of Canada announced that it would focus on an on-orbit solution called SIS (Space Infrastructure Servicing) (in 2010).
  - SIS is to supply propellant of communication satellite located on a stationary orbit, docking with Apogee Kick Motor of a subject satellite to inject propellant.
  - It was announced that Intelsat became the first partner in March 2011. However, MDA left the plan in January 2012. This project returned to the research phase again.
- SIS capability of MDA Corporation
  - First, focus on fuel supply/services at GEO.
  - Deliver fuel to Client satellite by “per kg” system. Therefore, the service is applicable to satellites of various sizes.
  - Services are performed quickly (within a few weeks) and effects on Client satellite are minimized.
  - Can also conduct services, such as inspection, towing, relocation and small repairs.

Each dot above represents a satellite in the Geostationary Earth Orbit (GEO) worth hundreds of millions of dollars

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Summary

- At the SJAC Committee for Next-generation Space Project Promotion in fiscal year 2004, we advocated the necessity of debris removal project utilizing space robot and recommend setup of the project. We also conducted further study at the committee in fiscal years 2006/2007 and advanced the study by setting up action items for it.
- In the meantime, the space basic law in Japan was established. We could incorporate the necessity in the law in the form of necessity of space environment preservation.
- However, we have not yet realized a satisfactory promotion/project.
- Meanwhile, studies by other countries, which had no movement at first, have made a rapid progress. Their on-orbit verification and the consideration as a project, which Japan had taken a lead, have reached at the same or advanced level compared to Japan.
- We would like to remind the current status and recommend you to promote the project as one of the Japan National Strategies.

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B5

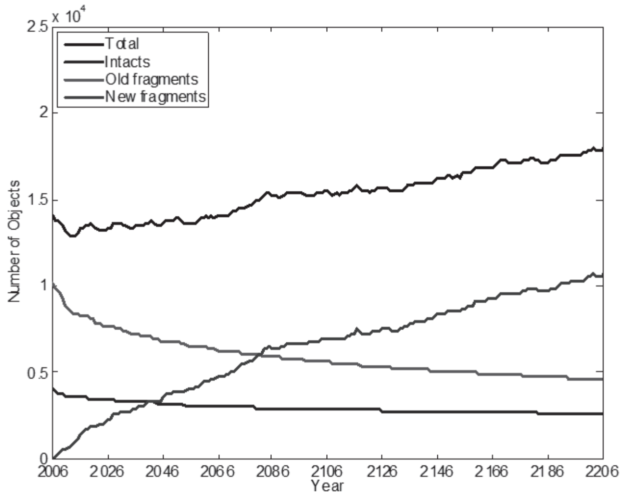
デブリ推移モデルによる将来予測

Prediction of Orbital Debris Population with an Orbital Debris Evolutionary Model

○有吉雄哉，花田俊也（九大），河本聡美（宇宙航空研究開発機構）
○Yuya Ariyoshi, Toshiya Hanada (Kyushu University), Satomi Kawamoto (JAXA)

宇宙航空研究開発機構と九州大学は，デブリ推移モデルの開発・維持と推移モデルを用いたデブリ分布の予測を行っている．このデブリ推移モデルは 10 cm 以上の軌道上物体の軌道伝播と衝突率の計算・判定により将来のデブリ分布を予測するものである．これまでに図のような低軌道でのデブリ分布の不安定性の確認やデブリ除去の効果について，推移モデルを用いて予測を行ってきた．本発表では，これらデブリ推移モデルによる結果として，特に種々のデブリ低減対策や除去条件を仮定した場合の将来のデブリ分布の予測結果について紹介する．

Japan Aerospace Exploration Agency (JAXA) and Kyushu University collaborated to develop an orbital debris evolutionary model. Kyushu University has maintained and operated the orbital debris evolutionary model under contract with JAXA. This presentation introduces the outcome of collaborative research with JAXA and Kyushu University. Especially, we introduce result from future projection of debris population under some orbital debris mitigation measures and remediation.



新規打ち上げ・爆発なしを仮定した時の低軌道の物体数の推移

デブリ推移モデルによる将来予測

Prediction of Orbital Debris Population
with an Orbital Debris Evolutionary Model

Yuya Ariyoshi, Toshiya Hanada
Department of Aeronautics and Astronautics, Kyushu University, Japan
Satomi Kawamoto
Japan Aerospace Exploration Agency, Japan

Orbital Debris Evolutionary Models in Japan

GEODEEM
- Developed by Kyushu University
- GEO region

LEODEEM
- Developed by JAXA and Kyushu University
- LEO region (< 2000 km)

NEODEEM
- Developed by JAXA and Kyushu University
- LEO-to-GEO region
- One by one collision detection
- Individual orbit propagation

2

Collaboration in Debris Modeling Study

- ■ Kyushu University has been conducting orbital debris modeling study under contract with JAXA
  - ● Updating orbital debris evolutionary model
    - - Insertion history
    - - Breakup history
  - ● Operating debris evolutionary model
    - • IADC's activities
      - - **Action Item (A/I) 27.1**
      - - WG 2 Internal Task
    - • Future projections based on JAXA's requirements
      - - **Effectiveness of active debris removal**

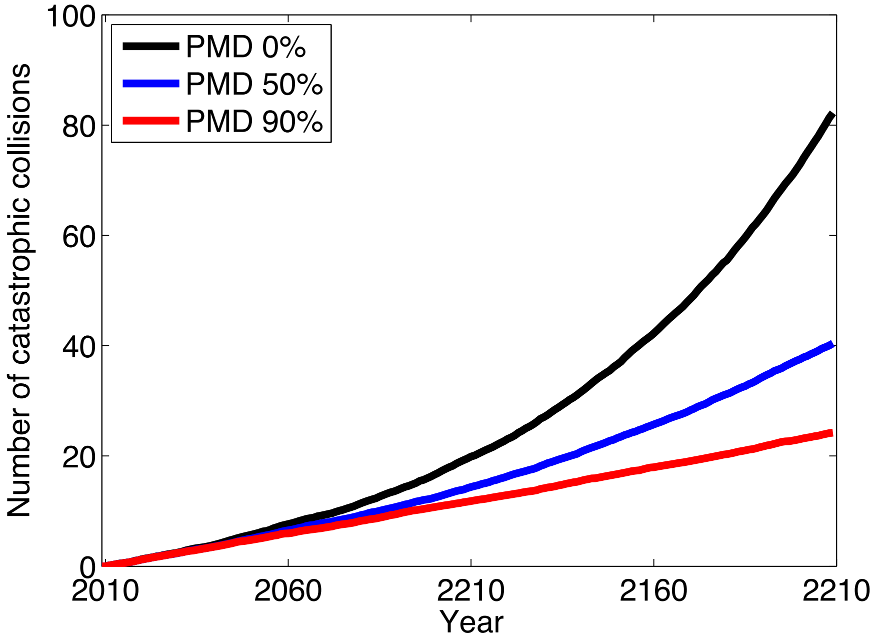
3

Effectiveness of post-mission disposal (PMD)

- ■ IADC A/I 27.1
  "Stability of the Future LEO Environment"
  - • To assess the stability of the LEO debris population
  - • To reach a consensus on the need to use active debris removal
- ● ASI, ESA, ISRO, NASA, UKSA and JAXA participated
- ● Kyushu University conducted this study under contract with JAXA
- ■ Scenarios
  - • Initial population as of May 1st 2009
  - • 8-year cycle launch traffic
  - • No new explosion
  - • 90% PMD compliance
  - • Additional scenarios with 0% and 50% PMD compliance
  - • Mean of 100 MC runs is result

4

Catastrophic collision



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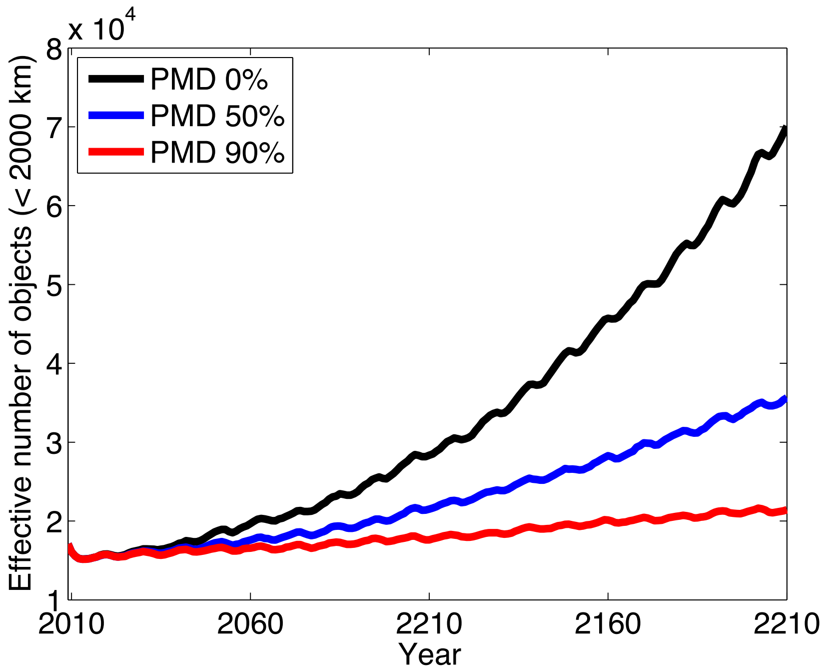
Population growth during next 200 years



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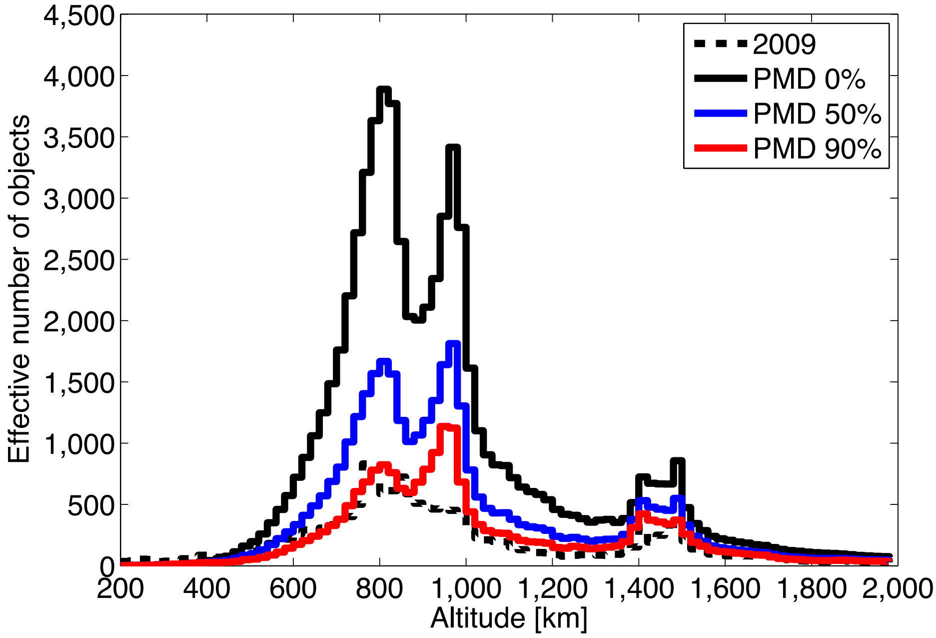
Population snapshot



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Strategies for selecting removal targets

- Orbital debris removal is essential for stabilizing the environment
- Some strategies for selecting removal targets are considered
- Defining regions for multiple removals
  - Region 1 (R1)
    900 – 1000 km altitudes, 82 – 84 degrees inclination
  - Region 2 (R2)
    700 – 1000 km altitudes, 98 – 100 degrees inclination
- Considering the influence of accidental collisions
  - Cumulative probability of accidental collisions (PC) during 25 years
  - Expected number of fragments (EN) during 25 years

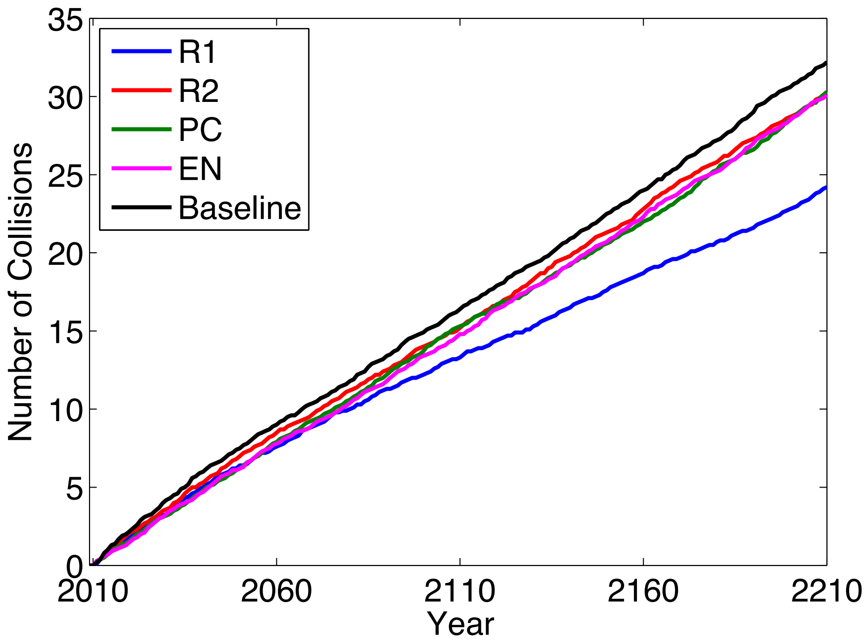
8

Evaluating the proposing strategies

- Projection scenario
  - Initial population as of May 1st 2009
  - No new launch and explosion
  - 100 targets are removed at initial
  - Mass of targets is limited between 500 – 4000 kg
  - Mean of 60 MC runs is result

9

Catastrophic collision



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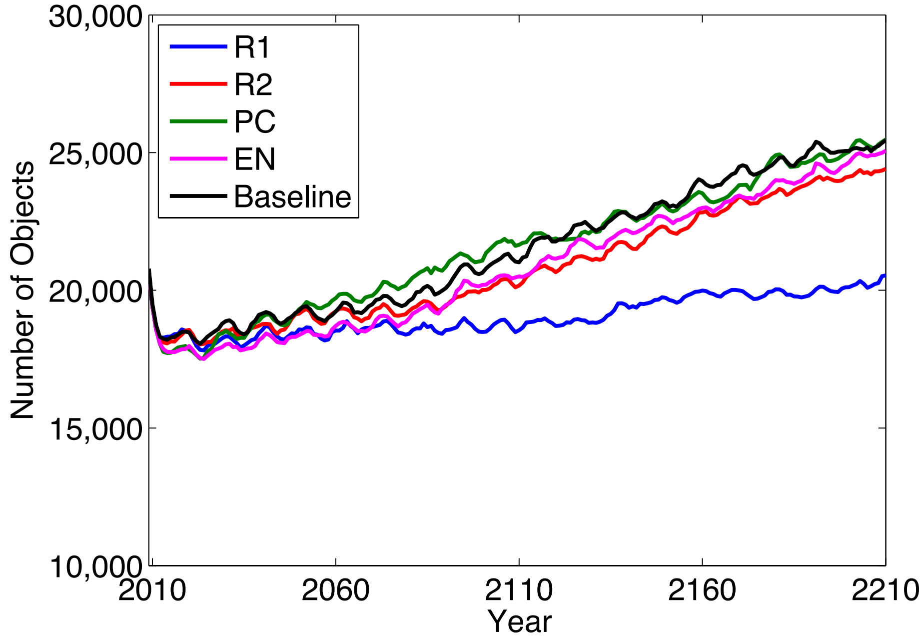
Population prediction during next 200 years



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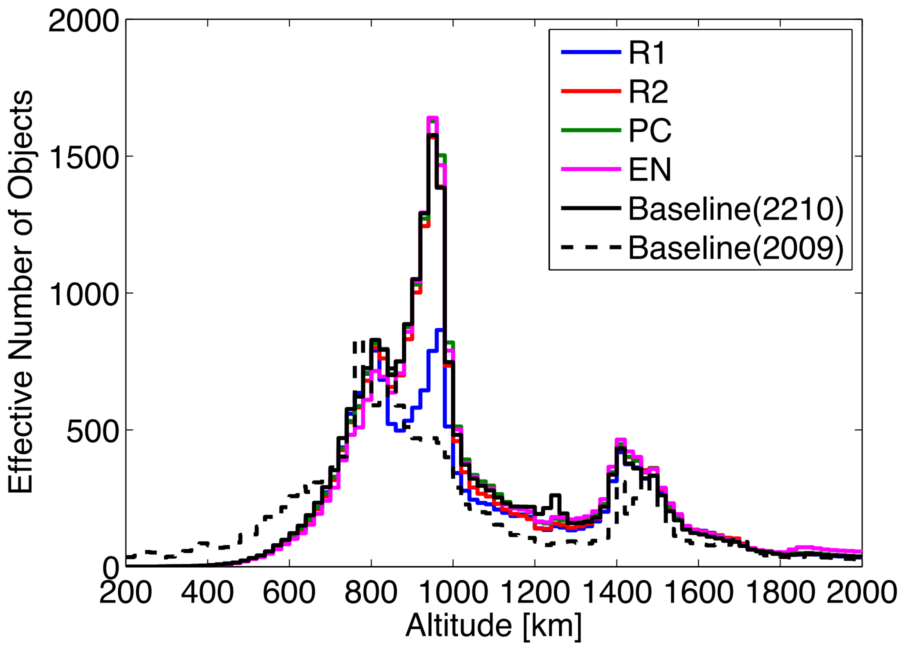
Population snapshot



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Summary

- This presentation introduced the future projection using NEODEEM, which is developed by JAXA and Kyushu University

- IADC A/I 27.1
  - Some scenario which the different PMD compliance
  - PMD compliance effects the growth of future debris population
  - PMD cannot stabilizes the future debris population
- Effectiveness of active debris removal
  - Four strategies for selecting targets is evaluated

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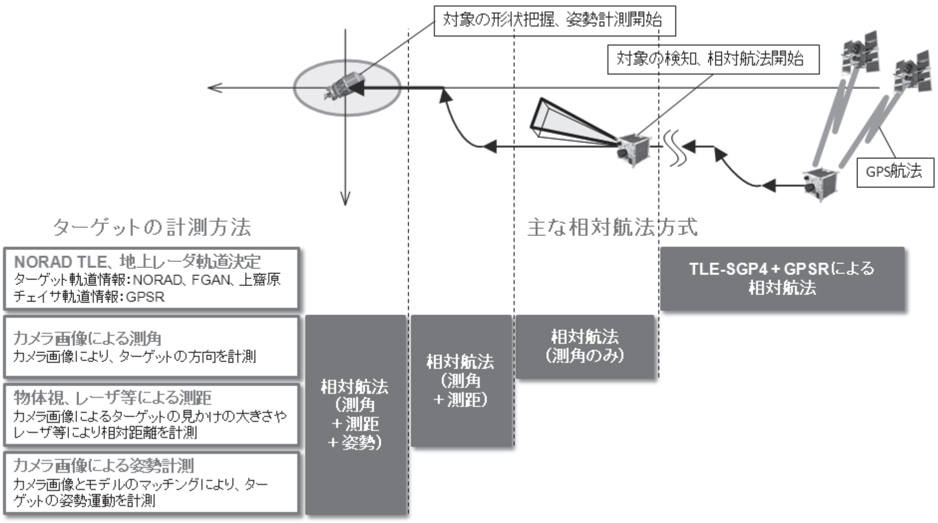
B6

非協力的ターゲットへの接近ストラテジ

Approach Strategy to a Non-Cooperative Target

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

デブリの積極的除去のために、接近し何らかの推進系を取り付ける必要がある。デブリのような非協力的ターゲットへの接近には、ISS のような協力的ターゲットと比較して、事前の軌道情報（NORAD TLE）の精度が低い、相対航法の継続性・安定性の確保が困難、といった技術的課題がある。これらの技術的課題を考慮した接近ストラテジの検討状況について紹介する。まず、非協力的ターゲット接近シナリオの全体像と必要技術を概観する。また、事前の軌道情報の精度の調査結果を示すとともに、相対航法センサシステムの概念的検討を示す。さらに、カメラによる相対航法においてキー技術となる、Angles-only navigation の簡易的検討結果を示し、可観測性と衝突安全を考慮した接近軌道設計の考え方を示す。最後に、今後の課題と技術開発プランについて述べる。



Approach Strategy to a Non-Cooperative Target 非協力的ターゲットへの接近ストラテジ

22 Jan 2013
Space debris workshop

Toru Yamamoto, Naomi Murakami, Koji Yamanaka
Guidance and Control Group
Japan Aerospace Exploration Agency

1

Outline

- Introduction
  - What is a "non-cooperative target" ?
  - Why approach to a non-cooperative target is challenging ?
- Structure of approach operation and necessary technologies
- Key technical issues
  - Orbit prediction accuracy of LEO space debris
  - Relative navigation sensors for space debris
  - Angles-only navigation
  - Trajectory design to avoid a collision with a target
- Approach case study by numerical simulations
- Conclusions

2

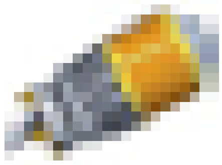
1. Introduction

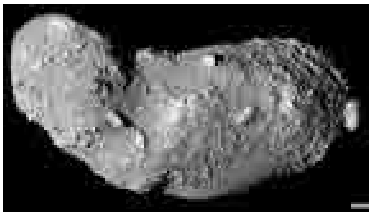
What is a "non-cooperative target" ?

- Non-cooperative target is
  - A rendezvous target which does not have any cooperative functionalities to support approach guidance, navigation and control
- Features of non-cooperative targets
  - Orbit determination by R&RR, GPSR is not available
  - No target markers or laser retroreflecters for vision/laser sensors are available
  - Knowledge about optical property (specular/diffuse reflectance, etc.) is limited
  - Attitude is not known and it is not controlled but in natural motion

"cooperative" target

"non-cooperative" targets





3

1. Introduction

Why approach to a non-cooperative target is challenging ?

- Approach to a non-cooperative target is mandatory for active debris removal (ADR), but it is NOT EASY
- Poor knowledge of a target orbit
  - Accurate orbit data by R&RR, GPSR is not available
  - Orbit data by radar tracking (TLE, etc.) is available but poor
- Poor knowledge to design S/N of relative navigation
  - Poor knowledge of optical property of surface and attitude
  - Wide range of lighting condition (Solar illumination, Earth albedo)
  - Difficult to confirm stable relative navigation
- Poor knowledge of location of target center of mass
  - Location of target center of mass should be known to establish stable relative orbit keeping
  - Estimation of target center of mass in the target body is not easy

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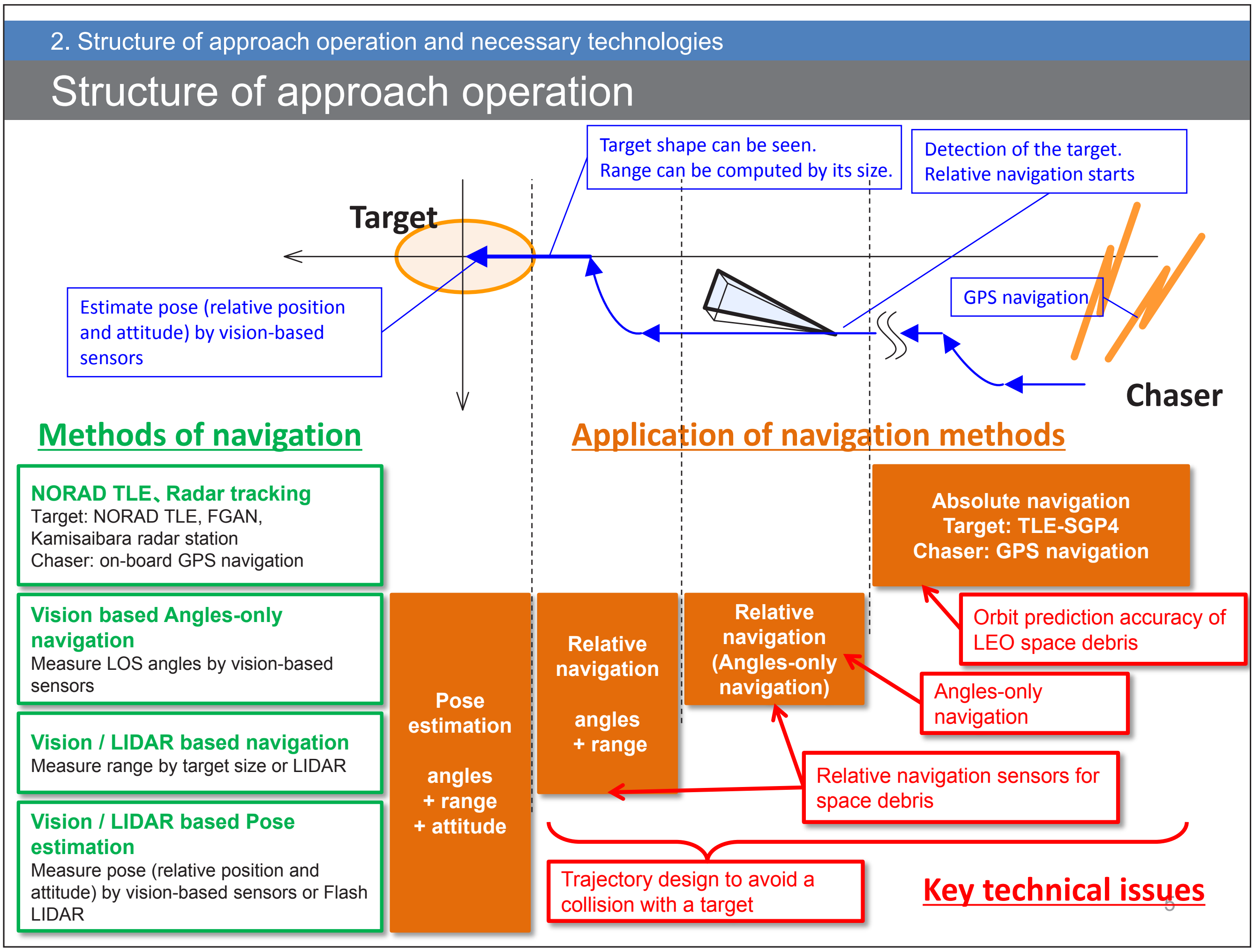
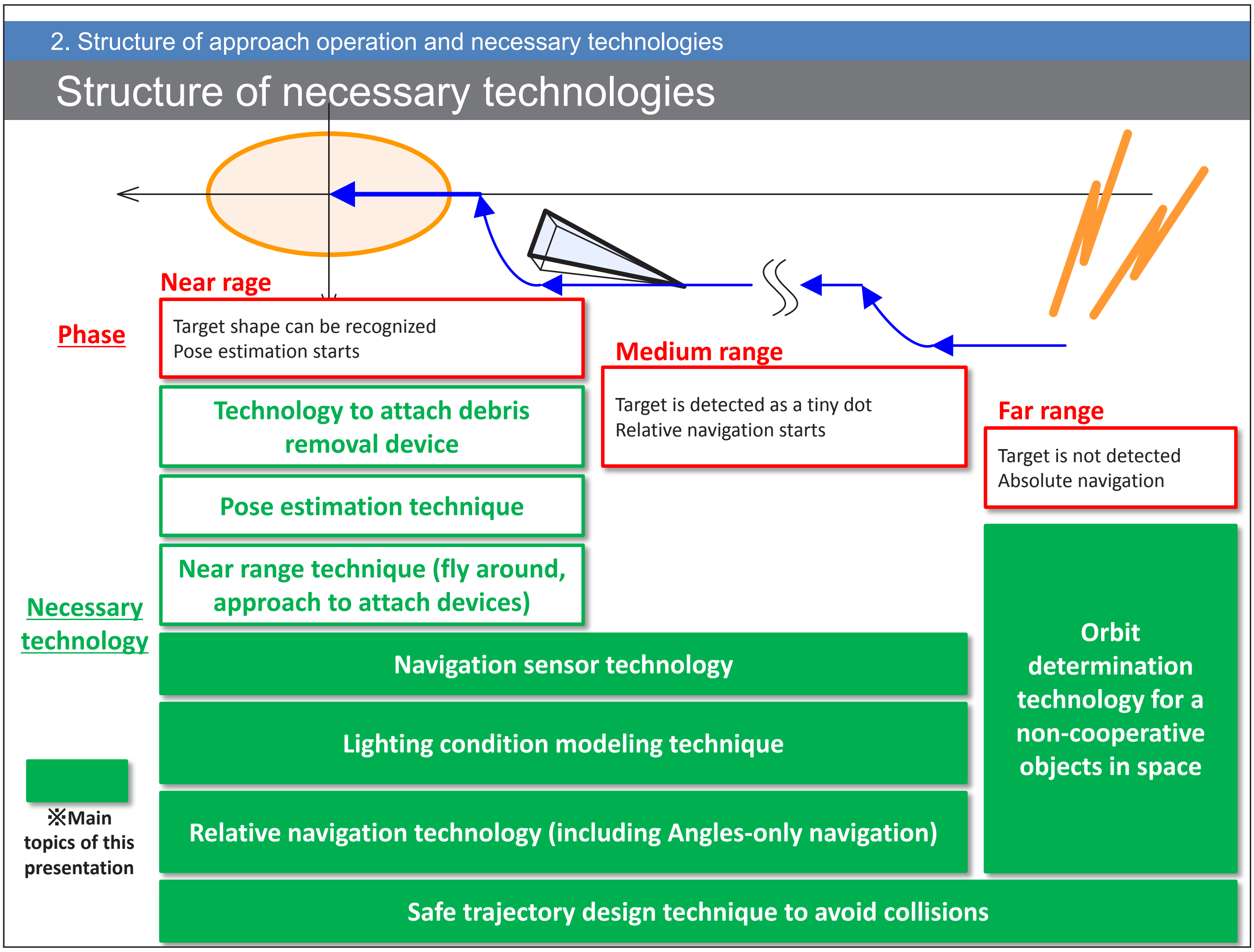

2. Structure of approach operation and necessary technologies
Structure of approach operation
Target shape can be seen.
Range can be computed by its size.
Detection of the target.
Relative navigation starts
Target
GPS navigation
Estimate pose (relative position and attitude) by vision-based sensors
Chaser
Methods of navigation
Application of navigation methods
NORAD TLE、Radar tracking
Target: NORAD TLE, FGAN, Kamisaibara radar station
Chaser: on-board GPS navigation
Absolute navigation
Target: TLE-SGP4
Chaser: GPS navigation
Vision based Angles-only navigation
Measure LOS angles by vision-based sensors
Pose estimation
angles + range + attitude
Relative navigation
angles + range
Relative navigation (Angles-only navigation)
Orbit prediction accuracy of LEO space debris
Angles-only navigation
Vision / LIDAR based navigation
Measure range by target size or LIDAR
Relative navigation sensors for space debris
Vision / LIDAR based Pose estimation
Measure pose (relative position and attitude) by vision-based sensors or Flash LIDAR
Trajectory design to avoid a collision with a target
Key technical issues


2. Structure of approach operation and necessary technologies
Structure of necessary technologies
Phase
Near rage
Target shape can be recognized
Pose estimation starts
Medium range
Target is detected as a tiny dot
Relative navigation starts
Far range
Target is not detected
Absolute navigation
Necessary technology
Technology to attach debris removal device
Pose estimation technique
Near range technique (fly around, approach to attach devices)
Orbit determination technology for a non-cooperative objects in space
Navigation sensor technology
Lighting condition modeling technique
Relative navigation technology (including Angles-only navigation)
Safe trajectory design technique to avoid collisions
※Main topics of this presentation

3.1 Key technical issues - Orbit prediction accuracy of LEO space debris

Orbit prediction accuracy of LEO space debris

- TLE is important apriori knowledge of target orbit
- Orbit prediction accuracy of TLE/SGP4 is investigated by several authors
  - Aida S., Kirschner M., "Collision Risk Assessment and Operational Experiences for LEO Satellites at GSOC", 22nd ISSFD, 28 Feb. - 4 March 2011, Sao Jose dos Campos, Brazil (2011)
  - 倉田育枝, 足立学, 矢里秀作, 亀山雅也, 松田郁未, 廣瀬史子, 工藤伸夫, "スペースデブリ軌道精度評価", 第54回宇宙科学技術連合講演会, 17 Nov., 静岡県コンベンションアーツセンター (2010)
- Typical TLE/SGP4 performance of LEO debris:

	1 day propagation		7day propagation	
	Radial Cross-Track	Tangential	Radial Cross-Track	Tangential
High solar activity	0.5 - 1 km	2 - 10 km	0.5 - 2 km	15 - 50 km
Low solar activity	0.5 - 1 km	1 - 2 km	0.5 - 2 km	2 - 8 km

  - During high solar activity period tangential errors after long propagation become large
  - Low altitude debris tend to have larger tangential errors after long propagation
  - Radar Cross Section (RCS) has sensitivity to accuracy of TLE
- Other radar tracking stations (ex. FGAN, Kamisaibara) have great functionalities to provide target orbit data timely

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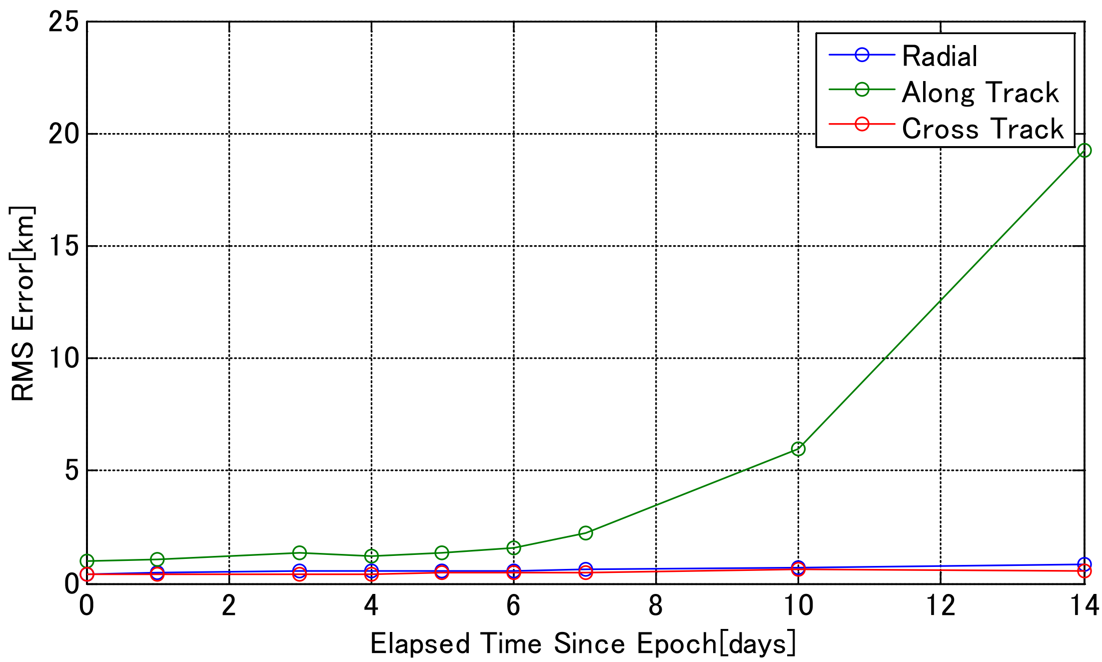
3.1 Key technical issues - Orbit prediction accuracy of LEO space debris

Example: TLE/SGP4 prediction accuracy of ADEOS-II

- ADEOS-2(803km), 2003/5/20, F10.7 flux = 117.1
- GPS orbit determination data is used as reference



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3.2 Key technical issues - Relative navigation sensors for space debris

Relative navigation sensors for space debris

- Visible Camera is low cost and available in long distance, but not available at night and sensitive to lighting conditions
- Infrared Camera is available at night and not sensitive to lighting conditions, but available distance is medium
- Laser sensors are available at night and stable, but need high power and high cost

		Attitude	Range		LOS Angles	Night	Pros	Cons	Examples
			Far	Near					
Visible Camera		○	×	○	○	×	Low cost Long distance High resolution	Not available at night Sensitive to lighting conditions Poor range accuracy	So many on-board visible cameras are flying in space
Infrared Camera		○	×	○	○	○	Available at night Robust to lighting conditions	Low resolution Available distance is medium Poor range accuracy	Planet-C, ALOS-2, Hayabusa-2, Orbital Express, Space-X Dragon
Laser Sensor	Laser Range Finder	×	○	○	×	○	Available at night Long distance Accurate	LOS angles NOT measured High power consumption High cost (?)	Hayabusa-1/2, SELENE, Orbital Express
	SCAN LIDAR	△	○	○	○	○	Available at night Long distance Accurate	High power consumption High cost (?)	XSS-11
	FLASH LIDAR	○	×	○	○	○	Available at night Attitude can be measured	Short distance only High power consumption High cost (?)	Space-X DRAGON

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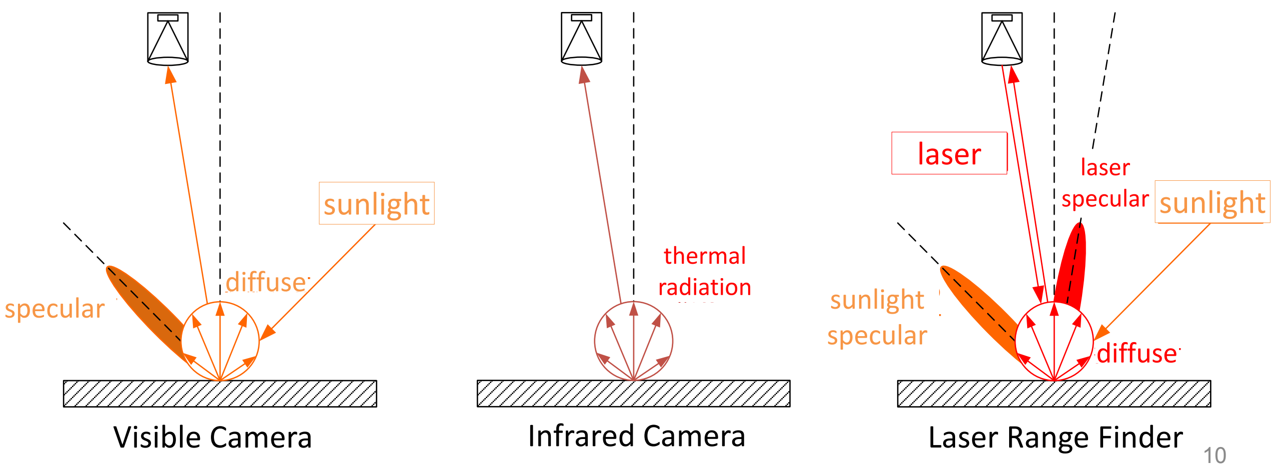
3.2 Key technical issues - Relative navigation sensors for space debris

Mathematical modeling of relative navigation sensors

- Visible camera detects reflection (both specular and diffuse) of sunlight from target surface
- Infrared camera detects thermal radiation from target surface
- Laser range finder detects reflection (both specular and diffuse) of transmitted laser pulses from target surface
- "Modified Phong model" is used as reflection model



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3.2 Key technical issues - Relative navigation sensors for space debris

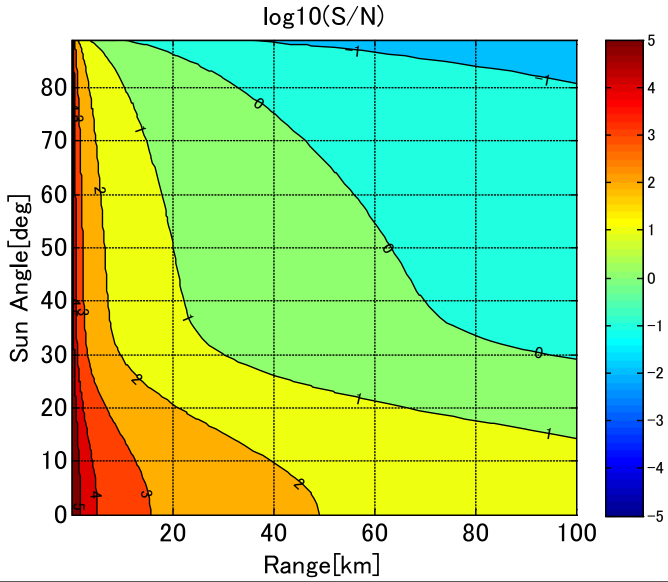
Case study: Visible camera detectability

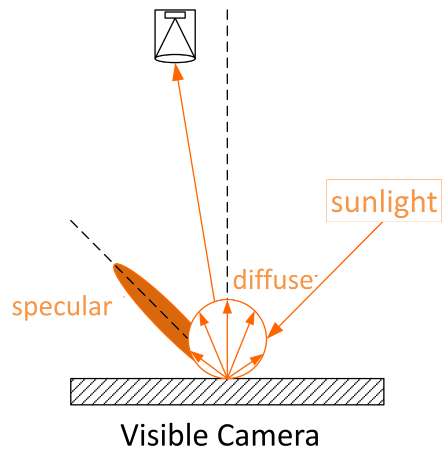
- Detectability strongly depends on optical property of target

⇒ This is just a case study!

- Visible camera may detect target
  - from 65km@20deg sun angle
  - from 30km@30deg sun angle
  - from 15km@80deg sun angle

```
Kd = 0.2;            % diffuse property
Ks = 0.5;            % specular property
D = 5.8e-3;          % diameter of optics[m]
A = pi*2*2;          % target size[m^2]
```





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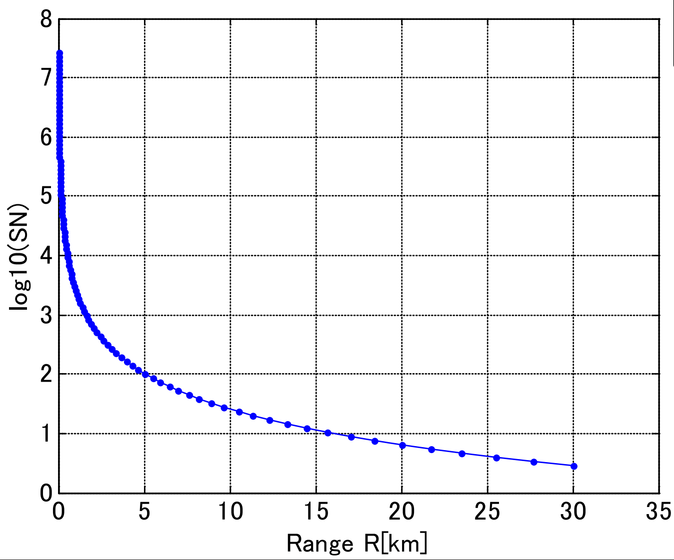
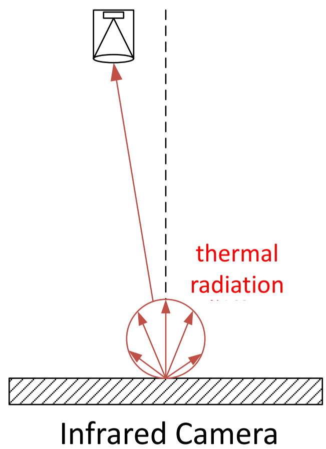
3.2 Key technical issues - Relative navigation sensors for space debris

Case study: Infrared camera detectability

- Detectability strongly depends on temprature and infrared emissivity of target ⇒ This is just a case study!
- Infrared camera may detect target from 15km
- Infrared camera is rather stable against solar lighting conditions

```
epsilon = 0.57;     % Emissivity of surface
A = pi*2^2;         % target size[m^2]
D = 47e-3;          % diameter of optics[m]
D_star = 2.00E+06;  % Specific detectivity[m Hz^1/2 W^-1]
```





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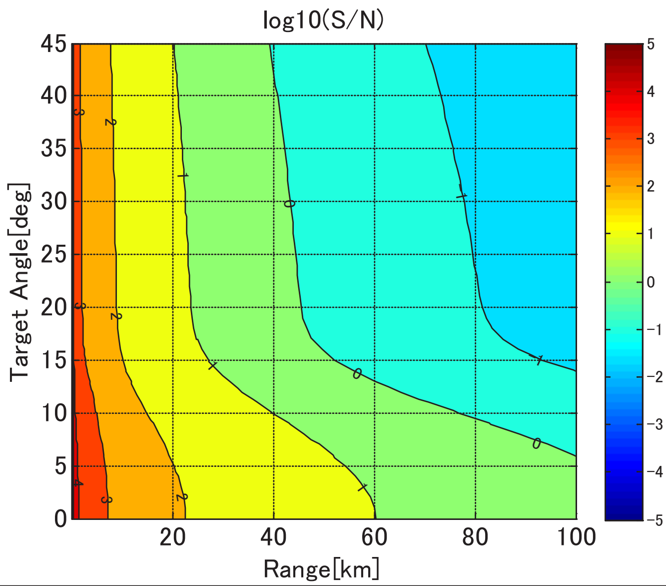
3.2 Key technical issues - Relative navigation sensors for space debris

Case study: Laser range finder detectability

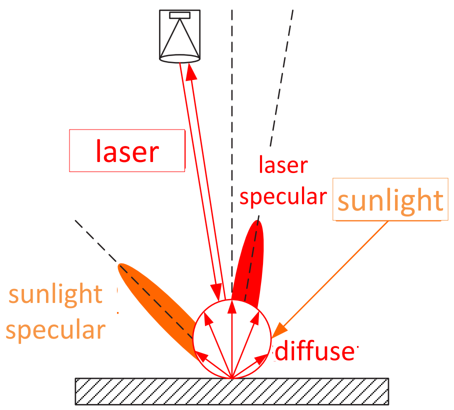
- Detectability strongly depends on optical property of target

⇒ This is just a case study!

- Laser range finder may detect target from 20 - 60km




```
Kd = 0.2;          % diffuse property
Ks = 0.5;          % specular property
Po = 1.00E+06;     % laser peak power[W]
D = 0.1;           % diameter of optics[m]
SA = 0.4;          % sensitivity[A/W]
A = pi*2*2;        % target size[m^2]
```



Laser Range Finder

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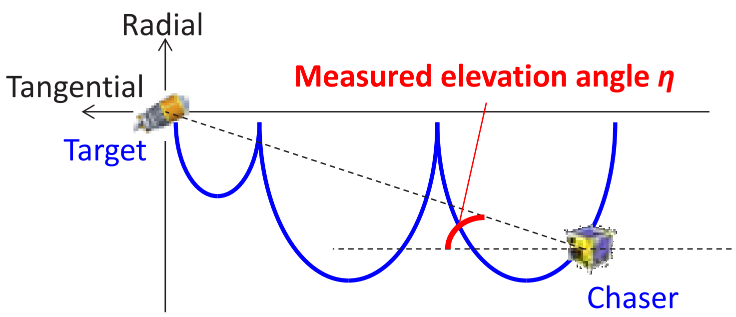
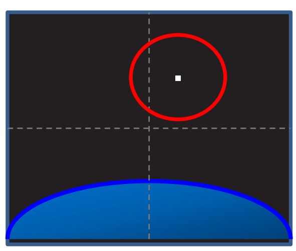
3.3 Key technical issues - Angles only navigation

Angles-only navigation

- What is Angles-only navigation ?
  - 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 in tangential direction





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3.3 Key technical issues - Angles only navigation

Navigation filter for Angles-only navigation

- Extended kalman filter is formulated for angles-only navigation of LEO rendezvous
  - Estimated states

$$\boldsymbol{x} = [\delta a, a\delta e_x, a\delta e_y, a\delta i_x, a\delta i_y a\delta u]^T$$

  - Measurement model

$$\boldsymbol{z} = [\eta, \phi]^T = h(\boldsymbol{x}) \quad \eta = a\tan(u_x^{CAM} / u_z^{CAM})$$

$$\phi = a\sin(u_y^{CAM})$$

$$\boldsymbol{z} = [r]^T = h(\boldsymbol{x}) \quad r = norm(\boldsymbol{r}^{CAM})$$

$$\boldsymbol{r}^{CAM} = C_{RTN}^{CAM} C_{CVL}^{RTN} C_{REL}^{CVL} \boldsymbol{x}, \quad \boldsymbol{u}^{CAM} = \boldsymbol{r}^{CAM} / r$$

  - Dynamics model

$$\boldsymbol{x}_{k+1} = \Phi(t_{k+1}, t_k)\boldsymbol{x}_k$$

Relative orbital elements

Elevation η and Azimuth ϕ are measurements from cameras

Range is measurement from laser range finder

Simple state transition matrix

CAM: camera coordinates
RTN: cartesian orbital coordinates
CVL: curvilinear orbital coordinates
REL: relative orbital elements

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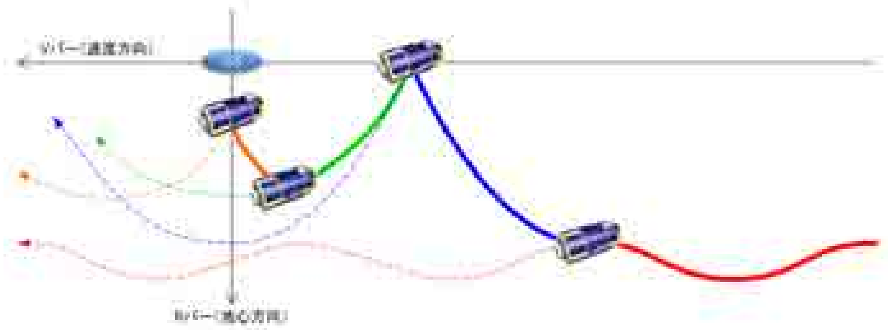
3.4 Key technical issues - Trajectory design to avoid a collision with a target

Trajectory design to avoid a collision with a target

- Tangential (Along-track) direction of a target is dangerous zone
  - Relative navigation to a non-cooperative target is unstable
  - Knowledge of tangential relative distance by angles-only navigation is poor
- Three basic principles to design safe trajectory
  - 1: Propagated trajectory should be safe even if a maneuver is cancelled
  - 2: Propagated trajectory should be safe even if navigation errors are considered
  - 3: Opportunities to be at the same height with a target should be minimized



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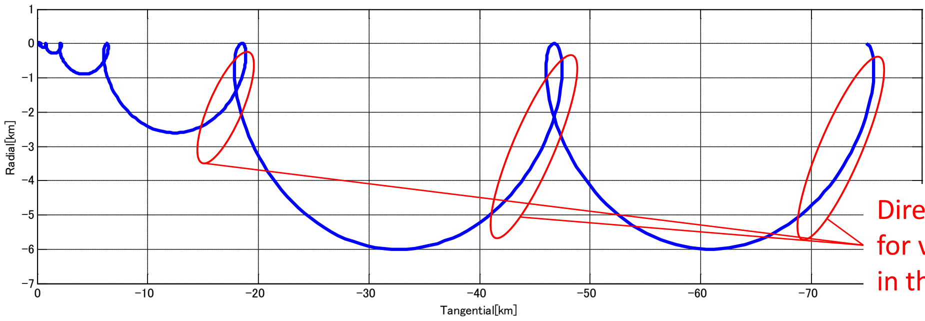
4 Approach case study by numerical simulations

Approach case study by numerical simulations

- A sample approach scenario has been designed
- Navigation simulation from far-range to medium-range phase
- Main interest is investigation of Angles-only navigation performance

Target true orbit	Actual GRACE-A orbit by precise GPS orbit determination.
Target TLE/SGP4 orbit	Actual GRACE-A TLE.
Chaser true orbit	Simulation data. 21x21 geopotential, Jacchia-Roberts atmospheric drag, SUN, MOON, Solar radiation pressure.
Chaser delta-V estimation error	5% (3σ) error.
Sensor measurements	Camera:0.1deg(1σ), Laser range finder:6m(1σ) random errors. Detectability computation based on mathematical model described above.

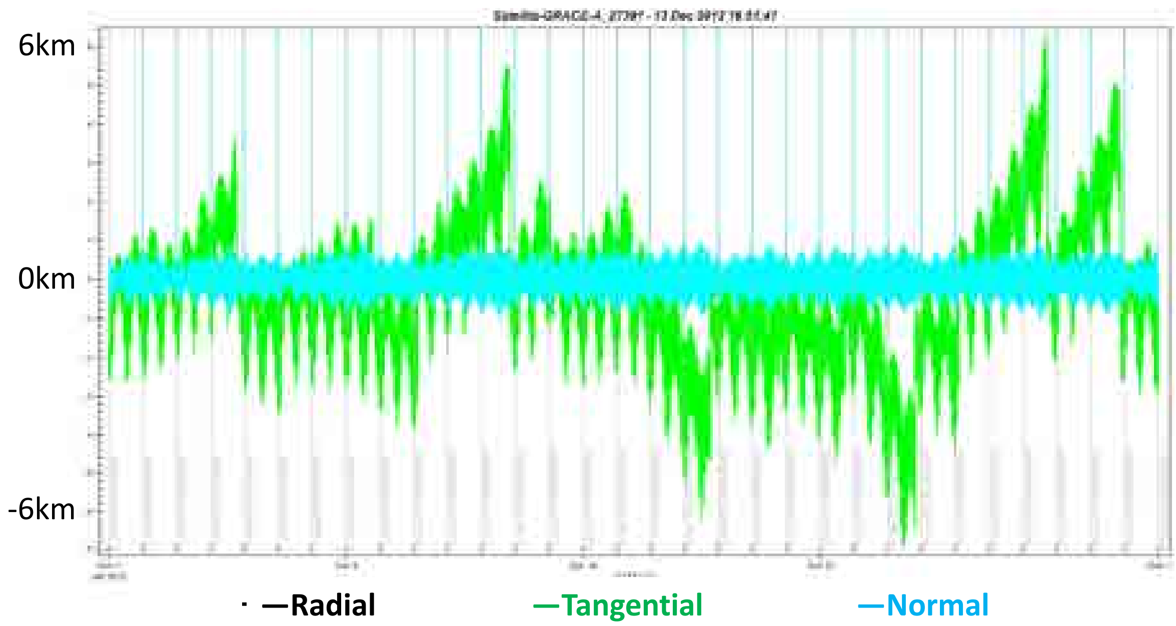


Approach trajectory is similar to "stable orbit rendezvous" used for space shuttle missions

4 Approach case study by numerical simulations

GRACE-A TLE/SGP4 accuracy

- Error of GRACE-A TLE/SGP4 is:
  - less than 7km in Tangential direction
  - less than 1km in Radial/Cross-track direction



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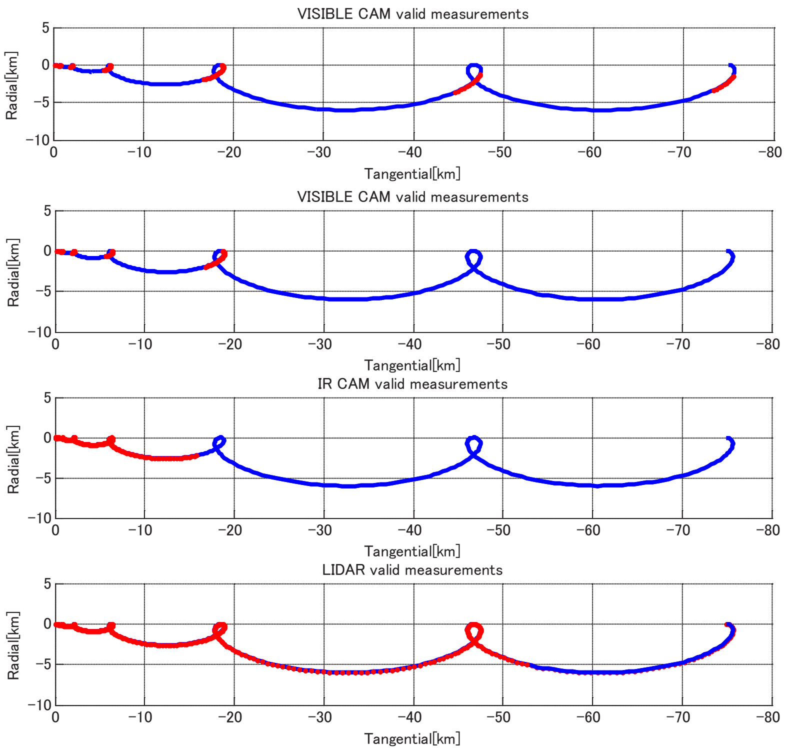
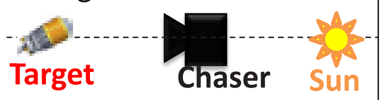
4 Approach case study by numerical simulations

Detectability of sensors

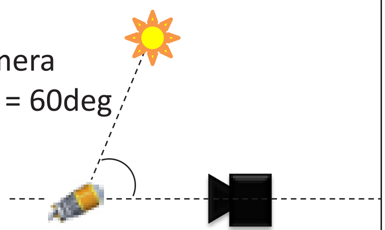
RED LINE ー : valid measurements



Visible Camera
beta angle = 0deg



Visible Camera
beta angle = 60deg



Infrared Camera

Laser Range Finder

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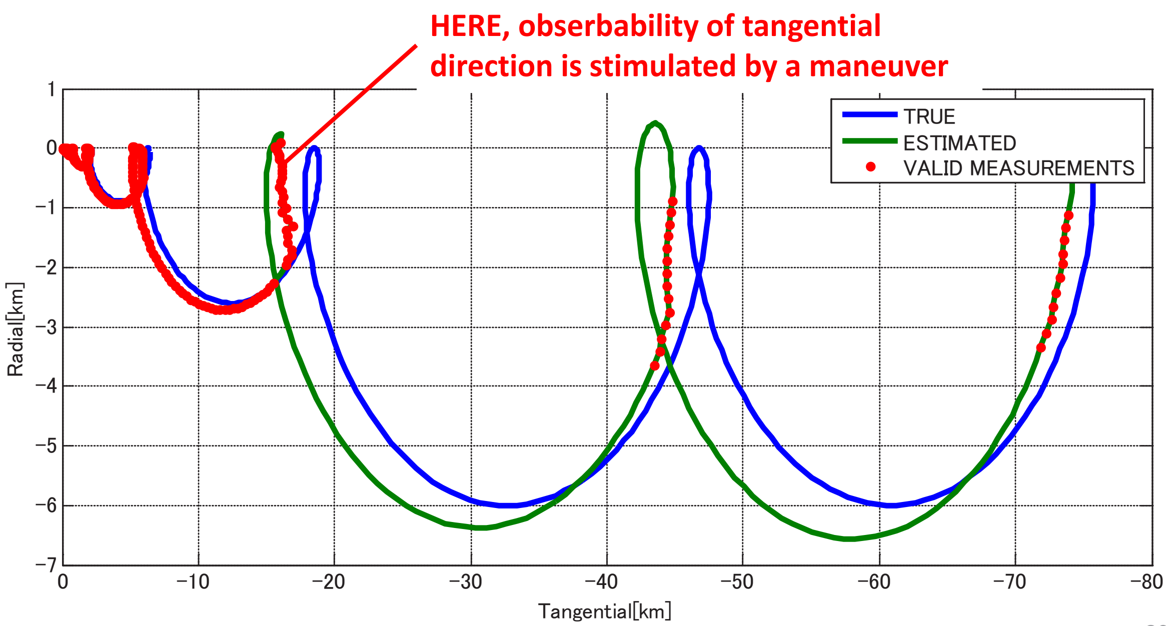
4 Approach case study by numerical simulations

Estimated trajectory by Angles-only navigation

- True and estimated trajectory by angles-only navigation
- Visible camera only, beta angle = 0deg



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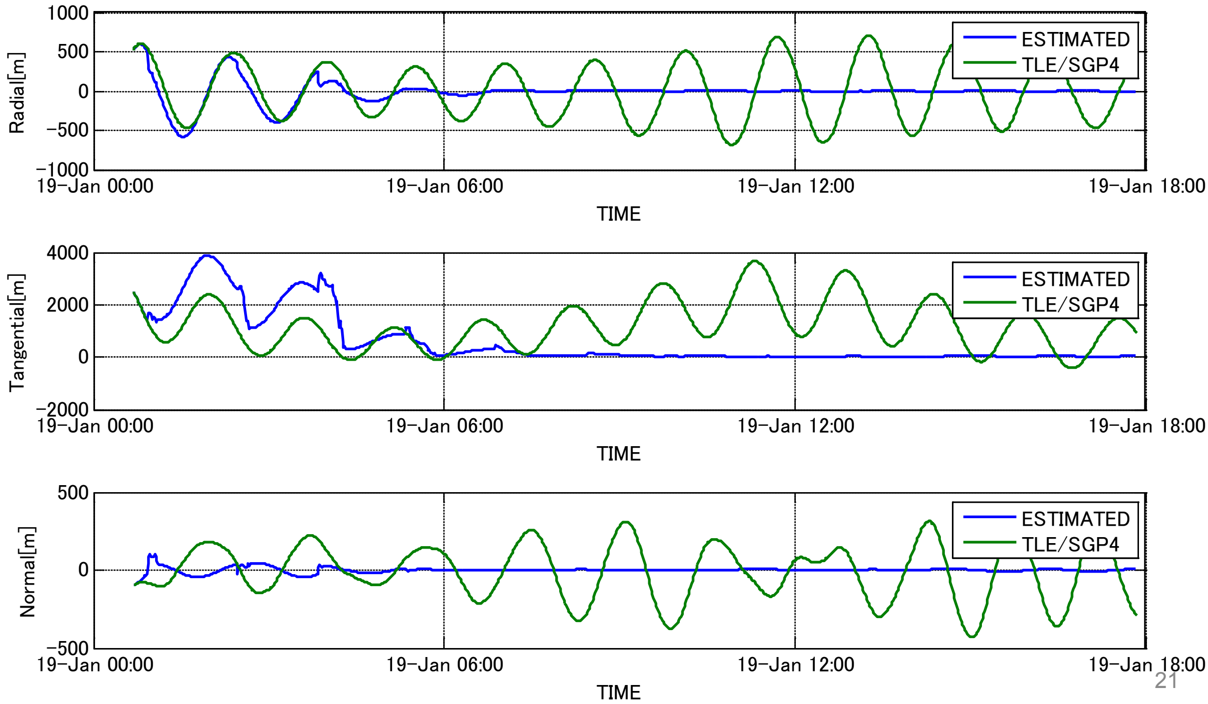
4 Approach case study by numerical simulations

Performance of Angles-only navigation V.S. TLE/SGP4

Navigation error in Radial, Tangential, and Cross-track direction
Visible camera only, beta angle = 0deg



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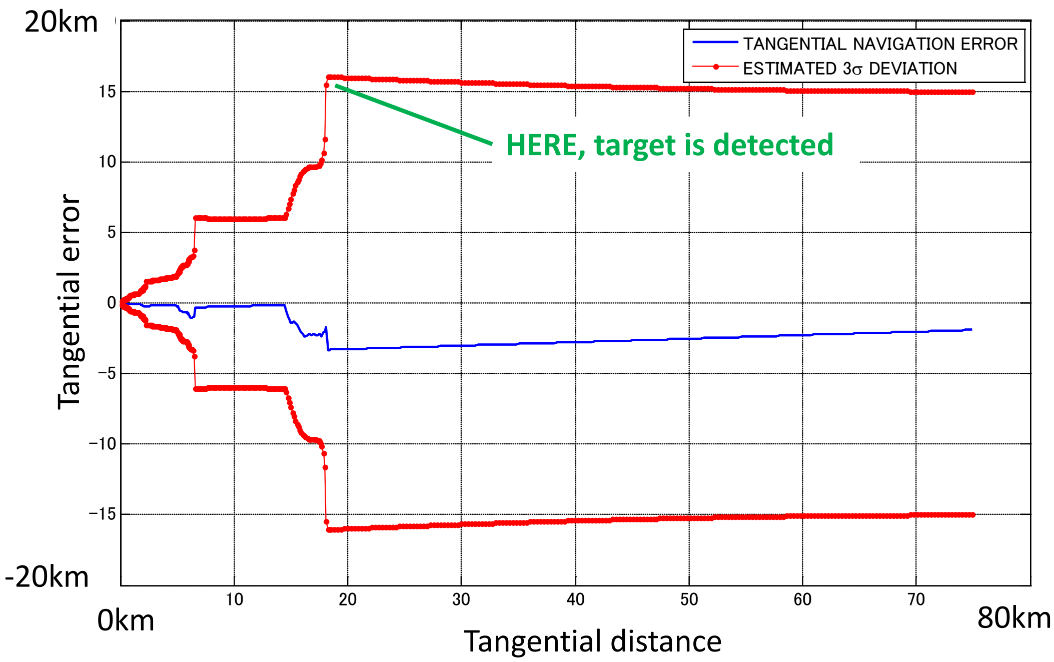
4 Approach case study by numerical simulations

Performance of Angles-only navigation in tangential direction

- Error in tangential direction
- Visible Camera only, beta angle = 60deg



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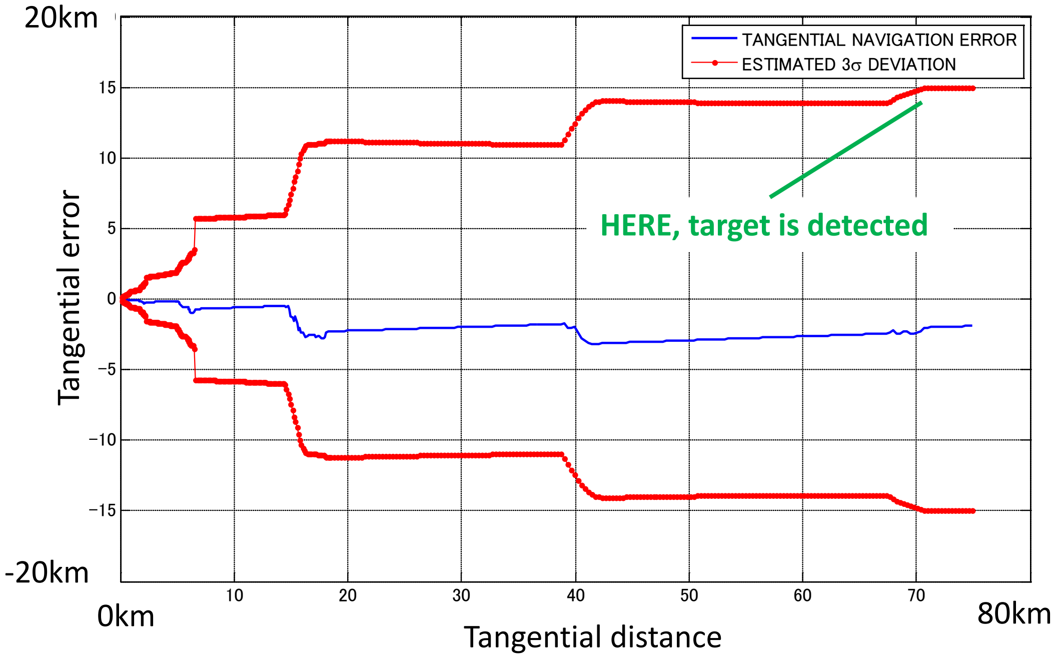
4 Approach case study by numerical simulations

Performance of Angles-only navigation in tangential direction

- Error in tangential direction
- Visible Camera only, beta angle = 0deg



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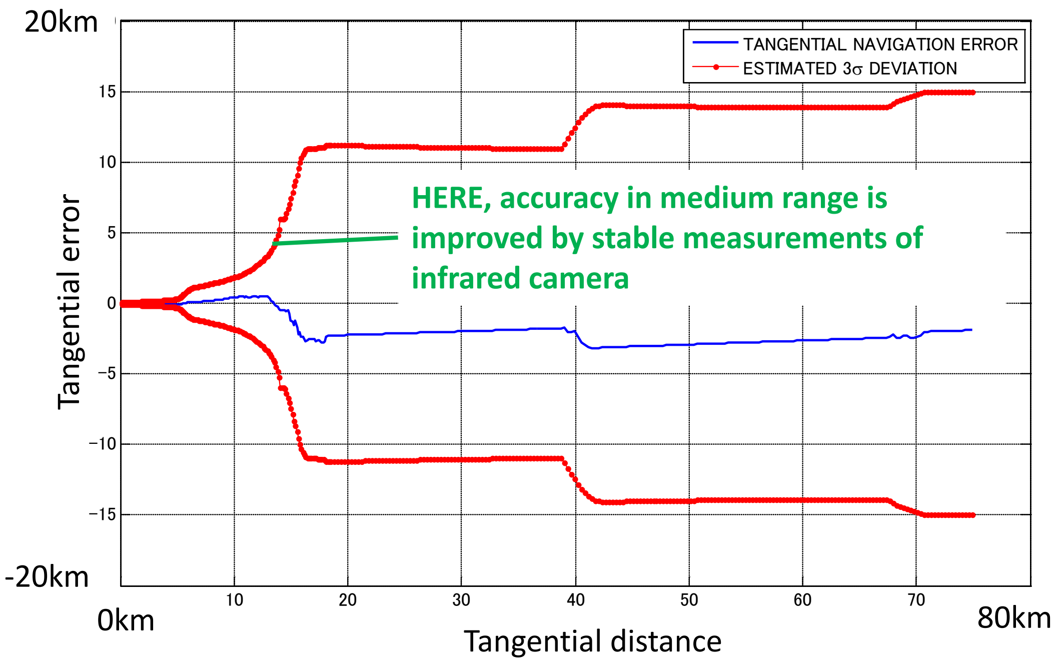
4 Approach case study by numerical simulations

Performance of Angles-only navigation in tangential direction

- Error in tangential direction
- Visible and infrared, beta angle = 0deg



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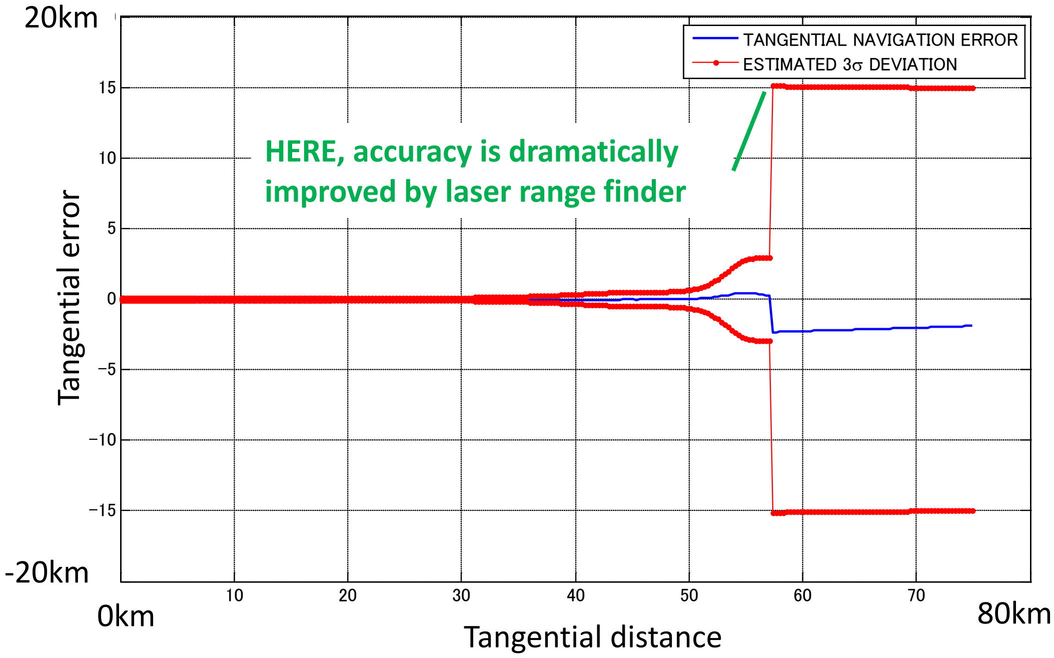
4 Approach case study by numerical simulations

Performance of Angles-only navigation in tangential direction

- Error in tangential direction
- Visible, infrared and laser range finder



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4 Approach case study by numerical simulations

Summary of navigation case study simulation

- Angles-only navigation may provide navigation data with sufficient accuracy to connect from TLE/SGP4 navigation to vision-based navigation using size of the target.
- Detectability of visible camera depends on beta angle.
- Detectability of visible camera strongly depends on sunlight direction. Measurements of visible camera are available in a limited portion of an orbital revolution.
- Infrared camera can be great stable navigation source in medium range.
- Direct range information from laser range finder dramatically improve navigation accuracy in tangential direction.
- Optical property of the target is the key factor of detectability and this case study strongly depends on it.

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Conclusions

- Approach to a non-cooperative target is not a easy task
- Poor knowledge of target optical property and motion is the key factor of the difficulty
- Rendezvous system for active debris removal should be able to absorb wide dynamic range of these uncertainties
- High fidelity modeling of target optical property, motion, and sensor hardware is important, but it may be challenging to be precise enough on ground
- The most important point is flexibility of rendezvous system and operation plan to be able to absorb remaining uncertainties during actual flight

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C1

デブリ除去における画像計測と運動推定の検討

Vision-based Measurement and Motion Estimation for Space Debris Removal

○片山保宏，上村平八郎，西田信一郎，河本聡美（宇宙航空研究開発機構）
○Yasuhiro Katayama, Heihachiro Kamimura, Shinichiro Nishida, Satomi Kawamoto (JAXA)

デブリ衛星の除去には、対象物に自律的に接近し、軌道から除去するための機構を取付けるアプローチが有効である。この接近、及び作業において、非協力であるデブリ対象の形状や位置姿勢、運動を推定する計測システムが必須となる。デブリ除去衛星に搭載したカメラによって得られた画像を用いる画像計測が、搭載性やコスト面で有効な計測手段と考えられており、遠方からのデブリ対象への接近から、除去機構の取付け作業までのほとんど全てのフェーズにおいて重要な役割を果たす。本発表では、デブリ除去のための画像計測と運動推定について、各運用フェーズでの役割や検討中の方式についての報告を行う。

The 5th Space Debris Workshop
Jan 22, 2013

Image-based Measurement and Motion Estimation for Space Debris Removal

デブリ除去における画像計測と運動推定の検討

*Yasuhiro Katayama, Heihachiro Kamimura,
Shinichiro Nishida, and Satomi Kawamoto (JAXA)

*片山保宏、上村平八郎、西田信一郎、河本聡美（宇宙航空研究開発機構）

Outline of Space Debris Removal

- The amount of space debris has been increasing over the years and has become a potential problem for space development.
- The prevention of new debris is required in order to continue space activities in the earth orbit.

- In particular, an operation to remove debris from orbit would be effective in curbing the amount of debris.
- Deorbiting a large-scale satellite would be effective in preventing the spread of many smaller pieces of debris from its breakage.
- Presently, the second stage of a launch vehicle, such as the HII-A, is considered an appropriate target for removal.

- The importance of space-debris removal is internationally recognized, and this activity is expected to become industrialized.

Contents of this presentation

- The second stage of the launch rocket is set as a target for removal from earth orbit.
- For deorbiting the target from orbit, a device that can shift its own orbit is attached on the target body.
- A measurement/perception system is required to accomplish this operation through remote and autonomous control.

- The progress of our image-based measurement and motion estimation systems is reported in this presentation.

(Topics of this presentation)

- Image-based measurement and motion estimation for debris removal
- Operational phases of debris removal
- Facilities for and difficulties in image-based measurement and motion estimation systems

3

Specific ways to remove debris

- Fixing a device for changing orbit to a debris body
  - By using the Lorentz force caused by the earth's magnetic field and the current of electricity through an Electro Dynamic Tether (EDT) that is stretched over a long distance from the device.
  - Or by using the propulsive force generated by thrusters.

When the removal device is attached to the object's body, we need to make a removal satellite

- approach and rendezvous with the target debris satellite, and
- attach a removal device or grapple the target.

These operations require remote and/or autonomous technology based on robotics.

Conceptual drawing of space debris removal operation by dragging EDT.

4

Sensor/perception technology for approach to and capture of debris satellite

In this presentation, an upper rocket, i.e., HII-A, is proposed as a debris target; it is large enough to be approximately observed in its orbit or have its motion observed from a ground telescope.

In addition, its design parameters and materials are preliminarily known.

With all these factors, we can place a removal satellite closer to the debris target by using GPS navigation.

In the final approach and capture phase, more precise perception is required as follows.

- Determination of orientation to the target
- Measurement of distance to the target
- Relative attitude and position between the target and the removal satellite
- Reconstruction of the target (if the design parameters are not available)
- Motion estimation of the target
- Sensing to assist robotic operations

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Comparison measurement/perception system: Image-based sensor and Active optical ranging sensor

The measurement/perception system is composed of an optical camera and/or a range sensor. A quick comparison of their characteristics is presented below.

Range Sensor: LIDAR (LIght Detection And Ranging), LRF (Laser Range Finder)
Advantage in precise measurement of distance or shape
Necessary in long/wide range, downsizing of power, dimensions, and weight

Image-based Sensor: Stereo vision, image-based measurement algorithm
Advantage in (potentially) long/wide range, compact resources
Necessary in speed, resolution, limitation of lighting; more research and development is required

We believe that the image-based measurement system is promising for future applications. Therefore, in this study, we focus on the application of image-based sensing for approaching and capturing the debris.

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Image-based 3D measurement and motion estimation

By analyzing 2D images obtained from the removal satellite, we can create a 3D information, consisting of pose and position estimation of the debris and motion estimation that reflects the nutation/tumbling of the debris.

In this case, the debris is supposed to be the second stage of a launch rocket, such as HII-A; therefore, we already know its designed CAD value. (Fortunately, we already know the debris' dimensions, weight, and materials.)

The 3D information estimated by image analysis will differ according to the projected size (pixels) of the target on images, i.e., the distance from an observer to an object. Therefore, several types of perception algorithms are required during the debris removal operation.

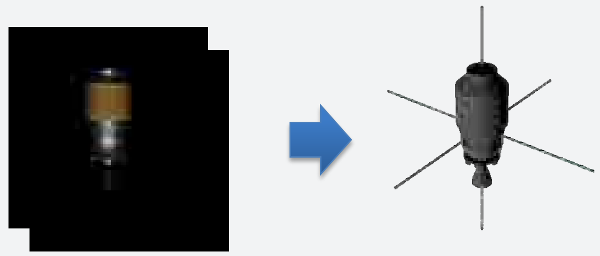

Image-based 3D perception and motion estimation　　Image-based 3D perception and motion estimation

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Phasing image-based perception for removing debris

Image-based perceptions (measurement and motion estimation) have different functions according to the distance to the target. (Distances below are T.B.D. values)

Approach Phase: finding a target from long-distance and coarse perception

Finding a target and determining its orientation	~dozens of kilometers
Coarse range finding of distance to the target and its shape	~10 kilometers

Observation Phase: precisely measuring shape and motion and turning around to the target

Precise reconstruction of the target and motion estimation	~50 meters

Removal operation Phase: attaching a removal device to the target

Visual support for the robotic operation	a few meters ~ 50 meters
Checking behavior of target with the device	~30 meters

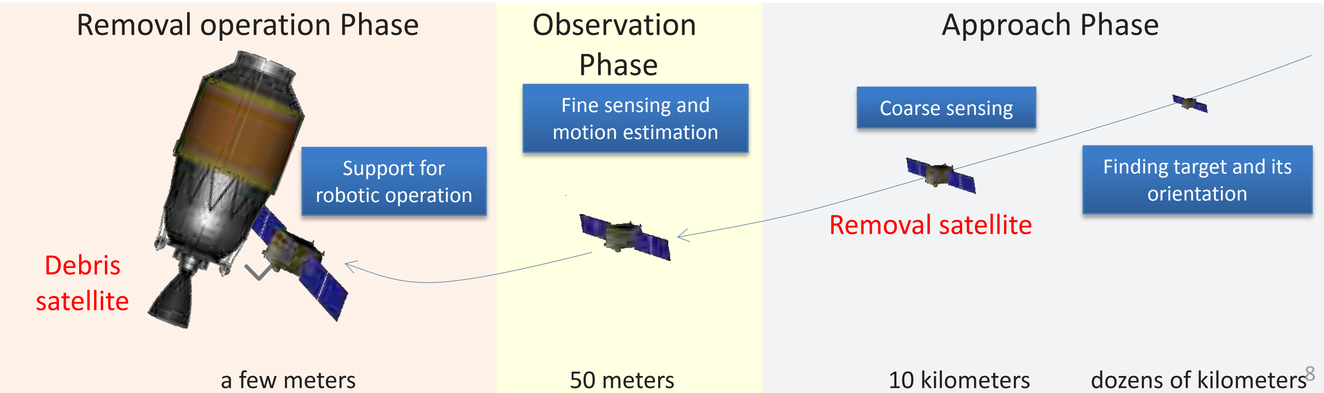

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Image-based perceptions on each phase

Approach Phase

- Finding target and determining its orientation

  From dozens of kilometers to the target, the target, which is projected as being one or a few pixels in size in a telescopic camera, is detected for estimating its orientation from the viewpoint of the removal satellite.

- Course range finding to the target and its shape

  Within about 10 kilometers, the target is projected to 10 pixels more on the image.

  Using a small projected target, the distance to the target and its shape are approximately estimated.

Observation Phase

- Precise 3D reconstruction of the target and motion estimation

  At around 50 meters from the target, its shape and the distance from the viewpoint are precisely measured through image-based perception, i.e., stereo-vision.

  The target motion, such as nutation/tumbling, is estimated by using sequential images.

  For the final approach in the next phase, all perception information of the target should be estimated in this phase.

Removal operation Phase

- Image-based perception for robotic operations

  Until contacting with the target, visual perception or target tracking is continually executed for a robotic operation, i.e., attaching a removal device on the body of debris.

  After attaching the device, the performance of the device is monitored in the middle distance.

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(Note) Debris satellite CG model: HII-A second rocket

In this part of the presentation, we describe how each image-based perception is synthesized using images through computer graphics. The information includes the debris satellite CG model, HII-A second rocket, and camera properties of the removal satellite.

- Cameras on the removal satellite:
  - A camera with a telescopic lens, FOV 6 [°], for long-range observation
  - Two cameras with a standard lens, FOV 20 [°], for stereo camera sets
  - Image-size: 1000 x 1000 [pixels]
- A debris satellite/target satellite and an upper (second) rocket of the HII-A

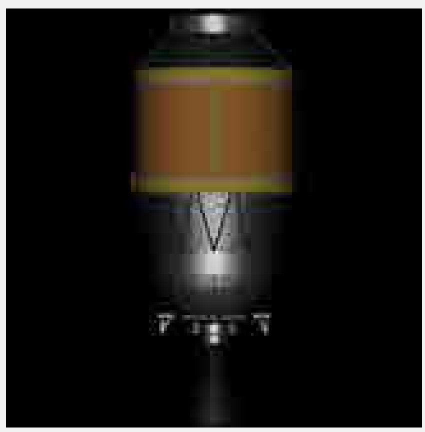
Dimensions of the debris target:
total height 10 [meters]
diameter of body 4 [meters]

Synthesized images from 100 [meters] distance

with standard lens, FOV 20 [°]

projection size of the target 117x273 [pixels]

with telescopic lens, FOV 6 [°]



projection size of the target 391x984 [pixels]

Light source; right behind the sun and under the earth's albedo

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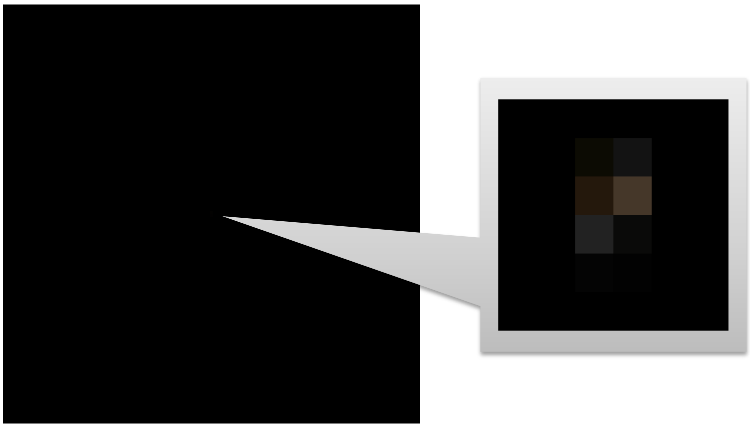
Finding target and determining its direction

- From a very long distance, for example, of the order of dozens of kilometers, the target projected on the image, with a size of one or a few pixels, is detected from an image obtained by a telescopic camera, and the direction from a viewer to the found target is concurrently estimated with the target positions.



Synthesized images from 10,000 [meters] distance with telescopic lens, FOV 6 [°]
Image size 1000x1000 [pixels]

Projection size of the target: 3x2 [pixels]

With a high-resolution camera with a telescopic camera, if the lighting environment is good, the target image can be projected on the image plane with one or a few pixels. As the approximate target position is known from orbital information and GPS navigation, it is relatively easy to find it and distinguish it from stars.

The direction of the target from the observer can be derived from the target position on the image.

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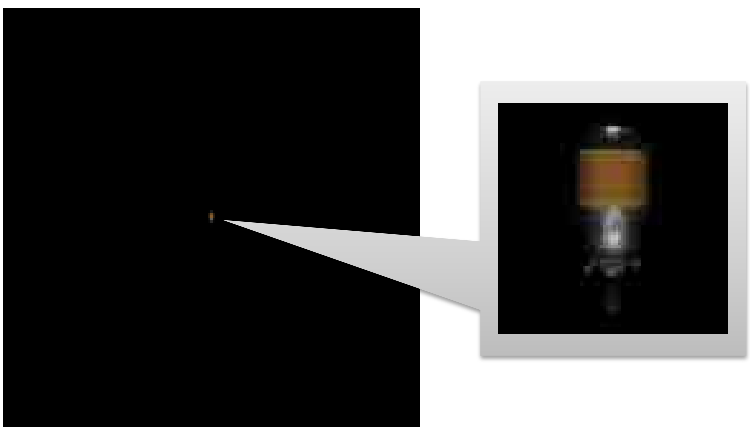
Course range finding with a telescopic image

- An approximate distance between the viewpoint to the target is estimated from the projection size of the target and its design parameters.



Synthesized images from 3,000 [meters] distance with telescopic lens, FOV 6 [°]
Image size 1000x1000 [pixels]

Projection size of the target: 14x34 [pixels]

From 10 kilometers to the target, the projection size of the target will increase by more than 10 pixels.

The estimation accuracy depends on the lighting condition, i.e., the positions of the sun and the earth (albedo).

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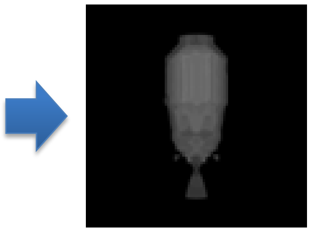
Precise 3D reconstruction with stereoscopic images at close range

- At close range, i.e., within 50 meters, a precise image-based perception, i.e., stereo-vision and/or SFM (Structure from Motion), can be obtained through images of sufficient resolution.

  (With design information of the target, this perception is not so important.)

Synthesized stereo images from 50 [meters] distance with FOV 20 [°] lens, base line distance 0.5 [meters]
Each projection size of the target: 233x591 [pixels]

Overlapped stereo images
left: red, right: blue



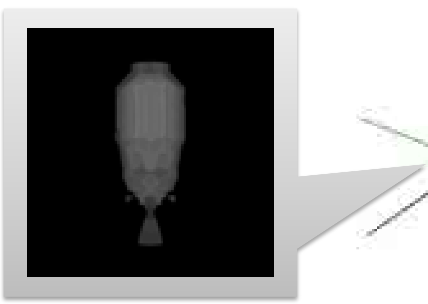
Estimated 3D information
disparity map

By using two camera set at a baseline distance of 0.5 meters, the stereo images obtained indicate the viewing disparity of the target; therefore, the target 3D information can be estimated by stereo matching.
This perception result is an estimate of the shape variation from the known design parameters of the target.

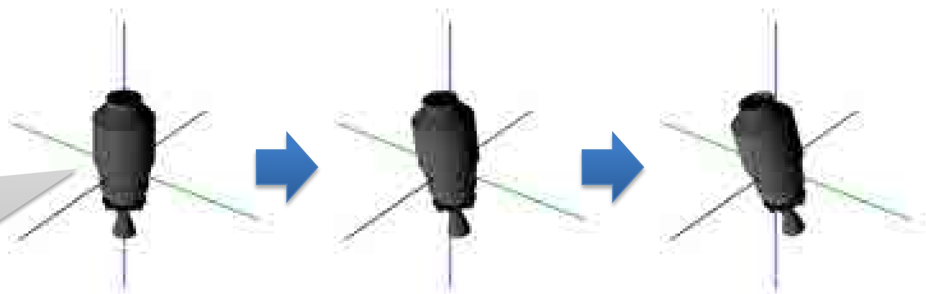
Moreover, from the design parameters, the target's 3D information can be estimated by the SFM estimation method.

Motion estimation at close range

- It is important to estimate the target's motion in order to capture it. At close range, i.e., within 50 meters, by using the 3D information that is obtained through stereo-vision and/or a design parameter, motion information of the target can be precisely estimated.



i.e., model fitting motion estimation



Estimated target motion, nutation/tumbling along one's own orbit.

By sequentially fitting a reconstructed target shape to the designed model, the target motion including nutation/tumbling can be estimated.
The debris motion and the removal satellite motion are included in one motion estimation; therefore, decomposition of the object from the viewer is required.

Properties of image-based perception for debris removal

Facilities of image-based perception:

- Design parameters and detailed shapes of the debris target are known, in which case the second rocket could be a debris target.
- If the target is sufficiently large, its motion is supposed to be simple and slow. The motion can be approximately estimated by an observation from the earth.
- By GPS navigation, a removal satellite can get close to the target.

-> This reduces the difficulties in image-based perception.

Basic difficulties in image-based perception:

- The only light sources are the sun and the albedo from the earth, but their location changes from hour to hour. The time required to circle the earth is about 90 minutes.
- Motion decomposition between the target and the observer
- Wide sensing range: from 10 kilometer (or of the order of dozens of kilometers) to 0 meter
- Limitation of resources on a spacecraft, i.e., camera, CPU, memory, etc.
- Unavailability of actual sample images

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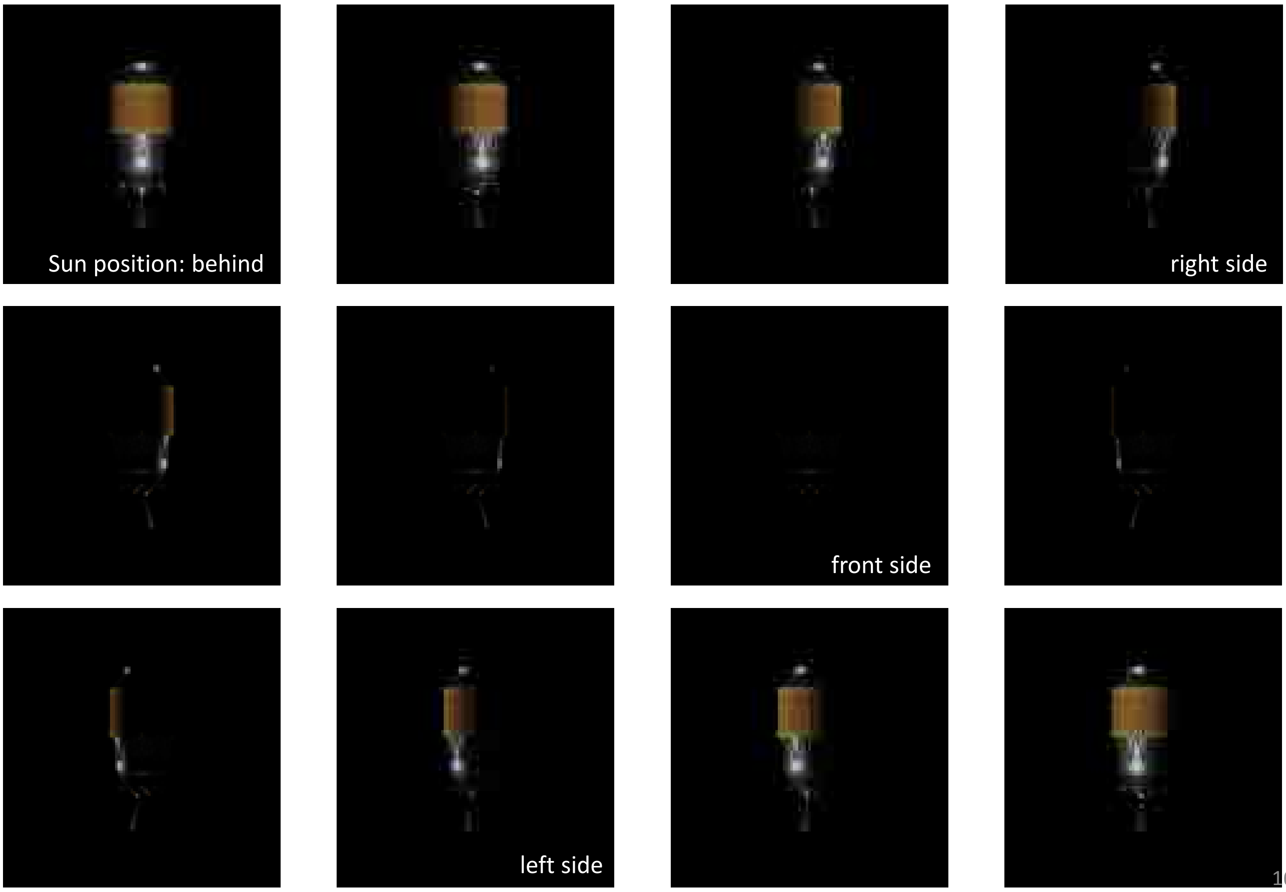
(Reference) Synthesized images from different positions of the sun



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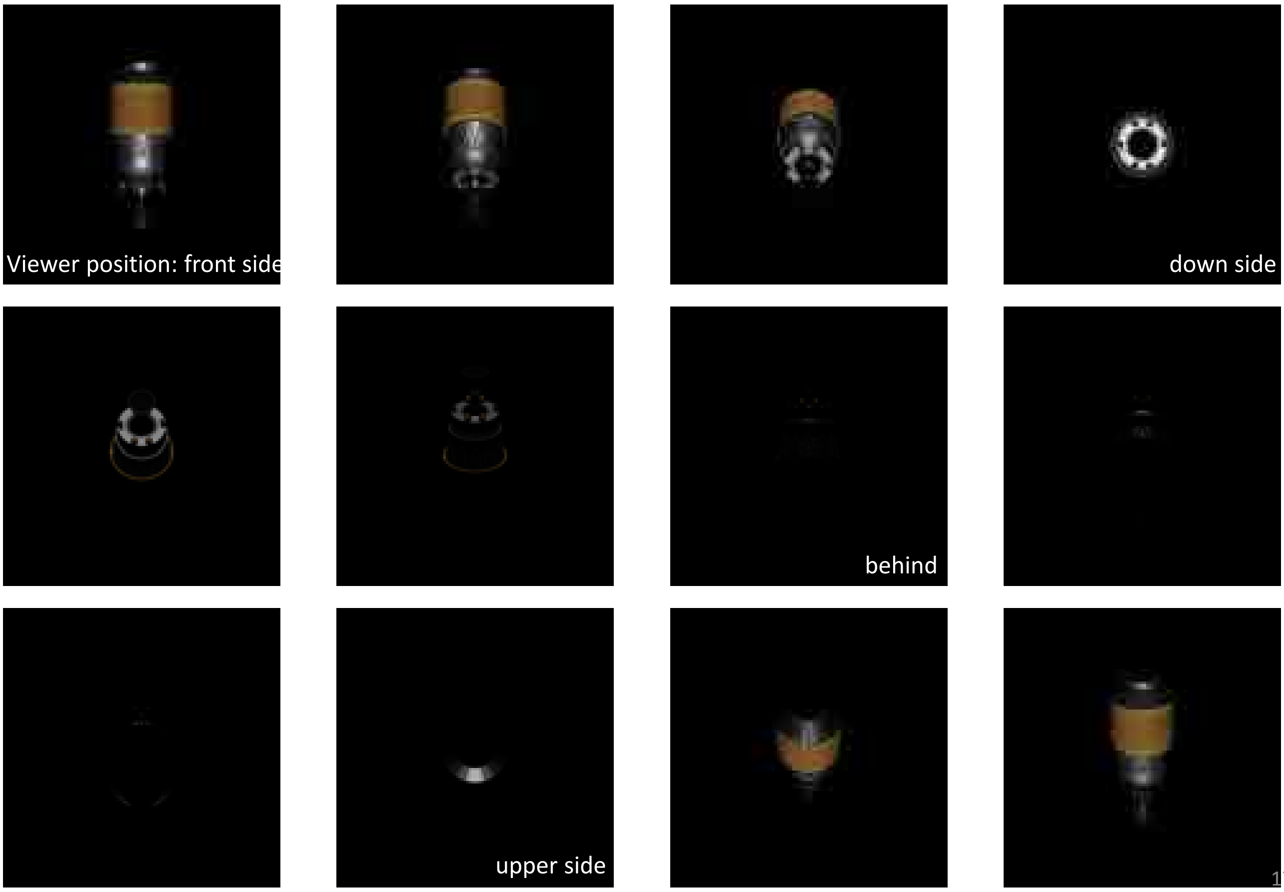
(Reference) Synthesized images from different viewing positions



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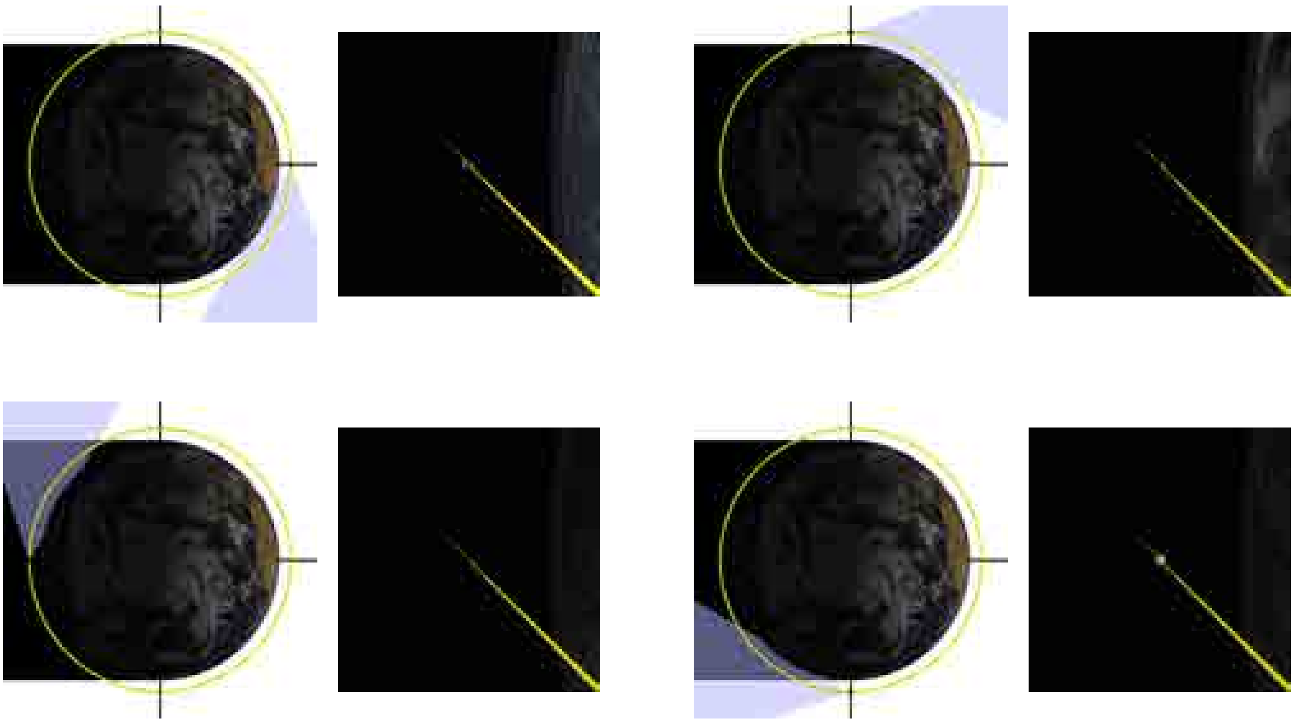
(Reference) Lightning changes in position of the observer rotation on its orbit



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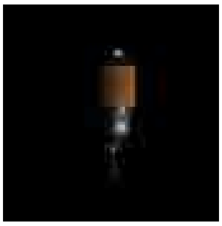
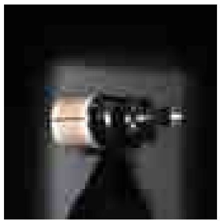
Our activities in image-based perception for debris removal

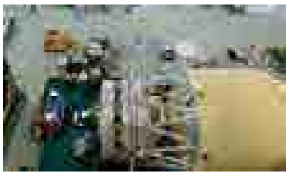
Usually, the research and development of image-based perception requires much experimental evaluation of the proposed methods with the actual images. In the debris removal operation, it is not easy to obtain the actual images of the debris in an earth orbit; therefore, we have to use other means to obtain more realistic images. The following are our activities in this regard.

- Synthesis of images through computer graphics
  - for the performance of the proposed algorithm, tests in many cases
- A miniature scaled model of the debris
  - for actual tests of the cameras, lens, and real material, i.e., refraction on MLI (multi-layer insulation)
- Images of the (actual) HII-A upper rocket in a facility
  - for actual scale tests of the camera, lens, and actual surface materials
- Actual similar images obtained from the ISS, HTV, and HII-A
  - for actual lighting environments

- Through a demonstration experiment on the orbit, actual images are obtained
  - this is a perfect experiment and a unique opportunity.


CG image


Miniature model


Actual satellite (HII-A)


Similar image on the scape (GOSAT)

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Conclusions

- Attaching a removal device to an upper rocket is effective in reducing new space debris in the earth orbit.
- This operation needs remote controlled and/or autonomic robotics technology, and 3D perception plays the most important role.

- This presentation provides an outline of the phases involved in the debris-removal operation in terms of image-based perception, and it describes our activities in this regard.

- In the debris removal operation, we believe that an important and key technology is 3D reconstruction and motion estimation using images obtained by the removal satellite.
- We continue to focus our research and development on image-based perception for debris removal.

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C2

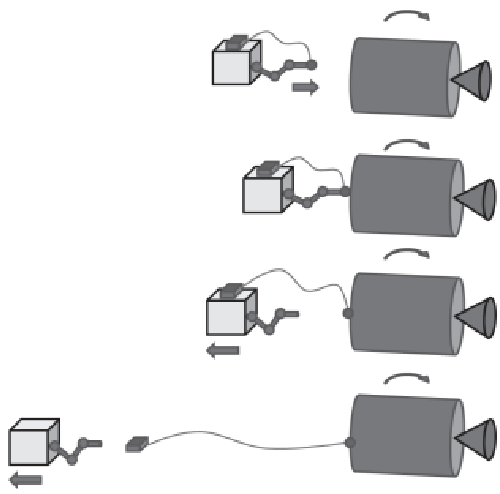
推進系取付のストラテジ・機構の検討

The Strategy and Technology for Non-cooperative Target Capture

○中西洋喜，河本聡美（宇宙航空研究開発機構）
○H. Nakanishi and S. Kawamoto (JAXA)

デブリの除去を継続的に実施していくためには、安全及びコストの面から無人の軌道上作業ロボットで行うことが必須であると考えられるが、実現には多くの技術的な課題がある。その中の大きな一つが、非協力ターゲットであるデブリを安全かつ確実に捕獲する技術である。ここで非協力ターゲットとは、専用の被把持機構を持たず、姿勢が制御されていない状態の捕獲対象のことを指す。現状、このようなターゲットの無人宇宙機による捕獲は成功例がなく、早急な技術確立が必要である。本発表では、デブリ捕獲技術に関する要求や必要技術の整理、および具体的な検討例について紹介する。

In the debris removal mission, the target (debris) capture is one of the biggest issues. The targets are non-cooperative in terms of the lack of dedicated fixtures and attitude stabilization. The established capture technology is not enough for such target. In this presentation, the requirements, strategy and technology for the capture of the non-cooperative target are discussed.



5th Space Debris Workshop, Jan. 22nd, 2013

推進系取付のストラテジ・機構の検討
The Strategy and Technology for Non-cooperative Target

Hiroki NAKANISHI and Satomi KAWAMOTO
Japan Aerospace Exploration Agency

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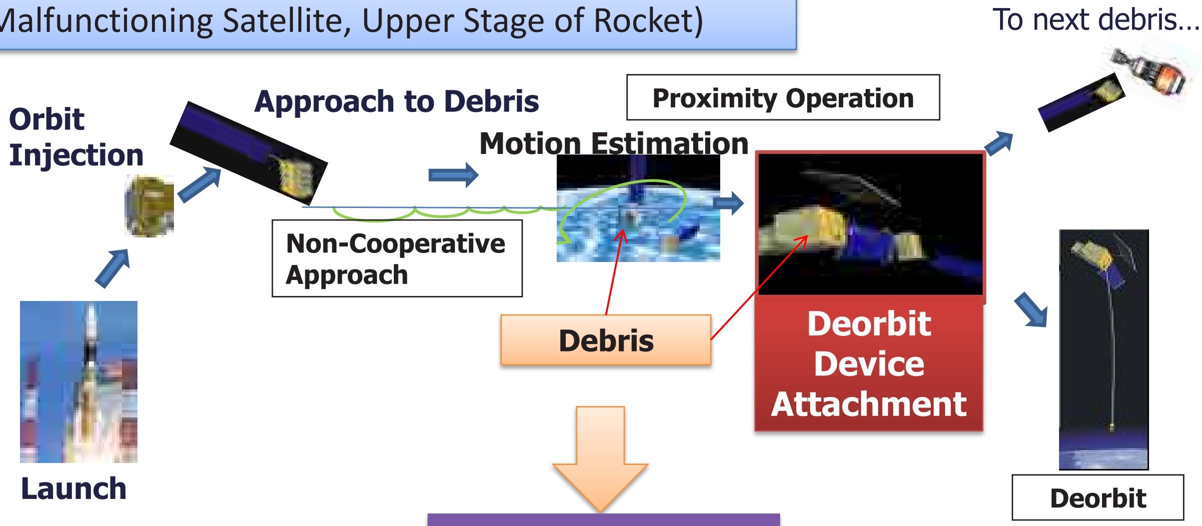
Debris Removal Mission

Removal mission for existing Debris
(Malfunctioning Satellite, Upper Stage of Rocket)



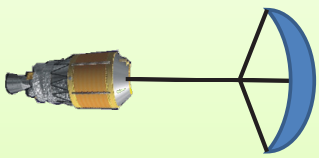
Non-Cooperative Target

- No Dedicated Fixture
- No Attitude Control (Tambling motion)

Breaking and Pushing away of the target should be avoided.
However, the capture system which provide safely capture has never been established yet.

Debris Deorbit Device

EDT(Electrodynamic Tether)



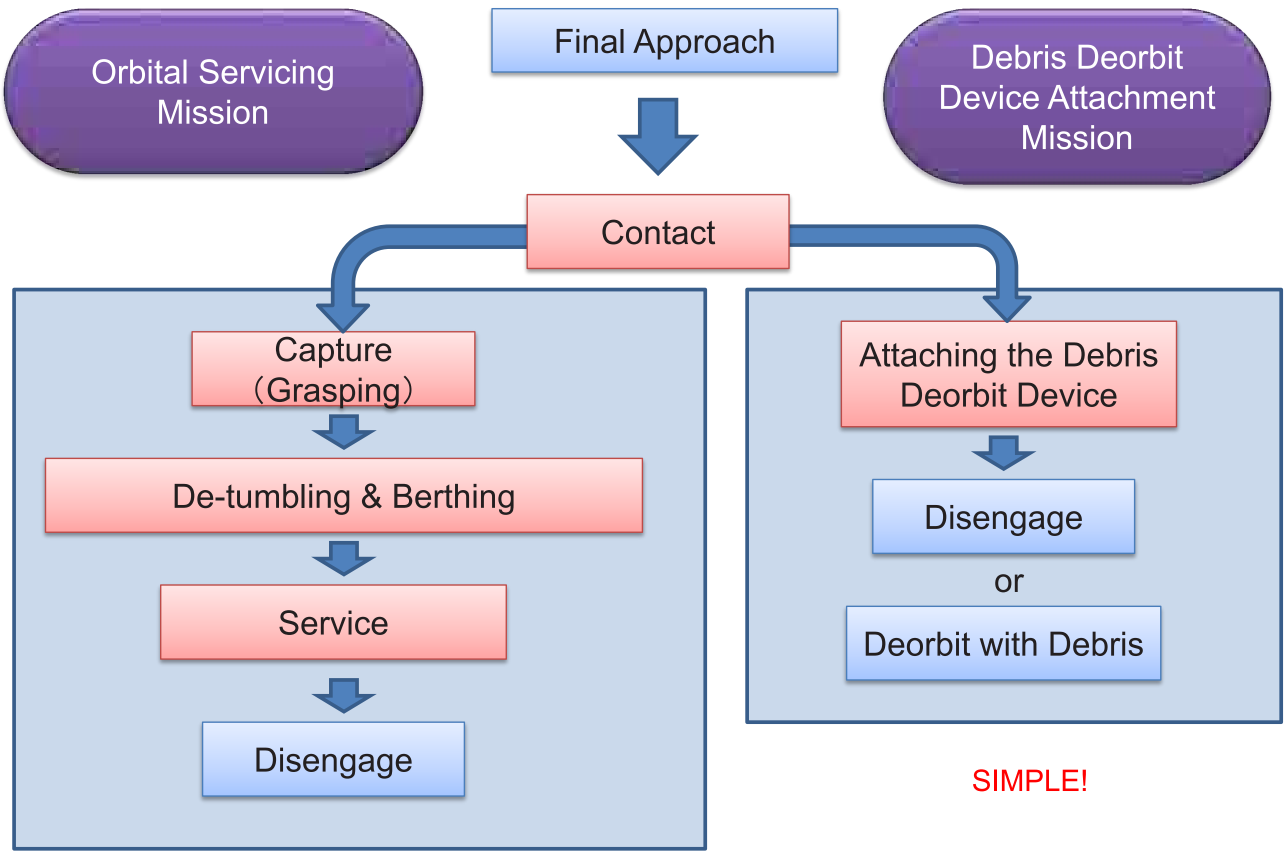
Air Brake

etc.

These Devices give the debris low-thrust over long term

Fixing the tether end of the de-orbit device
on the target surface is required!

Orbital Service and Debris De-orbit



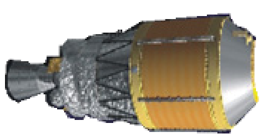
Assumed Target

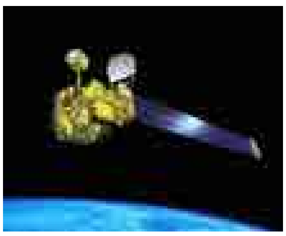
Over 10,000 Target ➡ Prioritization is important!

Preferential Target:
- Large size debris which makes more small debris with a collision.
- Debris which is easy to access and operation.

Upper stage of Rocket or Large satellite

- Weight: 3~4[t], Size: ~10[m]
- Max 1[deg/s] of flat-spin or swinging by gravity gradient





Mission Scenario

- Assume the EDT or tether towing type device.
- Attach the tether's end to the target while short time of relative control.
  (No target handling, No berthing)

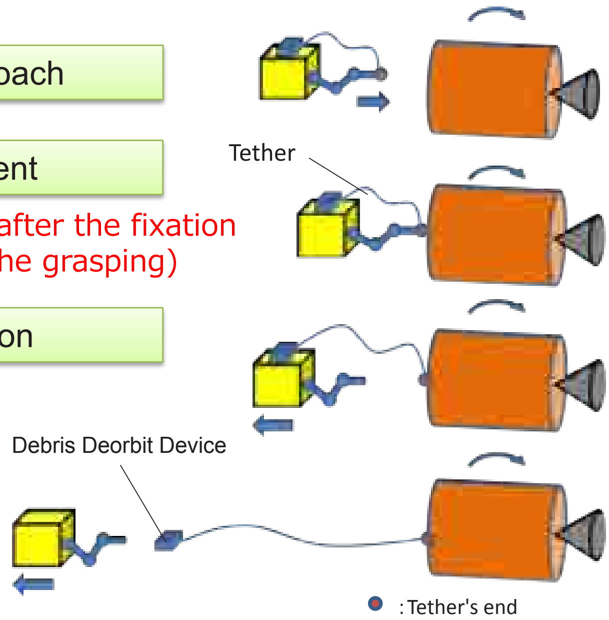
Final Approach

Attachment

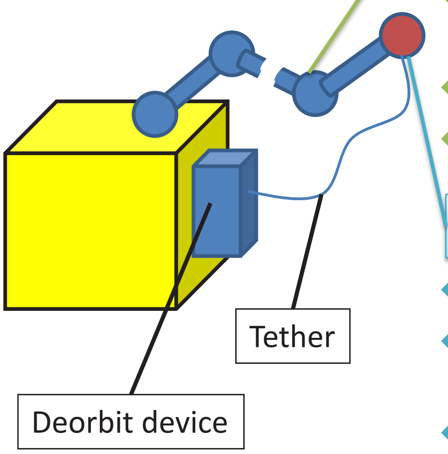
Separate the tether's end right after the fixation
(Separate the hand right after the grasping)

Separation

Disengagement
or
Deorbit with Target



Requirement for Device Attaching System



for Arm

- Stiffness against contact force and reaction force
- Enough clearance between main body and target (1~2m)
- Enough velocity and accuracy
- Light weight, Low power and simple mechanism

for End-effector

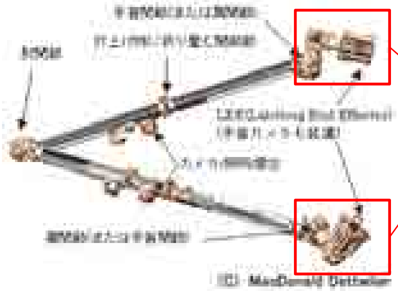
- Endurance and absorption for contact force
- Fixation with enough force
  (Endure de-orbit force > Low but long term)
- Wide allowable attitude for attach motion
- Quick fixation
- Light weight, Low power (no power after fixation) and simple mechanism

Time Constraint

Operation must be done within 1 AOS → 40min (with Data relay Sat) / 10min (w/o Data relay Sat)

Conventional Grasping System (for Cooperative Target)

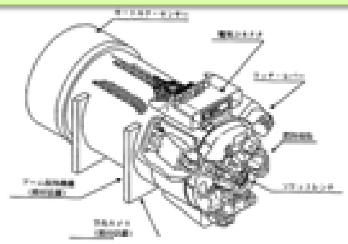
LEE (Latching End Effector)



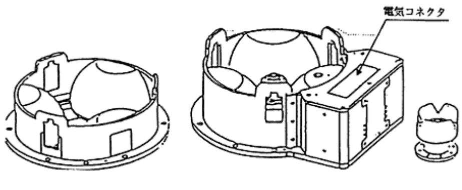
LEE

FRGF

JEMRMS Small Fine Arm End Effector



EE



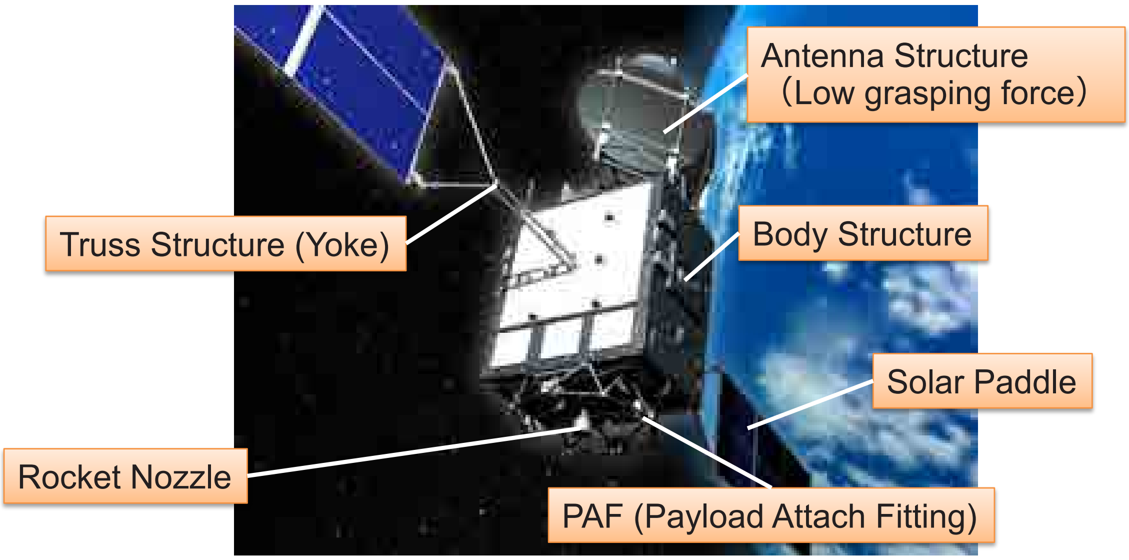
GF

Combination of EE and Dedicated GF is MUST ⇒ Useless for Non-cooperative Capture

Where is de-orbit device fixed?

Requirements for fixation/grasping point

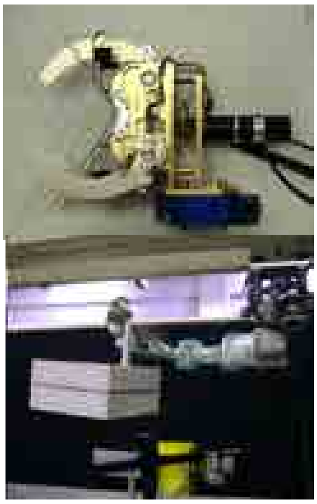
- Easy to access
- Easy to grasp
- Easy to identify
- Enough stiffness for grasping / contact force



PAF (Payload Attach Fitting)

- High Stiffness
- Suitable Shape for Grasp (Cylinder, Truss, etc.)
- Easy to Access (Edge of body)
- There are often Obstacles

Grasp

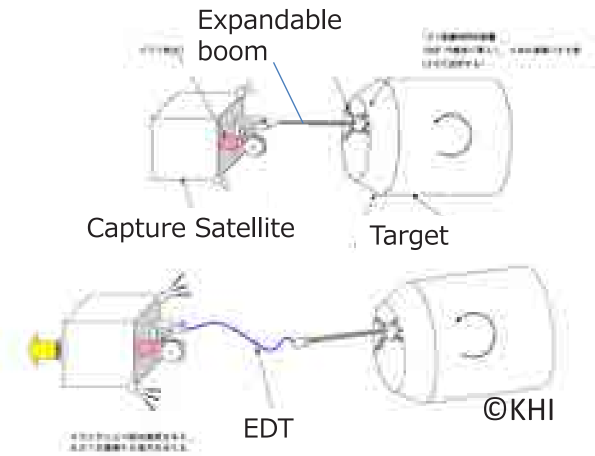


Truss Gripper

Cylinder Edge Gripper

JAXA-THK multi-purpose hand

Fix from Inside



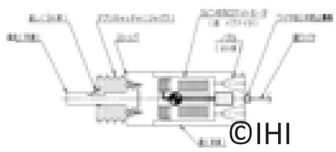
PAF Capture Tool

Main Body

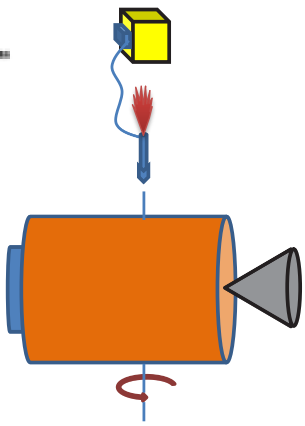
- High Stiffness
- Large Capturable Area

Harpoon (for Rocket)

- Stick a rocket harpoon to LH2 Tank
- Long range (~10m)
- 2DOF Control（Az・El）
- Prevent the penetration trough whole body and production of micro debris are issues.

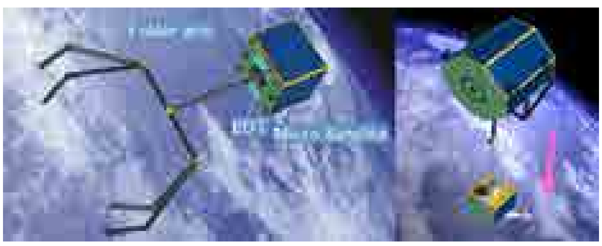


Rocket Harpoon



Grasp

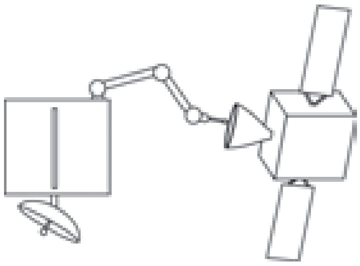
- Low requirement of relative motion.
- Large capture arm is required. (Larger than target)



Whole body capture with extendable arm

Thruster Nozzle

- Easy to Access
- High Stiffness (Base structure)
- Low Stiffness (Nozzle surface)



Nozzle probe insert experiment (for DRTS's nozzle)
(Corroborate with Tohoku University)

NASA's Satellite Capture tool for EVA

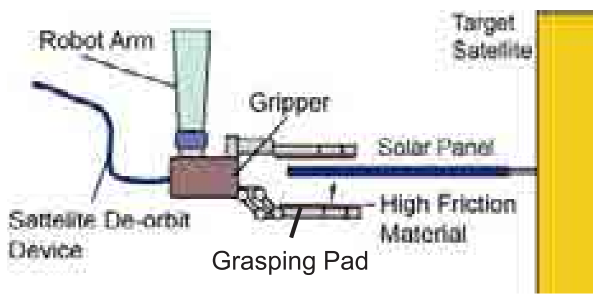
DLR's Nozzle Capture tool

- ➢ Capture probe is inserted into nozzle throat.
- ➢ The probe is extracted and hold from inside wall.
- ➢ Inside wall of nozzle skirt is used as a guide plate.

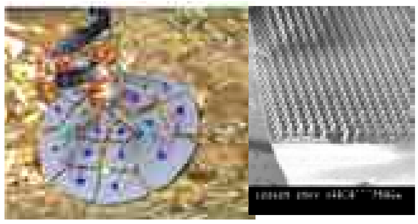
Solar Paddle, Antenna, Plate structure

- Easy to Access
- Low Stiffness

Panel Gripper



CNT Gecko Tape (©Nitto Denko Co.)



Silicon Gecko Hand (©NASA/JPL)

- ➢ Low Grasping force but High friction force
- ➢ Low concentrated load
- ➢ High friction material with resistance to space environment is required.

Summary

- The requirements, strategy and technology for the capture of the non-cooperative target are discussed.
  - ✓ The target assumption is clarified.
    ➡ The first targets are large debris (rocket and large satellite.)
  - ✓ A strategy of de-orbit device attachment to the debris is proposed.
  - ✓ Attachment (grasping) technologies for non-cooperative targets under development are introduced.

C3

軌道上実証を目指した導電性テザー技術の研究開発

R&D of Electrodynamic Tether for On-orbit Demonstration

○大川恭志，河本聡美，松本康司，塩見 裕，北村正治（宇宙航空研究開発機構）
○Yasushi Ohkawa, Satomi Kawamoto, Koji Matsumoto, Hiroshi Shiomi, and Shoji Kitamura（JAXA）

低軌道デブリ除去機のデオービット推進系への適用を目指して、JAXA 研究開発本部では導電性テザー（EDT）技術の研究開発を進めている。EDT は、導電性のひも（テザー）に流れる電流と地球磁場との干渉により発生するローレンツ力を推進力として利用する推進系であり、推進剤を必要とせずに大きな速度増分を得ることができる。低コスト・小型・軽量・簡素なシステムの開発が重要となるデブリ除去実現のためには、上記の EDT の特徴は大きな利点となる。本発表では、デブリ除去システム実現に向けた技術実証の1ステップとして検討されている EDT の軌道上技術実証実験に向けた各要素技術の研究開発状況について、その概要を紹介する。

Electrodynamic tether (EDT) technologies have been studied for future active debris removal systems in the Aerospace Research and Development Directorate, JAXA. The EDT is an advanced propulsion system which utilizes the interaction between an electric current through the tether and the geomagnetic field for thrust generation. In order to realize low-cost active debris removal systems, simple and efficient deorbit propulsion is needed, and the EDT is a promising candidate for such a propulsion system because of its propellant-less mechanism and high-efficiency in weight and electrical power. In this presentation, the current research and development status of some key EDT system components are presented.

5th Space Debris Workshop,
Chofu Aerospace Center, JAXA, January 22 & 23, 2013.

R&D of Electrodynamic Tether for On-orbit Demonstration

軌道上実証を目指した導電性テザー技術の研究開発

by
Yasushi Ohkawa, Satomi Kawamoto, Koji Matsumoto,
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(Aerospace Research and Development Directorate, JAXA)

1

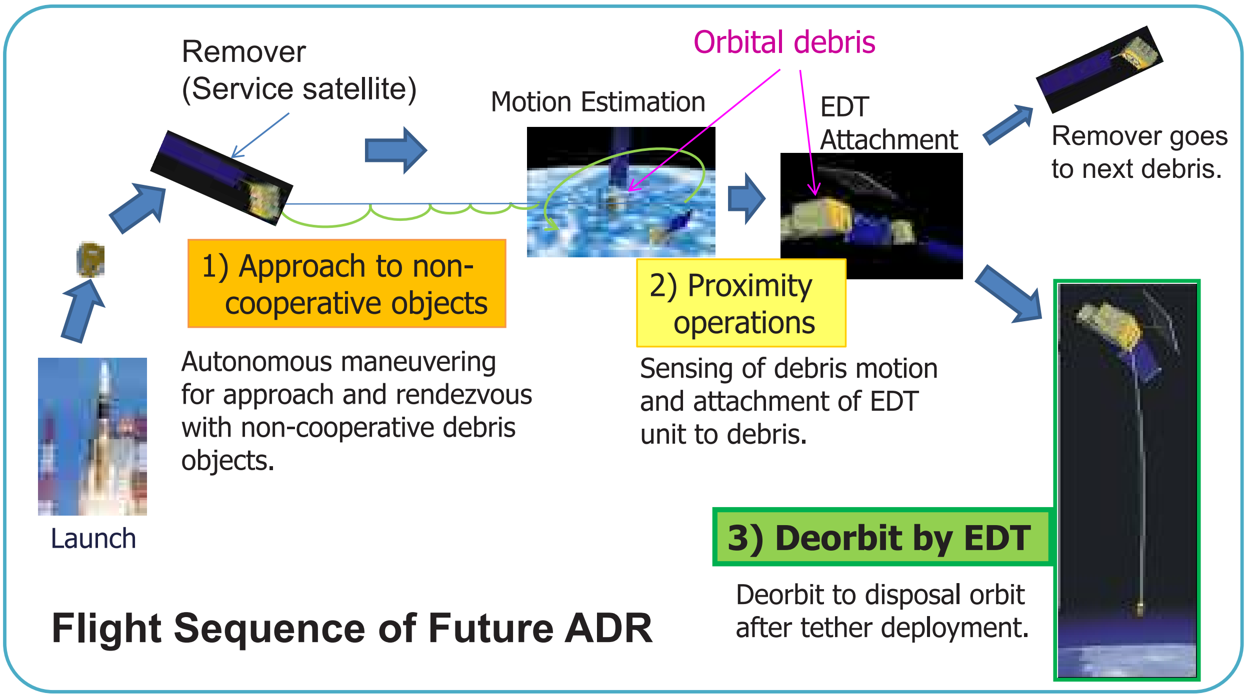
Outline of Presentation

- Concept of Active Debris Removal in LEO
- Electrodynamic Tether (EDT)
  - Fundamentals
  - Advantages and Disadvantages
  - EDT Operation in High Inclination Orbit
- Roadmap to realize ADR equipped with EDT
- Plan for On-Orbit Demonstration of EDT
- Development of Key Components
  - Tether - "Net-type Bare Tether"
  - Electron Emitter - "Field Emission Cathode"
- Conclusion

2

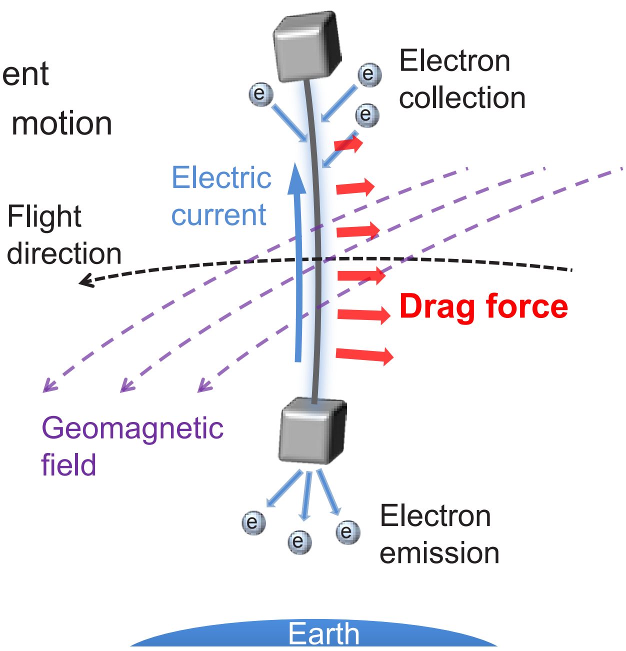
Concept of Active Debris Removal (ADR) in LEO

- Target: Large LEO debris (rocket bodies or defunct satellites)



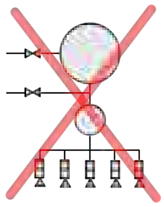
What is Electrodynamic Tether (EDT)

- EDT is “Propellant-free propulsion”
- Fundamentals
  - Attitude stabilization by gravity gradient
  - Electromotive force (EMF) by orbital motion
    - $V_{emf} = (v \times B) L$
  - Electron emission and collection
  - Electric current through tether
  - Lorentz force
    - $F = (J \times B) L$

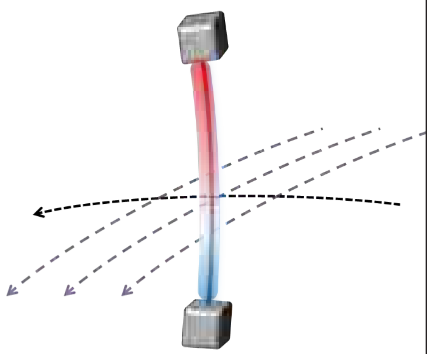


Advantages of EDT for ADR (1)

- Light weight
  - No propellant consumption
  - Large velocity inclement missions do not increase system mass
- Simple system
  - Propellant tanks, valves, and pipes are not required
  - System can be simple and small
- Low electrical power
  - Naturally induced voltage (electromotive force) can be used for thrust generation
  - Electrical power consumption is lower than that for general electric propulsion



No propellant



Voltage induction by EMF
(Power generation)

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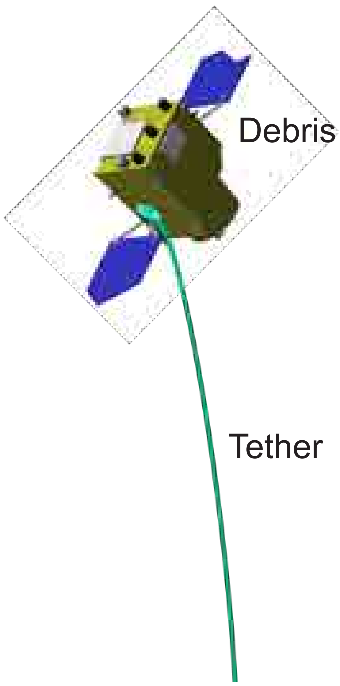
Advantages of EDT for ADR (2)

- Easy attachment to debris
  - Not requiring strong attachment force because of small thrust of EDT
  - Not requiring alignment between thrust axis and debris' center of mass because small thrust is distributed along tether
  - In general propulsion, thrust axis must be aligned precisely with center of mass of debris to avoid inducing rotation
- No thrust vector control
  - Thrust vector control is not required because EDT thrust is automatically directed towards lowering altitude
  - In general propulsion, thrust direction must be controlled by active attitude control for deorbit



Simple and small system for "Low cost" debris remover.

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Disadvantages of EDT and Countermeasures

- Long mission duration
  - Deorbit will require several months to a year because of EDT's low thrust
  - Autonomous operation is needed to reduce operation cost
- Possibility of mission failure due to tether being severed
  - There is a possibility of tether being severed by impacts of small debris objects or micrometeoroids
  - The risk can be reduced by adopting "net-type" tether
- Collision risk with operational satellites
  - There is a collision probability between EDT and operational satellites
  - The risk should be assessed against mission payoff in advance
- Difficulty of controlled re-entry
  - Controlled re-entry is difficult because of EDT's low thrust
  - Target for removal should be selected considering a hazard to the ground

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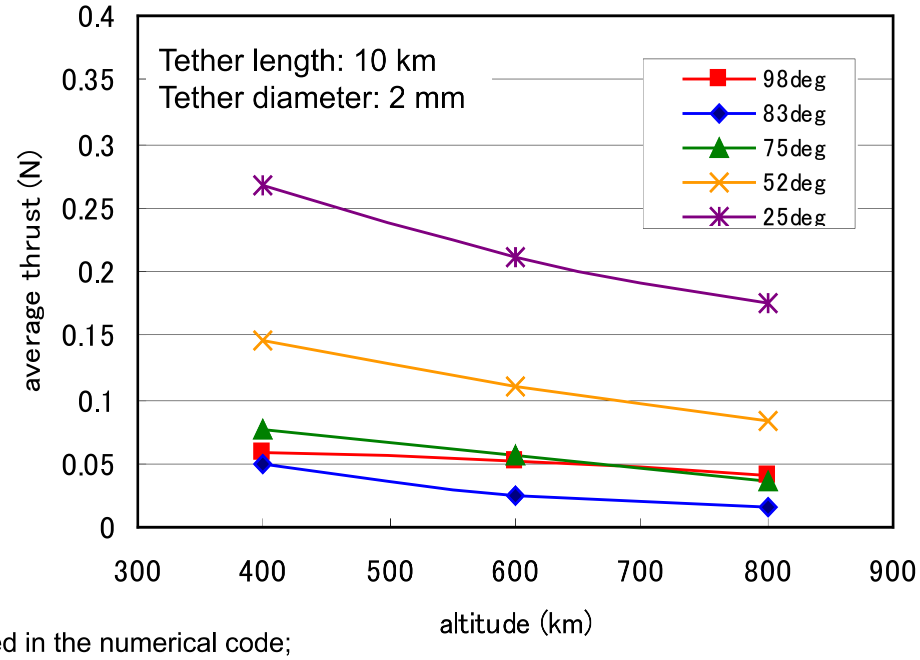
EDT Operation in High Inclination Orbit

- EDT thrust becomes smaller in higher inclination orbits, but is still great enough to transfer debris from SSO



Considered in the numerical code;
Orbital motion, tether flexibility, IGRF magnetic, IRI plasma, and OML electron collection model.

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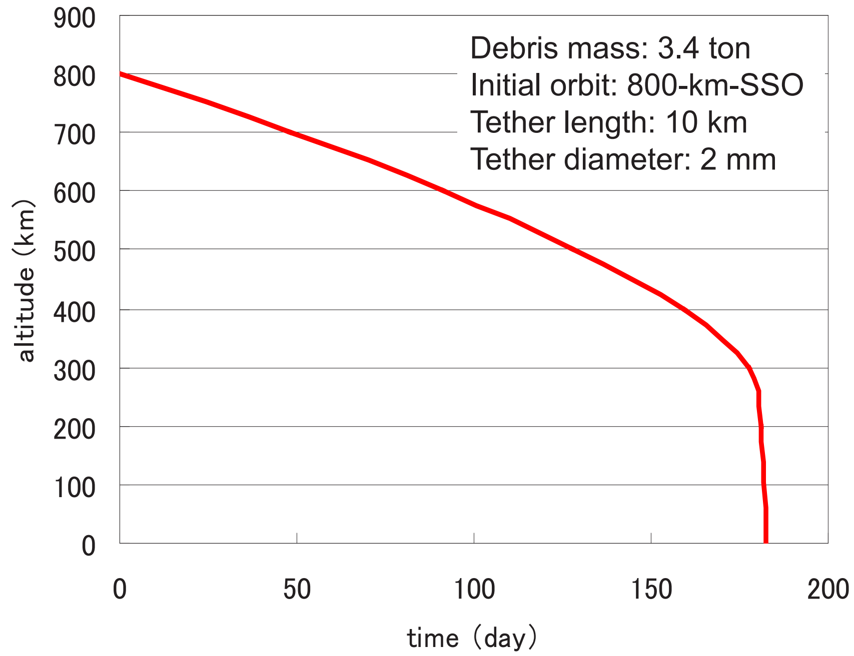
EDT Operation in High Inclination Orbit

- 10-km-EDT can transfer 3.4-ton SSO debris from 800-km-altitude to atmosphere within a year



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Roadmap to Realize ADR with EDT

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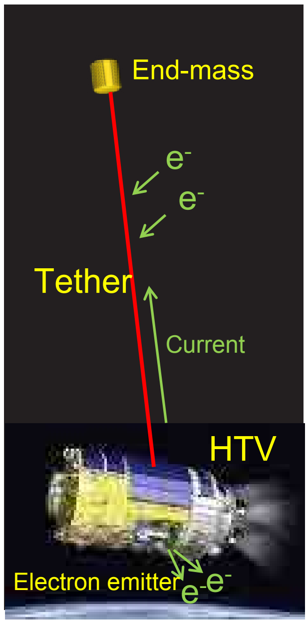
Feasibility Study of EDT Demonstration using HTV

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

(Tether deployment and EDT operation: 7 days for EDT mission)

Tether length	700 m
Max. tether current	10 mA

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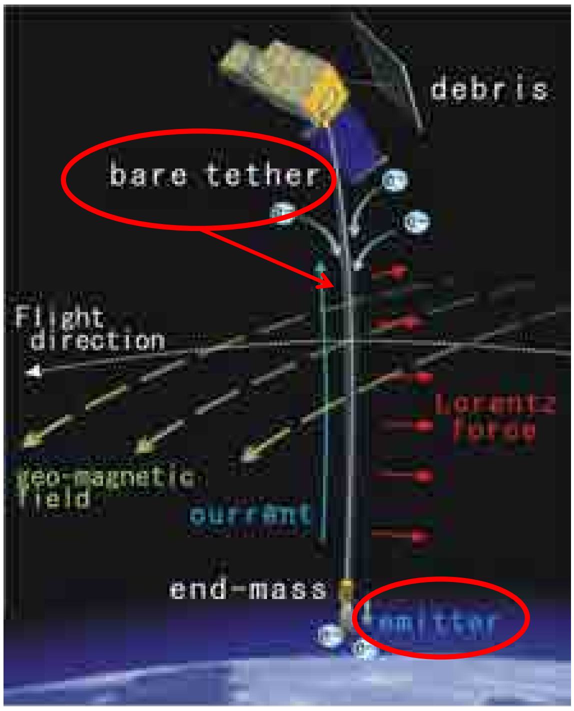
Key Components of EDT

Most important components in EDT system are:

- Bare Tether
  - Induces voltage along tether
  - Collects electrons from plasma
  - Generates thrust
- Electron Emitter
  - Emits electrons from tether end
  - Closes electrical current loop via plasma



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Bare Tether

- Major Requirements for Bare Tether
  - Sufficient strength to withstand tension forces
  - High electrical conductivity to pass electric current and to collect electrons
  - Low surface friction for smooth deployment from reel
  - Tolerance to impacts by small debris to survive in on-orbit environment
- Net-type Bare Tether
  - Fine aluminum wires and stainless steel wires are braided to form a cord
  - Three cords are connected to each other alternately
  - This arrangement creates physical gaps between three cords
    - High resistance to being severed by small debris impacts
    - High efficiency in electron collection from space plasma

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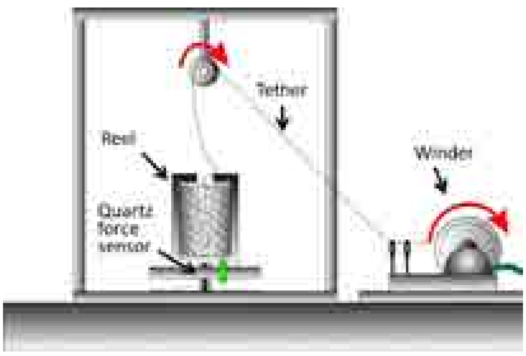
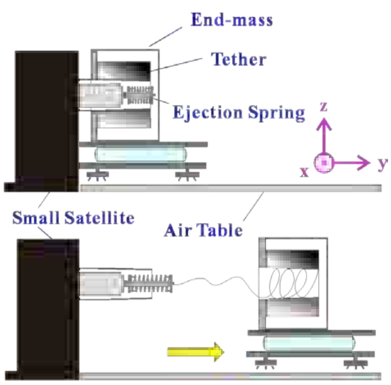
Bare Tether

- Various tests have been conducted



Tether deployment friction measurement



Tether deployment test on air table

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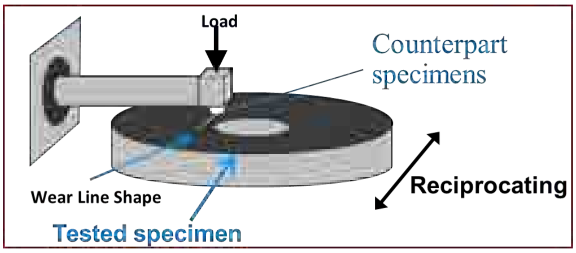
Bare Tether

- Various tests have been conducted



Reciprocating tribometer

Lubricant for smooth tether deployment

Hyper velocity impact test

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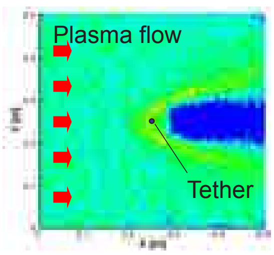
Bare Tether

- Various tests have been conducted



Electron collection test and analysis

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Electron Emitter

- Electron Emitter Selection for EDT

	Advantages	Disadvantages
Field Emission Cathode (FEC)	Small, Simple, Low power	Space charge limit, Not matured
Hollow Cathode	High current density, Matured	Tank and valves, Heat load
RF/ECR Cathode	High current density	Tank and valves, Not matured
Thermionic Cathode	Small, Simple, Matured	Space charge limit, Heat load
Passive Cathode (Photoemission, Ion collection)	Simple, No power	Large area, Low current density

FEC was selected because of its simplicity and potential capabilities.

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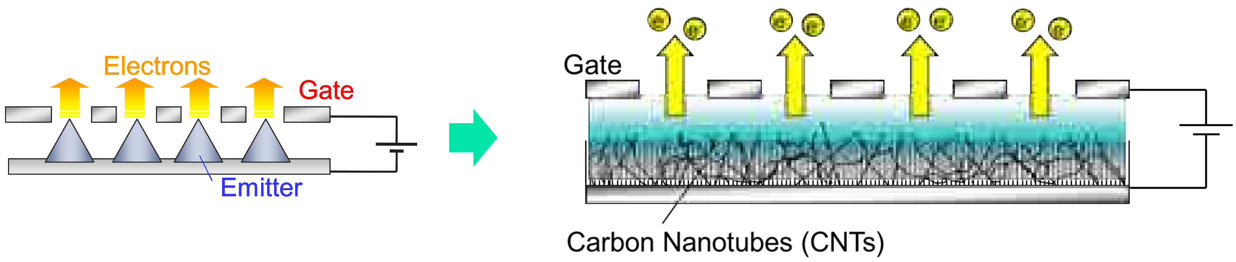
Carbon Nanotube FEC

- There are types of FEC
  - Spindt, Triple junction, Regenerative, Carbon nanotube, etc.
- Features of carbon nanotube (CNT) FEC
  - High field enhancement factor
  - High tolerance to ion impingement and electric breakdown: Operational in low vacuum condition in LEO environment
  - Nanotube structure and chemical stability



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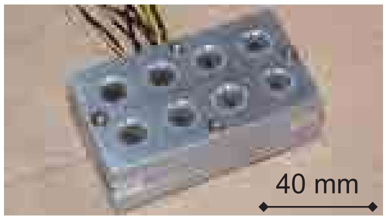
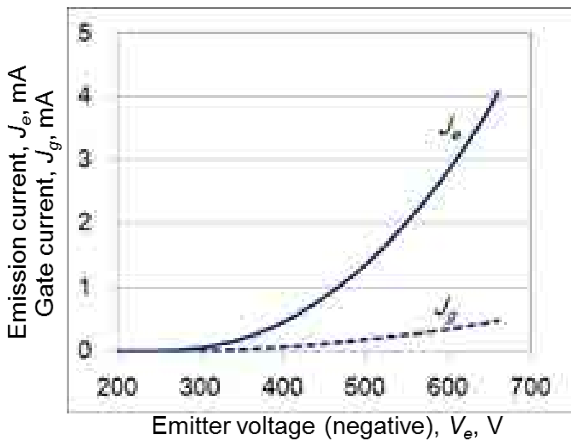
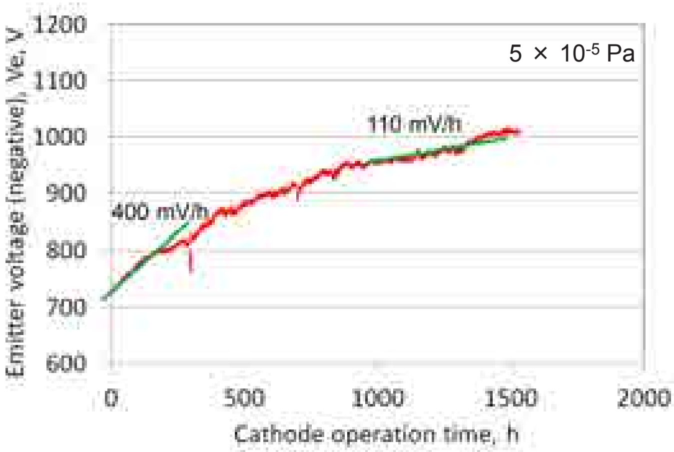
Electron Emitter

- Laboratory Model of FEC
  - Electron emission: 3 mA (nominal)
  - Extraction voltage: 1 kV (EOL)





Typical current-voltage characteristic (BOL)



Extraction voltage required to maintain 3 mA emission during 1,500-hour endurance test

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Conclusion

- Electrodynamic tether (EDT) is a promising candidate for deorbit propulsion of “active debris remover” because of its:
  - Propellant-less mechanism
  - High-efficiency in weight and electrical power
  - Ease of attachment to debris
  - Ease of operation

➡ “Low Cost” Debris Remover

- JAXA has a roadmap to realize “active debris removal” and is proposing a flight demonstration of EDT as the first step.

- Key technologies of EDT including “bare tether” and “field emission cathode” have been studied, so that we can start a project for the demonstration flight.

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C4

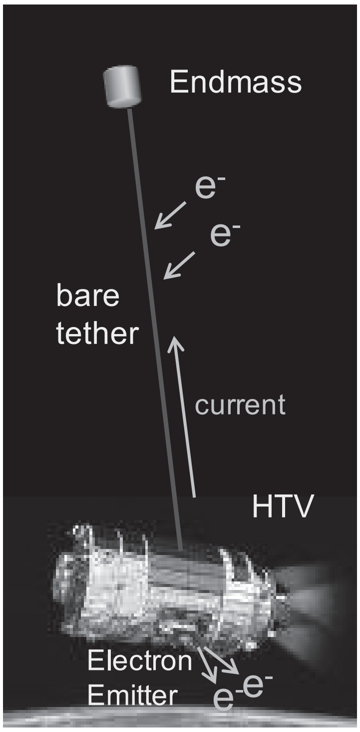
デブリ除去実現に向けたHTVによる導電性テザー実証実験

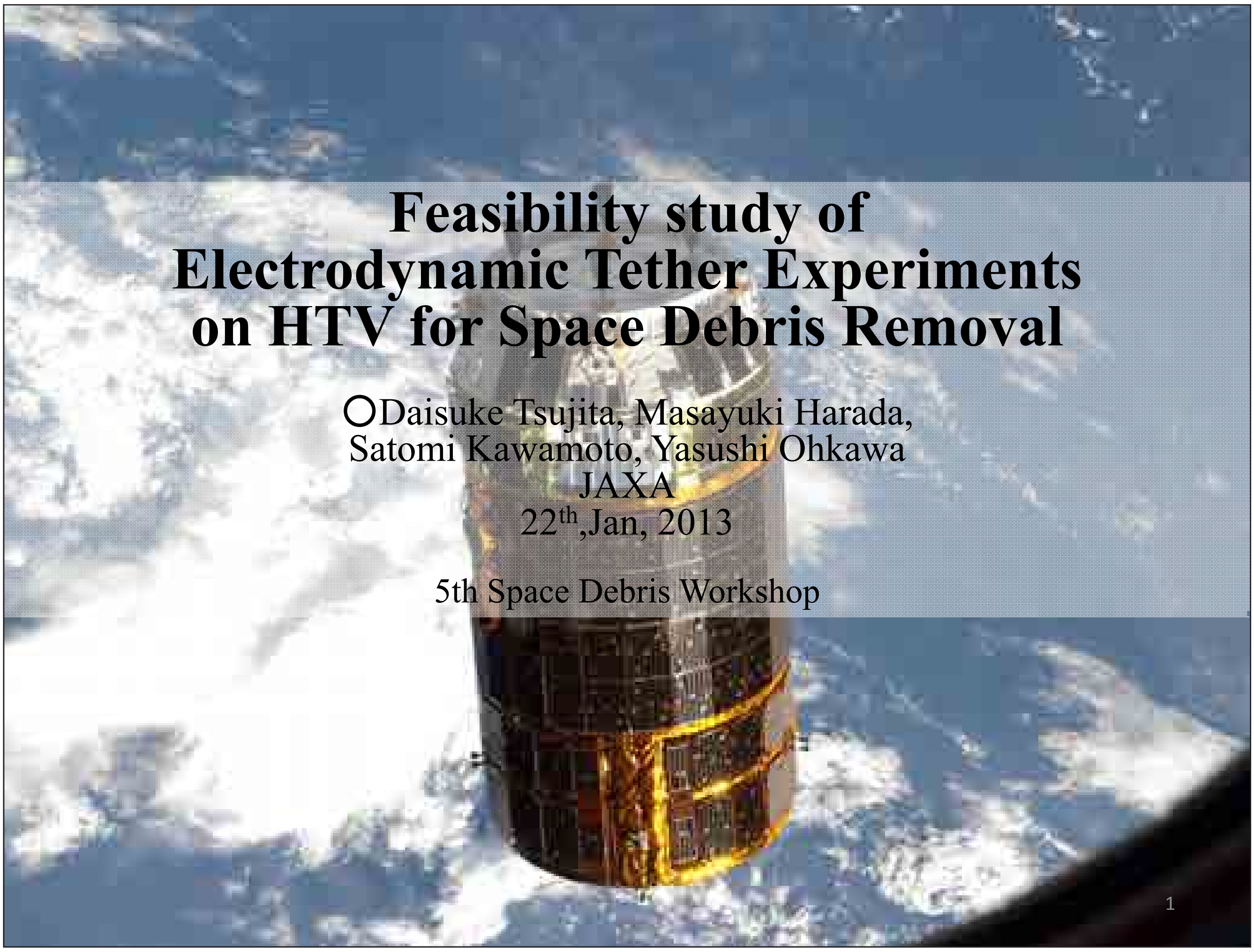
The Plan of Electrodynamic Tether Experiments on HTV for Debris Removal

○辻田大輔，原田正行，河本聡美，大川恭志（宇宙航空研究開発機構）
○Daisuke Tsujita, Masayuki Harada, Satomi Kawamoto, Yasushi Ohkawa (JAXA)

近年デブリの増加が大きな問題として認識されており、今すでに軌道上にあるデブリ同士の衝突によるデブリ数の自己増殖（ケスラーシンドローム）が低軌道で懸念されている。特に低軌道デブリを対象としたデオービット技術として、推薬不要な導電性テザーの利用を JAXA は検討している。その一環として既に 3 機打上実績のある HTV を実験プラットフォームとした導電性テザー実証実験の計画を発表する。

Recently, space debris increase is recognized to be a growing problem and the concern for Kessler Syndrome on Low Earth Orbit(LED) is being threat for spacecrafts. In order to remove orbital debris on LEO, JAXA have been studying the usage of Electrodynamic Tether (EDT) as a deorbit method, which needs no propellant. We present the plan of EDT experiments on H-II Transfer Vehicle (HTV) as one of the studies. Note that HTV has already performed the mission three times successfully, and four HTVs will be launched every year.





Content

1. HTV Overview
2. HTV Debris technique
3. Feasibility study of EDT Experiments on HTV
4. Summary

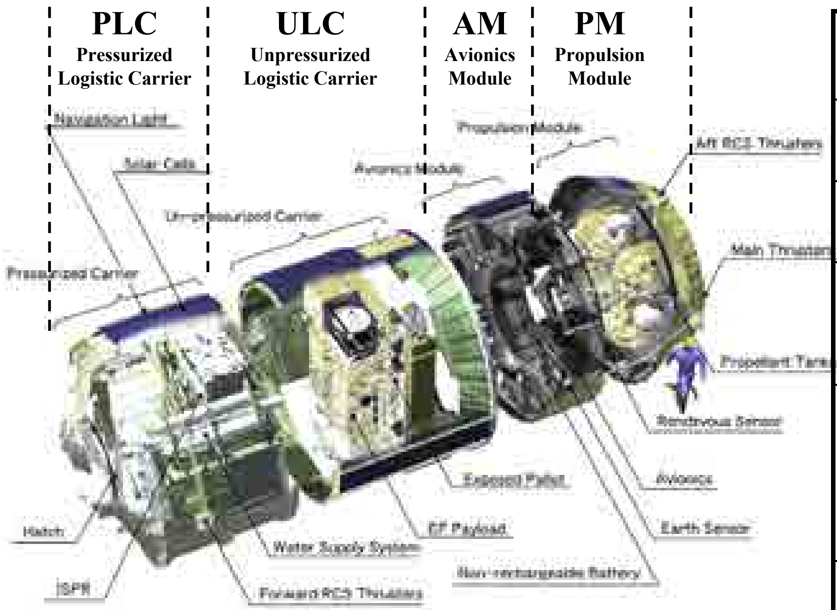
2

1. HTV Overview

1.1 HTV Configuration Overview

1.2 HTV Operation Overview

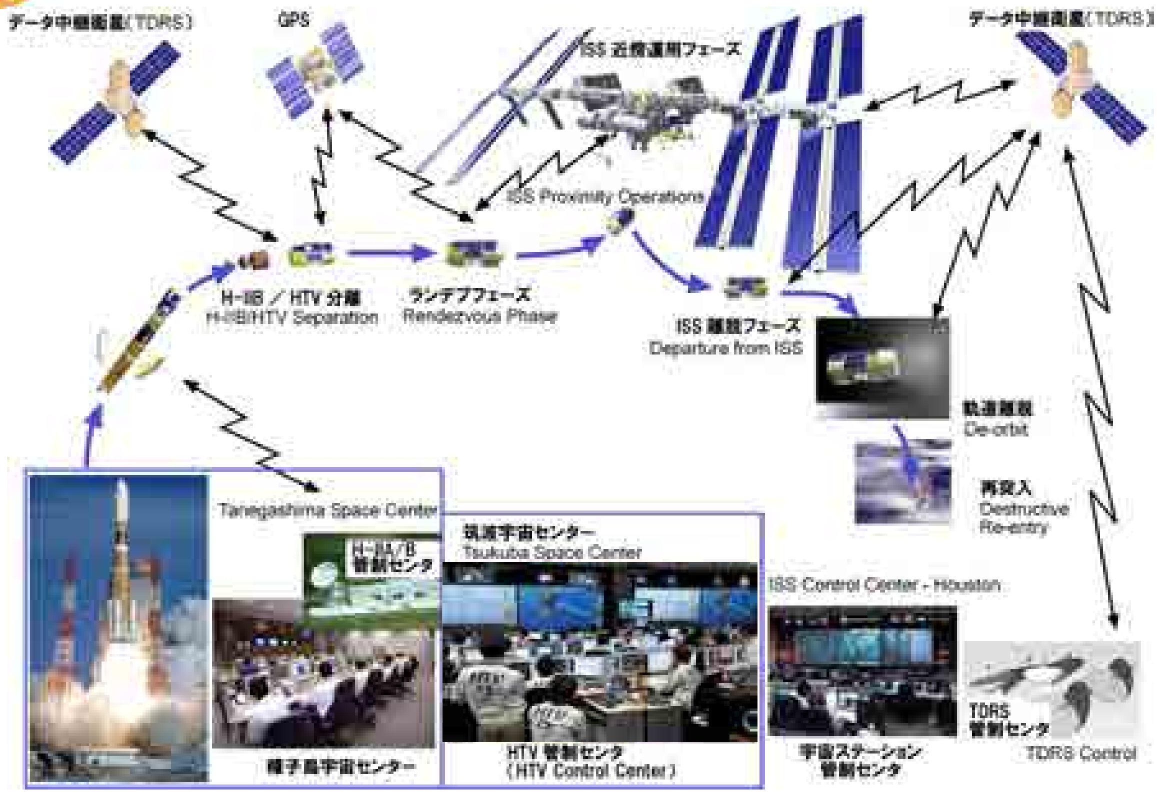
1.1 HTV Configuration Overview



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

1.2 HTV Operation Overview



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2. HTV Debris Technique

2.1 Current Debris Technique

2.2 Study Items for Debris Technique

2.1 Current Debris Technique

A. Debris bumper

It is for shielding HTV M/OD critical items as follows.

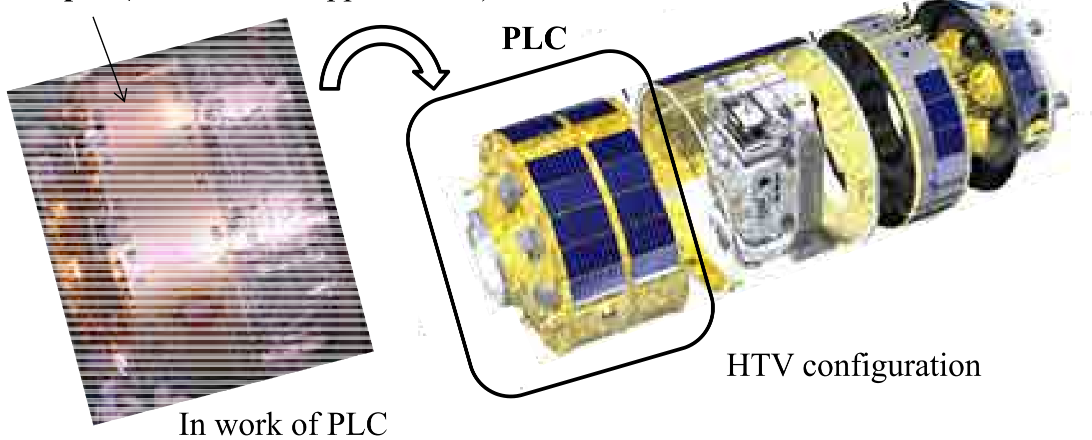
(a) Pressurized Logistic Carrier

(b) GHe pressure vessels in Propulsion Module

(c) Propellant tanks in Propulsion Module

 # HTV can perform Debris Avoidance Manuber based on tracking space debris data

Debris bumper (Al, thickness approx.1mm)



HTV configuration

In work of PLC

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2.1 Current Debris Technique

B. Reentry

HTV can perform controlled reentry into the atmosphere to prevent HTV itself from becoming debris.

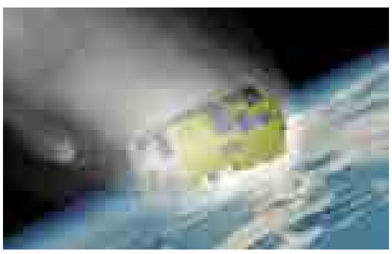

Fig. HTV Controlled Reentry Image

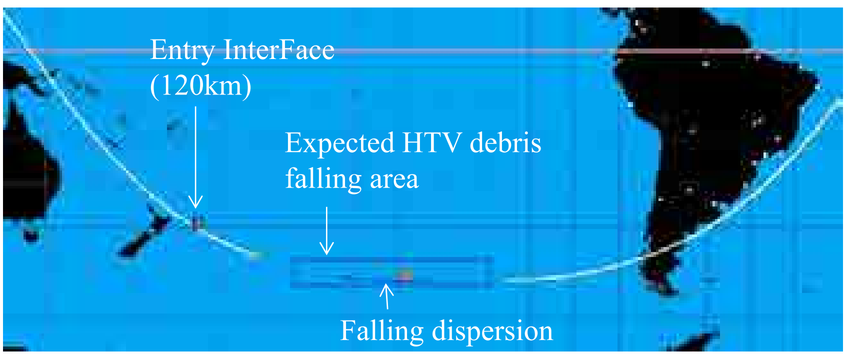

Fig. HTV's Projected Reentry Path

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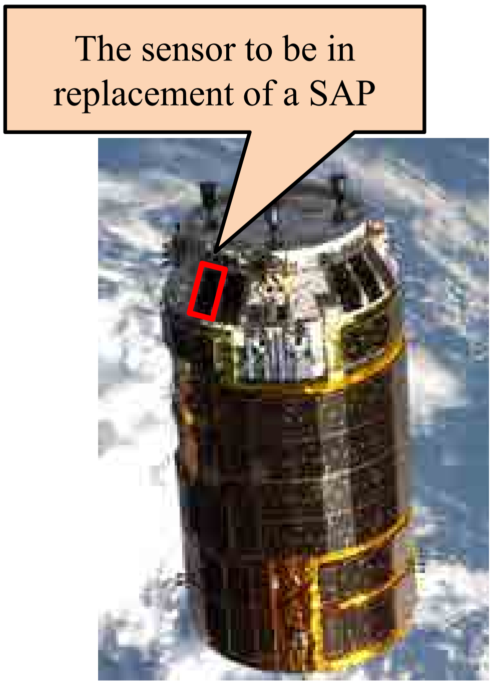
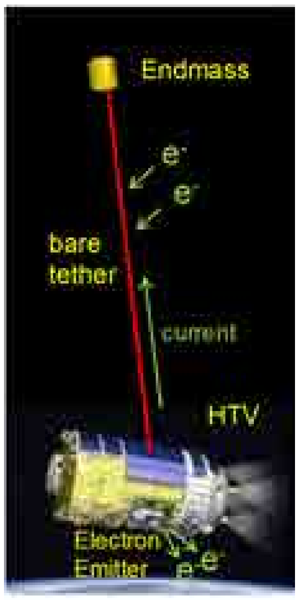
2.2 Study Items for Debris Technique

A.Debris Measuring Sensor



B.ElectroDynamic Tether(EDT) Experiment



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3. Feasibility Study of EDT Experiments on HTV

3.1 Introduction of Feasibility Study

3.2 Study of Configuration

3.3 Study of EDT Experiments Window

3.4 Study of EDT Experiments Sequence

3.5 Usage of HTV function on EDT Exp

3.1 Introduction of Feasibility Study

Status

HTV1 through HTV3 completed the missions successfully, and the plan of HTV4 and subs are proceeding steadily.

Characteristics

HTV has high quality, high reliability, promised launch opportunity and the operation skills matured at high level

HTV appears to be a good on-orbit platform and is very attractive for users who hope to make their instruments flight-proven.
We are studying some items for realizing the expectation, and introduce one of study results i.e. EDT experiments on HTV.

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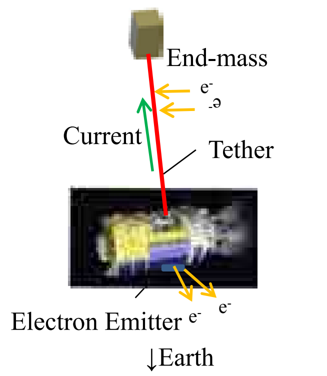
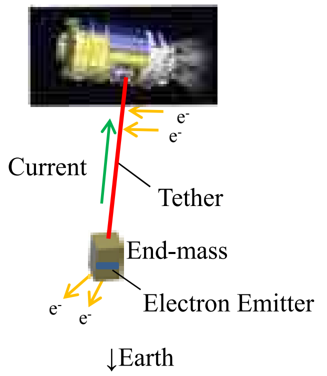
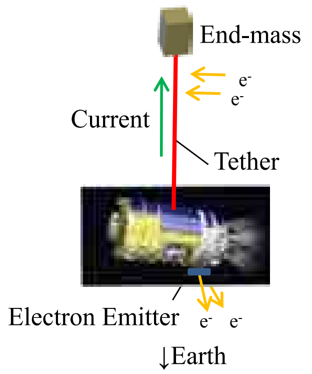
3.2 Study of Configuration

Prerequisites

-End-mass with tether should be ejected and deployed from HTV.
-Electron emitter should be positioned on the tether end toward the earth.
Reason) Lorenz force to be worked for the opposite flight direction by driving the current on the tether from nadir to zenith.

Trade-off

	Option1	Option2	Option3
Brief	End-mass should be deployed to the zenith from the open area of ULC	End-mass should be deployed to the nadir from the open area of ULC	End-mass should be deployed to the zenith from the back of ULC
Config			
Evaluation	×	×	○

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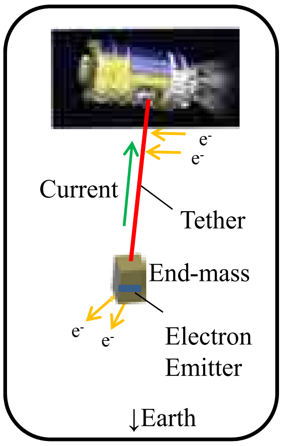
3.2 Study of Configuration

●Option1: ×

Impossible. The reason is why HTV is designed to fly with the ULC open area toward Earth.

●Option2 : ×

The end-mass system would be complex to install electron emitter and some support equipments.



Cofig

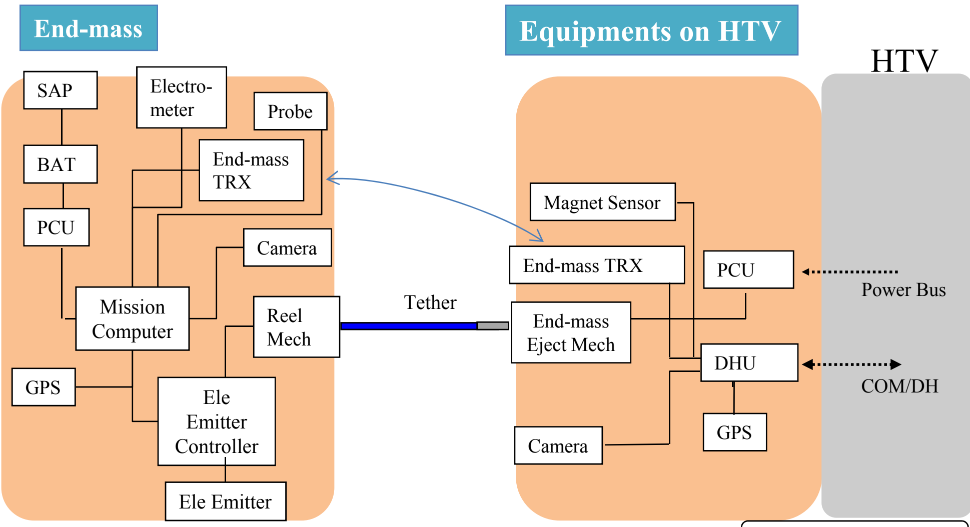


Fig. System Block Diagram

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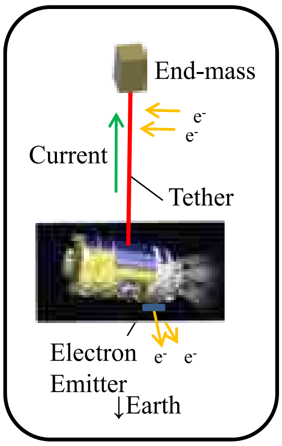
3.2 Study of Configuration

●Option3: ○

A solar array panel on the back of ULC could be removed based on power resource experience on HTV1 through HTV3. Then the end-mass could be deployed from there. And, the backside on HTV is covered by the rendezvous sensor (RVS) which is used in approaching ISS. The RVS could monitor the end-mass motion. Therefore, GPS for monitoring the end-mass position and transponder for transmitting the information would be unnecessary. As a result of that, EDT system could be much simpler.



Config

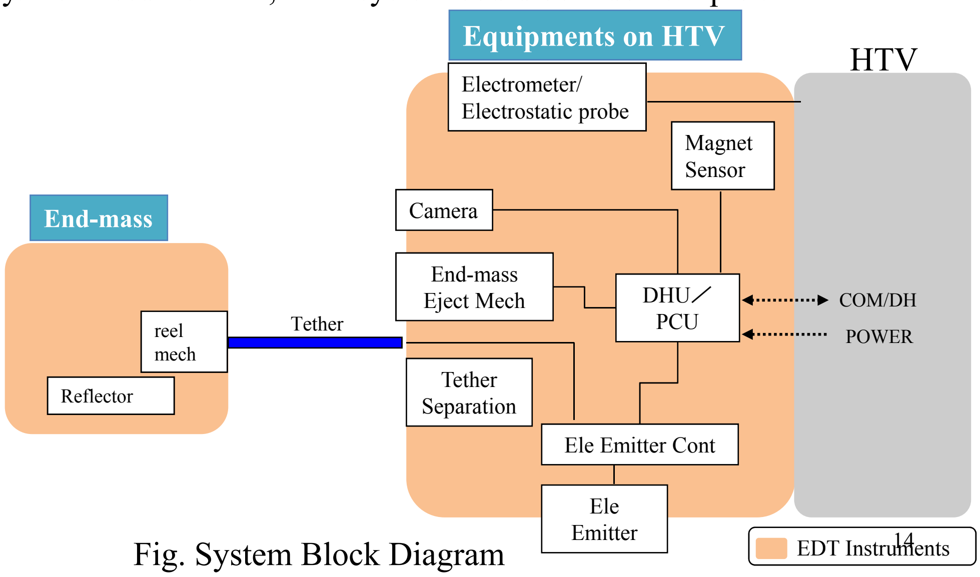


Fig. System Block Diagram

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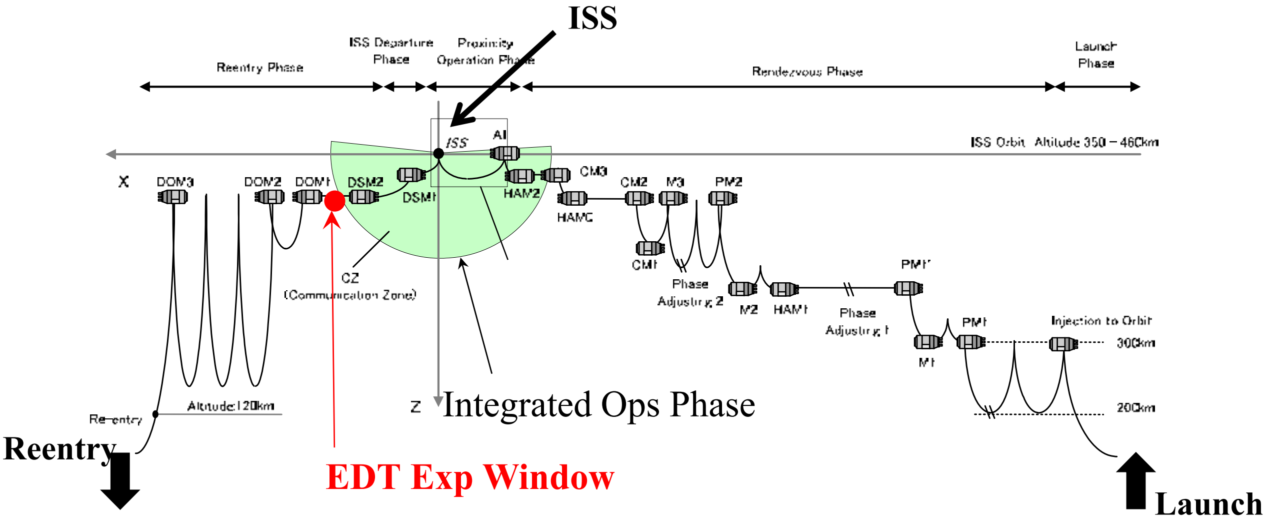
3.3 Study of EDT Exp Window

By prioritizing the HTV mission objective i.e. transport of cargo/supplies to the ISS, EDT Exp should be performed from the end of integrated operation until reentry.



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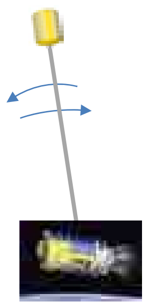
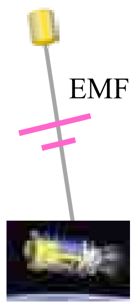
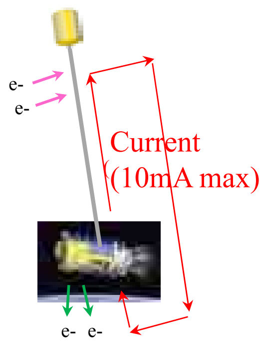
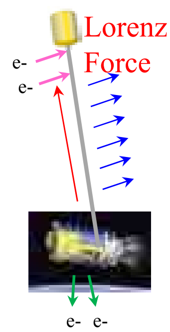
3.4 Study of EDT Exp Sequence

Phase	Deployment	Stable Libration		Electron Emitter Ops		
Phenomena	Eject & Deploy	Libration	EMF	Emission	Collecting	Lorenz Force
Config	700m deployment 					
Outcome	Acquire the characteristics - tether deployment - libration during deployment	Acquire the characteristics of libration after deployment	Confirm Mutual characteristics between orbital motion and generated voltage	Confirm driving current by emitting and collecting electron		Confirm Lorenz force

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3.5 Usage of HTV function on EDT Exp

Monitor the end-mass motion by RVS

The RVS filed of view is plus/minus 20 deg, and end-mass with tether could librate with plus/minus 60deg (max) in plane. RVS could trace the end-mass motion by controlling the HTV pitch angle via ground commands.

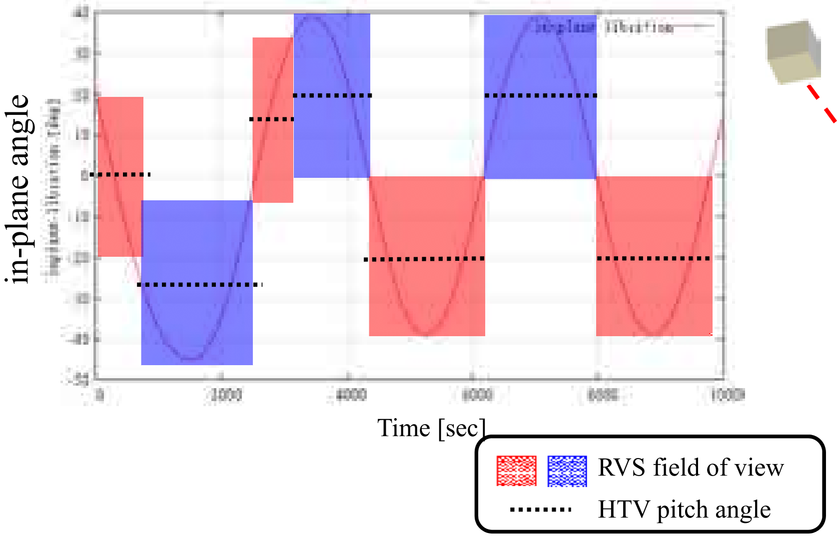


Fig. pitch angle control sequence

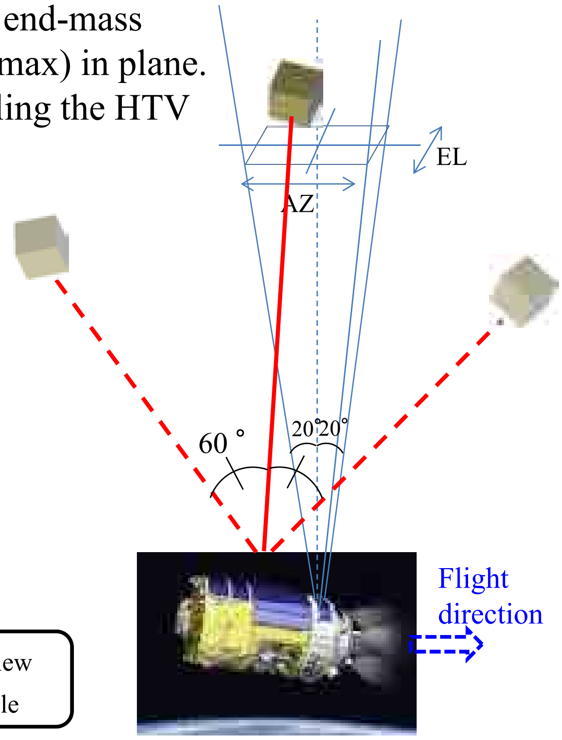


Fig. RVS field of view

4. Summary

- HTV is originally designed with consideration for space debris because it has pressurized section where crews enter.
- As above, Space Debris has to be considered with making human space ship fly into space.
- We would like to continue the study to contribute solving the space debris problem.

C5

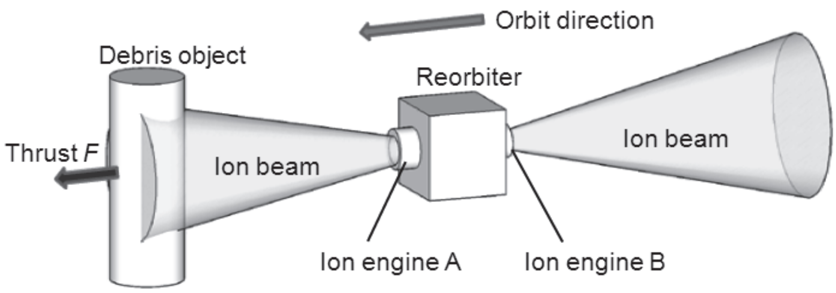
イオンビーム照射を用いる静止軌道デブリの除去

GEO Debris Removal using Ion Beam Irrradiation

○北村正治，早川幸男，大川恭志，河本聡美（宇宙航空研究開発機構）
○Shoji Kitamura, Yukio Hayakawa, Yasushi Ohkawa, Satomi Kawamoto (JAXA)

イオンエンジンを利用して静止軌道上の大型デブリを投棄軌道に輸送するデブリ除去方法を提案した。除去機にはイオンエンジンを 2 台搭載し、一方のイオンエンジンから噴射したイオンビームでデブリを照射して推力を与え、その軌道を変更する。他方のイオンエンジンの推力によってデブリとの間隔を一定範囲に保ちつつ、約 300 km 高い投棄軌道まで除去機の高度を上げる。本方式はデブリの把持が不要なため、デブリの詳細形状に依存しないし、回転しているデブリにも適用できる。ミッション検討例では、軌道上初期質量 1.5 ton の除去機を用いて約 170 日で 6 個のデブリが除去できた。本方法に特有な課題であるイオンビームの収束性については、数値計算と基礎実験によって必要な照射効率を達成する目処を得た。ビーム被照射面からのバックスパタリングについては、実験的な評価によって致命的な除去機の汚染問題がないことを確認した。

We proposed a concept for a reorbiter using ion engines to reorbit large GEO debris objects up to a disposal orbit. The reorbiter, equipped with two ion engines, exhausts an ion beam from one of the ion engines to irradiate and thrust a debris object to change its orbit. The other ion engine is operated so that the reorbiter follows the debris object. Their orbits are raised to a disposal orbit approximately 300 km higher. This system can operate without catching debris objects; thus, it can be applied without regard to their detailed shapes or rotations. A typical model mission was studied, and the results showed that six debris objects can be reorbited in about 170 days with a reorbiter of 1.5 ton. The beam convergence and the effects of beam irradiation were recognized as critical issues. Numerical calculations and basic experiments gave a feasibility of the required irradiation efficiency. The back-sputtered materials from the irradiated surfaces were experimentally evaluated, and the results indicated no serious contamination problems on the reorbiter.



イオンビーム照射を用いるデブリ軌道変更の概念
Concept of Space Debris Reorbiting Using Ion Beam Irradiation

January 22, 2013
The 5th Space Debris Workshop

GEO Debris Removal using Ion Beam Irradiation
イオンビーム照射を用いる静止軌道デブリの除去

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北村正治, 早川幸男, 大川恭志, 河本聡美

Japan Aerospace Exploration Agency

宇宙航 空研究開発機構

Outline

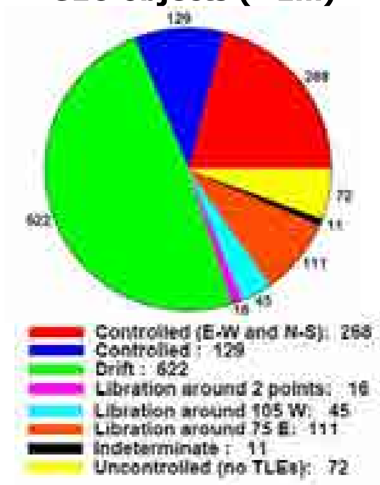
1. Background
2. Concept of the Reorbiter
3. Reorbiter System
4. Example Removal Plans
5. Issues to be Addressed
   - Ion Beam Convergence
   - Effects of Beam Irradiation
   - Non-Cooperative Rendezvous
6. Conclusions

2

Background

- **Features and Problems in GEO Debris**
  - Debris in GEO will stay there permanently.
  - Not all of GEO satellites have been reorbited after end of mission.
  - Number of debris objects is increasing.
  - Though no collisions have been reported so far, they would bring very serious effects if they occur (no decay by fragmentation).
  - Same librating objects repeatedly approach operational satellites.
  - Development of technologies of space debris removal should be supported (GEO satellite operator)
  - Thus, GEO debris removal will be needed in the near future.

GEO objects (>1m)



Total: 1274
Uncontrolled in total: 877
Status: January 2011
(Reference ESOC)

Object number		
Orbit	> 10 cm	> 1 m
LEO	12,000	1,600
GEO	3,200*	1,000

*Conservative estimate

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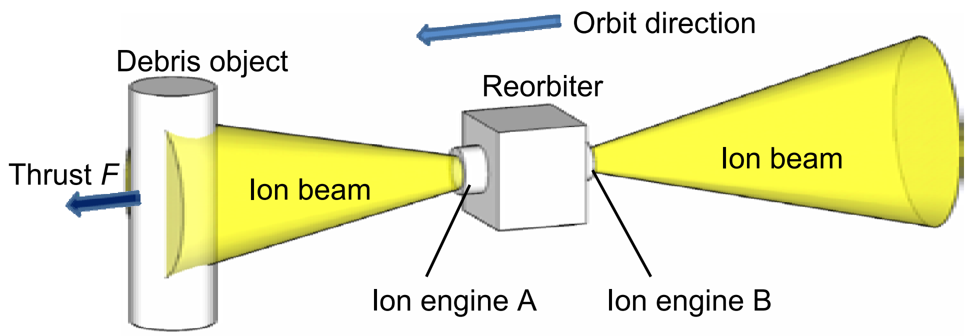
Concept of the Reorbiter (1/2)

- **Operation Procedure**
  1. The reorbiter with two ion engines A and B approaches a debris object.
  2. The ion beam from ion engine A irradiates the debris and gives it a thrust.
  3. This thrust raises the orbit of the debris gradually.
  4. Ion engine B is also operated so that the reorbiter can follow the debris.
  5. The thrusts of the ion engines are adjusted so that the distance between the debris and the reorbiter would be kept with a certain range.
  6. After they reach the disposal orbit about 300-km higher than GEO, the reorbiter returns to GEO to reorbit another debris object.



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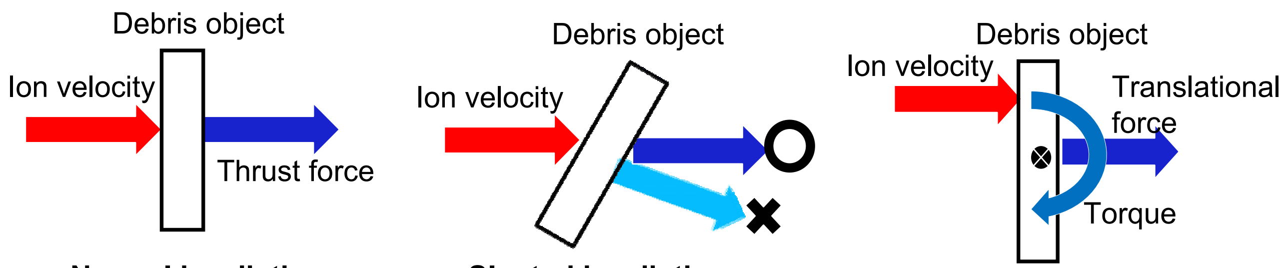
Concept of the Reorbiter (2/2)

- **Features in comparison with contact ADR**
  - No docking with non-cooperative debris objects
  - No dependence on the details of debris objects
  - No "single-shot" step like harpoon shooting or net casting
- **Features in dynamics**
  - Thrust to a debris object has the same direction as the ion beam, so the thrust direction is independent on its shape and attitude.
    - Collisions of ions to a debris object are almost perfectly inelastic, so momentum of the ions is almost perfectly transferred to the debris object.
    - Irradiation off the center of mass of a debris object causes torque to the debris object, but the translational force is not slanted.



Normal irradiation **Slanted irradiation** **Off-center irradiation**

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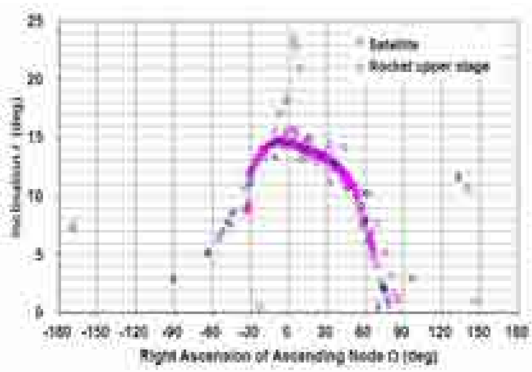
Reorbiter System (1/4)

- **Sample mission model**
  - Objects in GEO are concentrated near a single curve of RAAN vs. inclination, so efficient reorbit is possible.
  - Six objects with i < 2 deg and Ω < 5 deg.
  - Spin-stabilized satellites and rocket bodies were considered.



Sample Model

Debris object	Mass (kg)	Diameter (m)	*i* (deg)	Ω (deg)	Apogee above GEO (km)	Perigee above GEO (km)
Satellite#1	125	1.4	13.0	3	0	0
Satellite#2	250	1.6	13.4	2	125	30
Satellite#3	500	2.0	13.7	1	125	-30
Rocket upper stage#1	2000	3.0	14.0	0	125	-125
Rocket upper stage#2	2500	3.7	14.5	-1	30	-250
Rocket upper stage#3	3000	3.7	15.0	-2	-30	-250

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Reorbiter System (2/4)

- **Ion Engines**
  - **For Irradiating Debris Objects**
    - Highly converged ion beams are required for efficient irradiation.
    - Then, we can have longer separation to the debris object, safer orbit control and smaller back-sputtering effects, and a smaller system.
  - **For Orbit Control**
    - Conventional ion engines without special requirements.

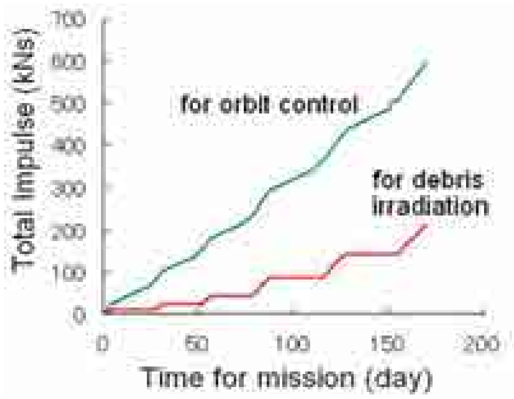
Ion Engine Requirements

Function	Debris irradiation	Orbit control
Thrust per thruster	20 mN	40 mN(*)
Number	4 + 4 backups	4 + 4 backups
Specific impulse	3000 s	3000 s
Thrust-to-power ratio	25 mN/kW	30 mN/kW
Propellant	Xenon	Xenon
Beam divergence	25% half angle < 3 deg 80% half angle < 6 deg	as is

* Throttled while ascending

Reorbiter System (3/4)

Total impulse and propellant mass		
Total impulse (kNs)	Orbit control	596
	Debris irradiation	212
	In total	808
Xenon mass (kg)	Required	27.5
	Margin (11%)	3.5
	Total	31.0

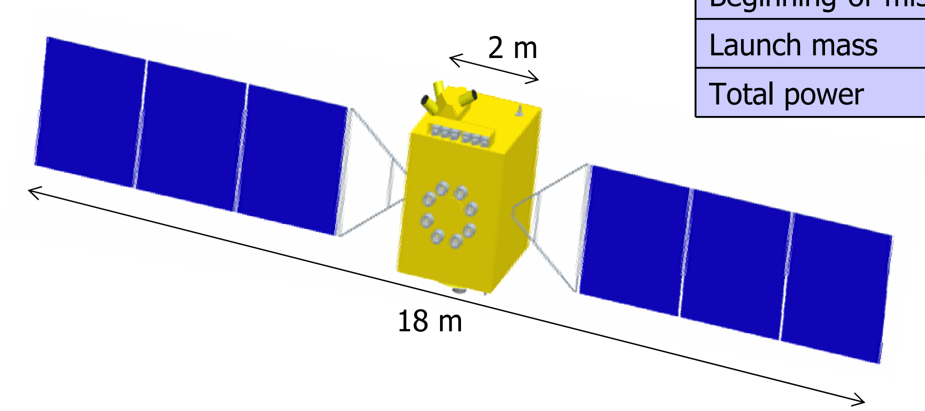


- **Calculation of ΔV**
  - We assumed the initial reorbiter mass of 1.5 ton and the distance to the debris object of 20 m.
  - Spiral circular orbit transfers, elliptic to circular orbit transfers, and inclination changes are considered.
- **Mission Summary**
  - Six debris objects can be reorbited in 170 days with 31 kg of xenon.
  - For a two-year mission, it would reorbit 24 debris objects.
  - Constraints on the mission period would be propellant mass, ion engine lifetime, and contamination due to back-sputtering.

Reorbiter System (4/4)

- **Scale of the Reorbiter System**
  - The scale of the reorbiter was estimated from the specifications of some geostationary satellites with similar power levels.
  - Power consumption of the ion engines is about 5.9 kW.

Mass and Power (Target)	
Dry mass	1240 kg
Propellant (Xenon)	31 kg
Beginning-of-mission mass	1271 kg
Launch mass	2500 kg
Total power	7 kW



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Example Removal Plans (1/4)

- **Candidates for removal**
- Objects in geopotential wells (librating objects)
- Objects repeatedly approaching operational satellites
- Threating objects for GEO satellite operators (forcing frequent collision avoidance maneuvers).

- **Examples**
- Raduga 1-7 (2004-010A)
- COSMOS 2379 (2001-037A)
- Proton-K forth stage Block DM
- Ekran 4 (1979-087)

- **Additional assumptions for 3-axis satellites**
  - Irradiation only for satellite body
  - 30-m distance apart

Objects in geopotential wells

Characteristic	East well (75 deg)	West well (105 deg)	Trapped in both wells
Payload: Radugas (29), Gorizonts (9), Ekrans (8), etc.	83	39	15
Rocket body: Largely Proton-K forth stages	17	0	3
Debris: 2006 Feng Yun and 1978 Ekran 2	2	0	0
Total	102	39	18
Reference: IAC-11-A6.2.6			

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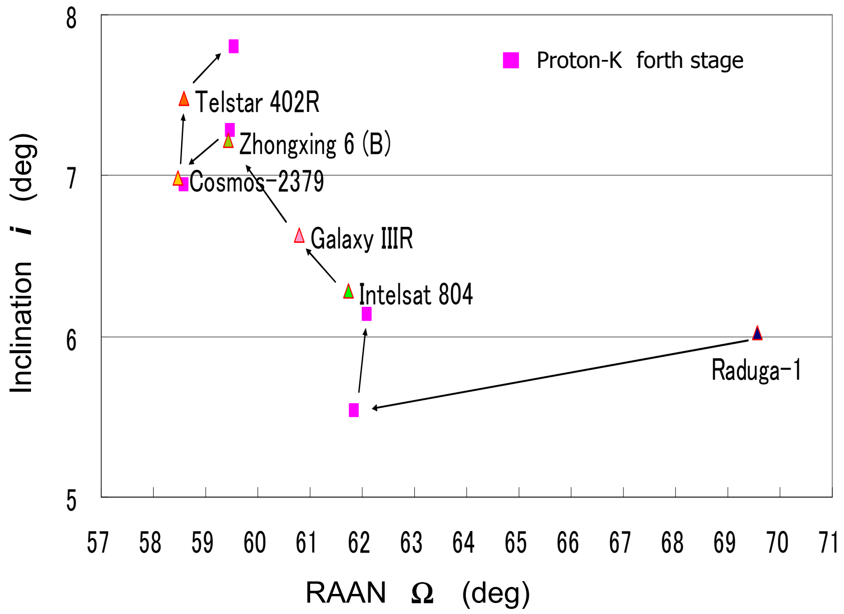
Example Removal Plans (2/4)

- **Removal plan A**
  - Raduga 1 and debris objects around in libration orbit

ID	Name	Class.
04010A	Raduga 1	3AX
03015F	Proton-K forth stage	R/B
05010f	Proton-K forth stage	R/B
97083A	Intelsat 804	R/B
95069A	Galaxy IIIR	3AX
03060D	Proton-K forth stage	R/B
97021A	Zhongxing 6(B)	3AX
01037D	Proton-K forth stage	R/B
01037A	Cosmos-2379	3AX
95049A	Telstar 402R	3AX
01045D	Proton-K forth stage	R/B



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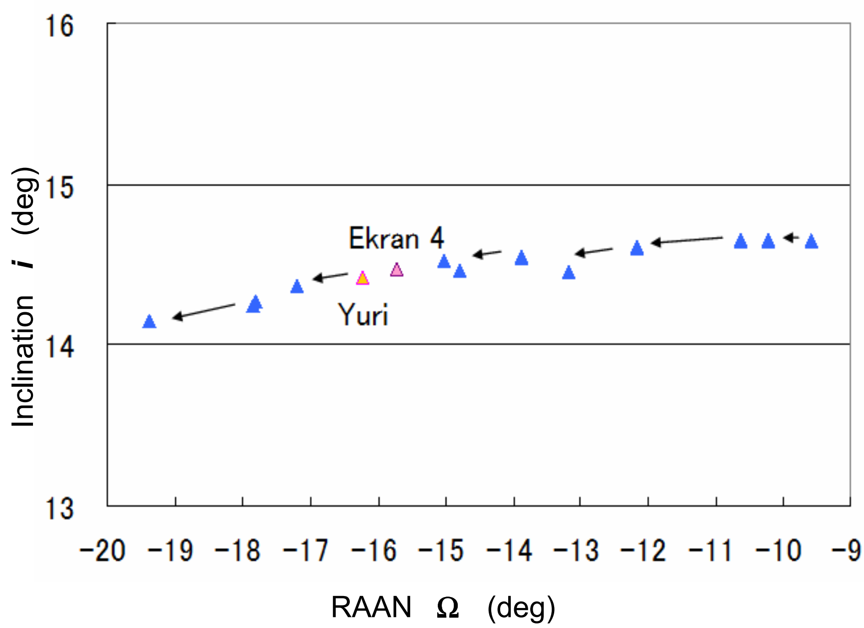
Example Removal Plans (3/4)

- **Removal plan B**
  - Ekran 4 and debris objects around in libration orbit

ID	Name	Class.
81102A	Raduga 10	3AX
81069A	Raduga 9	3AX
81061A	Ekran 7	3AX
80104A	Ekran 6	3AX
80081A	Raduga 7	3AX
79105A	Gorizont 3	3AX
80016A	Raduga 6	3AX
79062A	Gorizont 2	3AX
79087A	Ekran 4	3AX
78039A	Yuri	3AX
79035A	Raduga 5	3AX
79015A	Ekran 3	3AX
77108A	Meteosat 1	SP
78073A	Raduga	3AX



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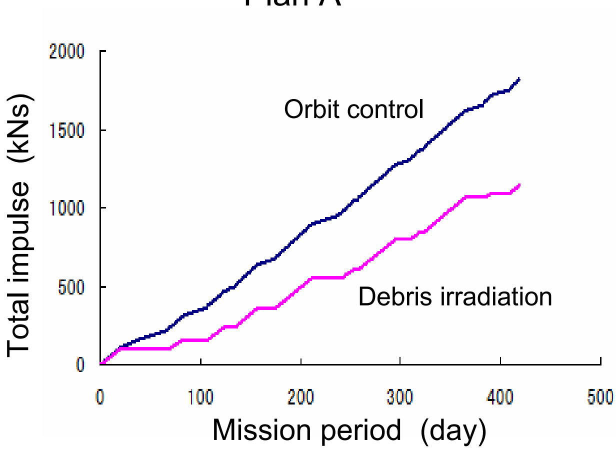
Example Removal Plans (4/4)

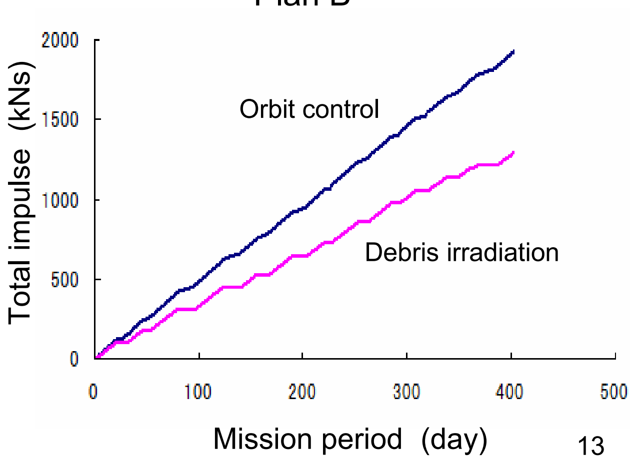
- **Result**
  - This system can conduct GEO debris removal at about 20 tons per year.

Case	# of removed objects	Total removed mass (ton)	Mission period (day)	Required xenon mass (kg)	Removed mass per year (ton/yr)
Plan A (Raduga 1 etc.)	11	26.6	419	101	23.2
Plan B (Ekran 4 etc.)	14	24.5	403	110	22.2

Plan A



Plan B



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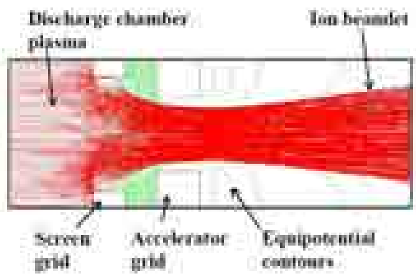
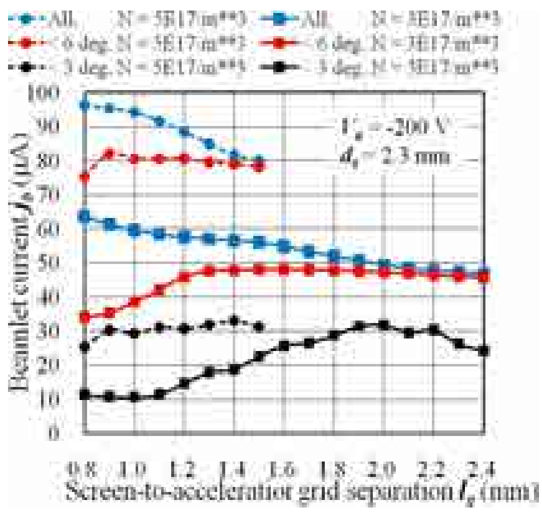
Issues to be Addressed (1/5)
Ion Beam Convergence

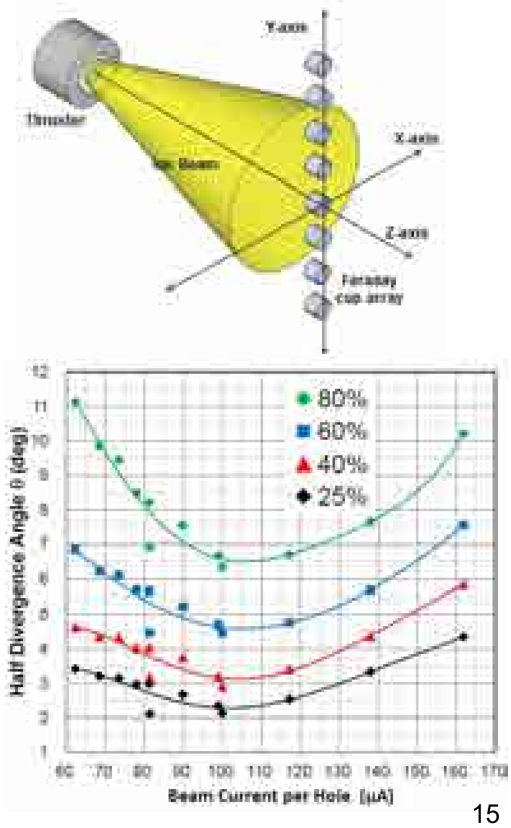
- **Objective**
  - To design ion engine grids for highly converged beam by numerical analysis, and to confirm the convergence capability by experiments.
- **Devices for beam convergence**
  - Reduction of ion density in the discharge chamber would bring smaller repulsive force among ions.
  - Increase in the separation between the two grids would make equi-potential contours flatter.
  - ***These are inconsistent with conventional ion engines.***





Issues to be Addressed (2/5)
Ion Beam Convergence (cont.)

- **Experiments**
  - A 10-cm thruster with model grids were used.
  - Ion beam was extracted only from the center region of the discharge chamber to achieve uniform beam extraction.
  - 3D beam profiles were measured using a Faraday cup array.
- **Results**
  - 25% divergence angle is smaller than 3 deg for J_b per hole of 80 to 130 μA, and good convergence was confirmed.
  - 80% divergence angle is 6.5 deg at the best case, and a little larger than assumed in the system study.

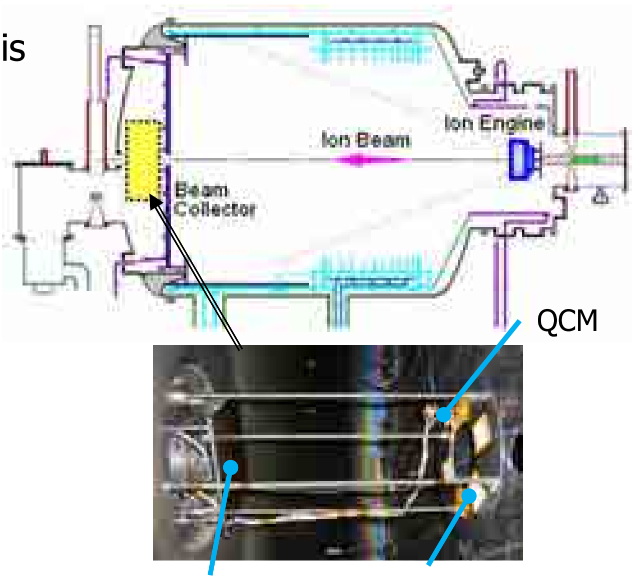


15

Issues to be Addressed (3/5)
Effects of Ion Beam Irradiation

- **Effects on debris objects and reorbiter**
  - Ion sputtering of debris surfaces is allowable because its effects are not so large to generate new debris.
  - Thermal effects and charging are negligible.
  - Back sputtering to the reorbiter can have contamination effects.
- **Measurements of back sputtering**
  - Sample: glass (solar cell cover) and polyimide (MLI)
  - Radiation surfaces are free of back-sputtering deposition; they usually face north or south.

Contamination measurement



Beam receiver
- Polyimide film or
- Cover glass

Contamination receiver
- Polyimide film
- Cover glass
- Al mirror

16

Issues to be Addressed (4/5)
Effects of Ion Beam Irradiation (cont.)

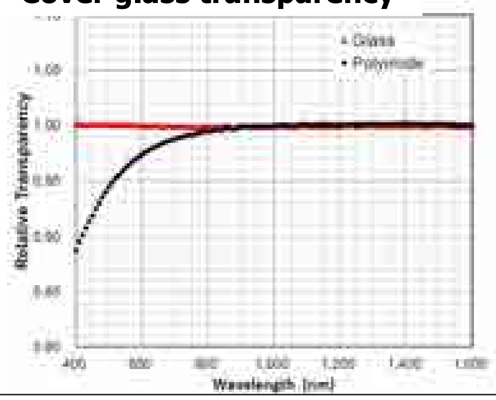
- **Thermal properties**
  - Changes are within permissible ranges.
    - Solar absorptivity (α_s) and infrared emissivity (ε) of polyimide increased by the back-sputtering from glass.
    - α_s of glass increased by the back-sputtering from polyimide.

Base material	Back-sputtered material	α_s	ε	Irradiation time*
Polyimide	N/A	0.235	0.506	0
	Polyimide	0.237	0.509	1.9
	Glass	0.252	0.519	1.5
Glass	N/A	0.029	0.737	0
	Polyimide	0.051	0.739	1.9
	Glass	0.030	0.737	1.5

*Equivalent # of reorbited 2-ton debris objects

- **Estimation of solar cell degradation**
  - Transparency decreased by the back-sputtering from polyimide in short-wavelength range.
  - Silicon: 94%, 3-junction: 97%
    - Reorbit of 2-ton 10 debris objects 18 m away and cell facing the sun

Cover glass transparency



Issues to be Addressed (5/5)
Non-Cooperative Rendezvous

- **General considerations**
  - Research on non-cooperative rendezvous is being conducted for ADR in LEO at JAXA. Its results will be applied to GEO.
  - Easer rendezvous is expected in GEO than in LEO because of weaker gravitation and more stable optical conditions.
  - GPS application in GEO is expected in the future.
- **Study on applicable measurement sensors**
  - **Long distance rendezvous**
    - Debris orbit determination by optical observation from ground
  - **Approach**
    - Capture of debris using long range cameras at 250 km
    - Approach up to 10 km by repeating the relative distance determination using long range and short range cameras
    - Approach up to 100 m and nearer using the cameras and laser sensors
  - **Relative separation maintenance during ion beam irradiation**
    - Navigation using short range cameras and laser sensors

Conclusions

1. **The proposed reorbiter has numerous advantages over other ADR systems for GEO debris removal.**
2. **This reorbiter can conduct effective GEO debris removal.**
3. **No critical problems are found.**
   - Required beam convergence is attainable.
   - No serious contamination problems are expected.

Issues below have to be addressed in future work.

- Detailed study on non-cooperative rendezvous with low thrusting.
- Operation plans on orbit determination and rendezvous including ground systems
- Evaluation of the beam convergence using real thrusters.
- Detailed study on contamination problems (other surface materials, optical parts, and so on).

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Appendix: Application to LEO Debris

- **Assumptions**
  - Reorbiter mass: 1500 kg
  - Thrust of ion engine for debris irradiation: 80 mN
  - Irradiation efficiency: 25% (Debris irradiating thrust: 20 mN)
  - Debris mass: 2000 kg
- **Results**
  - Long time operation is required for disposal in LEO.
  - Larger electric systems and solar arrays are required in LEO due to shorter sun-lit periods.

Comparison of debria removal time in GEO and LEO

Debris orbit	GEO	800-km alt.	900 km alt.
Disposal orbit	GEO+300 km	630 km alt.*	630 km alt.*
Velocity increment	11 m/s	90 m/s	140 m/s
Time of orbit change	12.6 days	103 days	160 days
No operation during eclipse**	N/A	155 days	241 days

* 25-year orbit life, **1/3 of orbit assumed

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C6

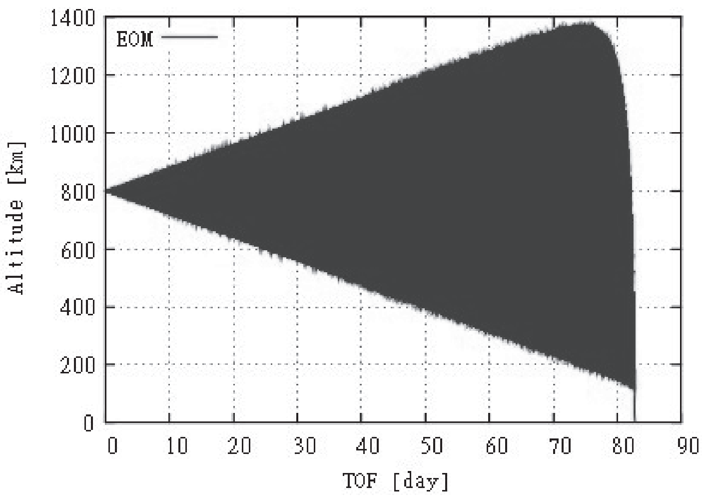
帯電衛星によるスペースデブリの軌道変換

Orbital change of space debris using the charged satellite

○中宮賢樹, 赤司陽介, 山川 宏（京大）
○Masaki Nakamiya, Yosuke Akashi, Hiroshi Yamakawa (Kyoto Univ.)

打ち上げで使用したロケット・スペースシャトルの破片や運用を終了して地球の周囲を浮遊している人工衛星等の宇宙ゴミ（スペースデブリ）は増え続けており、近年、能動的なデブリ除去の検討が盛んに行われている。デブリを除去する方法には、例えば、除去衛星を打ち上げてデブリを捕獲し、デブリの軌道を変更させて地球大気圏に突入させる方法がある。しかし、従来から人工衛星で使われているガスジェットを使ってデブリの軌道を変更させるには多量の推進剤が必要となる。そこで本研究では、帯電衛星によるデブリの軌道変換手法を提案する。一般に、宇宙プラズマによる生じる人工衛星の帯電は回避すべき現象であるが、この帯電を能動的に制御してデブリ除去に応用し、帯電衛星と地磁場が干渉して生じるローレンツ力を推力とすることで、推進剤無しでデブリの軌道を変換して大気圏に落下させる手法について検討を行った。

The number of the space debris is increasing every year. Thus, space debris has been a serious environmental problem. This study proposes the way of the orbital change of space debris using the charged satellite which generates a thrust without propellant by utilizing interactions between the charge of the satellite and the Earth's magnetic field.



帯電衛星による軌道変換

5th Workshop of Space Debris

January 22-23, 2013 @ JAXA Chofu

帯電衛星によるスペースデブリの軌道変換

Orbital Change of Space Debris Using the Charged Satellite

○中宮賢樹、赤司陽介、山川宏（京大　生存研）

M. Nakamiya, Y. Akashi, H. Yamakawa (Kyoto Univ.)

1

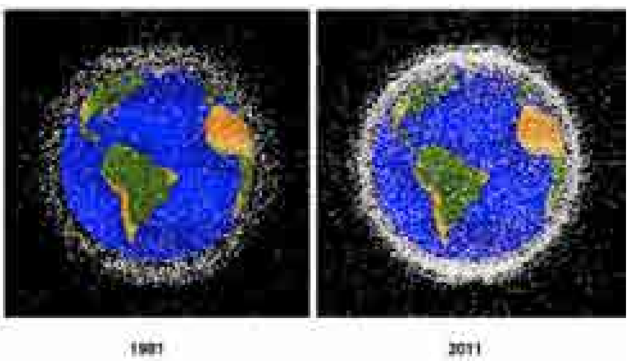
Background

Issue

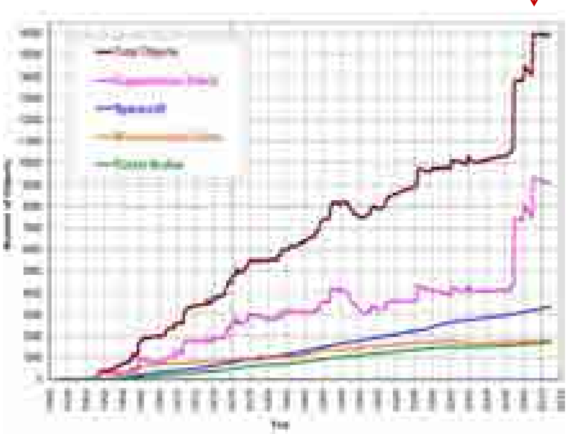
Increasing the Number of Space Debris
(spent rocket fragments and defunct satellites)

Huge problem for space exploration

As of July, 2011
About 16000



(NASA)

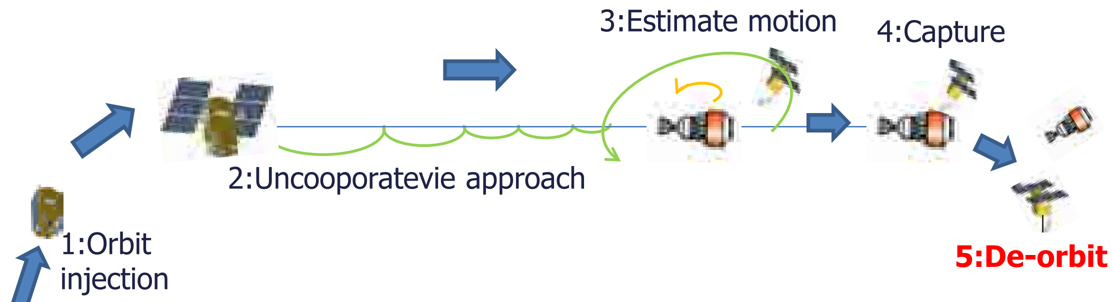


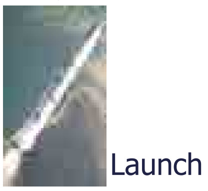
(NASA)

2

Active Debris Removal

Removal satellite





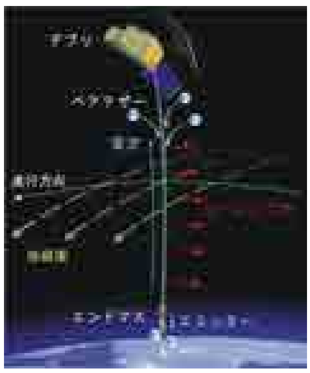
Using a removal satellite,
space debris is captured and is dropped into the Earth's atmosphere by changing its orbit !

Orbital Change

Method

<Chemical Engine>
- ○ Matured technology
- × Large amount of propellant
- × Fix with debris

<ElectroDynamic Tether (EDT)>
- ○ No propellant
- × Extending the tether



Propose

Orbital Change by Charged Satellite (CS)

New method of debris removal using a charged satellite

<Charged satellite>

× Natural charging on satellite due to space plasma should avoid

Generate a large charge on a satellite by ion and electron emitters passively

↓

Control the orbit utilizing the Lorentz force that is obtained
as the Charged Satellite travels through the Earth's magnetic field

- ○ No propellant
- ○ Small system (ion and electron emitters)
- × Not matured technology

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Objective

To investigate the orbital change of space debris using charged satellite

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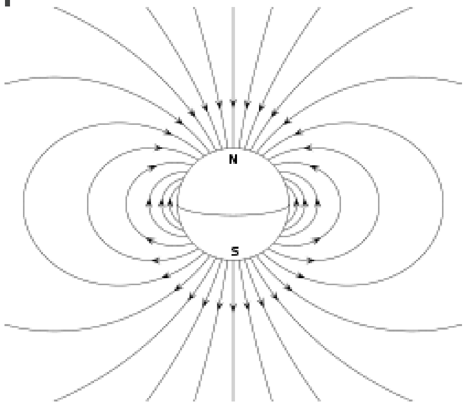
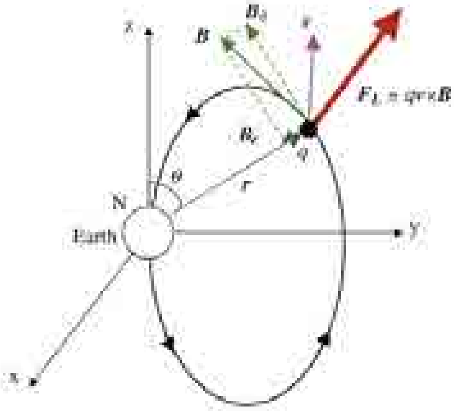
Assumption

Model





Dipolar Approximation
(Not tilted, Rotating with Earth)

$$\mathbf{B} = (B_0/r^3)\left(2\cos\theta\hat{\mathbf{r}} + \sin\theta\hat{\theta}\right)$$

$$\mathbf{F}_L = q(\mathbf{v} - \omega_E \times \mathbf{r}) \times \mathbf{B}$$

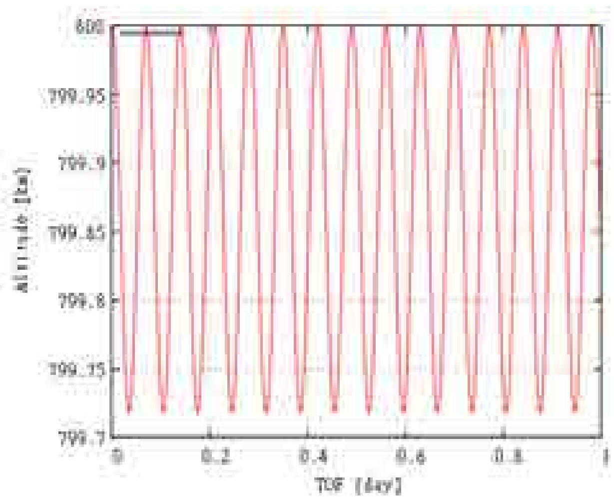
Equations of Motion: $\mathbf{a} = \mathbf{F}/m = -\frac{\mu}{r^3}\mathbf{r} + \frac{q}{m}(\mathbf{v} - \omega_E\hat{\mathbf{n}} \times \mathbf{r}) \times \mathbf{B}$

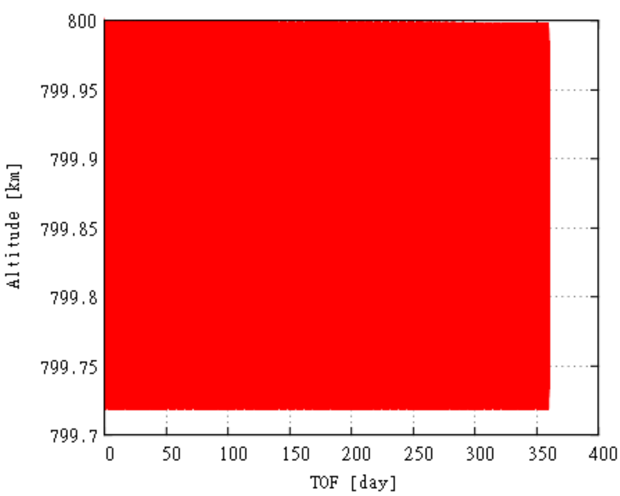
7

Characteristic of Orbit Change

By Charged Satellite

Initial condition: 800 x 800 km, Inclination = 0 deg (Mass = 500+500 kg)
Charge = -1 C (feasible [Peck])





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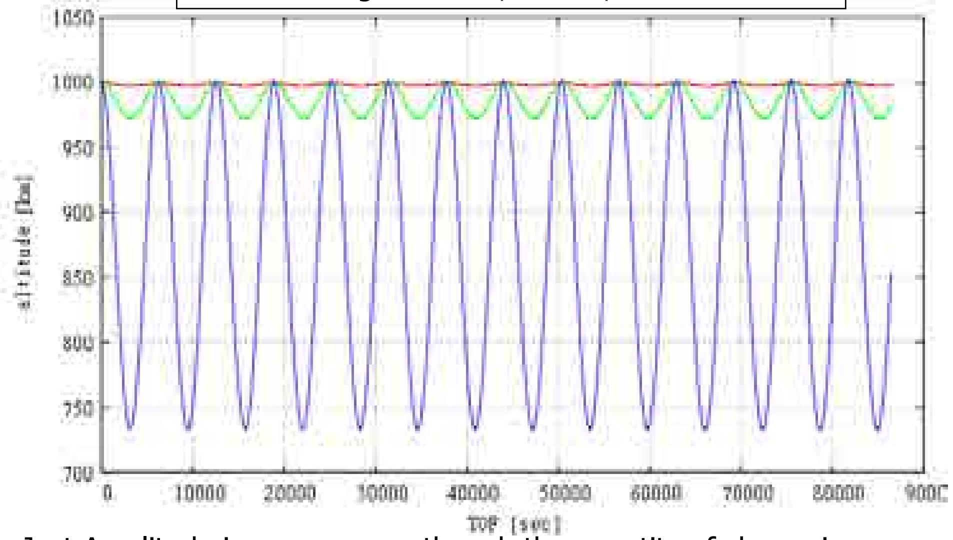
Characteristic of Orbit Change

Sensitive Analysis of Charge Amount

Initial condition：1000 x 1000 km, Inclination = 0 deg (Mass = 1000 kg)

Charge = -10 C, -100 C, -1000 C



Just Amplitude increases even though the quantity of charge increases.
(The quantity is not practical)

What if Controlling the Charge?

Linearized Equation of Motion

Control the charge amount periodically

Charge control (periodic) $q = q_0 \sin\omega t$

Conservation of angular momentum $\left[L = mr^2\dot{\theta} \rightarrow \dot{\theta} = \frac{L}{mr^2} \right]$

Equation of Motion (Radial component; No Earth's atmosphere and no inclination)

$$f(r) = \ddot{r} = r\dot{\theta}^2 - \frac{\mu}{r^2} + \frac{B_0}{m}\left(\frac{R_E}{r}\right)^3 (\dot{\theta} - \omega_E) r q_0 \sin\omega_0 t = \frac{L^2}{m^2 r^3} - \frac{\mu}{r^2} + \frac{B_0 L {R_E}^3}{m^2}\left(\frac{1}{r^4} - \frac{m\omega_E}{r^2}\right) q_0 \sin\omega t$$

Linearized around initial altitude, r0

$$f(r_0 + \Delta r) = \ddot{r_0} + \Delta\ddot{r} = \Delta\ddot{r} \approx f(r_0) + \left.\frac{\partial f}{\partial r}\right|_{r_0} \Delta r$$

$$= \boxed{\frac{L_0^2}{m^2 r_0^3} - \frac{\mu}{r_0^2}} + \boxed{\frac{B_0 L {R_E}^3}{m^2}\left(\frac{1}{r_0^4} - \frac{m\omega_E}{r_0^2}\right) q_0 \sin\omega t} + \left\{ \boxed{-3\frac{L^2}{m^2 r^4} + 2\frac{\mu}{r^3}} + \boxed{\frac{B_0 L {R_E}^3}{m^2}\left(-\frac{4}{r^5} + 2\frac{m\omega_E}{r^3}\right) q_0 \sin\omega t} \right\} \Delta r$$

$$= 0 + q_1 \sin\omega t + \{-\omega_0^2 + q_2 \sin\omega t\}\Delta r$$

$(\because \omega_0^2 \gg q_2)$

$\therefore \quad \Delta\ddot{r} + \omega_0^2 \Delta r = q_1 \sin\omega t \quad \cdots ①$ Forced Oscillation!

11

Resonance is occurred!

with charge control period = orbital period

General and particular solution $\Delta r = C_1 \cos\omega_0 t + C_2 \sin\omega_0 t + \frac{q_1}{\omega_0^2 - \omega^2} \sin\omega t$

From initial cond. $\Delta r(0) = C_1 = 0$ $\quad \Delta\dot{r}(0) = C_2\omega_0 = \frac{\omega q_1}{\omega_0^2 - \omega^2} = 0$ $\quad \therefore C_2 = -\frac{\omega}{\omega_0}\frac{q_1}{\omega_0^2 - \omega^2}$

$$\Delta r = \frac{q_1}{\omega_0^2 - \omega^2}\left(\sin\omega t - \frac{\omega}{\omega_0}\sin\omega_0 t\right)$$

$\omega \rightarrow \omega_0$ $\quad \Delta r = \frac{q_1}{2\omega_0}\left(-t\cos\omega_0 t + \frac{1}{\omega_0}\sin\omega_0 t\right)$

Secular term --> Resonance is occurred!

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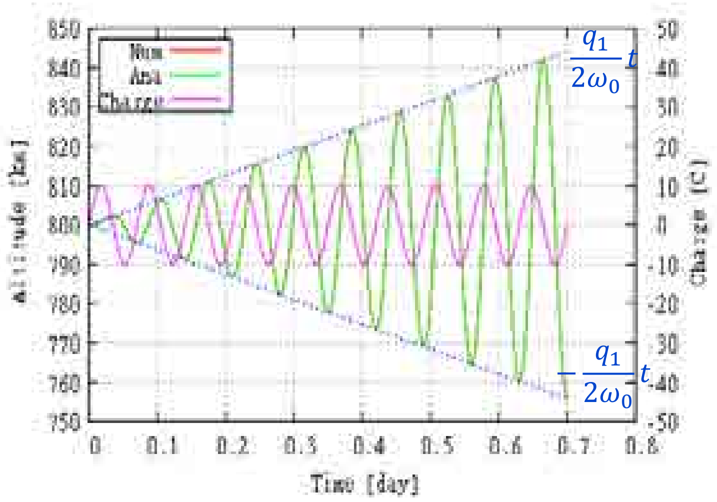
Analytic vs. Numeric

Resonance Oscillation

Initial condition：800 x 800 km, Inclination = 0 deg (Mass = 500+500 kg)
Charge = 1 C （feasible）



Amplitude increases due to the resonance
when the period of charge control corresponds to the orbital period!

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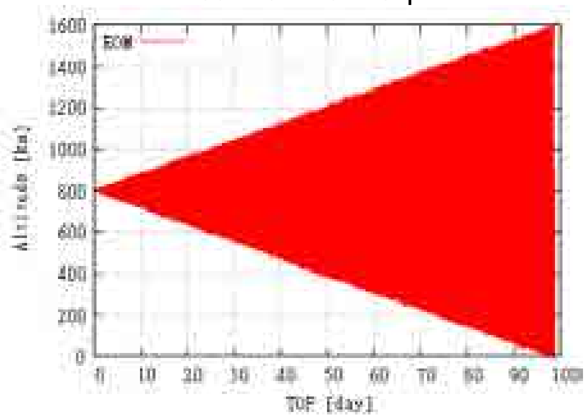
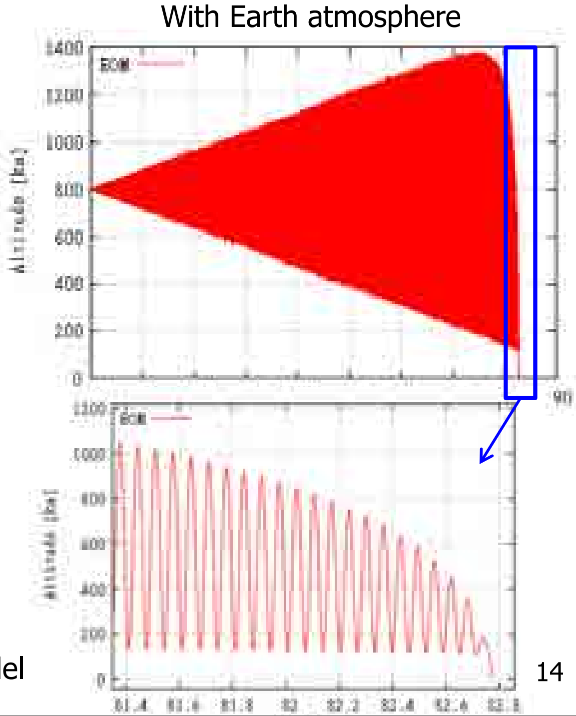
Orbital Charge by Controlled Charged Satellite

Re-entry Time

Without Earth atmosphere



With Earth atmosphere



Charge amount = 1 C
Mass of Debris & CS = 500+500kg
Area = 10 m^2
Coefficient of drag= 2

Atmosphere density = Modified Exponential Model

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Comparison between Charged Satellite and Electrodynamic Tethers

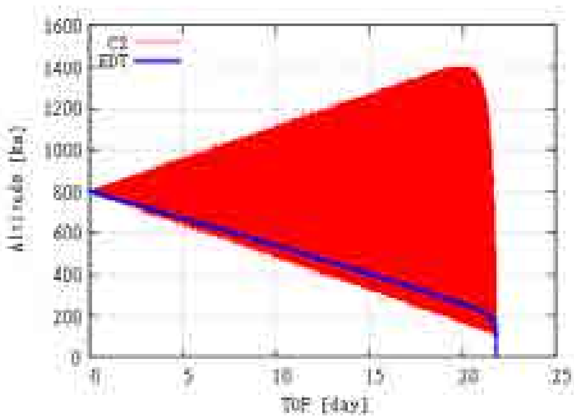
Re-entry Time

Charged Satellite (CS) vs. Electrodynamic Tether (EDT)

Parameters are adjusted so that the re-entry time of CS & EDT becomes equal.
(Altitude=800km, Inclination=0deg, Eccentricity=0)

CS : Charge amount=-3.91C
EDT: Tether length= 10 km, current value= 0.7 A

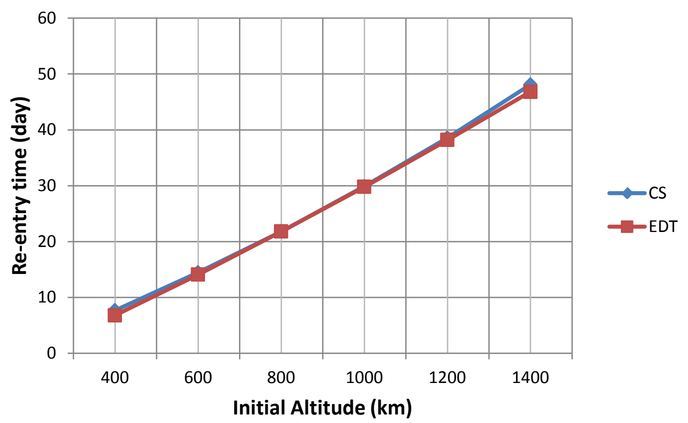
Compare CS with EDT based on this criteria!



Charged Satellite vs. Electrodynamic Tether

Sensitive Analysis of Altitude

<Initial condition>
Inclination = 0 deg, Eccentricity = 0
Charge = -3.91 C, Tether length = 10 km, Current = 0.7 A



Re-entry times of two method are almost same even the altitude increase !

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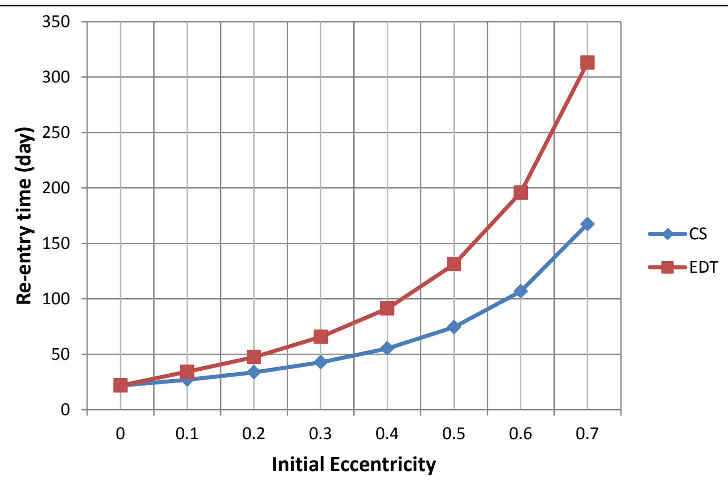
Charged Satellite vs. Electrodynamic Tether

Sensitive Analysis of Eccentricity

<Initial condition>
Altitude = 800 km, Inclination = 0 deg
Charge = -3.91 C, Tether length = 10 km, Current = 0.7 A



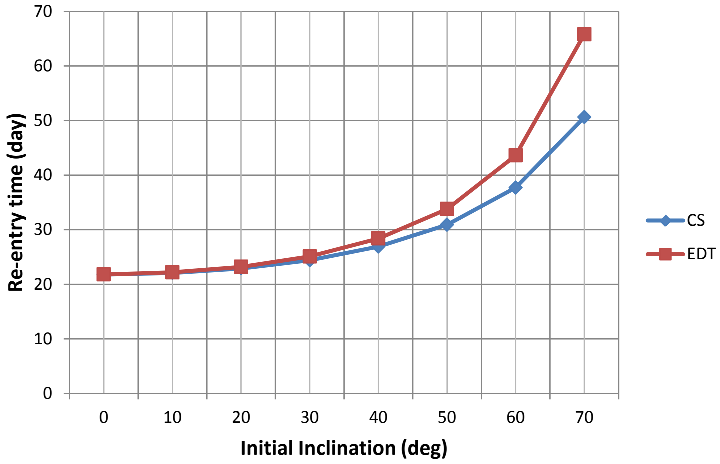
Charged satellite is more efficient with increasing eccentricity !

18

Charged Satellite vs. Electrodynamic Tether

Sensitive Analysis of Inclination

<Initial condition>
Altitude = 800 km, Eccentricity = 0
Charge = -3.91 C, Tether length = 10 km, Current = 0.7 A



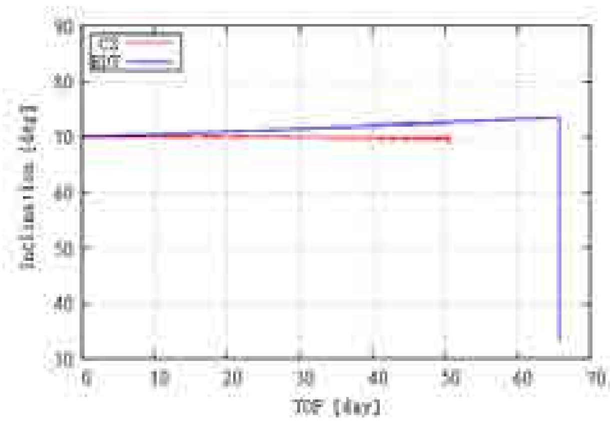
Charged satellite is more efficient
with increasing Inclination!

19

Charged Satellite vs. Electrodynamic Tether

Sensitive Analysis of Inclination

Why CS is more efficient than EDT?



During the orbital change,
the inclination of CS decreases, but that of EDT increases!

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Conclusions

1. Increasing the number of space debris
   → Removal actively by charged satellite!

2. By controlling charge
   → Efficient orbital change by resonance

3. Comparison with Electrodynamic tether
   → Charged satellite is efficient with conditions

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Future Work

1. To derive the approximation solution for the orbit with inclination

2. To analyze the system design of charged satellite

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C7

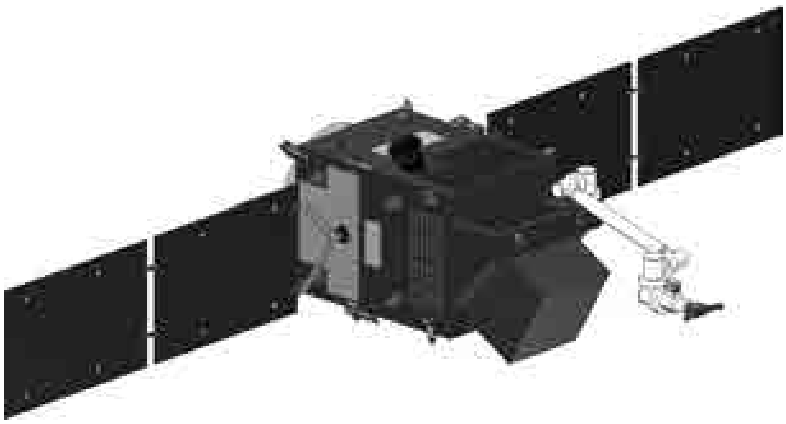
デブリ除去プロジェクト考察

Study of Active Debris Removal Project

○大塚聡子，桑尾文博（NEC），河本聡美（JAXA），池内正之（NT スペース），
廣田賢治，渡辺順一郎（TECS）
○Akiko Otsuka, Fumihiro Kuwao (NEC), Satomi Kawamoto (JAXA), Masayuki Ikeuchi (NTS),
Kenji Hirota, Jun-ichiro Watanabe (TECS)

人工衛星クラスのデブリの除去は、デブリそのものの低減と共に、更なるデブリ発生を抑制するという点で、重要なミッションである。人工衛星クラスのデブリに相対接近、搭載ロボットアームでの把持、EDT 装置取付、EDT によるデブリの軌道離脱というミッションを想定し、そのミッションを遂行する衛星に対するシステム概念、機器構成、ミッション機器／バス機器性能、軌道上シナリオなどのシステム設計を報告する。合わせて、デブリ除去の事業の仕組み／原資調達などの観点からの成立性を検討する。

Active removal of satellite-sized space debris is very useful to reduce both of the number of space debris and the collision between orbital debris. Suppose the mission by an active-debris-removal satellite (ADR satellite) to approach a satellite-size space debris, capture by a manipulator, set an EDT equipment and de-orbit the debris by EDT, system design concept for ADR satellite will be reported. And from the business point of view, investigation of the space debris removal project will be discussed.



Empowered by Innovation NEC

Space Debris Work Shop#5

Study of Debris Removal Project

Jan. 22, 2013

NEC
Project Promotion Department
Akiko OTSUKA

Sustainable Space Development & Utilization for Humankind

UNCOPUOS2010 NASA

ESA HP

NASA HP

An Active Debris Removal Parametric Study for LEO Environment Remediation
Dr. J.-C. Liou NASA, ASR-D-11-00022R1

ISS always operates Debris Maneuver

Studies of the debris population in the LEO indicate that the LEO population will increase without any new launches.
To preserve the environment for future generations, ADR must be considered.

Space Debris Control Measures

★★Control Measures★★

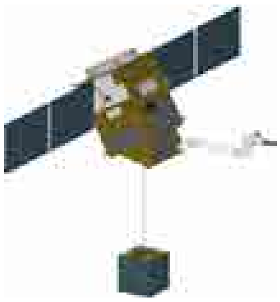
- Space debris model
- Mitigate the number of new debris
- Active Debris Removal (ADR)

To be studied as a business project

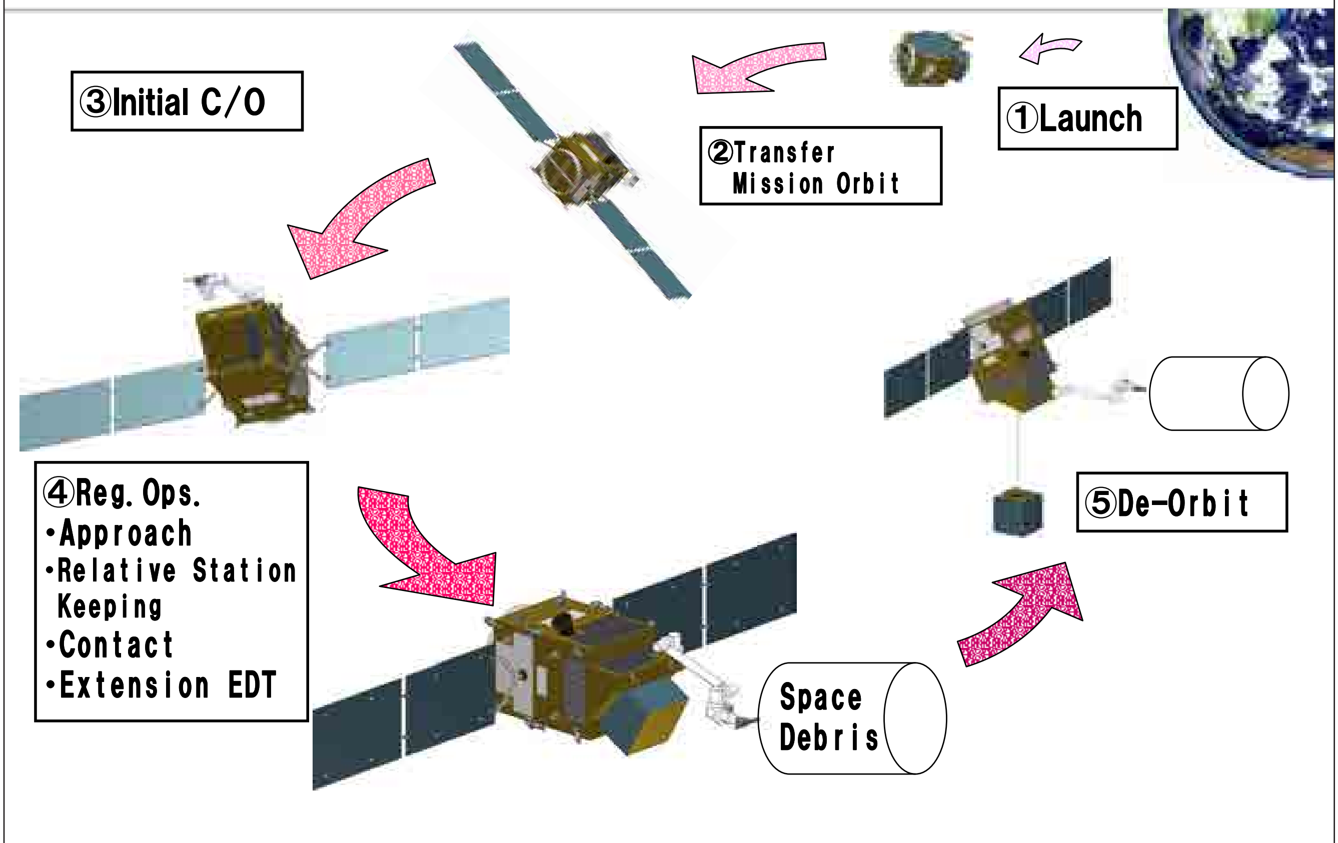
ADR Project

●Points to be considered

Technology
Scheme
Cost
Law

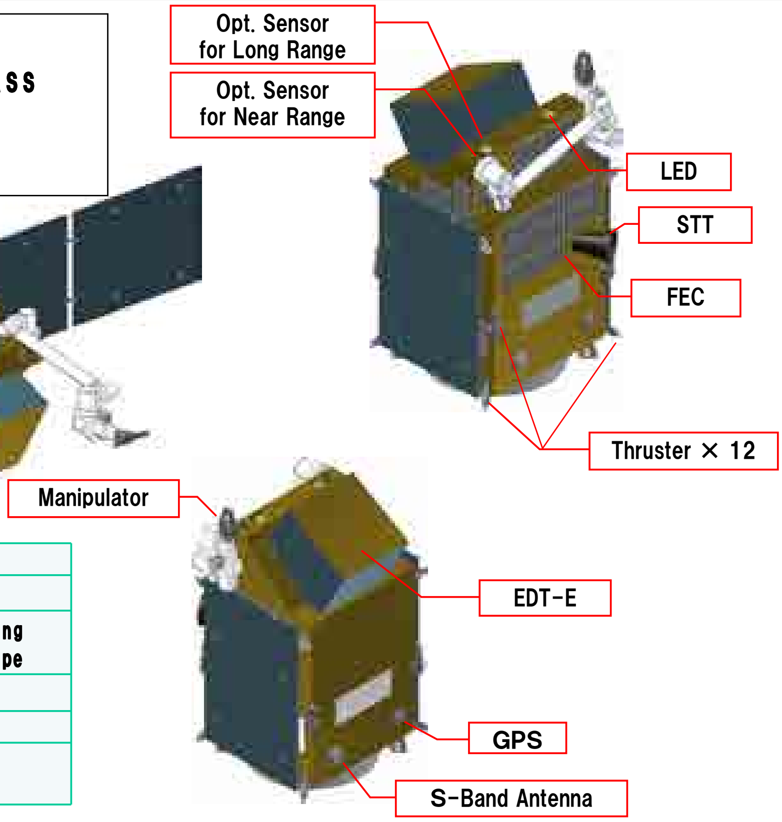


ADR Operation Sequence



ADR Satellite

Condition
Satellite Bus:NEXTAR 300kg-class
Space Debris：Alt. 800-1000km
Inc. 98°

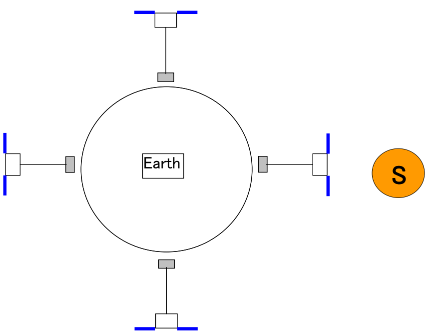


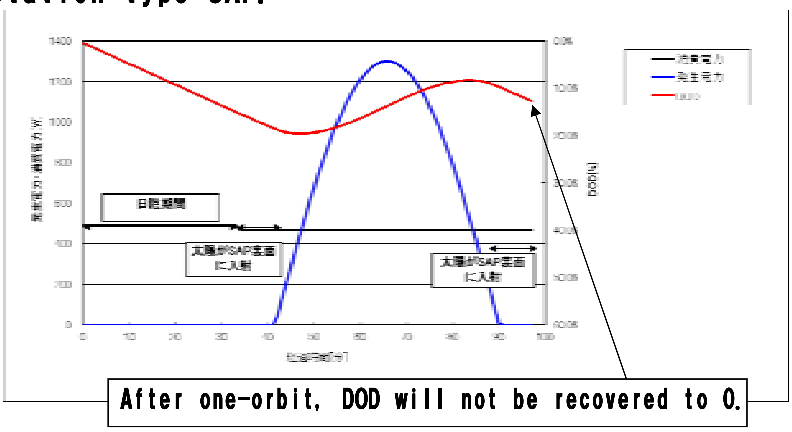
Item		Spec.
Mass		500kg
EPS	Paddle	2 panels/wing Rotation type
	Power	900W@EOL
RCS	Thruster	4N×12
	Propellant capacity	60kg

ADR Satellite Key Technology

●Solar Array Panel

Simulation of Power Balance indicates that ADR satellite should be equipped with rotation type SAP.





●Location of thrusters

12 thrusters are needed for approach and relative station keeping
→Detail analysis should be needed
on design of pipe lay-out or assembly work

ADR Satellite Key Technology

●Approach and Observing

Approach and observing Space Debris will be done by Attitude and Orbit control system and Optical system.

Optical system

Item	Spec.
Star Sensor FOV dynamic range	Relative range >50 km 15° 1 ～ 4 Visual Magnitude (Detect of more darker stars than camera for near range)
Opt. Sensor for long range FOV Mim. range Max. range	 6° (H-direction) (focal point 90mm) 10m 300km
Opt. Sensor for near range FOV Mim. range Max. range	 20° (H-direction) (focal point 9mm) 0.5m 20m for approach/10km for observing

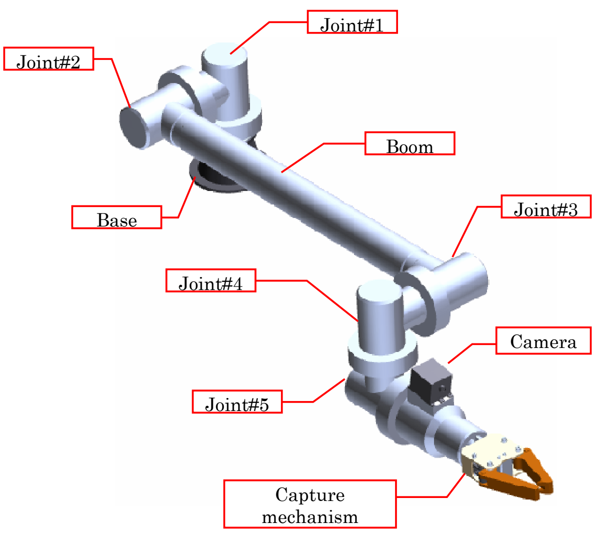
→Detail analysis should be needed on selection of effective optical sensors

ADR Satellite Key Technology

●Manipulator system

Manipulator with 5 joints

- 6-DOF will be achieved by collaborating with Attitude and Orbit Control system.
- Small and light-weight manipulator system

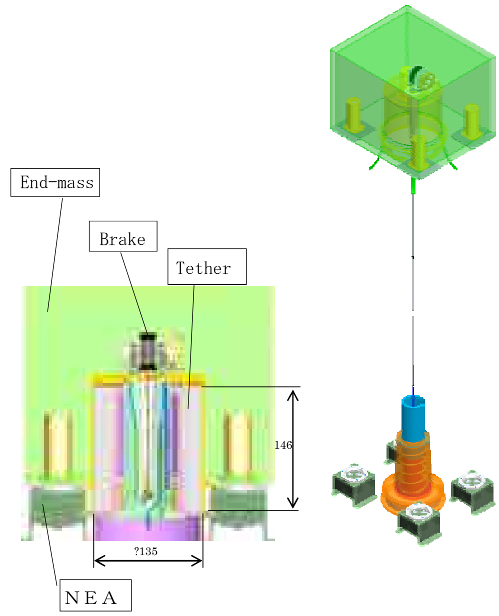


→The most critical operation, to contact with Space Debris should be studied.

ADR Satellite Key Technology

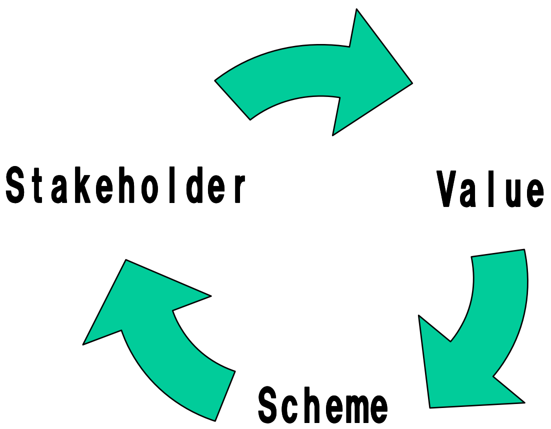
●Extension Mechanism of EDT

Requirements
Prevent End-mass tumbling during ejection
Prevent tether loosening before extension
Prevent tether cut-off during extension
Prevent tether entwisting by loosening during extension
The tether tension directs to center of ADR satellite mass.



ADR Project

Three key items of business model



●CVCA (Customer Value Chain Analysis)
Diagram to illustrate stakeholder interface by value/money/service

Notes:
In our study, "Scheme" is defined as the system how to manage/operate the business.

Ref :
Ishii, K. Course Materials, Design for Manufacturability (ME317).
Stanford University. USA, 2003.

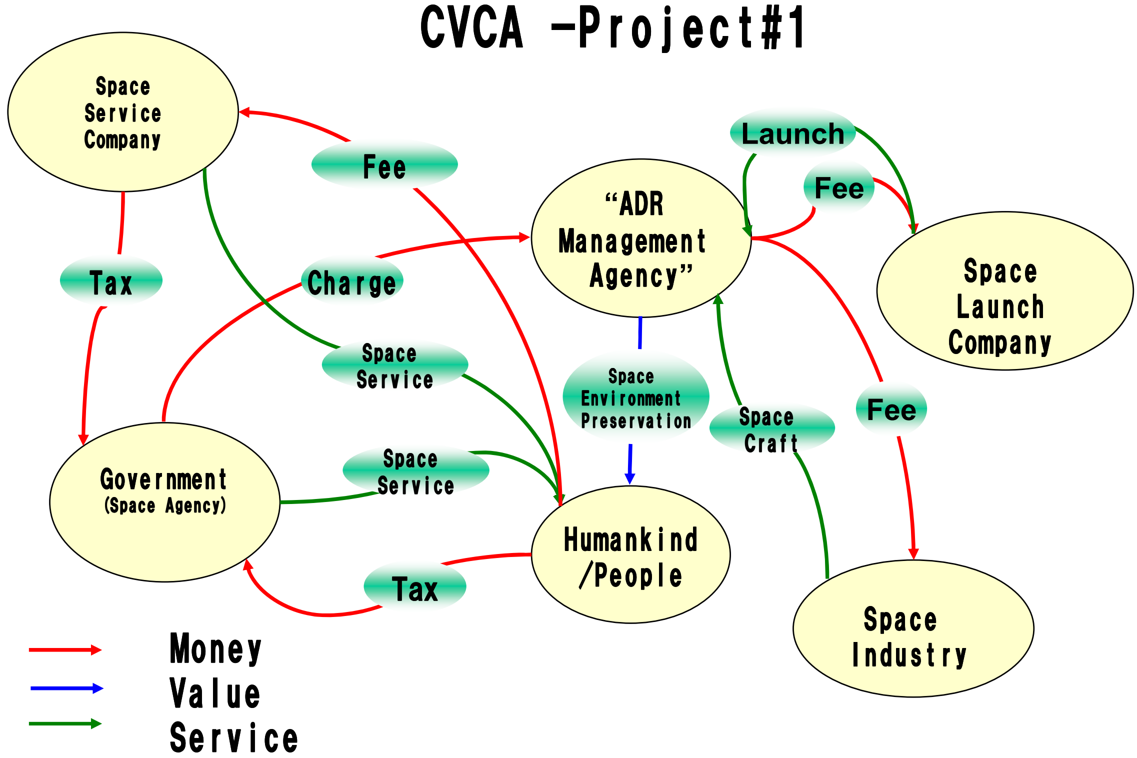
ADR Project ～CVCA～

Project#1

- Value :
  To preserve space environment
- Stake holder:
  Humankind
- Scheme:
  Manage by “ADR management agency”
  Charge each country based
  on the number of existing space debris

ADR Project ～CVCA～

CVCA -Project#1



ADR Project ～CVCA～

Project#1 Issue

●Space Service Company gets benefit by ADR and is free to be charged.

→Need some scheme to charge Space Service Company

●Risk to accept value (=activity to preserve space environment) by humankind/people

→Need to enlighten people on space environment

ADR Project ～CVCA～

Project#2

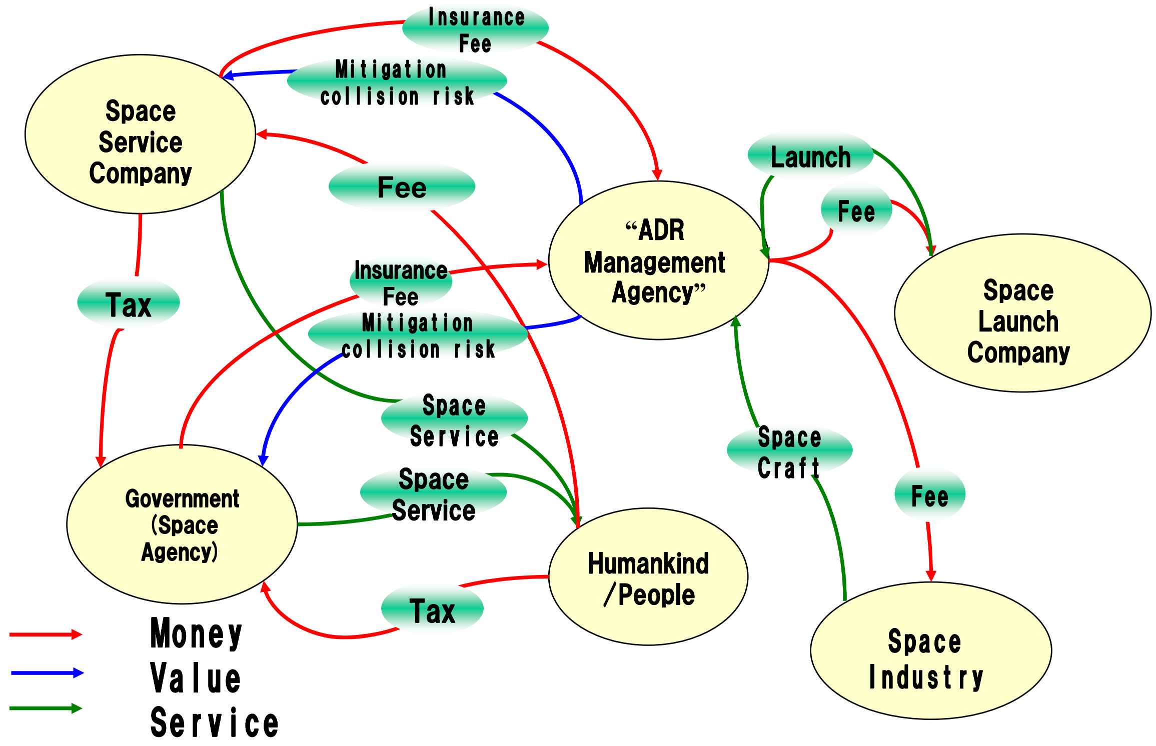
●Value :
To mitigate collision risk for specific spacecraft

●Stake holder:
Space Agency or Commercial company to operate the spacecraft

● Scheme :
Manage by "ADR management agency"
Charge each space agency or commercial company as insurance fee when they launch their spacecraft

ADR Project ～CVCA～

CVCA -Project#2



ADR Project ～CVCA～

Project#2 Issue

●Space debris to collide is different from each spacecraft
→Select space debris to be removed and set the priority

Conclusion

- Several studies on ADR project are done.
- Some hard issues of technical and/or scheme are identified.
- To solve these issues and realize ADR as business project, we will keep further studies .

Empowered by Innovation

NEC

D1

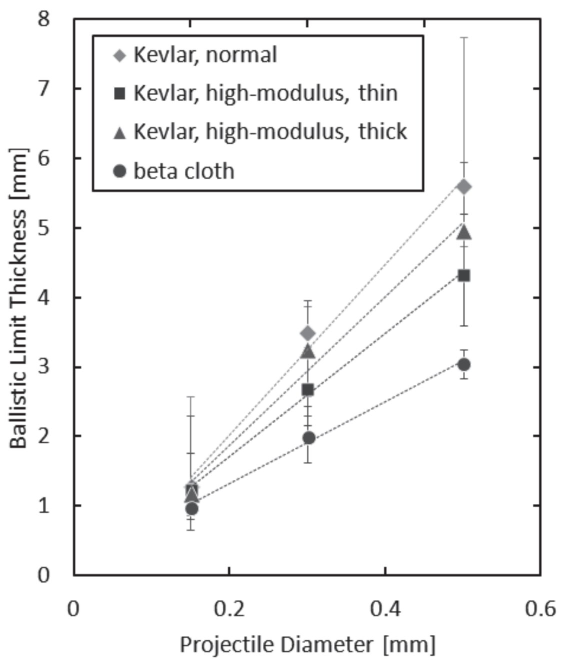
Kevlar・Beta Clothの微小デブリ貫通限界重量と厚さ

Ballistic Limit Weight and Thickness of Kevlar and Beta Cloth for Sub-millimeter Debris Impact

○東出真澄，小野瀬直美，長谷川直（宇宙航空研究開発機構）
○Masumi Higashide, Naomi Onose, Sunao Hasegawa (JAXA)

デブリ衝突頻度の高いコンポーネントには防護性能の高い材料を採用することが望ましい．しかし，進展部やハーネス等の柔軟な構造は防護性能の高い材料を適用することが困難で，衝突に対して脆弱である．これらを防護するために，形状に柔軟性のあるバンパ材料が必要とされている．本研究では高強度繊維織布に着目をした．高強度繊維のうち，アラミド繊維は超高速衝突に対しても優れた防御性能を持つことが知られており，国際宇宙ステーションに搭載されているデブリバンパ材料として使用されている．デブリ環境モデルによると，低高度軌道の人工衛星は1mm以下のデブリ衝突頻度が高い．従って，本研究では高強度繊維織布に1mm以下の微小デブリが衝突した時の貫通限界について調べた．Kevlar織布とBeta Clothの貫通限界について報告する．

To protect a satellite from space debris impact threat, a satellite designer should employ structure material which has enough protection capability against debris impact.　However, for some flexible components, it is impossible to use such strong materials, for example, expandable structures and wire harnesses.　To protect these flexible components, a flexible debris bumper is needed. High strength fiber fabric is one of flexible debris bumper material.　Since the alamido fiber has high tensile and shear strength, the alamido fiber fabric is known to be also useful for high velocity impact protection.　The alamido fiber fabric was used as a part of the Staffed Whipple Bumper installed on the International Space Station. A satellite on the low earth orbit needs to pay attention to impacts on debris smaller than 1 mm, because debris environment models show such small debris will impact on the satellite during its operation lifetime.　Therefore, to employ the alamido fiber fabric as a debris bumper, it is necessary to know their sub-millimeter debris impact damage.　The purpose of this study is to investigate sub-millimeter debris impact damage of the fiber fabric.



Ballistic Limit Weight and Thickness of Kevlar and Beta Cloth for Sub-millimeter Debris Impact

Kevlar･Beta Clothの微小デブリ貫通限界重量と厚さ

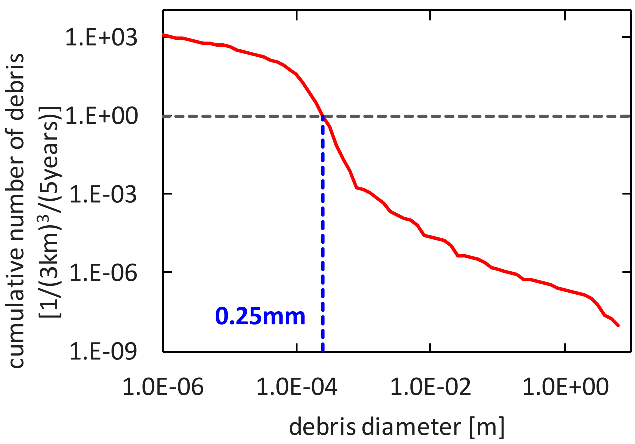
○Masumi Higashide, Naomi Onose, Sunao Hasegawa
Japan Aerospace Exploration Agency
○東出 真澄，小野瀬 直美，長谷川 直

Background

Sub-millimeter debris impact is threat of mission failure for LEO satellites.

Important components, their failure means critical damage for the satellite, should be installed inside of satellite structure.

However, it is impossible for some components. (expandable structure, harnesses, etc.)



debris flux in LEO calculated by MASTER2009

Purpose

To protect components installed on the outside of the satellite structure, flexible debris bumper is needed.

→ **Fabric bumper shield** made of high strength fiber

Investigate ballistic limit weight and thickness of fabric bumper shield

- Alamido fiber fabric (Kevlar cloth)
- Glass fiber fabric coated with aluminum (Beta cloth)

Procedure

1. Perform HVI experiments on a stack of high strength fiber fabrics
2. Count perforated layers in the impacted stack
3. Calculate perforated thickness from the perforated layers
   → Ballistic limit thickness
4. From the ballistic limit thickness, calculate areal density of the perforated layers
   → Ballistic limit weight

Kevlar Fiber

Kevlar: Alamido fiber

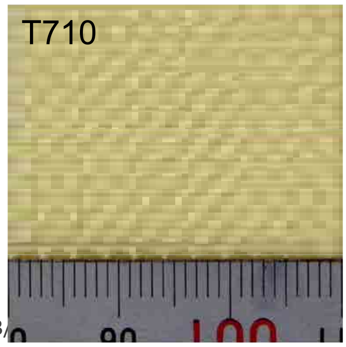
特性	単位	KEVLAR®29	KEVLAR®49
原糸			
繊度（フィラメント数）	dtex（本）	1,670（1,000）	1,270（ 768）
密度	g/cm³	1.44	1.45
平衡水分率＊1	%	4.5	3.5
＊1 一度絶乾にした後24℃、55%RHで保持			
機械的性質（原糸）		ASTM D885-85 （参考）JIS L1017	
引張強力	N	338.0	264.0
引張強度	cN/tex（g/d）	203（23.0）	208（23.6）
tensile strength	MPa	2,920	3,000
引張弾性率	cN/tex（g/d）	4,900（555）	7,810（885）
tensile modulus	GPa	70.5	112.4
破断時伸度	%	3.6	2.4

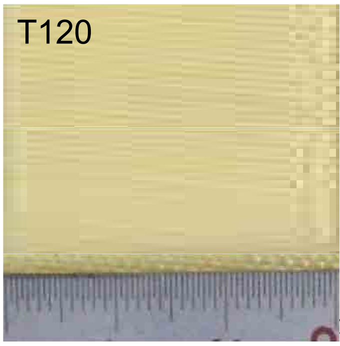
fracture elongation

Ref. DuPont

Kevlar Cloth

	T710	T120	T328
Fiber	K29（normal）	K49（high-modulus）	K49（high-modulus）
Weave	Plain		
Fabric Density [bundle/inch]	24x24	34x34	17x17
Areal Density	319g/m²	58g/m²	217g/m²
Thickness	0.43mm	0.08mm	0.33mm





Beta Cloth

Beta Cloth: Glass fiber fabric coated with aluminum

Parameter (independent of film)	Specified Value	
Cloth type	Beta Cloth	1060
Intermittent temperature range	-151° C to 315° C (-240° F to 600° F)	-185° C to 260° C (-300° F to 500° F)
Continuous temperature range	-151° C to 260° C (-240° F to 500° F)	-185° C to 200° C (-300° F to 400° F)
Fabric side solar absorptance	0.45	0.85
Fabric side hemispherical emittance	0.80	0.80
Aluminum side absorptance	0.22	
Aluminum side hemispherical emittance	0.30	
Weight (g/m²)	274 Typical	170
Thickness	0.008±0.001 in.	
Tensile strength (lb./in. of width)	90 Warp 80 Fill	40 Warp 39 Fill
Tear strength (lb.)	4.0 Warp 4.0 Fill	
Width (in.)	51 (1.30 m)	36 (0.91 m)
Item number	146626	146585
Old part number	G423800	G414500

Ref. Sheldahl

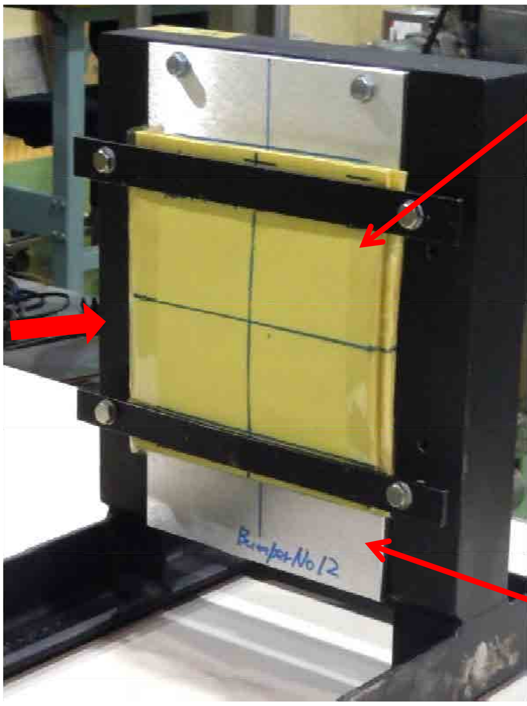
Glass Fiber Fabric in Beta Cloth

Fiber	ECD450 - Tensile Strength 3200MPa - Tensile Modulus 78GPa
Weave	Plain
Fabric Density	60x46 bundle/inch
Areal Density	47g/m^2
Thickness	0.055mm

Impact Experiment Condition

Impact velocity
6 km/sec

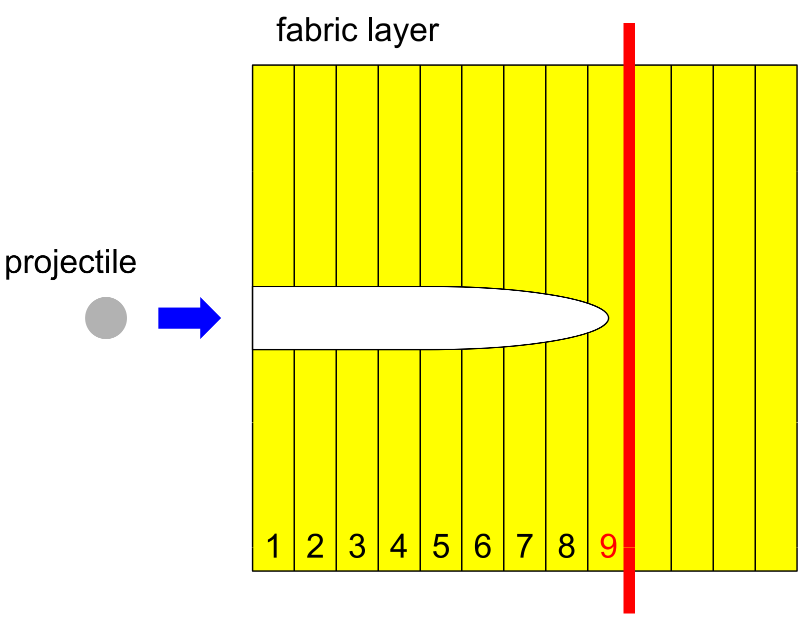
Projectiles
SUS304, sphere
ϕ0.15, 0.3, 0.5mm



Bumper

Aluminum alloy plate
A2024, t=5mm

Definition of "Perforation"



"Perforated layer + 1 layer" is defined as ballistic limit.

Kevlar T710 (ϕ0.3mm projectiles)

Front layer
Impact surface

9th layer
Front surface

9th layer
Back surface

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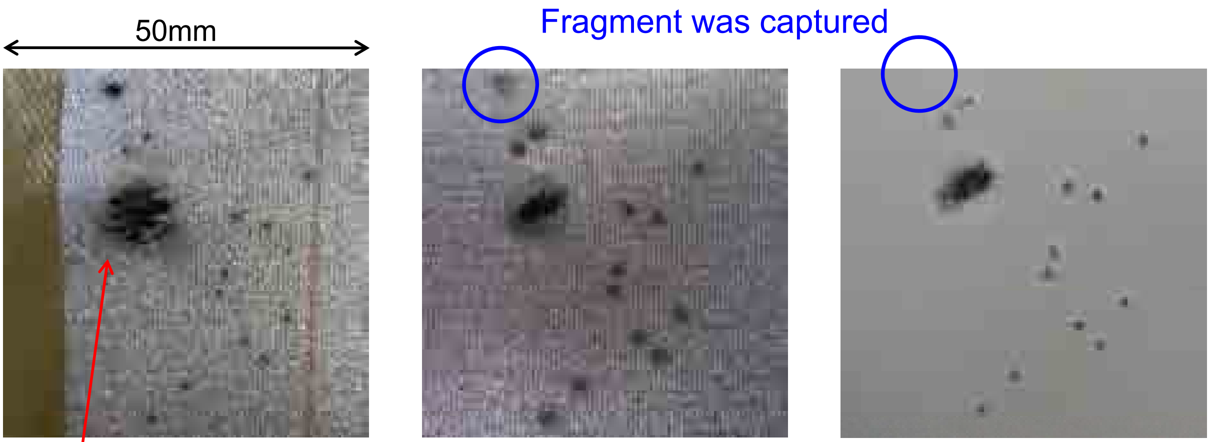
Beta cloth (ϕ0.3mm projectiles)



Front layer
Impact surface

7th layer
Front surface

7th layer
Back surface

Sabot fragment impact

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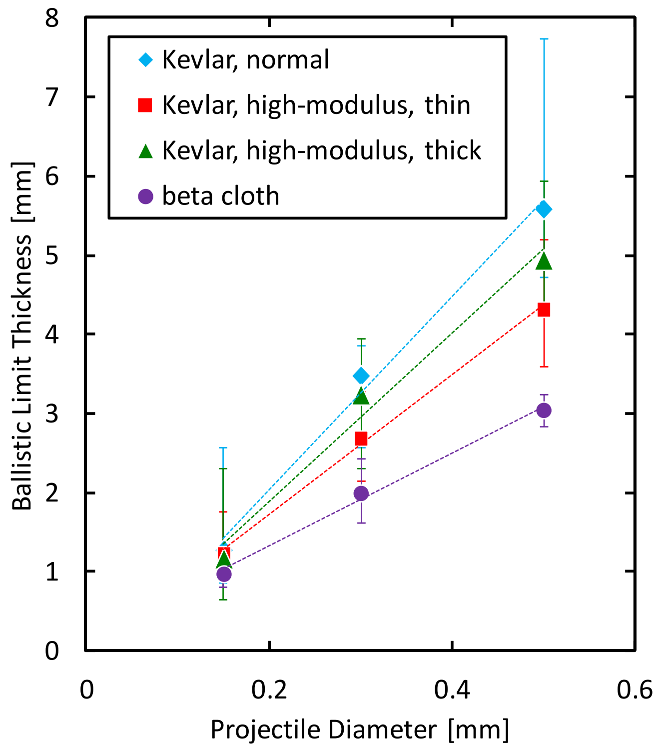
Experiment Results

Impact velocity: 5.61～6.30 km/sec

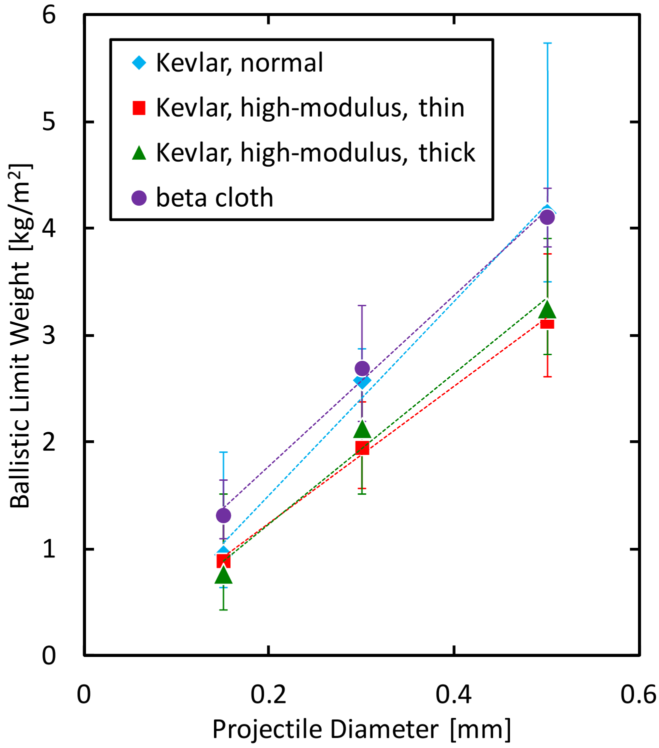
projectile dia.		Kevlar, normal	Kevlar, high-modulus, thin	Kevlar, high-modulus, thick	Beta Cloth
0.15mm	data	**51**	**53**	**131**	**42**
	BL	**2-6ply**	**12-22ply**	**2-7ply**	**4-6ply**
0.3mm	data	**10**	**22**	**31**	**12**
	BL	**6-9ply**	**27-41ply**	**7-12ply**	**8-12ply**
0.5mm	data	**9**	**11**	**14**	**3**
	BL	**11-18ply**	**45-65ply**	**13-18ply**	**14-16ply**

Ballistic Limit Thickness



- Beta Cloth was the thinnest bumper.
- Kevlar cloth made of high modulus fiber showed better protection capability than normal fiber.
- To stack thinner clothes was effective to decrease the ballistic limit thickness.

Ballistic Limit Weight



- High modulus Kevlar cloth was the lightest weight bumper.
- Beta Cloth was the heaviest bumper.
  → To increase areal density contributes to decrease the ballistic limit thickness.
- Kevlar cloth made of high modulus fiber showed better protection capability than normal fiber.

Comparison with Aluminum Bumper

E.Christiansen, Meteoroid/debris shielding, *NASA TP 2003-210788*, 2003.

$$\text{when } \frac{\rho_p}{\rho_t} < 1.5 \quad t_w = 1.8 \times 5.24\, d^{19/18} H^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{1/2} \left(\frac{V_n}{C}\right)^{2/3}$$

$$\text{when } \frac{\rho_p}{\rho_t} \geq 1.5 \quad t_w = 1.8 \times 5.24\, d^{19/18} H^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{2/3} \left(\frac{V_n}{C}\right)^{2/3}$$

ρ_p: Projectile Density (g/cm^3)

ρ_t: Target Density (g/cm^3)

t_w: Target Perforation Thickness (cm)

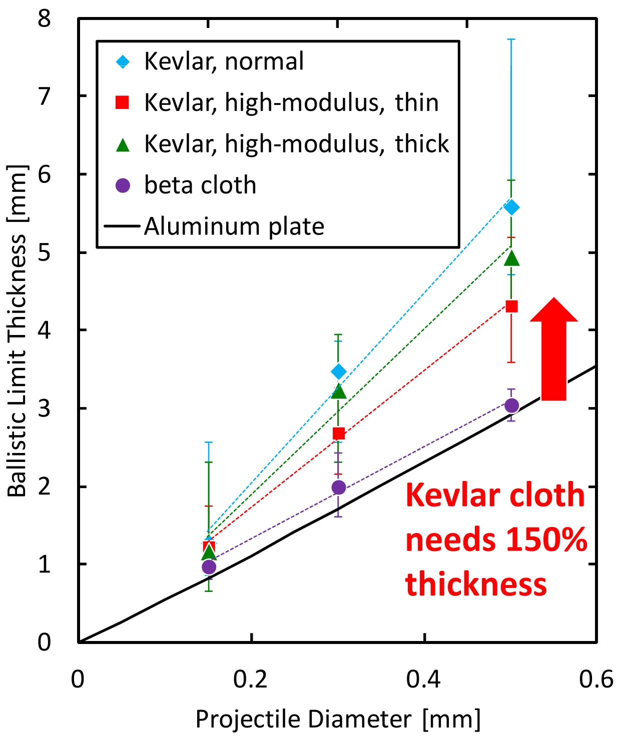
d: Projectile Diameter (cm)

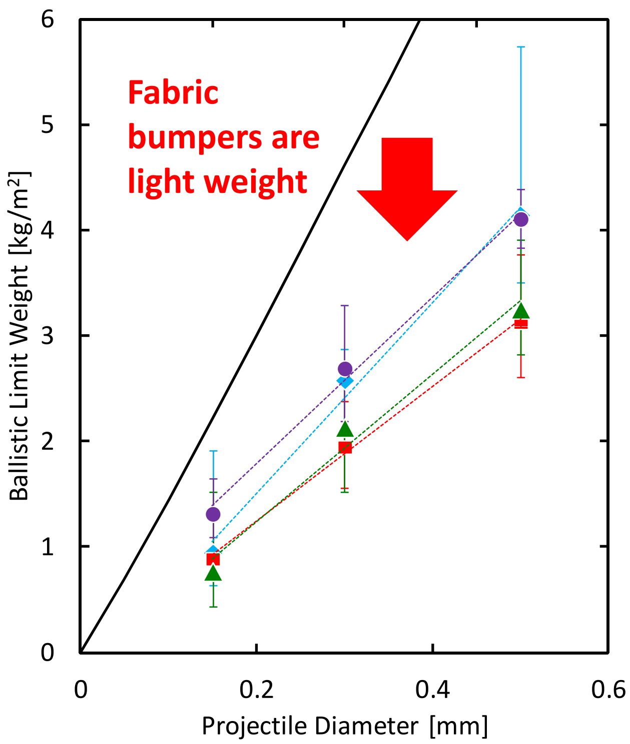
H: Brinell Hardness of Target

C: Speed of Sound in Target (km/s)

V_n: Normal Component of Impact Velocity (km/s)

Results





Summary

- 3種類のKevlar織布とBeta Clothに超高速衝突試験を実施し，貫通限界を求めた
- 薄いバンパが必要な場合はBeta Cloth，軽いバンパが必要な場合は高弾性のKevlar織布が有効
- 弾性率が高いKevlar原糸で作られた織布の方がデブリバンパとしての性能が高い

Handbook

材料名	Kevlar T710	Kevlar T120	・・・	
材料構成	Kevlar（アラミド繊維）織布 原糸：K29（通常タイプ） 織り方：平織り 密度：24×24本/inch	Kevlar（アラミド繊維）織布 原糸：K49（高弾性タイプ） 織り方：平織り 密度：34×34本/inch	・・・	セラミック繊維織布とガラス繊維織布について同様の評価を実施予定
1層の厚さ	0.43mm	0.08mm		
1層の重さ	319g/m^2	58g/m^2		
貫通限界式	n=28d-0.97	n=110d-0.46		
入手性	数日	数週間		
作業性	-切断面から繊維がほつれる	-切断面から繊維がほつれる -張力をかけると織目が崩れる		
コメント	-紫外線に弱い	-紫外線に弱い		

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D2

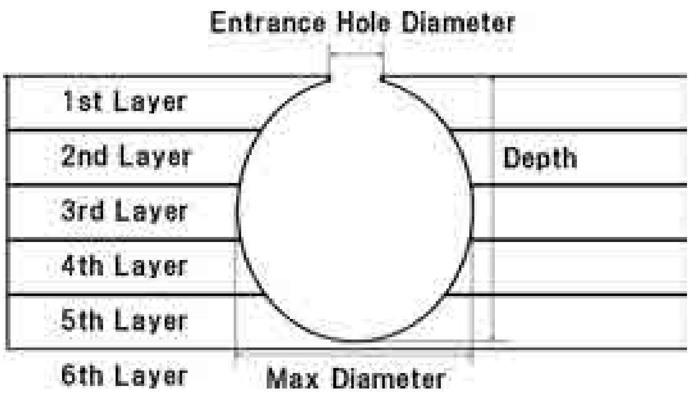
発泡アルミに対する衝突実験：
軽量デブリバンパの開発に向けて

Impact experiments on aluminum foam targets: as a favored candidate material for a light-weight space debris bumper shield

○小野瀬直美，東出真澄，長谷川直（宇宙航空研究開発機構）
○Naomi Onose, Masumi Higashide, Sunao Hasegawa (JAXA)

軽量デブリバンパの素材として提案するため，発泡アルミに対する衝突実験を行った．ターゲットは，直径数十μm のアルミ粒子を焼結させた板を積層させたものである．空隙率は 82 %，密度は 500 kg/m^3，呼び孔径は 0.3 mm である．呼び孔径が小さいため，比較的小さいサイズのデブリにも対応することができると考えられる．
模擬デブリとして，直径 0.3, 1.0 mm の金属球を 4 - 7 km/sec で衝突させ，貫通限界並びにクレータ形状の変化を調べた．クレータの入口は飛翔体直径の 2 倍程度であるが，内側には飛翔体直径の 7 – 10 倍の直径を持つ空洞が形成された．発泡アルミの貫通限界は，単位面積当たりの質量がひとしいアルミ板と比べて，40 %程度有利になる．実験を行った範囲では，衝突速度が上がるほど効率が上がること，飛翔体密度依存性がほとんど見られないことが判明した．高速度カメラの画像からは，高速度の放出物は見られなかった．

Aluminum Foam targets were tested as a favored candidate material for a light-weight space debris bumper shield. A target consists of layers of aluminum foam plates, and each plate was made of aluminum powder, tens of micro-meters in diameter. Their porosity, density, and nominal diameters of pores is 82 %, 500 kg/m3, and 0.3 mm, respectively. Metal spheres are employed as simulated debris and accelerated to 4 to 7 km/sec. Bulb shaped craters with small entrance holes are observed. No high-speed ejecta is observed by use of a high-speed video camera.



弾道を含む面で切断したターゲットの模式図

発泡アルミに対する衝突実験：軽量デブリバンパの開発に向けて

Impact experiments on aluminum foam targets: as a favored candidate material for a light-weight space debris bumper shield

N. Onose, M. Higashide, and S. Hasegawa,
Japan Aerospace Exploration Agency,

1

Overview

- Introduction
  - The number of debris has been increasing
  - Porous materials absorb shocks efficiently
- Experiments
  - Aluminum foam (Mitsubishi Materials)
  - Shapes of craters
  - Crater dimensions
  - Dependences of crater dimensions on
    - Particle Size , Impact velocity , and Particle density

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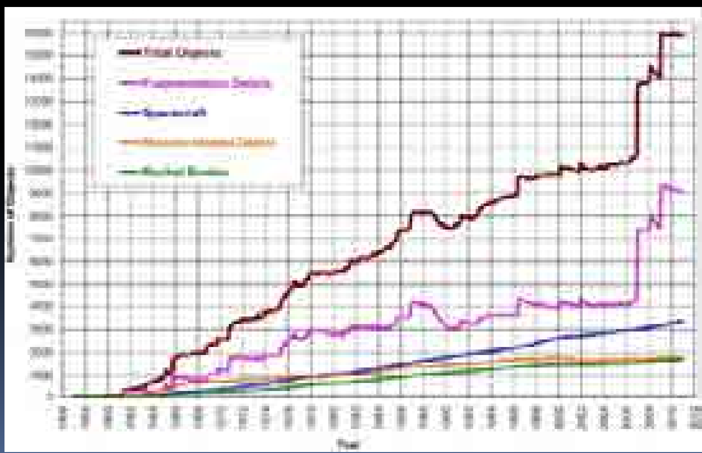
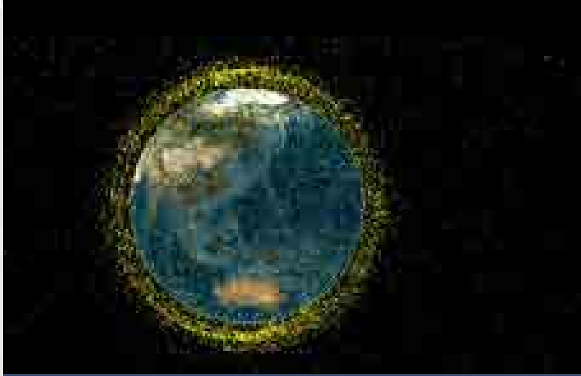
Introduction: Number of debris

- Number of Space debris **increasing** year by year.
- Averaged impact velocity of debris in LEO is
  10 km/sec
- It is very dangerous for our satellites.





From NASA
The Orbital Debris Quarterly News

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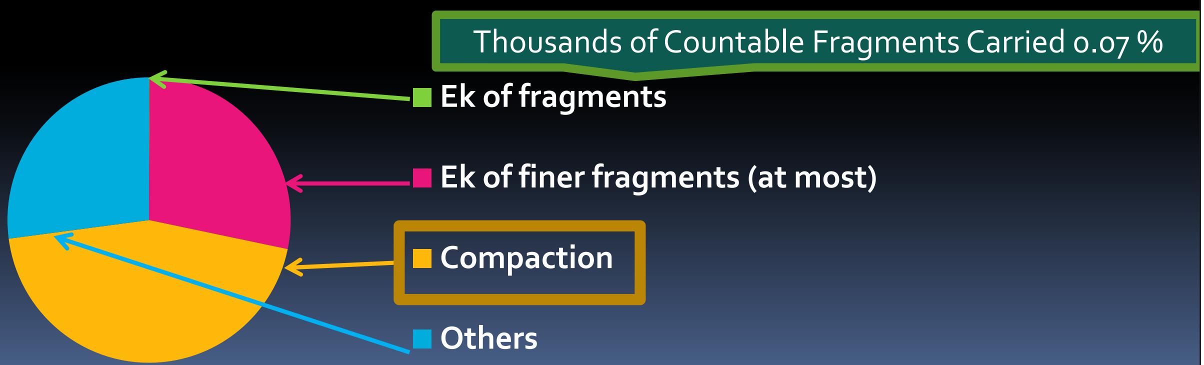
Introduction: Energy absorption in Porous Matter

- Porous materials convert the impact energy into heat efficiently.

ex. Porous gypsum targets absorb 31 – 62 % of the impact energy, in impacts at 4 km/sec (Onose et al. 2008).



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Experiments

- Aluminum foam (Mitsubishi Materials)
- Hypervelocity Impact Experiments
- Shapes of craters
- Crater depths and Ballistic limits
- Dependences of BL on
  - Particle Size , Impact velocity , and Particle density

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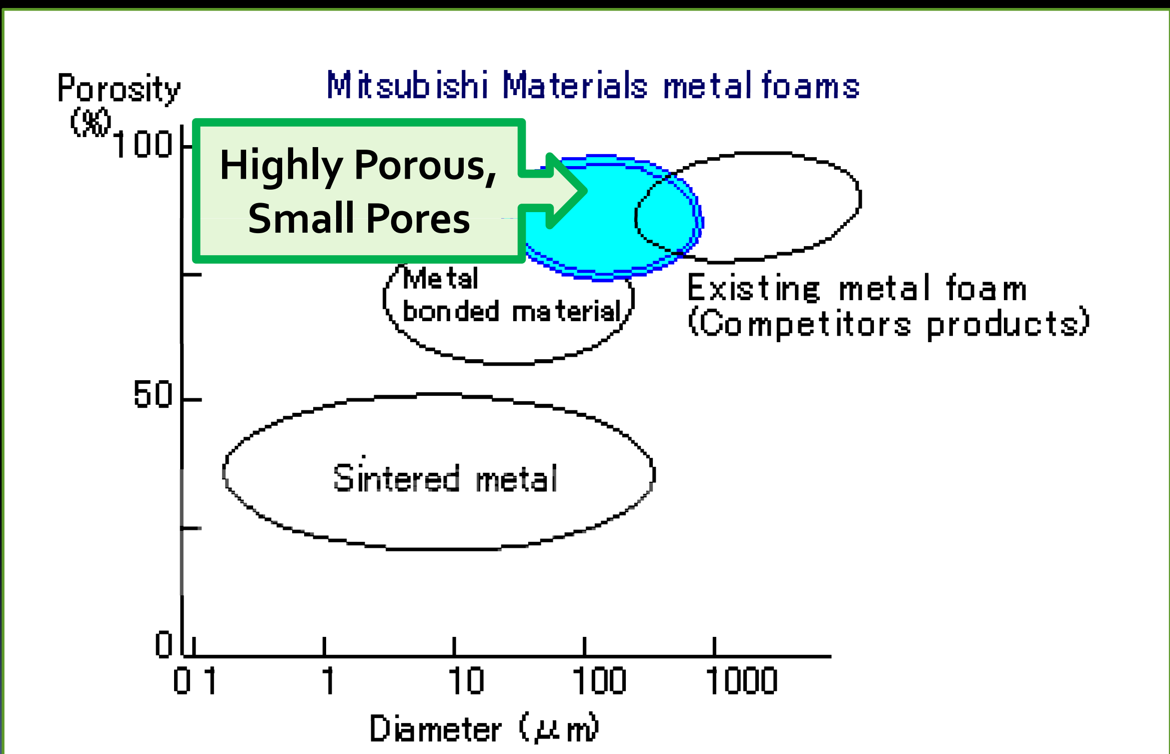
Aluminum foam I



from MITSUBISHI MATERIALS website

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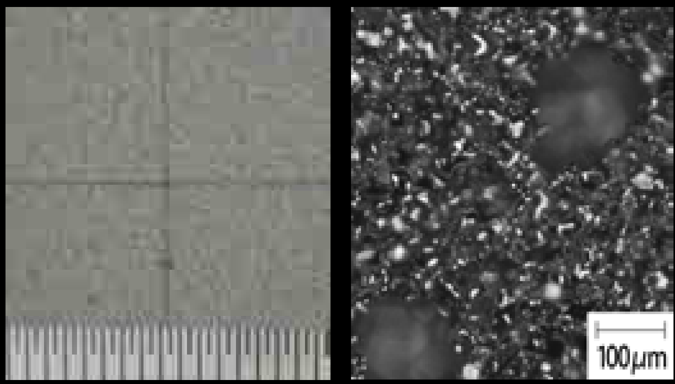
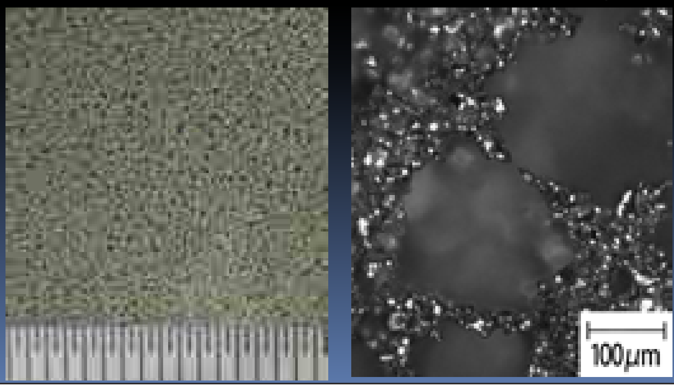
Aluminum foam II

obverse: size and number of pores are small



reverse: size and number of pores are large



- porosity: 82 %
- density: 0.5 g/cm^3
- pore diameter: 300μm in maximum
- thickness of each plate:

  0.4, 1.0, 2.0 mm

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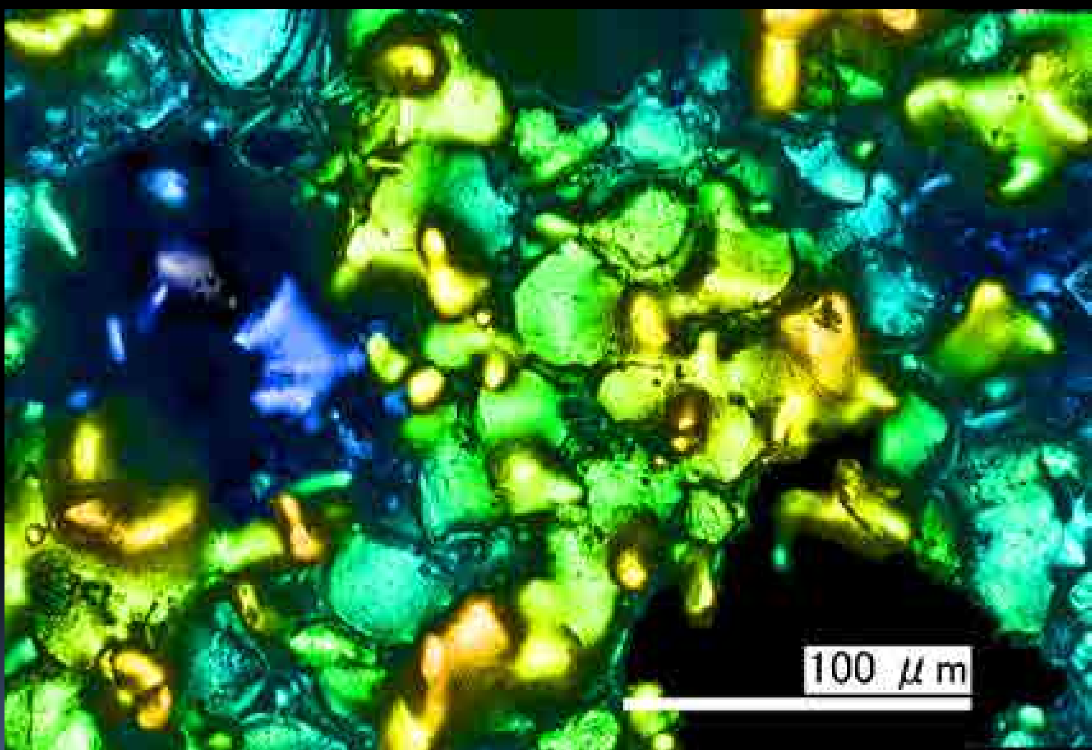
Aluminum foam III Obverse



height

High ⟷ Low

キーエンス レーザー顕微鏡 VKX-100

2013/1/24

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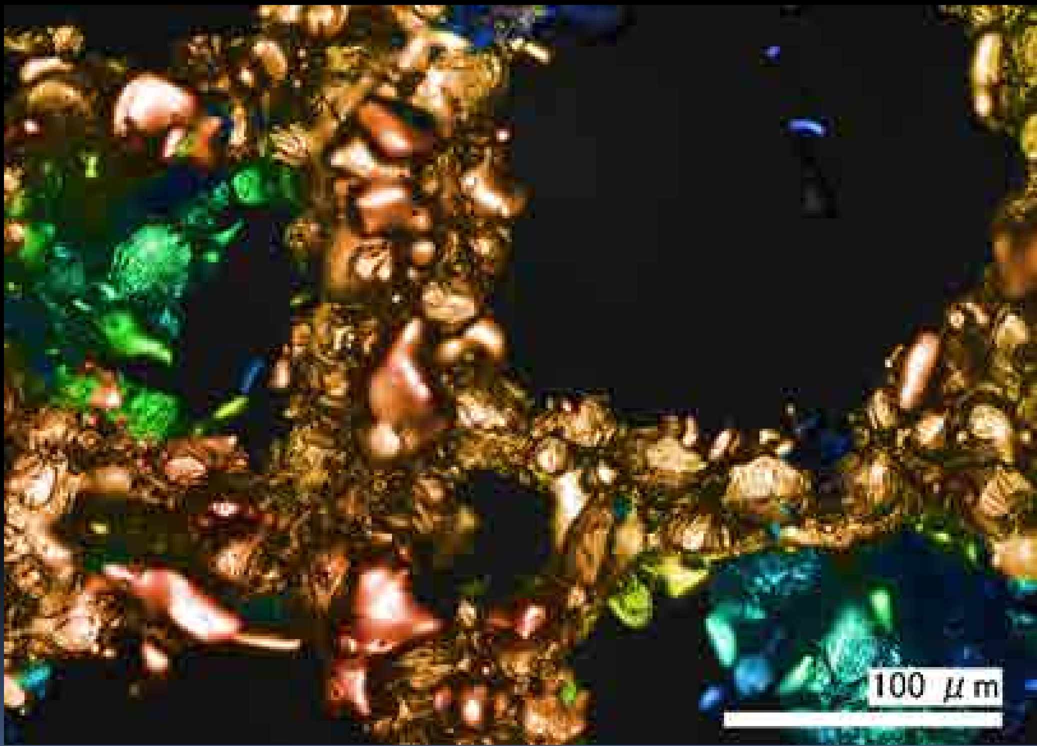
Aluminum foam IV Reverse



height
High ⟷ Low

キーエンス レーザー顕微鏡 VKX-100

2013/1/24

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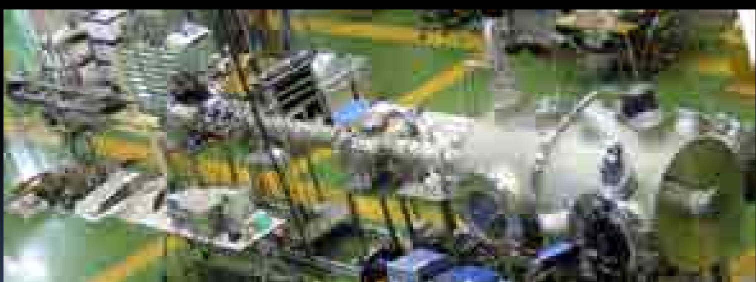
Hypervelocity Impact Experiments

- Target: Stacked plates of aluminum foam
- Projectile: Al, Sus, Cu spheres, 1 mm and 0.3 mm in diameter
- Impact velocity: 4 - 7 km/sec

(cf. averaged impact velocity of space debris in LEO: 10 km/sec)



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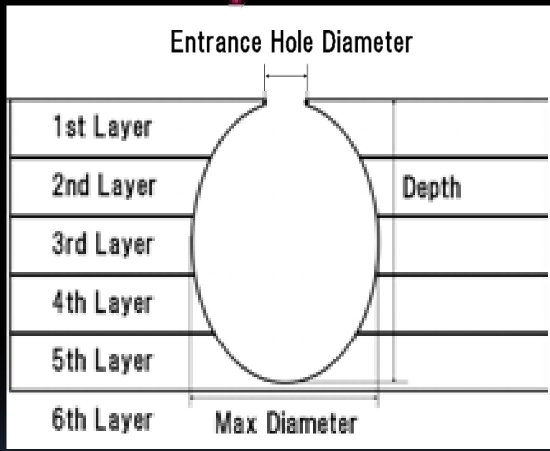
Crater Dimensions：Al 1 mm @6 km/sec

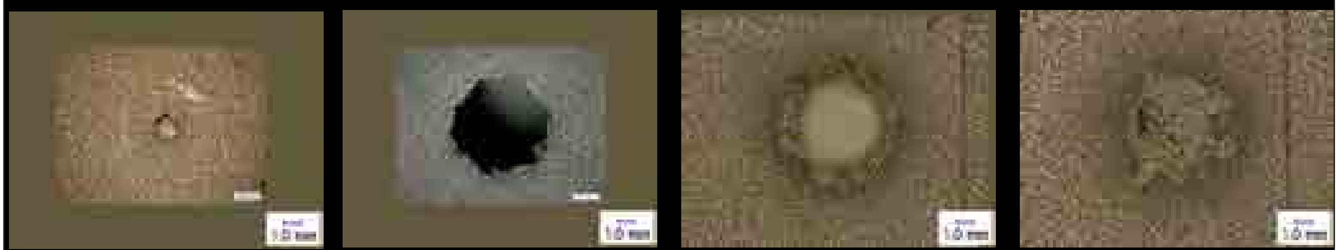
- Entrance Hole Diameter：
  1.8 mm ±0.3 mm
- Maximum Diameter：
  5.6 mm ±0.6 mm
- Depth： 9.8 mm ±1.01 mm
- Volume：0.20 mm³ ±0.02 mm³
- N = 4



Small entrance hole
＝ Little fragments are ejected

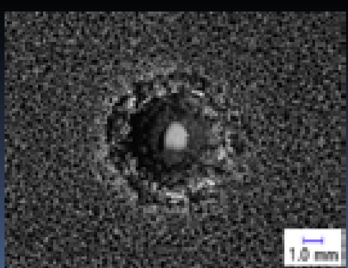
A Shape of a crater: A Result on each Target Plate

1st slice obverse 2nd slice obverse 3rd slice obverse 4th slice obverse

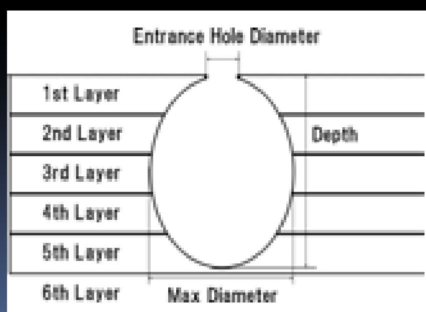


entrance hole maximum diameter maximum diameter crater floor

1st slice reverse

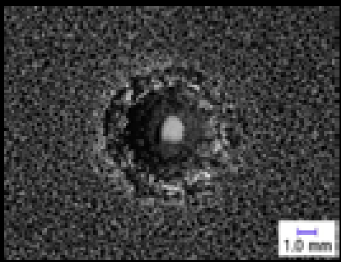


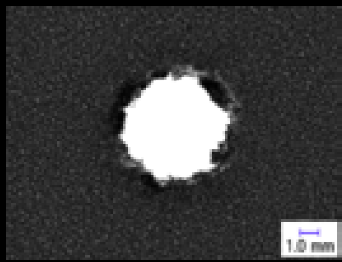
large cavity
deformation of pore



Where is the Material evacuated from the cavity

Compaction of Pores

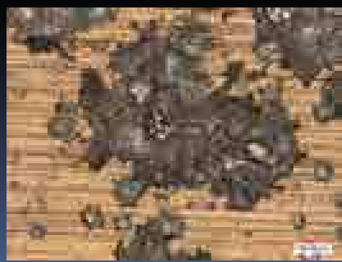




Melted and splashed toward downrange

nearly bottom layer of the crater

Melt on the crater floor



Splash on the witness plate

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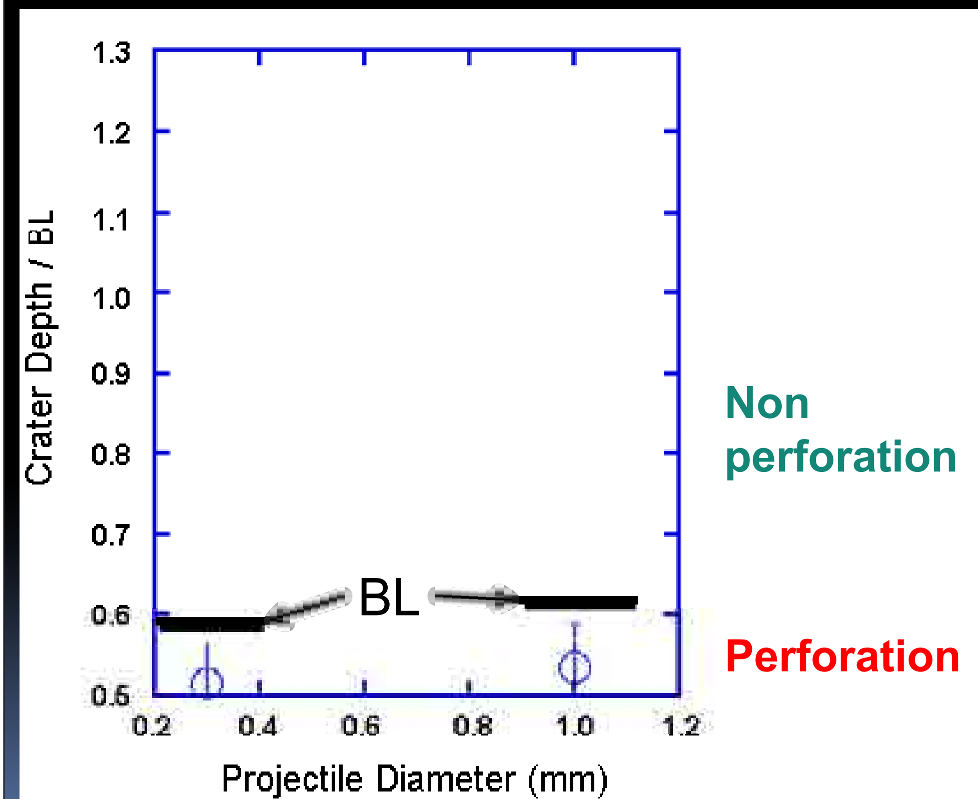
BL of aluminum foam



BL：Christiansenの式で同素材のアルミ板でのBLを計算し，これと単位面積当たりの質量が同等な発泡アルミの厚さ

実際の発泡アルミのBLは，アルミ板のBLから推定されるものより

40 % off

BLはCrater深さよりもやや大きい値をとる.

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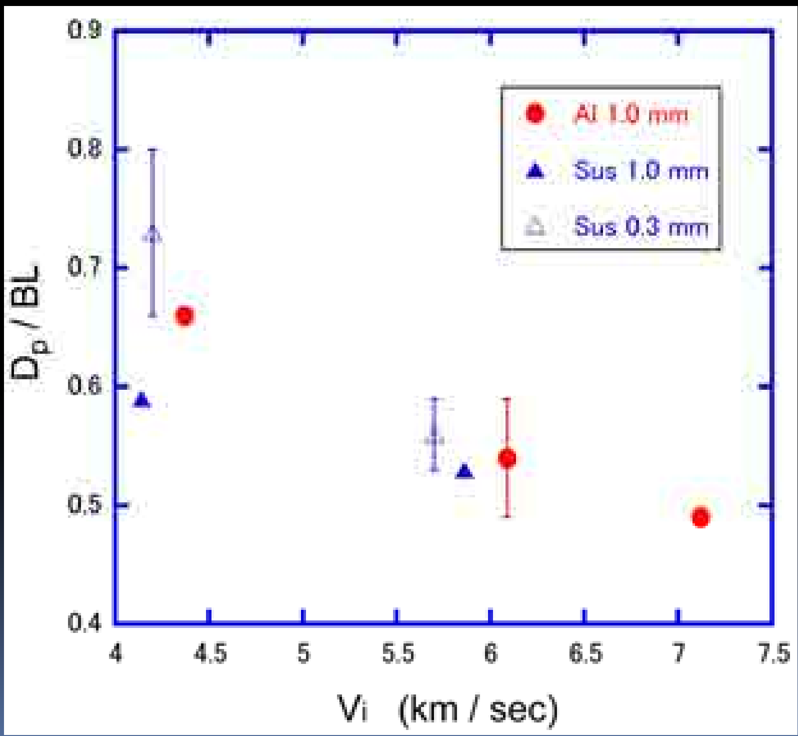
Impact velocity dependence：crater Depth/BL



BL：Calculated from the BL for an aluminum plate shearing the same weight per unit area as the aluminum foam, employing equations of Christiansen.

More effective for the higher velocity debris

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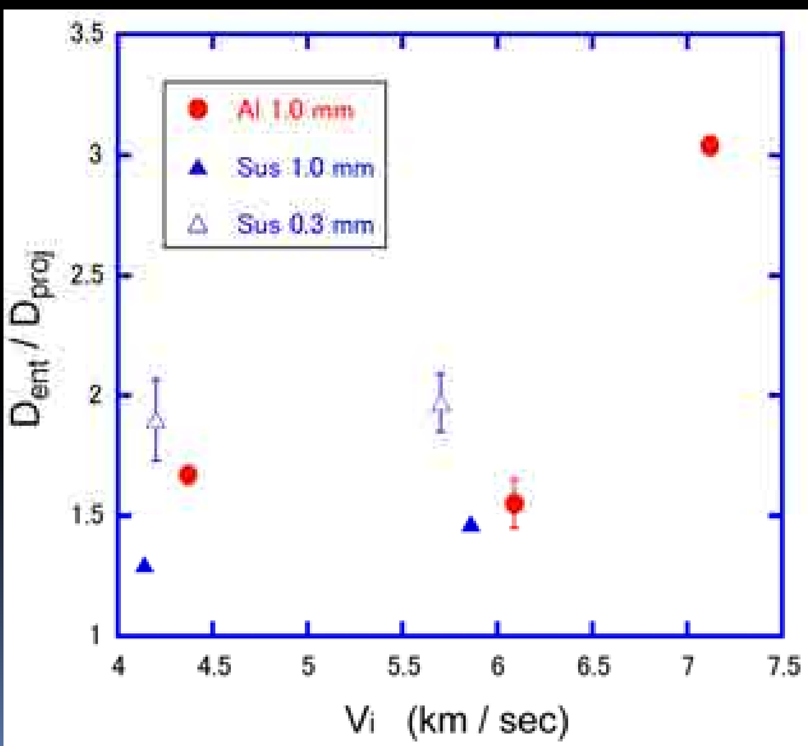
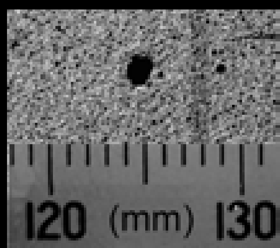
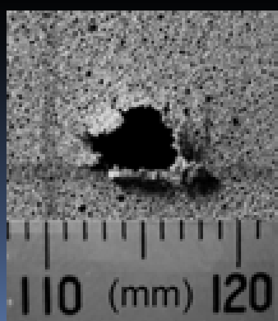
Impact velocity dependence：crater D_{ent}/D_{proj}



～6 km/sec：Small entrance hole



7 km/sec：Entrance hole is enlarged (posssively because of the blust at the impact)



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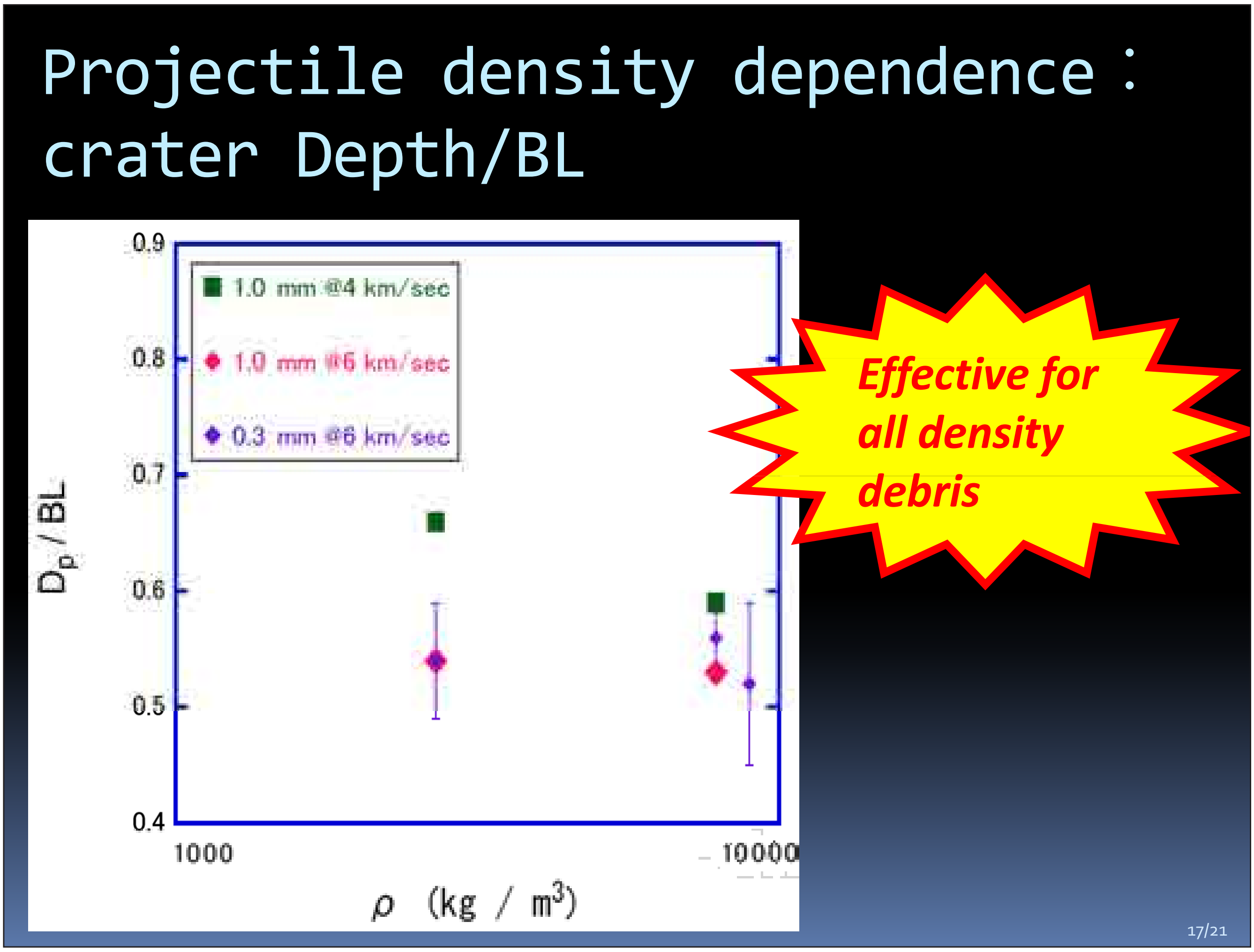
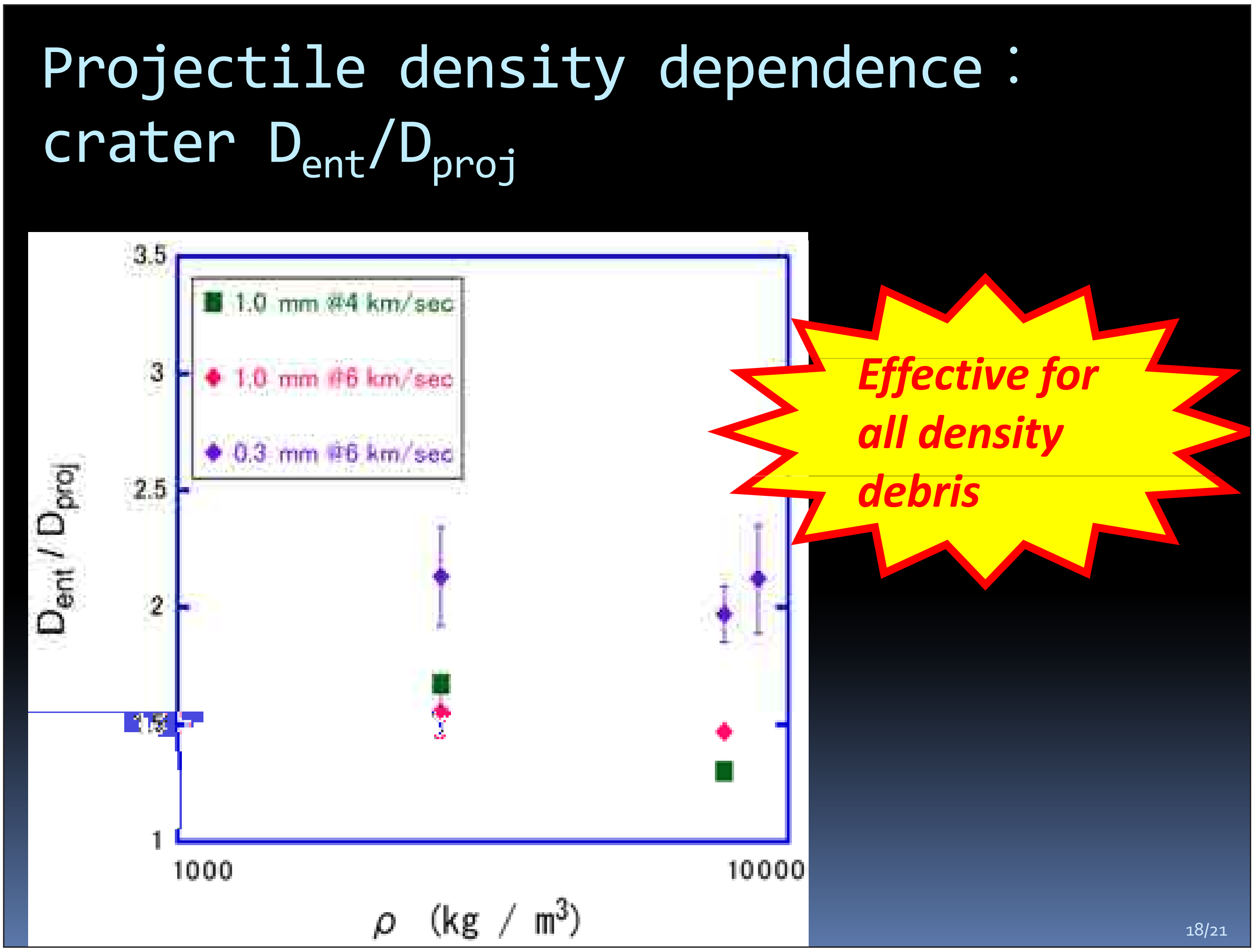

Projectile density dependence：
crater Depth/BL
1.0 mm @4 km/sec
1.0 mm @6 km/sec
0.3 mm @6 km/sec
D_p / BL
0.9
0.8
0.7
0.6
0.5
0.4
1000
10000
ρ (kg / m^3)
Effective for all density debris
17/21


Projectile density dependence：
crater D_{ent}/D_{proj}
1.0 mm @4 km/sec
1.0 mm @6 km/sec
0.3 mm @6 km/sec
D_{ent} / D_{proj}
3.5
3
2.5
2
1
1000
10000
ρ (kg / m^3)
Effective for all density debris
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Conclusion

- Impact Cratering on Aluminum Foam, 82 % in Porosity, Result in a Bulb Shaped Crater
- Melting and Deformation of The Target was observed
- Aluminum foam is more effective in the higher velocity debris
- Aluminum foam can stop debris made of aluminum, Sus, and Cu.
- The entrance hole of the crater was enlarged in the case of the impact at 7 km/sec

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Conclusions

- Aluminum foam is a favored candidate material for a light-weight space debris bumper shield !

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D3

スラスタ用窒化ケイ素セラミックスの超高速衝突損傷評価

Damage evaluation of silicon nitride ceramics subjected to hypervelocity impact

○川合伸明，長谷川直，佐藤英一（宇宙航空研究開発機構）
○N. Kawai, S. Hasegawa, E. Sato (JAXA)

ISAS/JAXA では人工衛星・惑星探査機用スラスタの高性能化を目的に、高耐熱温度・高強度・高靭性の構造用セラミックスである窒化ケイ素セラミックスを用いたスラスタを開発している。
宇宙用構造部材として脆性材料を用いる際には、熱的・機械的な準静的強度特性に加えて、スペースデブリやメテオロイドなどの宇宙浮遊物との超高速衝突に対する動的破壊特性の評価も必要となる。
そこで、窒化珪素セラミックスの超高速衝突に対する損傷評価を目的に、超高速衝突実験を行った。衝突により生じるクレータ深さを、衝突体の直径・密度・速度の指数関数として表現することにより、超高速衝突に対する貫入方程式を構築した。超高速衝突損傷形態は、クレータ損傷、クレータ＋スポール損傷、貫通損傷に分類された。各損傷形態が生じる衝突条件は、損傷形態に依存した係数を貫入方程式に掛け合わせることにより記述され、窒化珪素セラミックスの超高速衝突に対する損傷形態の予測が可能となった。

A new advanced ceramic thruster made of monolithic silicon nitride has been developed in ISAS/JAXA. In order for secure operation of a spacecraft, the reliability of the ceramic component against space debri and micrometeoroid impact has been investigated through hypervelocity impact tests. Silicon nitride plates were impacted by spheres of stainless-steel and other materials with 0.2-0.8-mm diameters in the velocity range up to 8.0 km/s using a two-stage light-gas gun. Using crater depth data under various impact conditions, the penetration equation of silicon nitride was determined. The impacted samples showed fracture patterns of three types: cratering, cratering with spallation, and perforation. These fracture patterns were well categorized by the multiple forms of the penetration equation.

Damage evaluation of silicon nitride ceramics subjected to hypervelocity impact

スラスタ用窒化ケイ素セラミックスの超高速衝突損傷評価

N. Kawai, S. Hasegawa, E. Sato
Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)

川合伸明, 長谷川直, 佐藤英一
宇宙航空研究開発機構・宇宙科学研究所

第5回スペースデブリワークショップ@JAXA調布航空宇宙センター 2013/1/22-23

Ceramic thruster

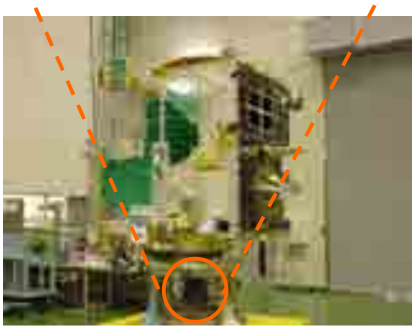
Ceramic:
Although its fracture pattern is brittle, it has good mechanical property.
✓high strength, high heat resistance, low density, high corrosion resistance

Si_3N_4 ceramic thruster

Thruster: Small rocket engine for a spacecraft

- Higher thrust performance than a conventional Nb-alloy thruster because of its high combustion temperature
  - ✓Temperature limit: 1350℃→1500℃

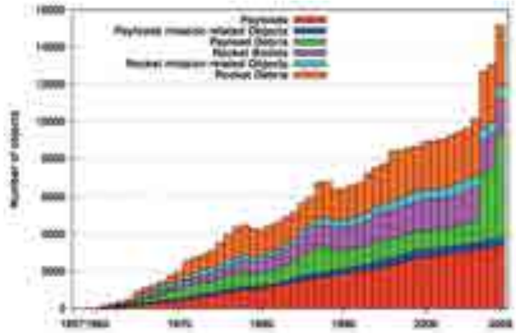
Installed on a Venus climate orbiter "AKATSUKI"



Space debris

All non-functional, man-made objects in Earth orbit
(e.g., derelict spacecraft, debris released during mission operations)

- The space objects bigger than 10 cm in Earth orbit



H. Klinkrad, Proc. HVIS2010

The number of debris is increasing accompanied with the space development.
(the number of 1~10 cm: 500,000 , < 1 cm: 100 million)

Damage caused by impact of debris is a growing concern

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Damage evaluation of ceramic thruster

To use of brittle materials for structural application in space:

- Evaluation of static strength under operating environment (e.g., thermal stress state at thruster-firing condition)

Brittle material: sensitive to hypervelocity impact (HVI)

Importance of the evaluation of damage induced by debris and meteoroids impact

1. Evaluation of damage geometry induced by HVI
   - Generate the equation of to predict the failure pattern
     (This talk or N.Kawai et al., Int. J. Impact Eng. **38**, 542 (2011).)
2. Internal damage structure induced by HVI
   - Observation of internal damage and numerical simulation
     (N. Kawai et al., Proc. HVIS 2010, pp. 722-733.)

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Hypervelocity-impact experiment

Two-stage light-gas gan

✓ It can accelerate a single particle with diameter of 0.1~3.5 mm up to 7.0 km/s using a sabot.

N. Kawai et al., Rev. Sci. Instrum. 81, 115105 (2010).

Projectile condition

Size: 0.2~1.0-mm sphere

Material: Steel, Al, Al_2O_3, Glass, Ir, Pt, WC

Impact velocity: 1.5~7.0 km/s

Si_2N_3 target

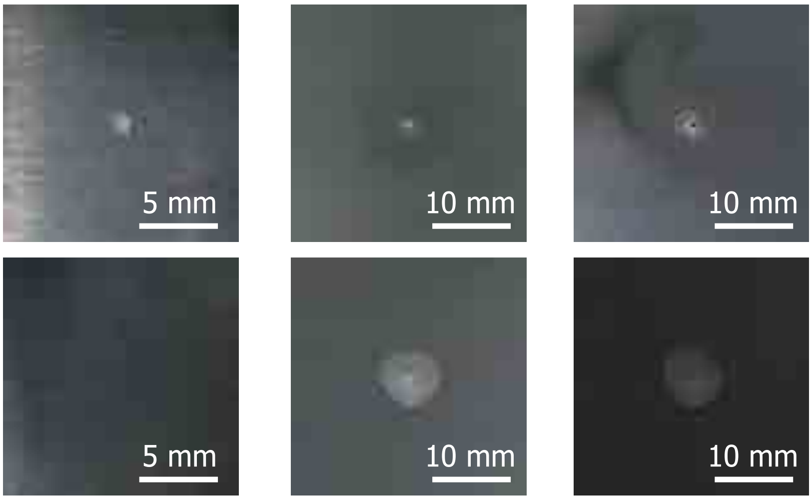
Material: SN282 by Kyocera Corp.

Size: 50 × 50 × 1.5~3 mm

Impact-induced fracture pattern

Impact surface

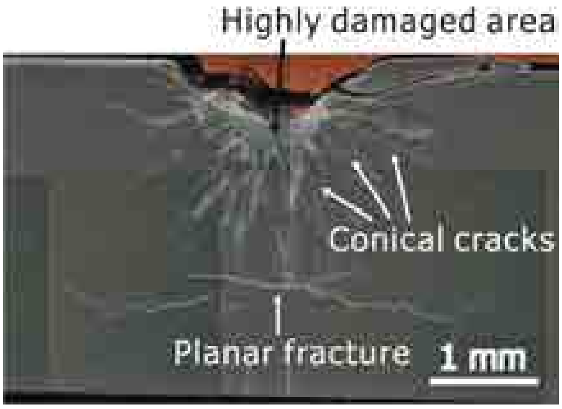
Rear surface



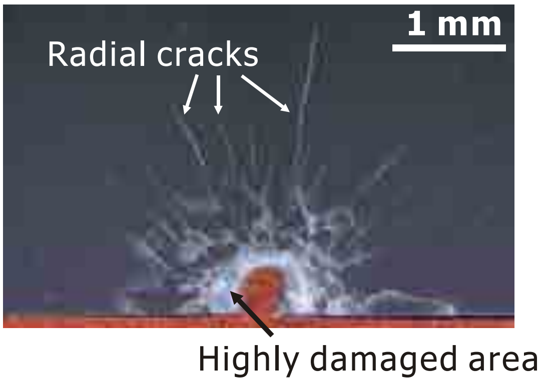
Projectile	Steel 300 μm	Steel 500 μm	Steel 500 μm
Impact velocity	4.43 km/s	3.52 km/s	3.85 km/s
Kinetic energy	1.10 J	3.22 J	3.85 J
Fracture pattern	Crater	Crater + Spall	Perforation

Impact-induced damage

Along impact axis



Perpendicular to impact axis (at a depth of 0.5mm)



- Highly damaged Si_3N_4 was observed immediately beneath and around the crater.
- Conical and radial cracks propagated inside the sample from the highly damaged region.

Impact-induced damage pattern

Cratering

- Highly deformed area beneath the crater
- Conical crack propagation

Planar spallation

- Thin planar fracture induced by rarefaction

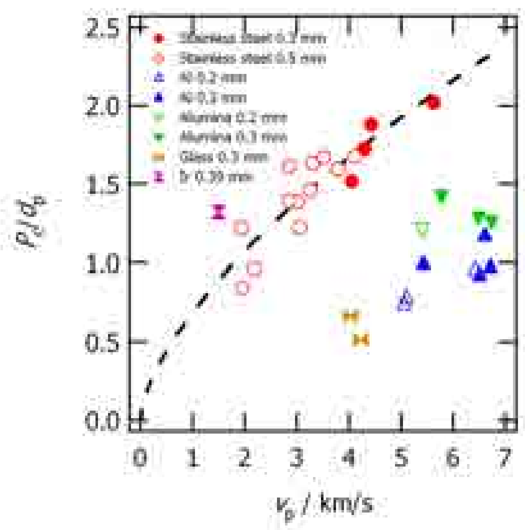
Conical spallation

- Fracture by conical cracks

Perforation

- By linking the crater and the conical spall

Crater depth



Crater depth is taken as a damage cracteristic.

Crater depth measurement: by a laser microscope

■ Crater depth formed by the impact of a steel sphere

$$P_{ss} = 0.69 d_p v_p^{0.64}$$

P_c:crater depth, d_p:projectile diameter, v_p:projectile velocity

□ The differences of crater depths between steel and other materials are caused by differences of the material density.

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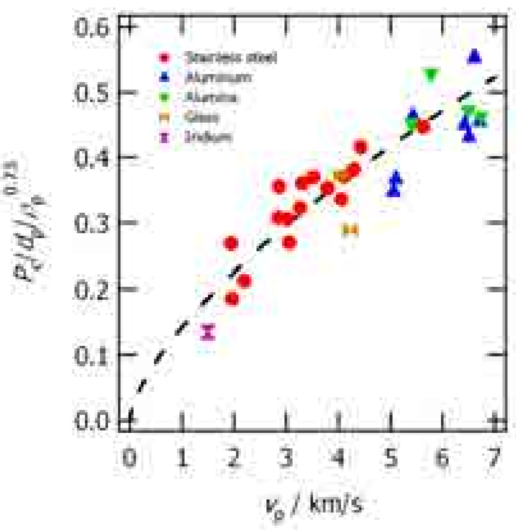
Penetration equation



Effect of projectile density

✓ Assuming a power-low relation

α:exponent for density

$$\left(\frac{P_c}{P_{ss}}\right) = \left(\frac{\rho_p}{\rho_{ss}}\right)^{\alpha}$$

ρ_p:projectile density,
ρ_{ss}:steel density=7.8 Mg/m^3

Penetration equation

$$P_c = 0.142 d_p \rho_p^{0.73} v_p^{0.67}$$

In the case of other brittle materials

For Glass

$$P_c = 0.53 d_p^{1.06} \rho_p^{0.5} v_p^{2/3}$$

B. G. Cour-Palais, IJIE **23**, 137 (1999).

For C/C composite coated by SiC

$$P_c = 0.61 d_p \left(\rho_p / \rho_t\right)^{0.5} \left(v \cos\theta\right)^{2/3}$$

Christiansen and Friesen, IJIE **20**, 153 (1997).

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Impact-induced damage pattern

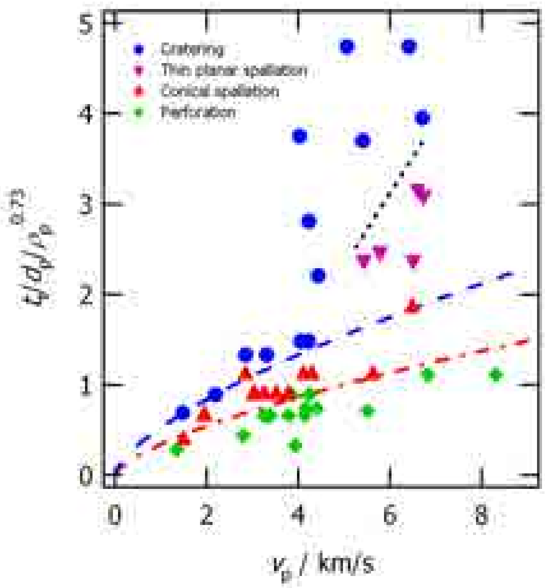
Cratering
- Highly deformed area beneath the crater
- Conical crack propagation

Planar spallation
- Thin planar fracture induced by rarefaction

Conical spallation
- Fracture by conical cracks

Perforation
- By linking the crater and the conical spall

Failure morphology map



t_t: Target thickness

- Critical target thickness for each fracture pattern is described by a multiple form of the penetration equation.

Critical thickness equation

$$t_f = 0.142 k d_p \rho_p^{0.73} v_p^{0.67}$$

k: Fracture factor

t_f: Critical thickness to prevent fracture

for Conical spallation

$k = 3.7$ Metal: 2.2 Glass: 7.0

for Perforation

$k = 2.4$ Metal: 2.2

Impact test of nozzle throat model

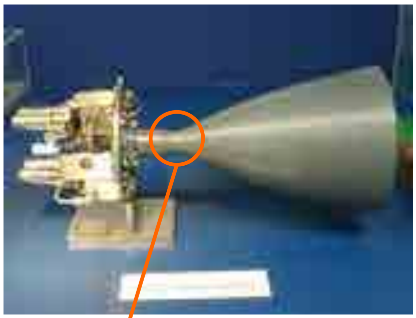
Impact test of nozzle throat model

Size：φ29 mm×φ23 mm×L60 mm
t=3.0 mm

Projectile：Al sphere φ0.3 mm

Impact velocity：5.07 km/s

Impact energy：0.49 J
(99.9% of cumulative probability of impacts during "AKATSUKI" mission.)



Nozzle throat model after impact

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Thermal stress test after impact

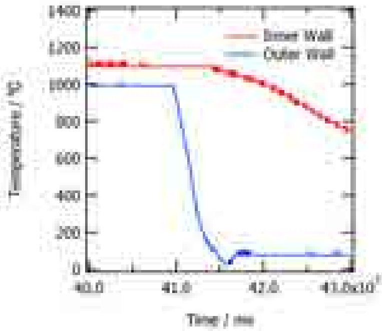
Impact test of nozzle throat model

Size：φ29 mm×φ23 mm×L60 mm
t=3.0 mm

Projectile：Al sphere φ0.3 mm

Impact velocity：5.07 km/s

Impact energy：0.49 J
(99.9% of cumulative probability of impacts during "AKATSUKI" mission.)



Thermal stress test

Impact crater after impact

after thermal stress test

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Summary

- HVI tests were performed on a silicon nitride plate in the velocity range up to 8 km/s to investigate its HVI-induced fracture behavior.
- The penetration equation of silicon nitride was determined.
- Impact-induced fracture patterns of three types were observed: cratering, cratering with spallation, and perforation.
- The boundaries of each fracture pattern were well described by the multiple form of the penetration equation.

D4

衛星設計を目的とした微小デブリの２重壁への衝突過程の数値解析による貫通限界曲線の推定

An Estimation of the Ballistic Limit Curves by Performing Numerical Analyses of the Small-Size Space Debris Impacts on the Components of Satellites for the Purpose of their Designs

○竹場敦史，片山雅英（伊藤忠テクノソリューションズ㈱，CTC），仁田工美（JAXA）
○Atsushi TAKEBA, Masahide KATAYAMA (ITOCHU-Techno Solutions Corp., CTC),
Kumi NITTA (JAXA)

1991 年、NASA/MSFC の K.B.Hayashida らは、1960 年代にアポロ計画を中心にして検討されたメテオロイド防護技術としての 2 重板シールドシステム、いわゆる、Whipple バンパーシールドの貫通限界式、及びその後スペースデブリの脅威を踏まえて見直された式について概観した報告書を出している。そこで検討された式は、膨大な数の 2 段式軽ガス銃を中心とした試験結果に基づいたものであるが、1947 年に F. L. Whipple が提案したアイデアを物理的に精査しメカニズムを明らかにすることによって、その防護システムの有効性を確認したものである。Fig.1(a)は同報告書に記載された、Ballistic, Shattering, Hypervelocity の 3 つの Regime の存在を示した図であり、Fig.1 (b)はこの 3 つの領域の存在のために、1 枚板の貫通限界式に比べて 2 重板シールドシステムの防護性能が如何に向上するかを示した図である。筆者らは、JAXA 宇宙機設計標準推進委員会デブリ防護設計 WG の活動の一環として、「スペースデブリ防護設計マニュアル」の作成を行っているが、その過程で、衛星設計に資するため、実験によるのではなく、数値解析によって貫通限界式の検討を行った。その一例をFig.1(c)に示す。数値解析のみによって気化領域を含むWhippleシールドの貫通限界曲線(式)の推定を行ったのは世界的に見ても初めての試みであると思われる。

In 1991, K. B. Hayashida et al. at MSFC/NASA published a report reviewing the ballistic limit equations (BLE’s)for the “Double-Plate”, so-called Whipple bumper shield, which was investigated as a protection technology for the space vehicle from interplanetary meteoroid impacts mainly for the purpose of the Apollo program in 1960’s. The report also reviews the modified equations applicable for the space debris impact, after the space debris problem emerged in 1970's. The BLE’s referred to in the report were derived on the basis of vast amounts of hypervelocity impact tests using launchers like two-stage light gas gun, it was confirmed and proven that the Whipple bumper shield is indeed effective for the meteoroid protection by investigating and clarifying the mechanism of it, of which idea was proposed by F. L. Whipple in 1947. Figure 1(a) depicts the existence of three regimes of the ballistic, shattering and hypervelocity, and Fig.1(b) indicates the effectiveness of the “Double-Plate” in comparison to the “Single-Plate”, both graphs are published in the report. The authors have been writing the “Design Manual on Space Debris Protection” as an activity of the Working Group of the Space Debris Protection Design at JAXA, and they tried to derive the ballistic limit curves (equations) of small projectile impacts on the “Double-Sheet” targets only by the numerical analysis, not by the experiment. Figure l(c) shows one of such curves. The derivation of the BLE’s for the Whipple bumper shield only by the numerical method, taking into account the shock-induced vaporization, is probably recognized as the first trial in the world.

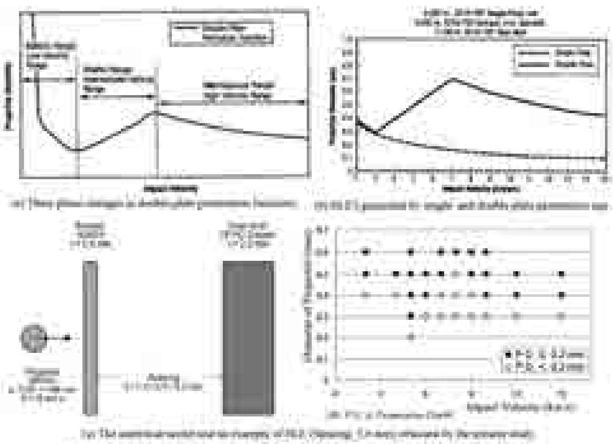


Fig. 1 Ballistic limit equations (BLE's) of "Double-Plate" targets (Whipple bumper shield)

Challenging Tomorrow's Changes

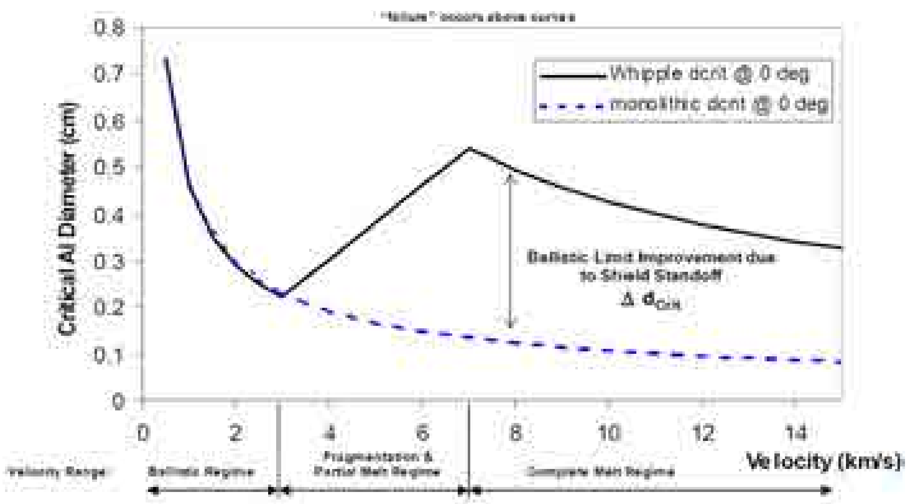
衛星設計を目的とした微小デブリの2重壁への衝突過程の数値解析による貫通限界曲線の推定

An Estimation of the Ballistic Limit Curves by Performing Numerical Analyses of the Small-Size Space Debris Impacts on the Components of Satellites for the Purpose of their Designs

2013年1月23日

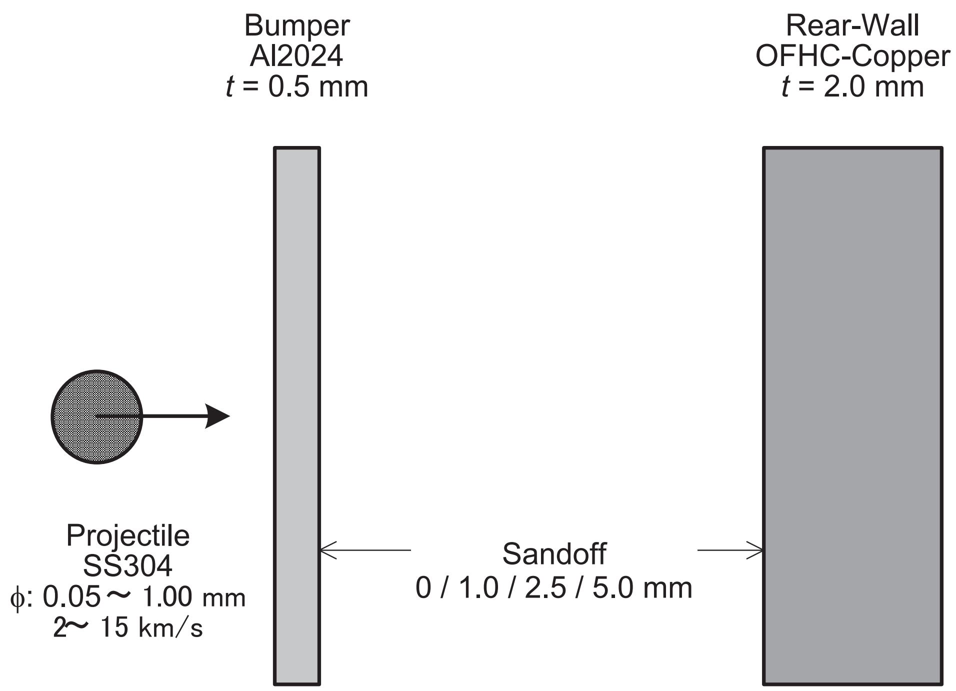
竹場 敦史、片山 雅英 (CTC)
仁田 工美 (ISAS/JAXA)

- Ballistic limits for equal mass monolithic target and Whipple shield



- Ballistic limit curve for the small-size space debris was estimated by the numerical analysis. A hydrocode: ANSYS AUTODYN was applied to the analysis.

Numerical Analysis Model



Numerical Analysis Model

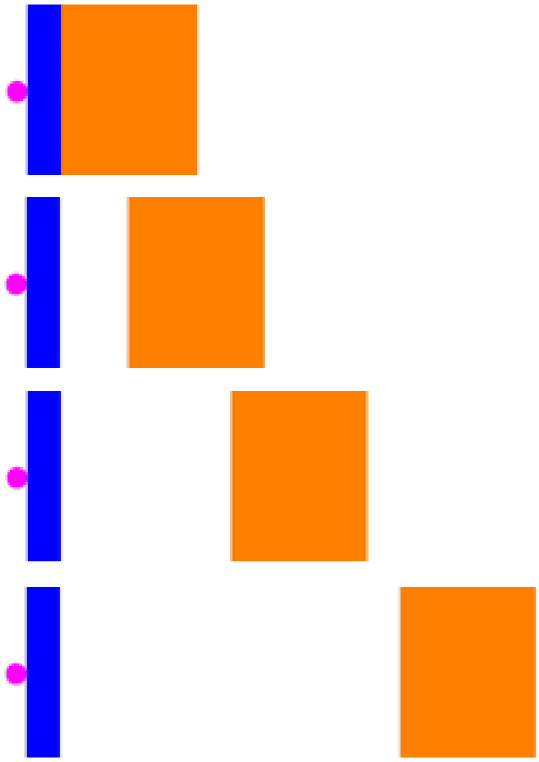
CTC

Standoff 0mm

Standoff 1mm

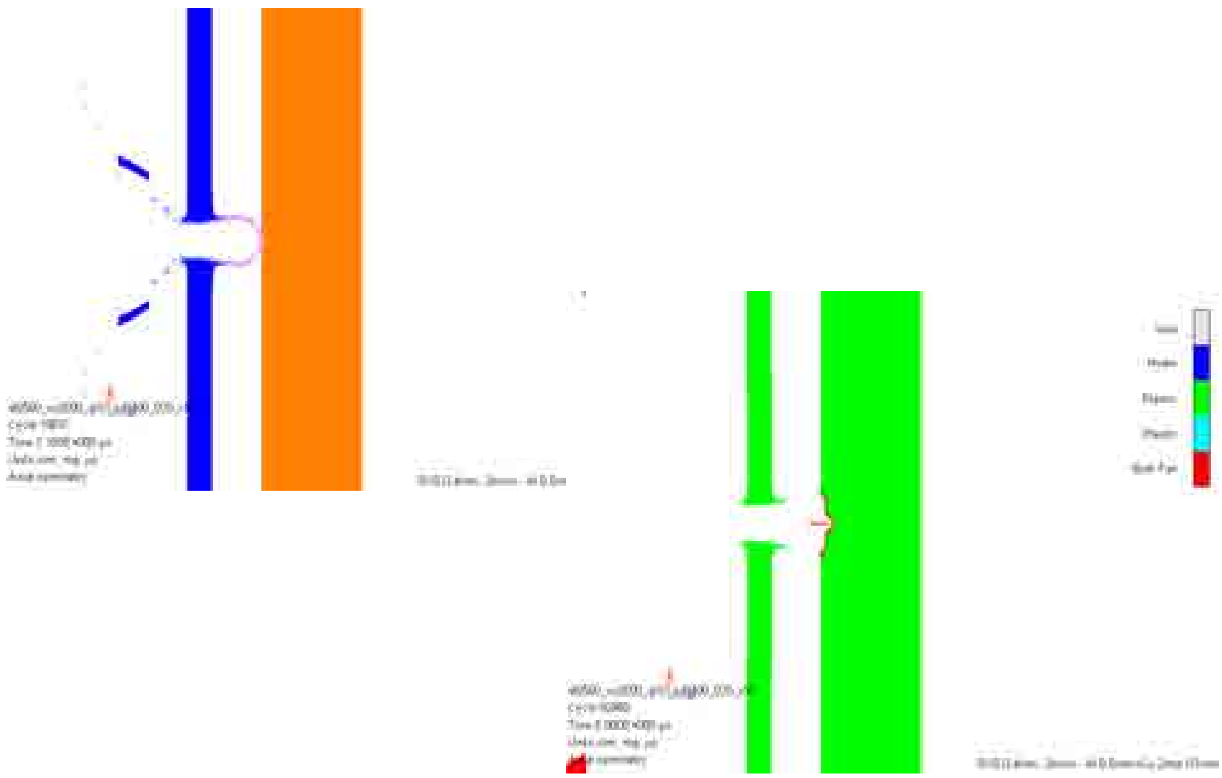
Standoff 2.5mm

Standoff 5mm



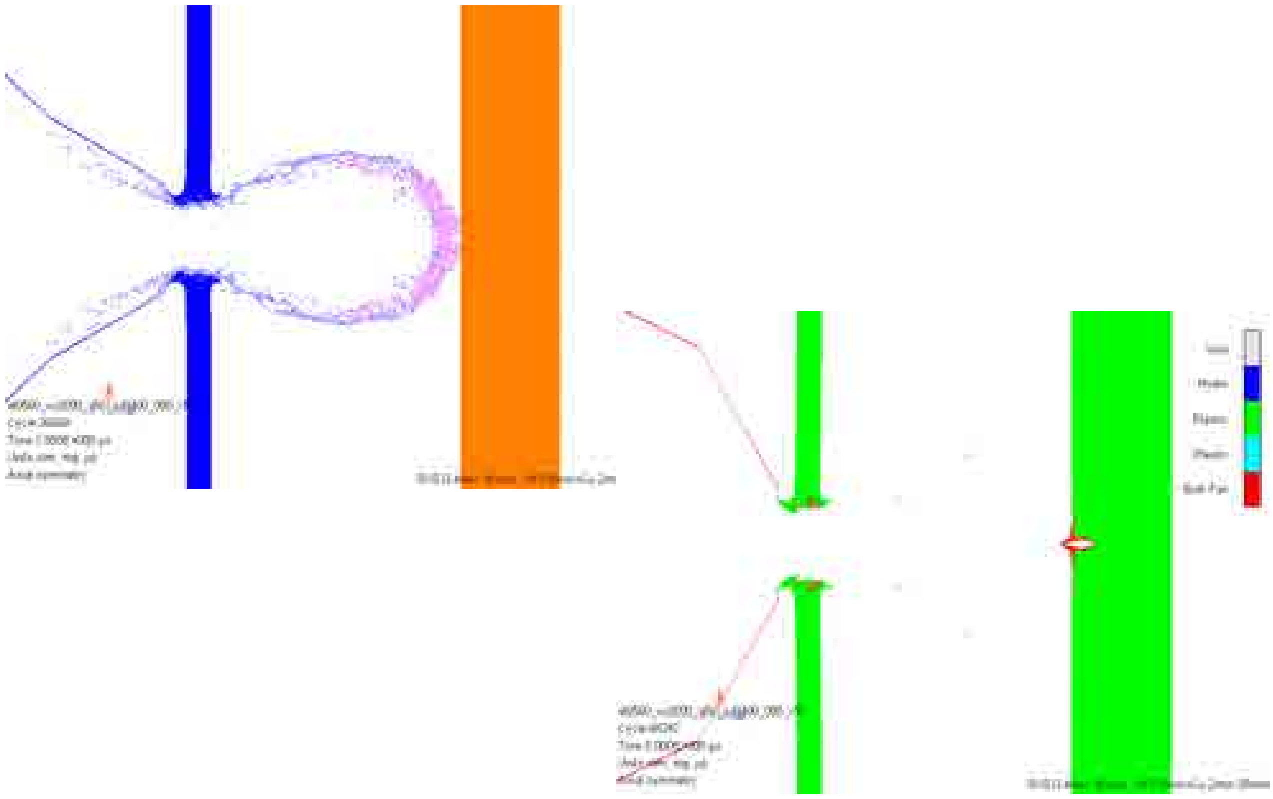
Standoff : 1mm Projectile : ϕ 0.4mm 2km/s

CTC



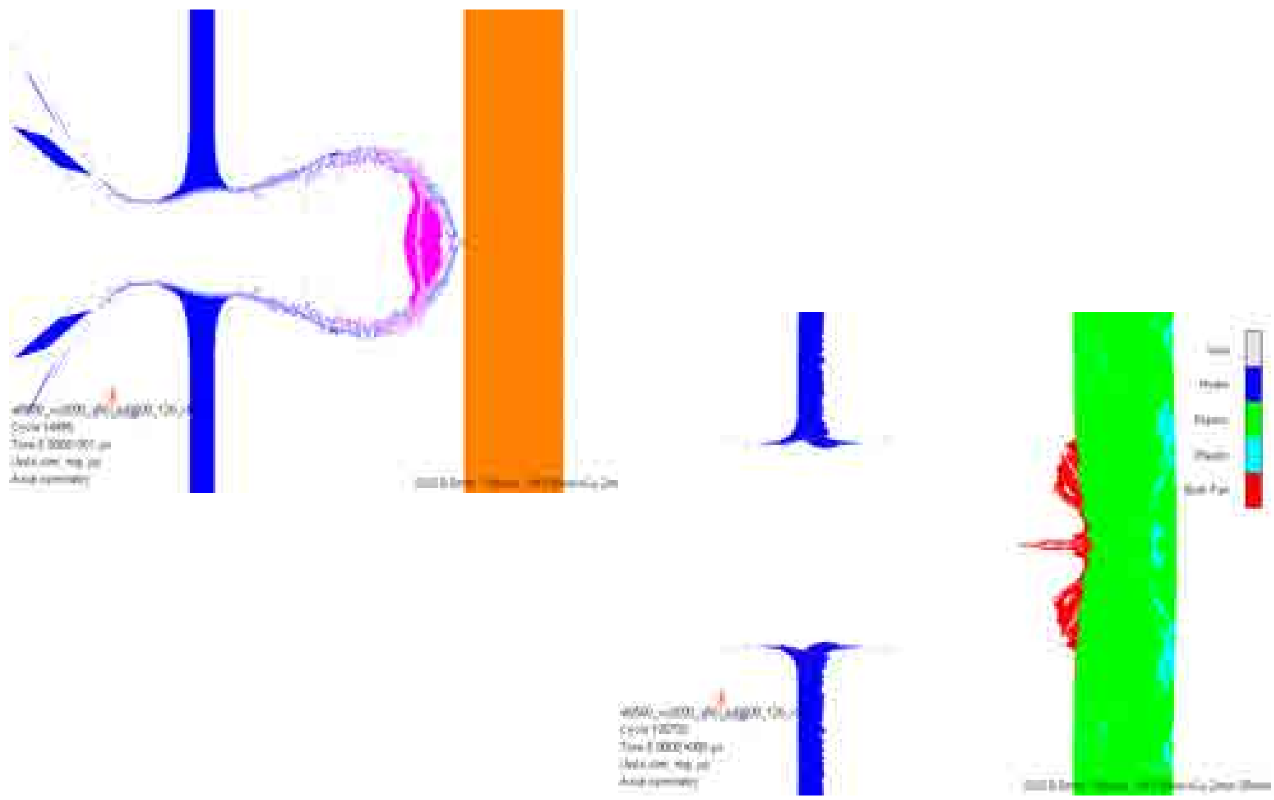
Standoff : 5mm Projectile : ϕ0.4mm 5km/s

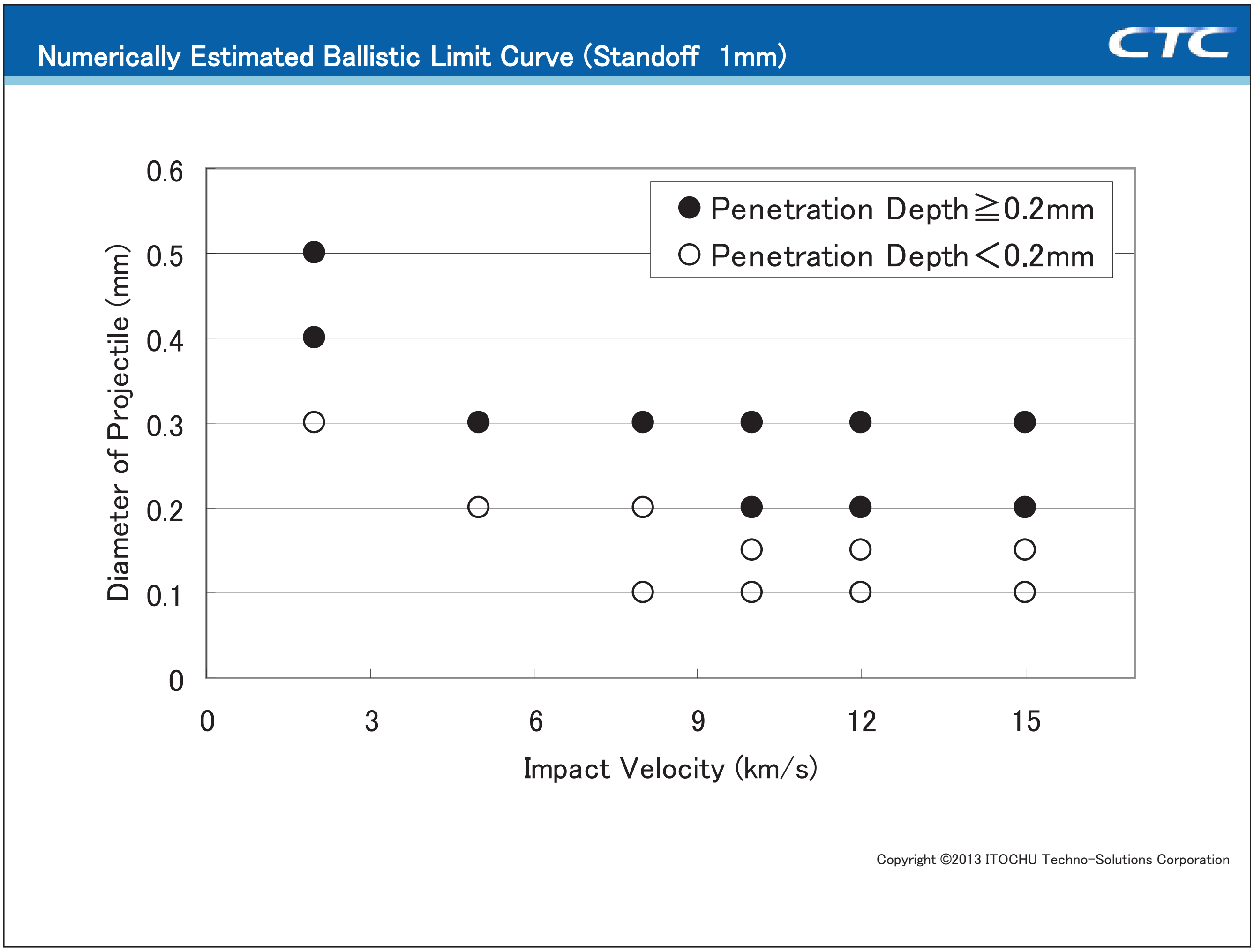
CTC

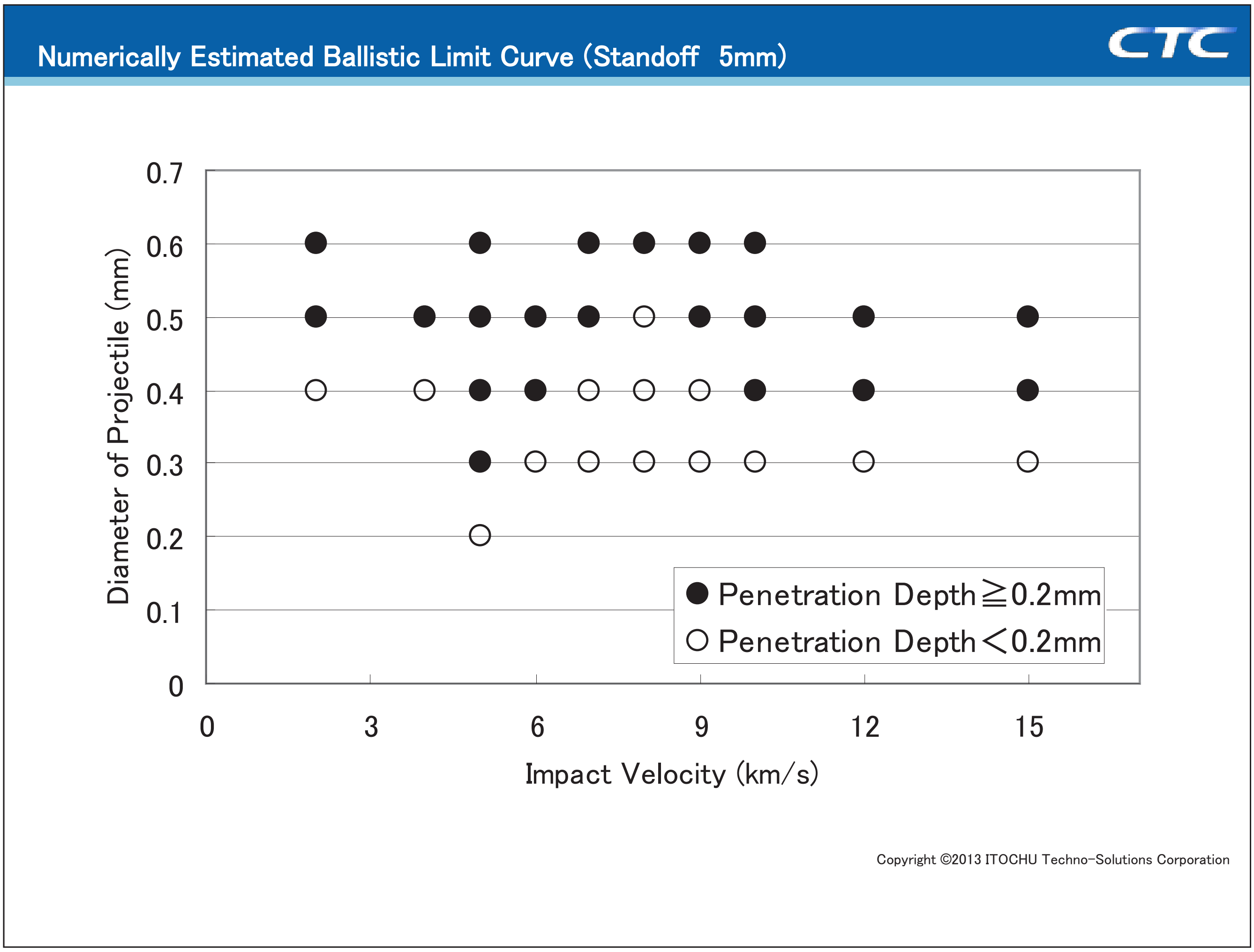


Standoff : 5mm Projectile : ϕ0.5mm 12km/s

CTC




Numerically Estimated Ballistic Limit Curve (Standoff 1mm)
CTC
Penetration Depth≧0.2mm
Penetration Depth<0.2mm
Diameter of Projectile (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
3
6
9
12
15
Impact Velocity (km/s)
Copyright ©2013 ITOCHU Techno-Solutions Corporation


Numerically Estimated Ballistic Limit Curve (Standoff 5mm)
CTC
Penetration Depth≧0.2mm
Penetration Depth<0.2mm
Diameter of Projectile (mm)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
3
6
9
12
15
Impact Velocity (km/s)
Copyright ©2013 ITOCHU Techno-Solutions Corporation

まとめ、課題

- The authors tried to derive the ballistic limit curves (equations) of small projectile impacts on the “Double-Sheet” targets only by the numerical analysis, not by the experiment. The derivation of the BLE’s for the Whipple bumper shield only by the numerical method, taking into account the shock-induced vaporization, is probably recognized as the first trial in the world.

D5

薄板への超高速衝突におけるプラズマ発生の研究

Plasma Generation caused by Hypervelocity Impact against Thin Sheet Materials

○田中孝治（JAXA），長岡洋一（総研大），佐々木進（JAXA）
○Koji Tanaka (JAXA), Yoichi Nagaoka (Sokendai), Susumu Sasaki (JAXA)

衛星軌道上に存在するメテオロイドや宇宙デブリのような超高速飛翔体の脅威は年々深刻化しており、デブリバンパをはじめ、その対策が活発に研究されている。超高速飛翔体との衝突は、衛星の物理的破壊とともに、電気回路には衝突時に発生するプラズマが影響を与える可能性がある。超高速飛翔体による衝突破壊において、衝突した瞬間に運動エネルギーの一部は熱に変換され、その周囲の固体が気化する。気化した物質がイオン化してプラズマを発生させる。特に最近の衛星の大電力化に伴い、バス電圧や太陽電池パドルにおける発生電圧は高電圧化しており、衝突により発生したプラズマが契機となって、ショートやアーク放電を引き起こし、それにより高電圧機器を損傷させる可能性がある。また、プラズマの発生に伴い、電位変動現象も確認されている。

我々は、超高速飛翔体との衝突破壊現象において発生するプラズマの定量的計測や電位変動に関して研究を行っている。本報告では、宇宙科学研究所のレールガンや2段式軽ガス銃を使用した薄膜材料への衝突破壊実験に関して述べる。

Space debris is recognized as a serious threat to man's utilization of space. When debris collide the spacecraft, plasma will be generated and may make a impact on the spacecraft's equipments. To simulate the debris impact against the spacecraft, we carried out the experiments on the detection of the generated plasma by the hypervelocity impacts concerning the thin sheet materials using a two stage light gas gun and a rail gun accelerator of the Institute of Space and Astronautical Science. We observed phenomena when the projectile collided a target using a high-speed video camera, plasma probes and spectral photo sensors. Figure 1 shows a bright cloud of the impact experiment. After the projectile impacted against the target, a bright cloud was generated and moved both forward and backward directions from the target. Results of the experiments were compared with the estimations by our simple impact model for thin sheet targets.

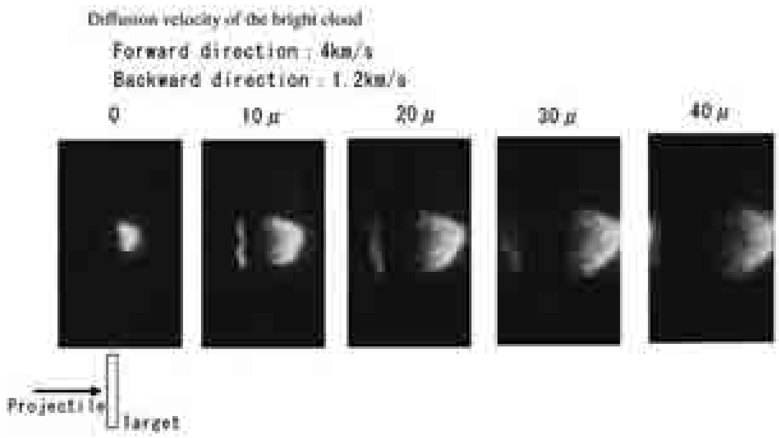


Fig1 Impact event recorded by the high speed video camera. Target : Al, Velocity of Projectile ; around 4km/s, Projectile: Polycarbonate, around 1g.

Plasma Generation by Hypervelocity Impact on Thin Sheet Materials

〇Koji Tanaka(ISAS/JAXA), Yoichi Nagaoka (SOKENDAI), Susumu Sasaki (ISAS/JAXA)

1

Background

- The increase of the orbital debris are recognized as a serious and growing threat to man's utilization and exploration of space.
- Typical debris impacts against a spacecraft in orbit are thought to occur at a velocity of around 10 km/s .
- Such hypervelocity impact against the spacecraft will possibly cause serious damages mechanically and electrically.

The Habble Space Telescope

Impact damage caused by meteoroid

Thin film solar array of IKAROS

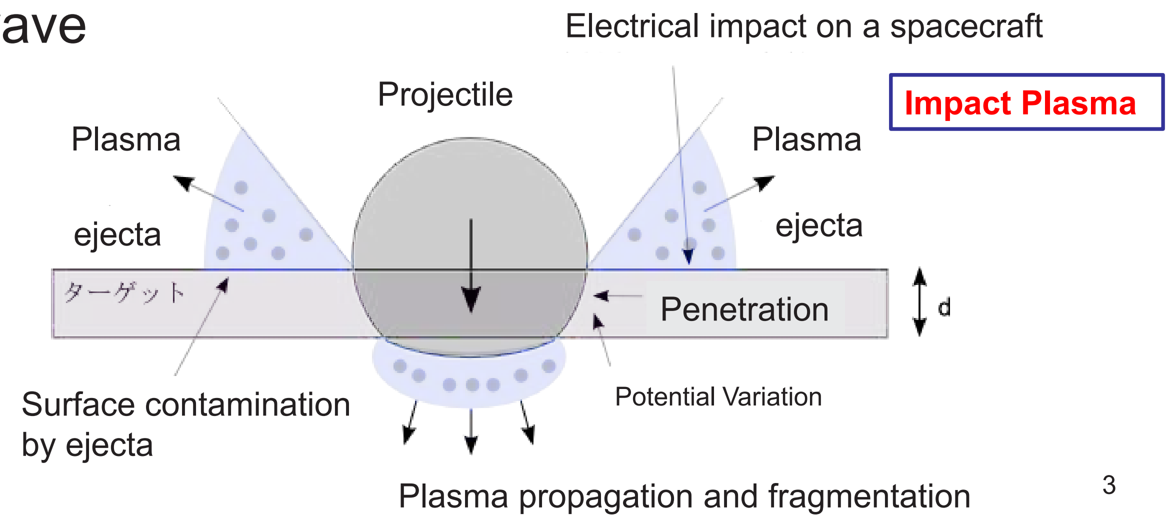
2

B.Henson *et al*., Preparing for the Future, Vol.5, No.4, 1995, pp.16-17.

Phenomena by Hypervelocity Impact

Mechanical Phenomena : Crater, Penetration, Impact fragmentation

Electrical Phenomena : Plasma generation, Potential variation, Radiation of electromagnetic wave



3

The purpose of this study

Measurement and estimation of the plasma generated by the hypervelocity impact.

Clarify the effect of the debris impact against the thin sheet materials of the spacecraft.

4

Experimental Method

- Impact experiment concerning the thin sheet materials using a two stage light gas gun.
- Phenomena when the projectile collided targets were observed using a high-speed video camera, plasma probes and spectroscopic measurement.

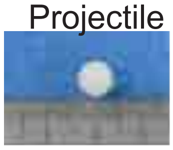
5

ISAS Two Stage Light Gas Gun

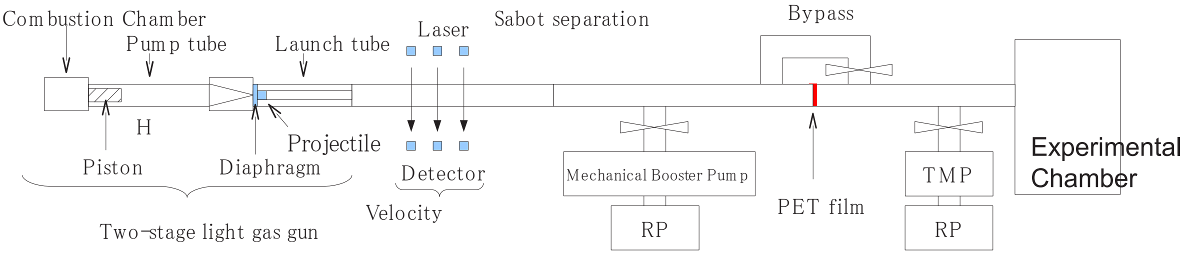
Maximum Speed of the Projectile
: 6 km/s
Light Gas : H2, He

High Speed Video Camera

Projectile



Material : Nylon 66
Aluminum



Vacuum conditions in the experimental chamber : less than 4×10^{-2} Pa (to avoid the collisional effect of the residual gas to the plasma propagation)

6

Temperature Measurement by Photo diode

- Black body approximation was assumed.
- Wavelength : 500nm, 700nm, 900nm

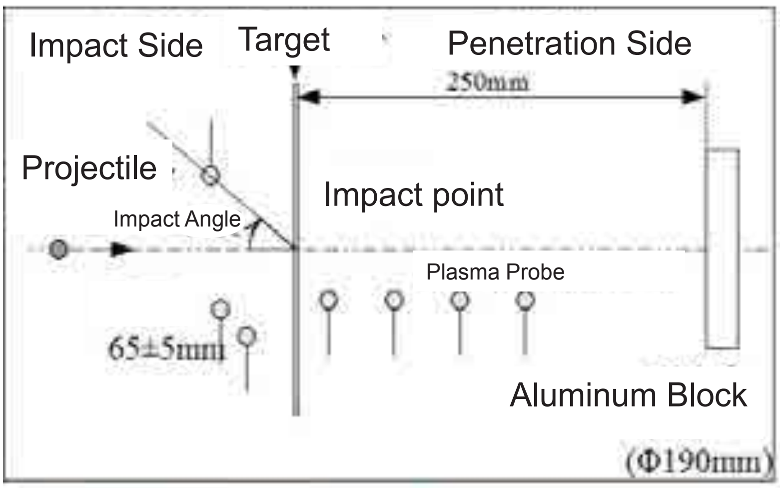

Configuration of photo diodes

Calibration of light intensities by photo diodes

Wavelength [nm]	Spectral sensitivity [A/W]	Transmission factor [%]	Corresponding value
500	0.30	66	5.05
700	0.48	61	3.42
900	0.57	66	2.66

7

Plasma Measurement



Impact Side
Penetration Side

Double Probe

Measurement Circuit

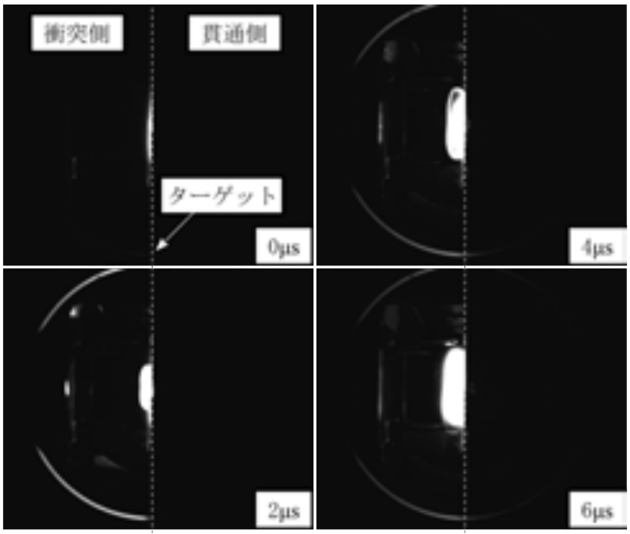
κ=0.61

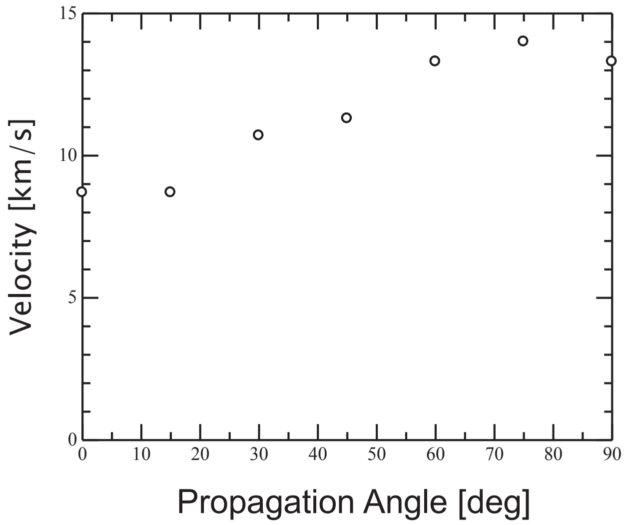
$$I_{i0} = \kappa N_e e S \left(\frac{kT_e}{m_i}\right)^{1/2}$$

Probe current

8

Propagation of luminous cloud
（Al500μm）



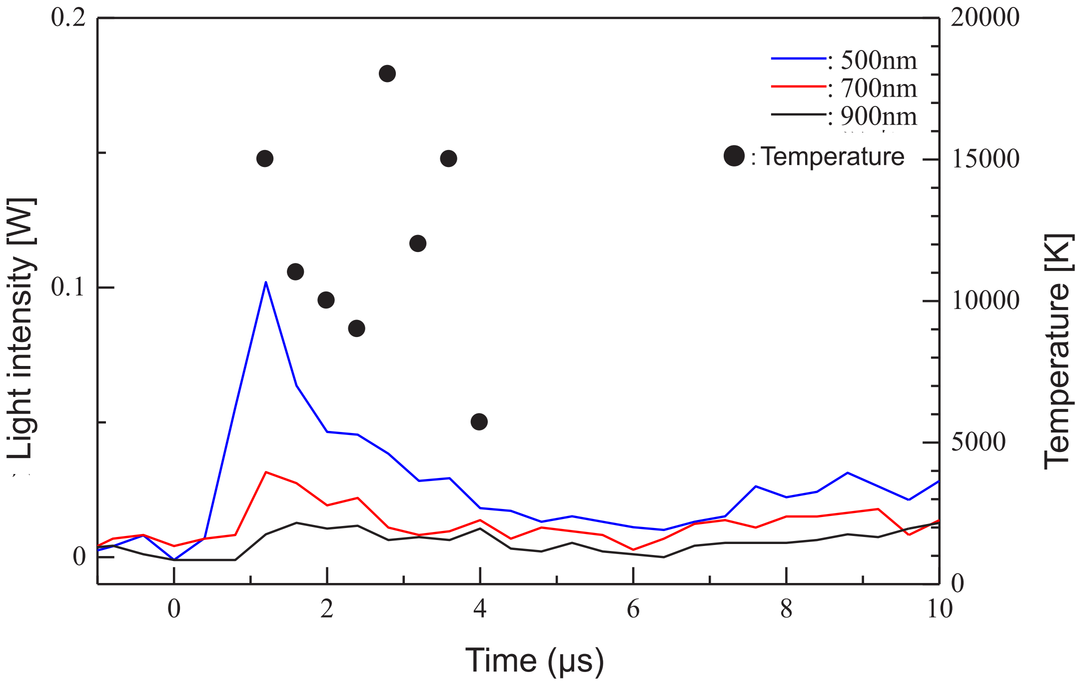


Photograph by high speed video camera

Propagation velocity of luminous cloud

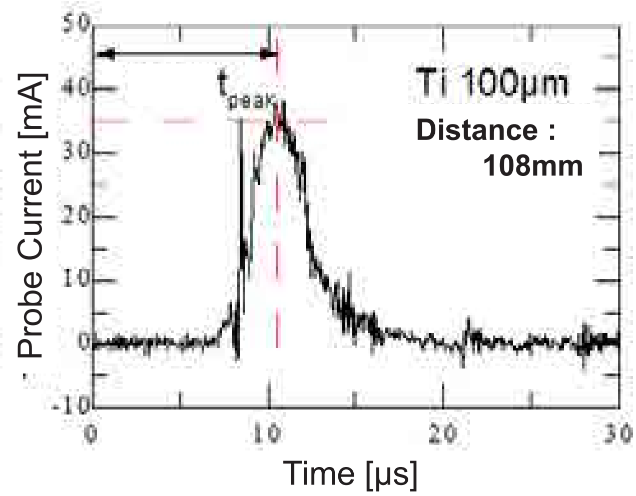
9

Light Intensity Variation
Target : Al（Thickness: 500μm）



10

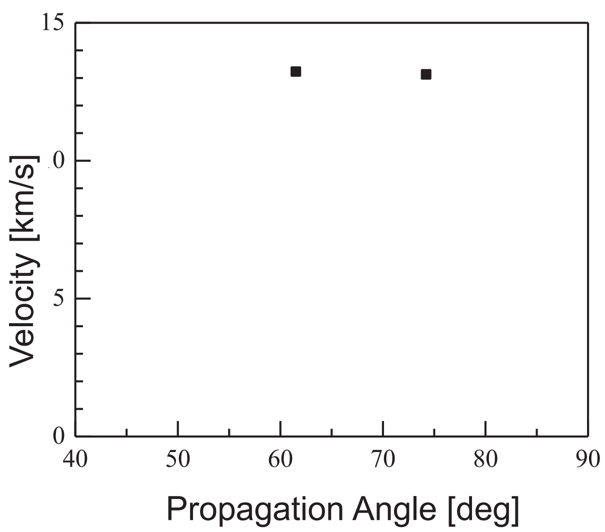
Waveform measured by plasma probe



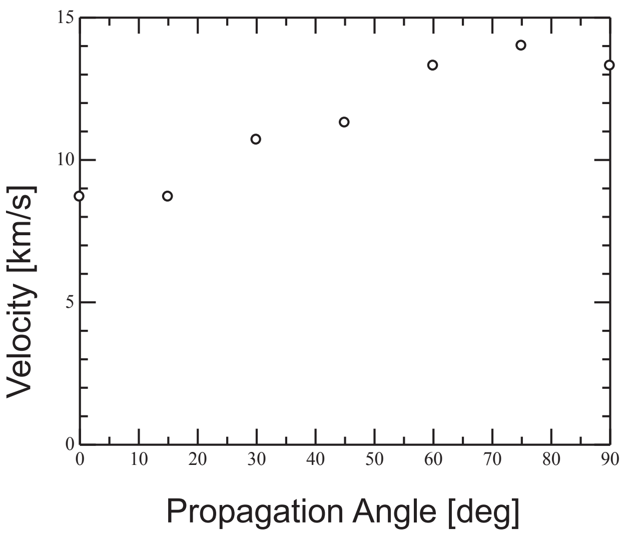
Plasma propagation velocity was calculated by hitting time of plasma at the probe.

11

Comparison between Propagation Velocity by Luminous Cloud and one by Plasma（Al, Thickness:500μm）



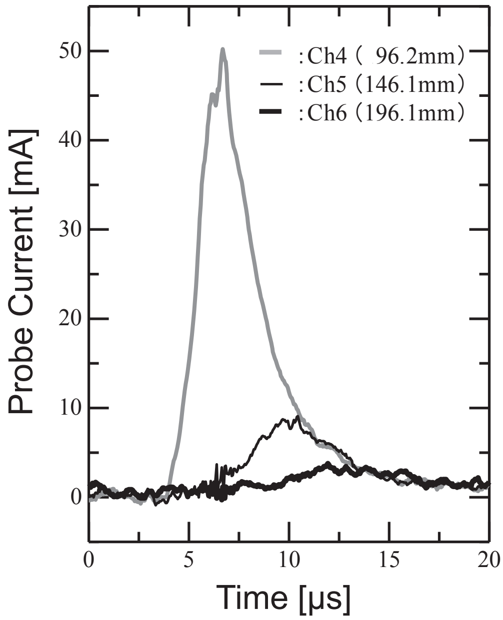
Plasma

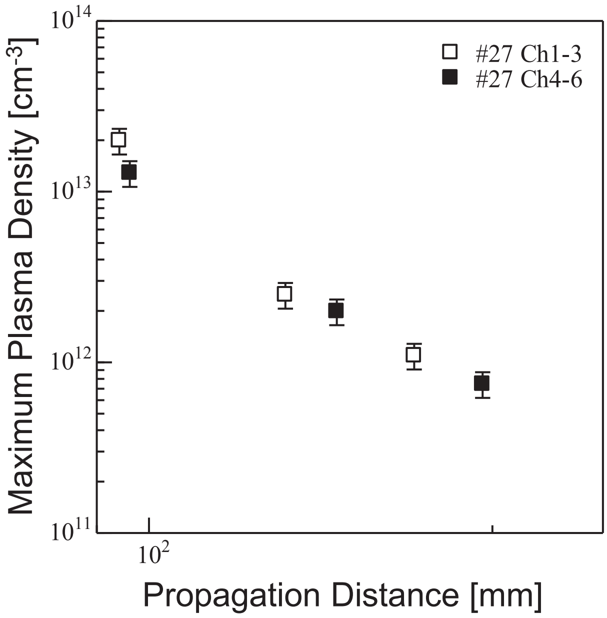


Luminous Cloud

12

Plasma density – Distance Relationship

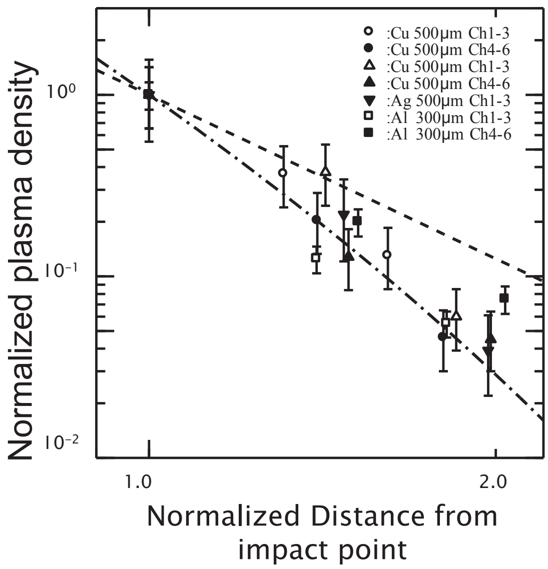




Plasma density decayed with propagation distance.

13

Relationship between plasma density and propagation distance



The experimental results show that the maximum plasma density decreased as L^{-4} ~ L^{-5}.

L：mean free path

If we assume that the background gas density temporarily increased at the impact, the experimental results should be affected.

14

Propagation of impact plasma

The model based on a drift Maxwellian distribution suggests that the maximum plasma density n_{max} is deceased with the distance from the impact point (L) as L^{-3}.

$$n_{max} \propto \frac{1}{L^3}$$

15

Results

- The experimental results show that the plasma density was maximum between 70° and 90° and decreased with the decreasing angle.
- The maximum plasma density is deceased with the distance from the impact point as L^{-3} when a drift Maxwellian distribution is assumed. However, the experimental results show that the maximum plasma density decreased as $L^{-4} \sim L^{-5}$.
- The plasma velocity was generally highest along the target surface and decreased with the angle from the surface.

16

Conclusions

- The plasma density observed in the experiment was as much as 10^{13} cm^{-3} at 10 cm from the impact point, which is much higher than the plasma density in ionosphere by the 7th order of magnitude.
- It is reported that the high voltage solar array with more than 100 V has a potential risk for the electrical discharge in the ambient plasma density more than 10^{10} cm^{-3}.
- The amount of the plasma production depends on the impact velocity, mass and material of the projectile, and thickness and material of the target.
- Our experimental results suggests that the area with the discharge risk on the solar array panel of the spacecraft in space could be extended 1-2 m around the impact point of space debris.

D6

超高速飛翔体衝突により生ずるイジェクタのサイズ分布

Size distribution of ejecta resulting from hypervelocity impacts of projectiles

○西田政弘，林 浩一（名工大），長谷川直（宇宙航空研究開発機構）
○Masahiro Nishida, Koichi Hayashi (NITech), Sunao Hasegawa (JAXA)

デブリ衝突によってイジェクタが発生し，それらが二次デブリとなるため，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．イジェクタに影響を与える要因として，ターゲットの材料特性や温度，飛翔体の衝突速度，衝突角度，材料特性，形状や衝突速度が考えられるが，それらを調べつつある．講演ではこれまでの研究成果の一部を紹介する．発生したイジェクタについては，実験後，チェンバーから回収し，その形状，質量，面積質量比を測定した．高速度カメラによる画像およびターゲット前方に設置した検証板の衝突痕からイジェクタの噴出角度も調べた．

Space debris often strikes spacecraft and space stations at very high velocities, forming ejecta fragments. A significant fraction of the secondary debris in LEO results from such ejecta fragments. Therefore, it is important to understand ejecta composition and mechanisms of ejecta formation. We can expect that many factors, such as temperature and material properties of targets, impact velocity, impact angles, material properties and shape of projectiles, will affect the ejecta formation and composition.
We are now examining the effects of such factors, and I will present some of our results. After impact experiments, the mass, size and aspect ratio of the ejecta fragments collected from the test chamber were measured. The ejecta cone angles were examined using a high-speed video camera and indentations on witness plates in front of the targets.

第5回スペースデブリワークショップ
5th Space Debris Workshop, Jan 22-23, 2013

超高速飛翔体衝突により生ずるイジェクタのサイズ分布

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Masahiro Nishida, Koichi Hayashi (NITech), Sunao Hasegawa (JAXA/ISAS)

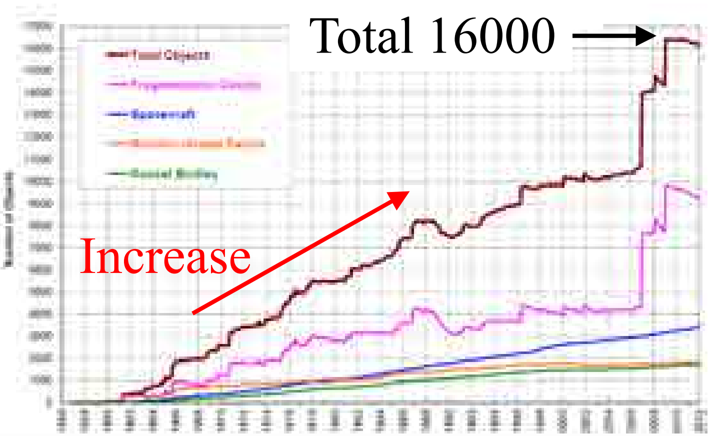
Space Debris

Image of space debris

Low Earth orbit (LEO)

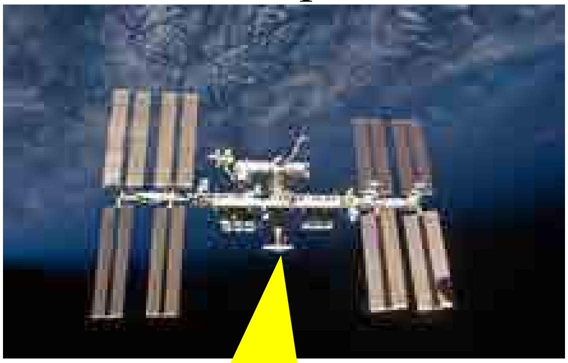
NASA Orbital Debris Program Office
http://orbitaldebris.jsc.nasa.gov/photogallery/beehives.html#leo

Number of cataloged objects



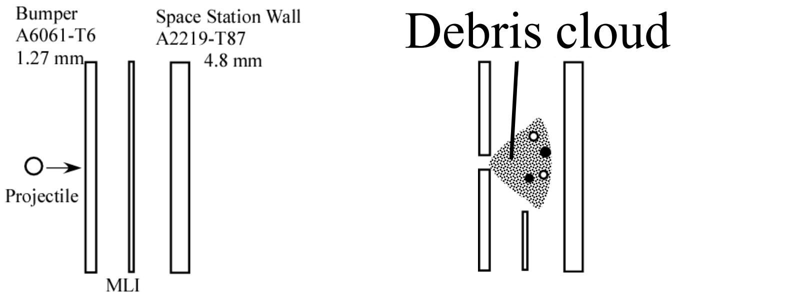
Debris Quarterly News, Vol. 16, Issue 1, 2012

International Space Station



NASA
http://spaceflight.nasa.gov/gallery/images/shuttle/sts-127/html/s127e011212.html

Bumper shields

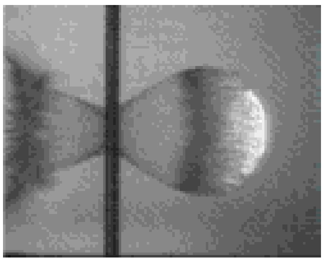


Whipple bumper   Thin-plate perforation

Debris Cloud & Ejecta Study for Thin Plates

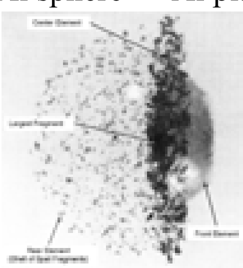
Formation of debris clouds

6 mm Al sphere → Al plate 2 mm
6.7 km/s



K. Thoma, *et al.*, Proc 3rd European Conf on Space Debris, 2001, p. 555-567

12.7 mm Al sphere → Al plate 0.59 mm
6.26 km/s



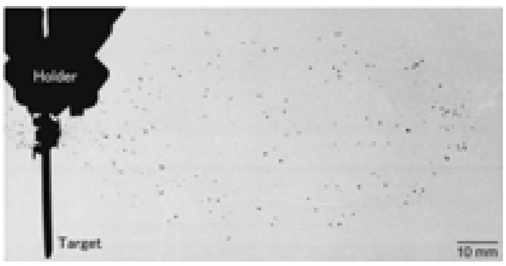
A.J. Piekutowski, Int. J. Impact Engineering, 1997, p. 639-650

Improvements to bumpers

7.9 mm Al sphere → CFRP[0°/45°]$_6$
1.7 km/s

R. Kubota, *et al.*, J. JSEM, 2010, p. 110-115

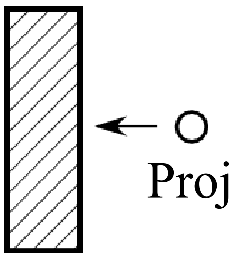
1.01 mm Al sphere → SiC-fiber/Al composite
4.31km/s



H. Tamura *et al.*, Int. J. Impact Engineering, 2011, p. 686-696

Penetration of Thick Targets (1 of 2)

Thick targets

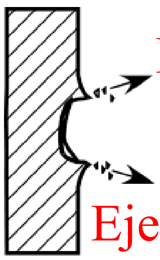


Projectile

Composition of ejecta

Numata, Kikuchi, Sun, Kaiho, Takayama, Proc JSSW, (2006), pp. 221-222.

Cratering

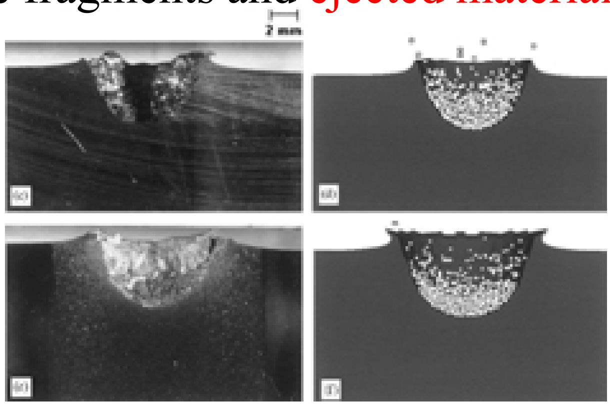


Projectile fragments

Ejecta

Secondary debris in LEO

Projectile fragments and ejected materials



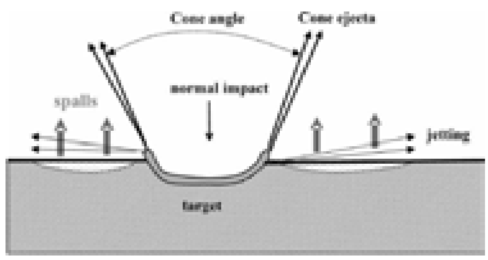
Murr, Int. J Impact Eng., (2006), pp. 1981-1999.

Penetration of Thick Targets (2 of 2)

Distribution chart of impact craters

Sugawara, K *et al.*, 60th International Astronautical Congress, IAC-09-A6.3.06, Daejeon, 2009.

Ejecta production mechanism on a brittle target



Siguier, J.M. & Mandeville, J.C., Proc. IMechE, 221, G, pp. 969-974, 2007.

Draft ISO (ISO/TC20/SC14/CD11227)

International standardization (ISO/DIS11227 "Space Systems – Test procedures to evaluate spacecraft material ejecta upon hypervelocity impact")

Important factors

- Temperature of targets (Nishida *et al.,* Int. J. Impact Eng., 2012, ISTS2013)
- Shape of targets
- Material properties of targets
- Impact velocity of projectiles (Nishida *et al.*, Int. J. Impact Eng., 2013)
- Material properties of projectiles (Nishida *et al.*, J. JSEM, 2012)
- Shape of projectiles
- Impact angle of projectiles (Proc. DYMAT, 2012)

Objectives of Our Research

To investigate effects of such factors on ejecta & crater shape

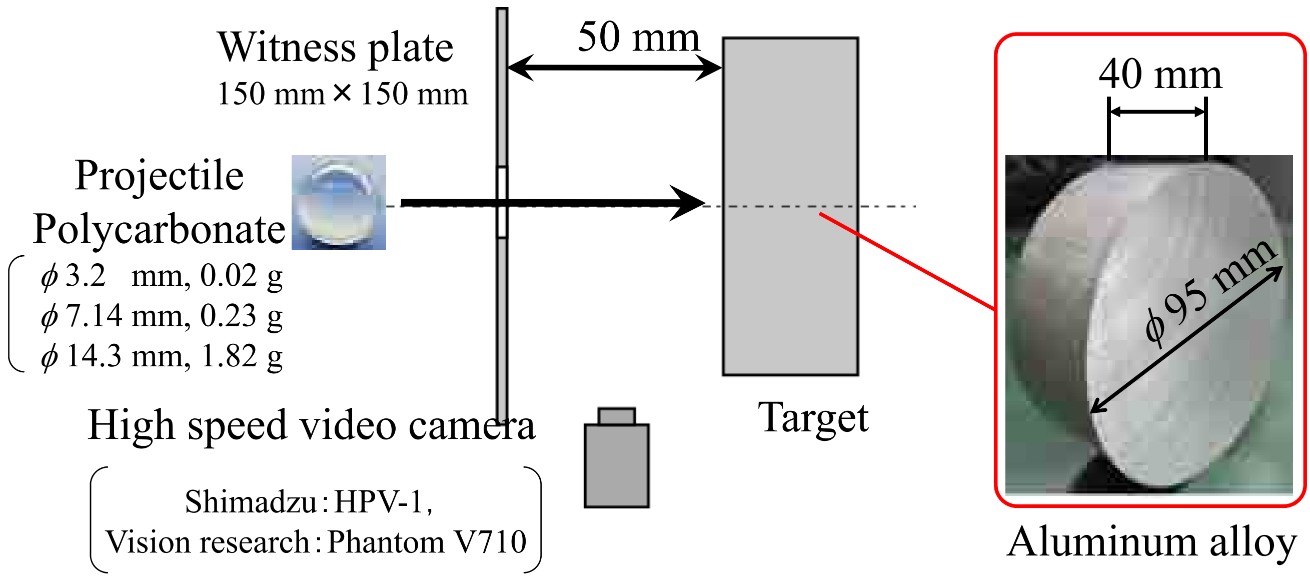
Long Term Goal of Our Research

- Understanding ejecta composition and mechanisms of ejecta formation when projectiles strike thick targets at very high velocities
- Obtaining basic data for new orbital debris models

Effects of Material Properties of Targets

Nishida, et. al, Int. J. Impact Engineering, Vol. 54, (2013), pp. 161-176.

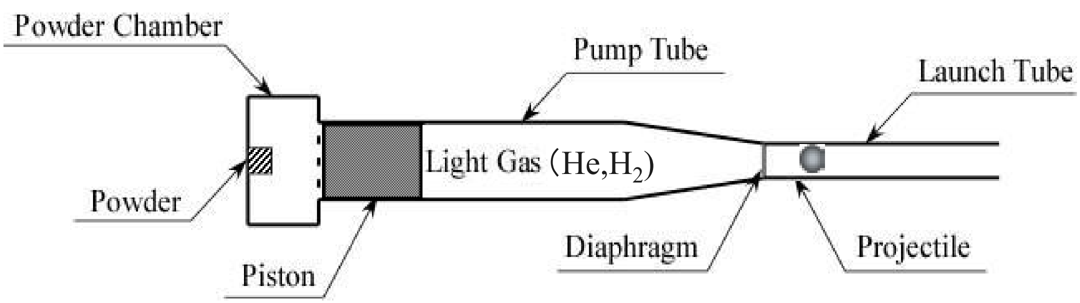
Experimental Setup



	A1100-O	A1100-H	A6061-O	A6061-T6
Tensile strength [MPa]	80	84	124	322
Yield stress [MPa]	42	48	61	287
Vickers hardness	24	35	38	110
Elongation [%]	60	46	30	9

Two-Stage Light Gas-Gun

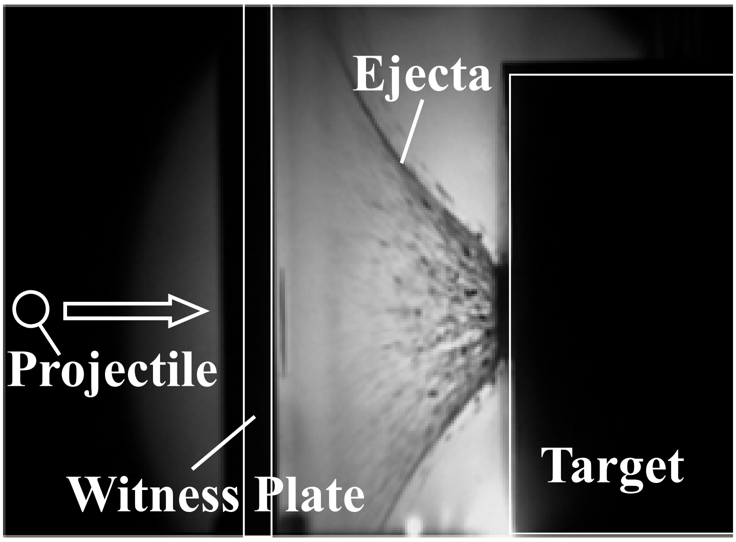
(ISAS, JAXA)



10

Image by High-Speed Video Camera

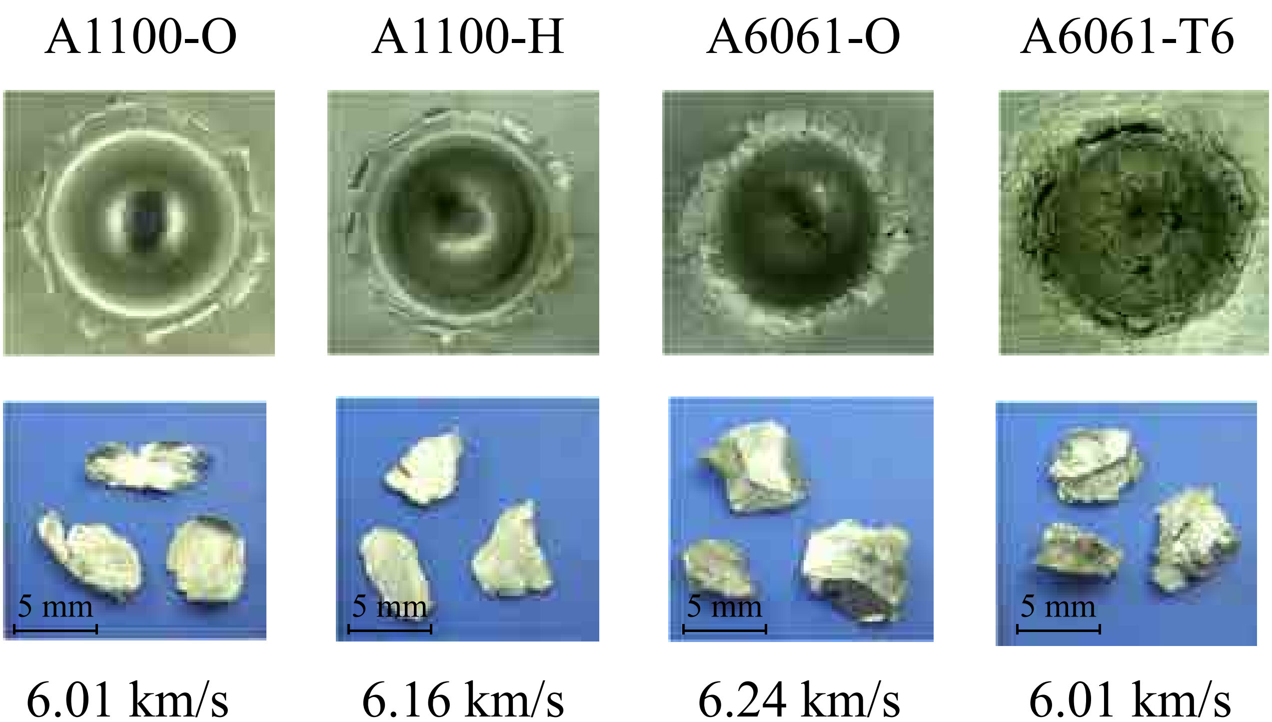
A1100-H, 1.98 km/s



16 μs after impact

11

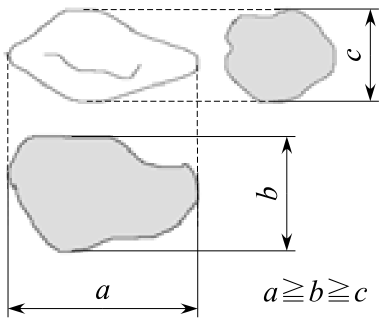
Crater and Ejecta



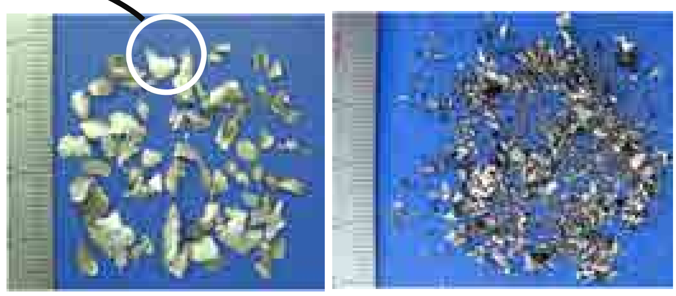
12

Definition of Ejecta

Measurement of mass distribution & size distribution of ejecta collected from chambers after experiments.



Condition
- Ejecta mass; > 1 mg
- Target origin



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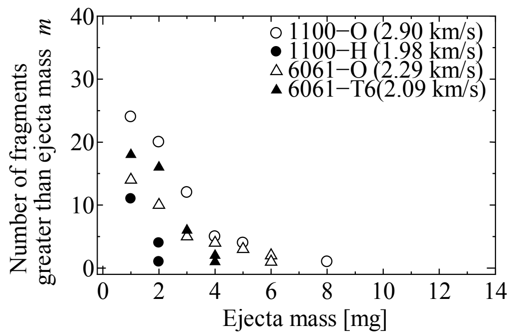
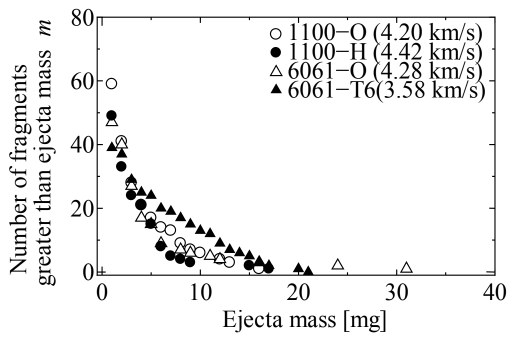
Distribution of Ejecta Mass

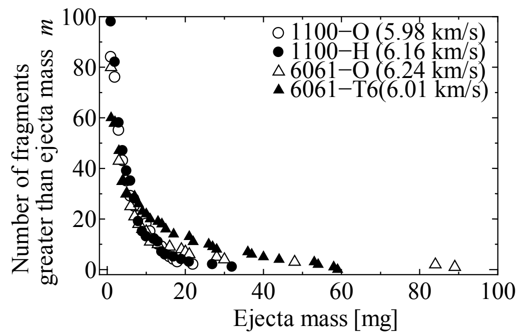
Impact velocity : 2 km/s



1100 < 6061



Impact velocity : 4 km/s



Impact velocity : 6 km/s

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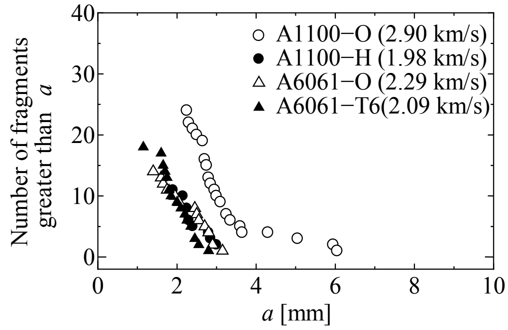
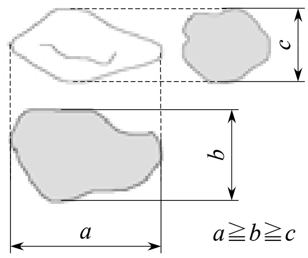
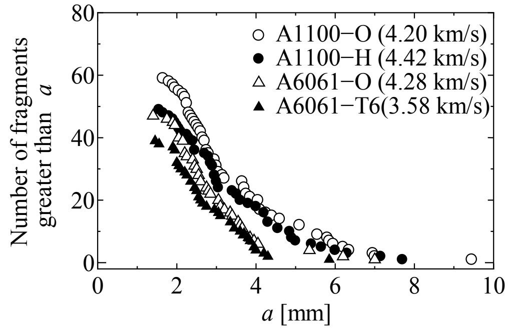
Ejecta Length *a*

Impact velocity : 2 km/s

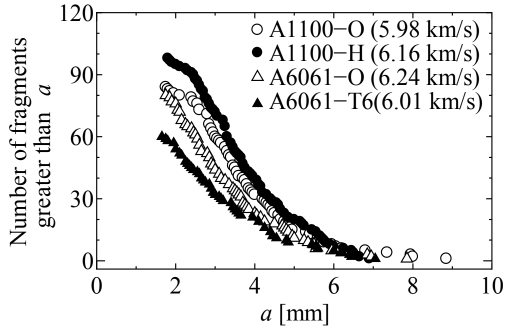




1100 > 6061



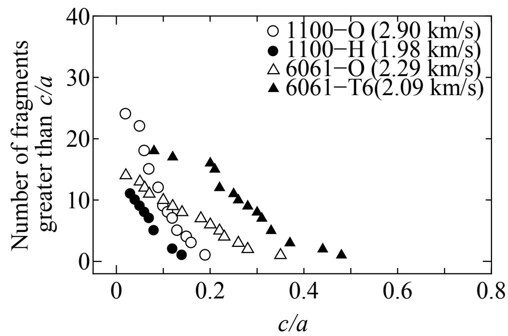
Impact velocity : 4 km/s

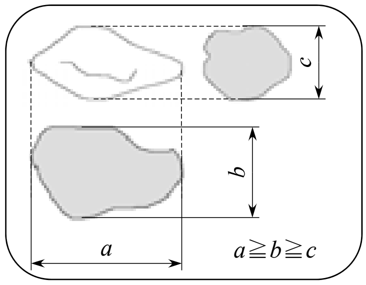


Impact velocity : 6 km/s

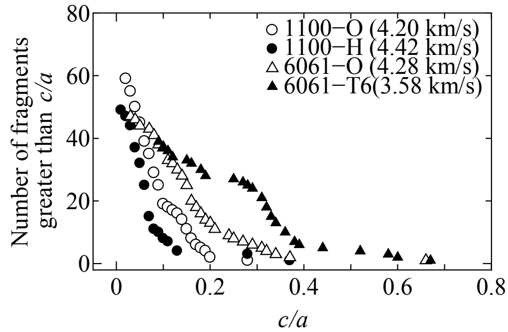
Ejecta Thickness, *c/a*

Impact velocity : 2 km/s

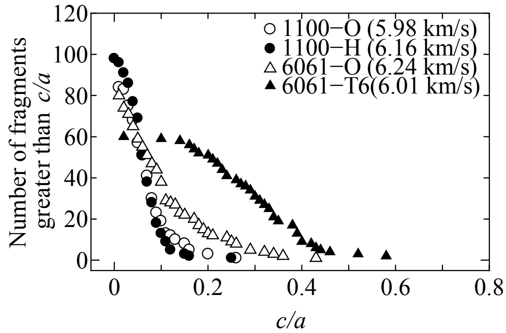




1100 Thinner　　6061 Ticker

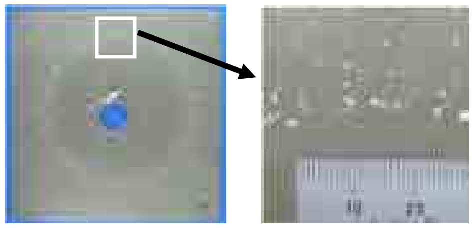


Impact velocity : 4 km/s

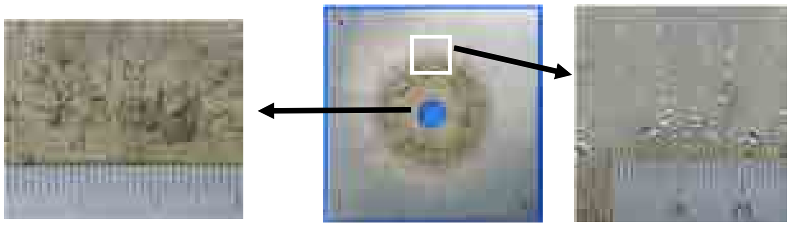


Impact velocity : 6 km/s

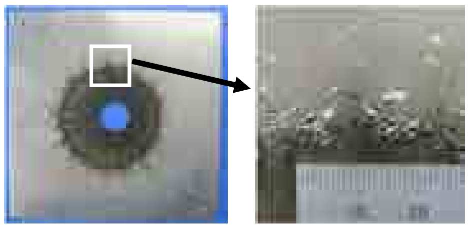
Witness Plates (Aluminum Alloy 1100-O Target)



Impact velocity : 2.90 km/s



Impact velocity : 4.20 km/s



Impact velocity : 5.98 km/s

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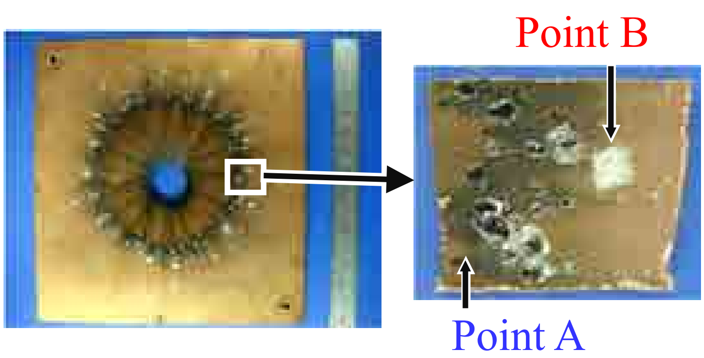
Energy Dispersive X-ray Spectroscopy



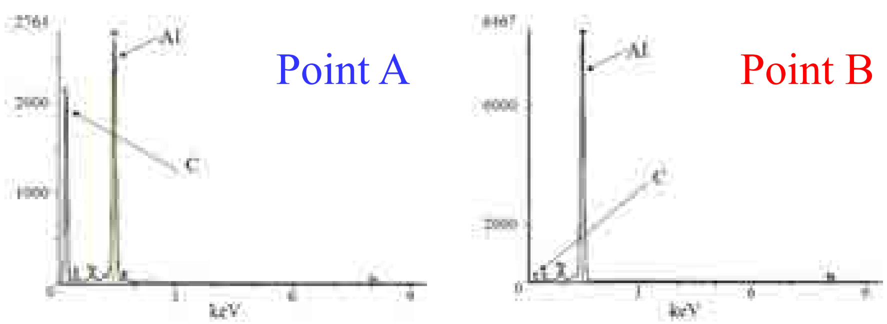


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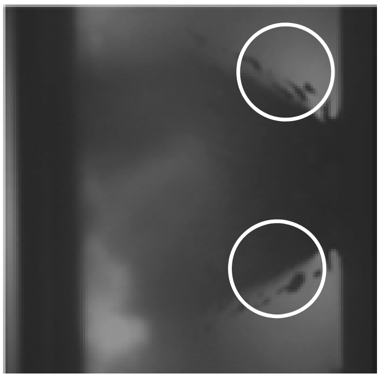
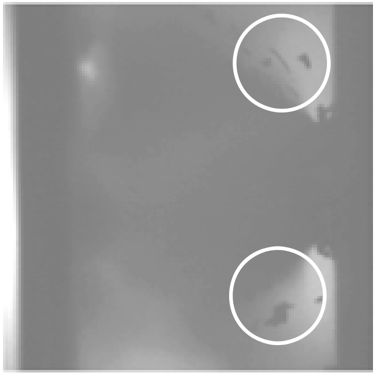
Image of High-speed Video Camera

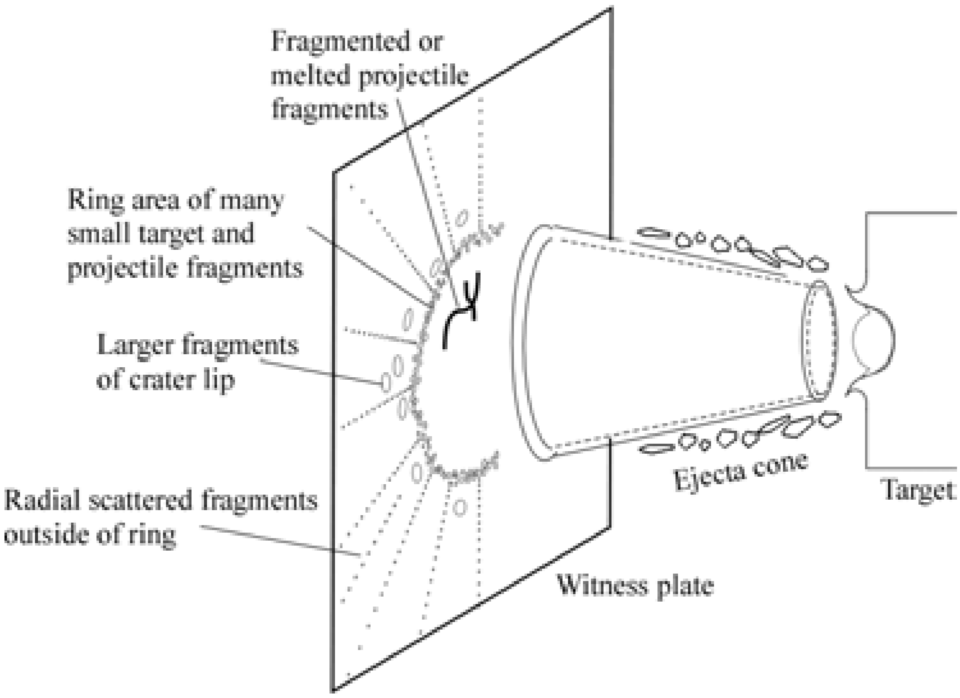


(a) 40 μs after impact

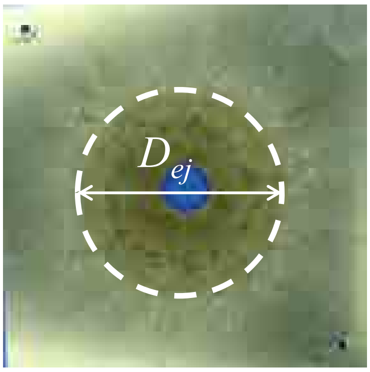


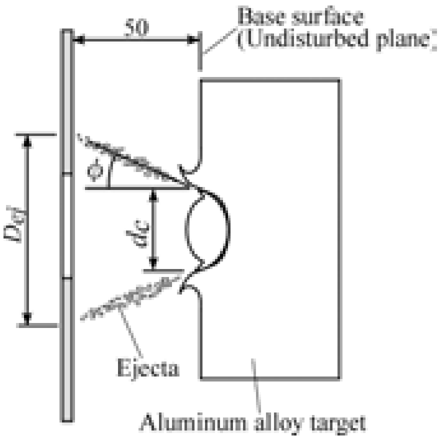
(b) 64 μs after impact

Schematic Diagram of Ejecta Composition

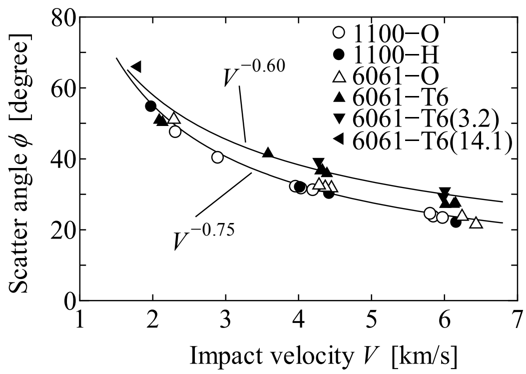


Scatter Angle of Ejecta





$$\phi = \tan^{-1}\left(\frac{D_{ej} - d_c}{2} \times \frac{1}{50}\right)$$



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Similarity Rule

Nishida, et. al, Int. J. Impact Engineering, Vol. 54, (2013), pp. 161-176.

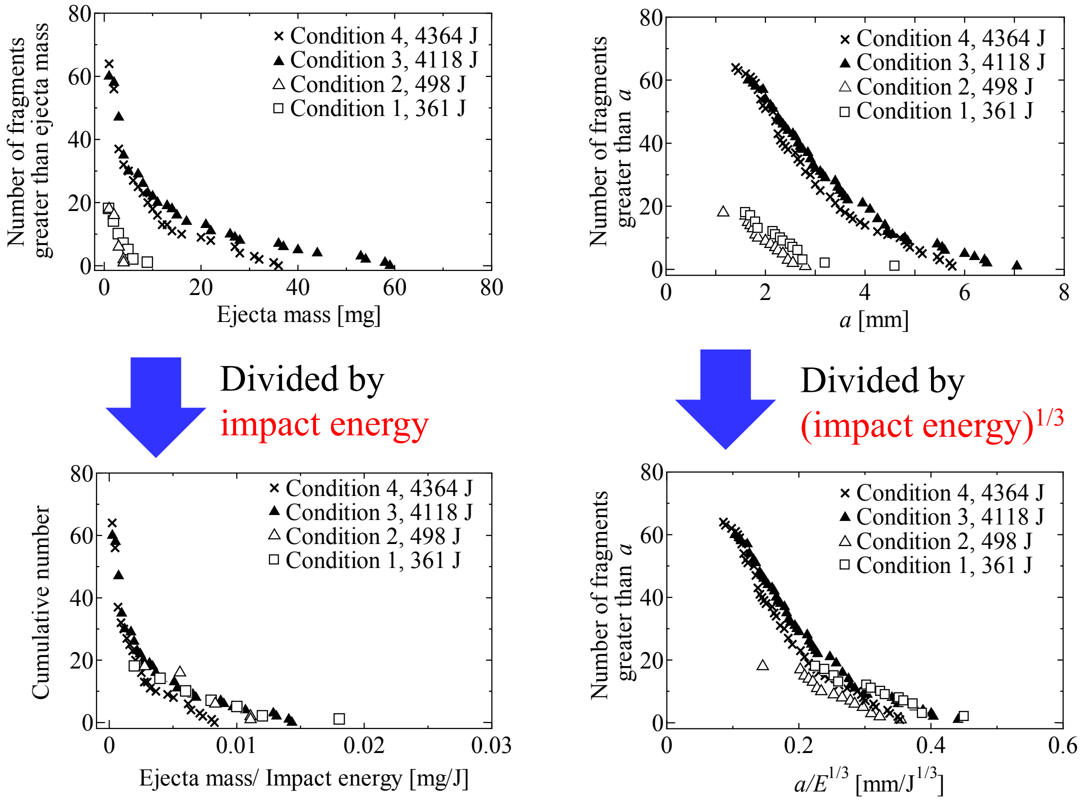
Two-Stage Light Gas-Gun

(Nagoya Institute of Technology)

Experimental Condition

Condition	Projectile diameter	Projectile mass	Impact velocity	Impact energy
1	3.20 mm	0.02 g	6.01 km/s	361 J
2	7.14 mm	0.23 g	2.09 km/s	498 J
3	7.14 mm	0.23 g	6.01 km/s	4118 J
4	14.3 mm	1.82 g	2.19 km/s	4364 J

Ejecta Mass & Ejecta Length



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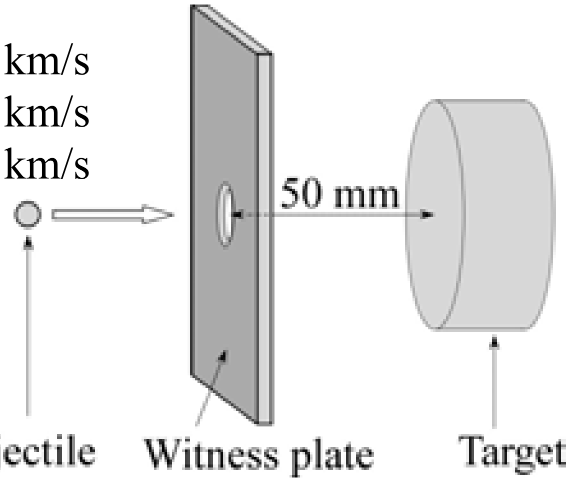
Formulation of Size Distribution (Fragmentation model)

Nishida, et. al, Int. J. Impact Engineering, Vol. 54, (2013), pp. 161-176.

Experimental Setup

Impact velocity 2 km/s
4 km/s
6 km/s



3.2 mm Al 2017-T4 spheres

Al 6061-T6 targets

High-speed video camera

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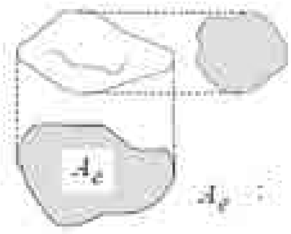
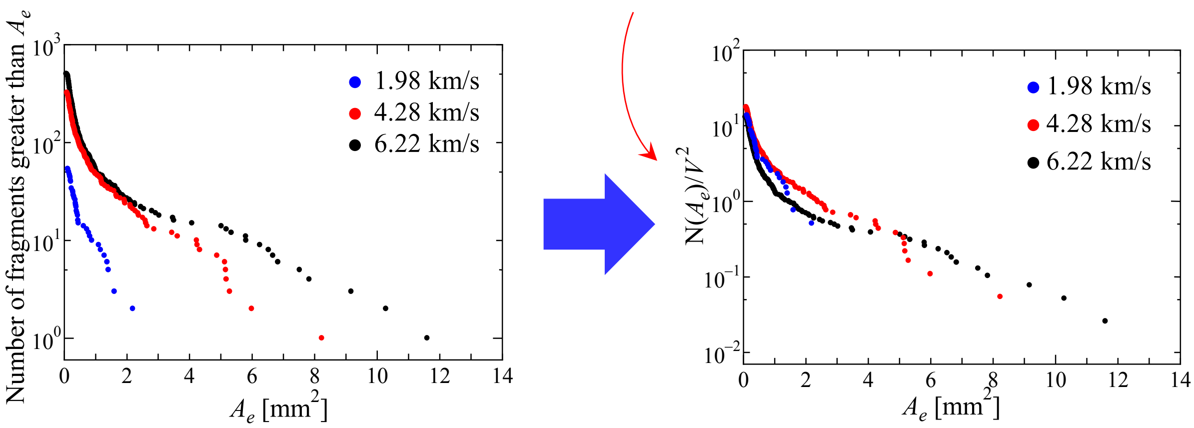
Distribution of Projected Area



Projected area of ejecta

Divided by square of impact velocity



Good agreement

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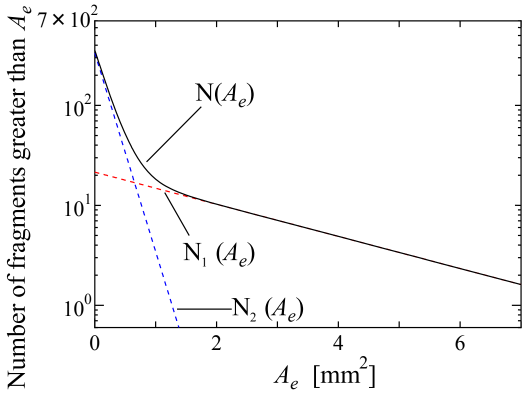
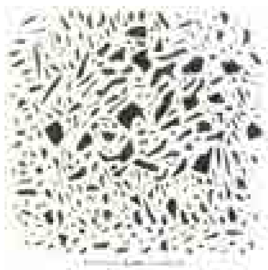
Fragmentation Model

Bi-liner form

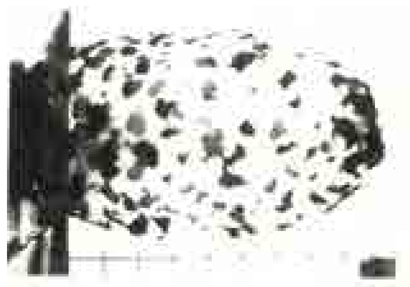
Cumulative number
$N(A_e) = a_1 \exp(a_2 A_e) + a_3 \exp(a_4 A_e)$

Bi-liner exponential description





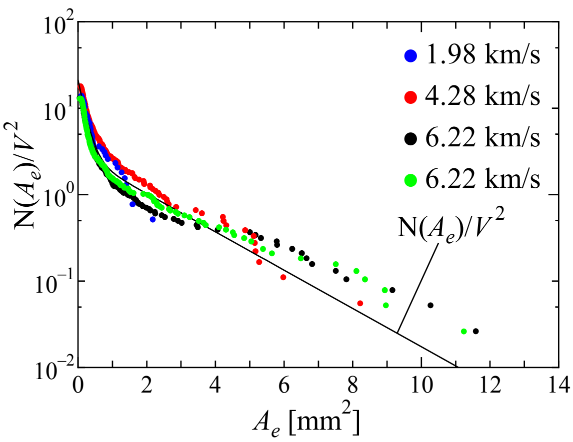
Dynamic fracture of thin plate



Hypervelocity impact of lead (1.5 km/s)

D.E.Grady, M.E.Kipp: APPLIED PHYSICS LETTERS, (2006) 88
D.Grady, Shock Wave and High Pressure Phenomena,(2006) 7-32

Projected Area Distribution of Ejecta Fragments

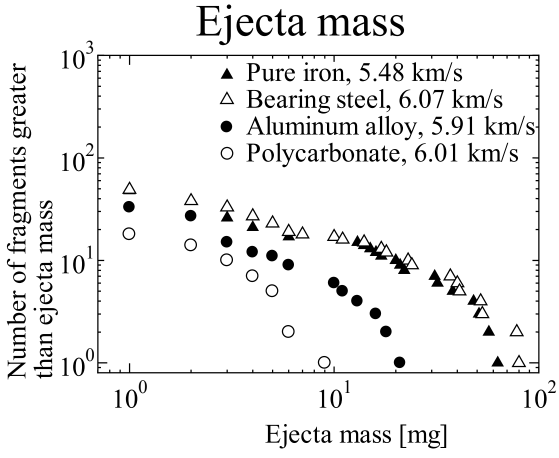


Bi-liner exponential description

$$\frac{N(A_e)}{V^2} = 18.48\exp(-5.07A_e) + 2.85\exp(-0.51A_e)$$

Effects of Projectile's Materials & Impact Angle of Projectiles

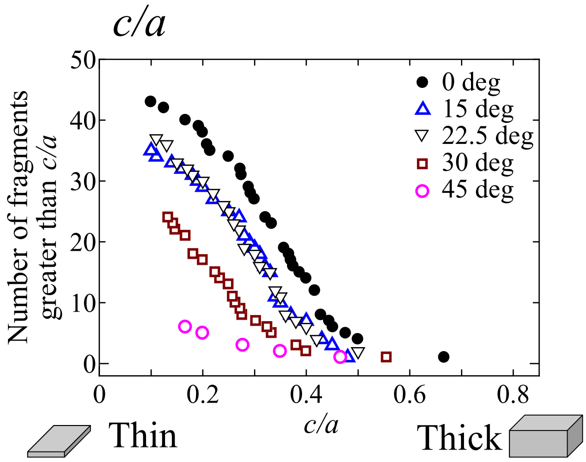
Effects of projectile's materials



3.2 mm projectiles impacting on aluminum alloy 6061-T6 target (Impact velocity of 6 km/s)

Nishida et al., J. JSEM, 2012

Effects of impact angle



14.4 mm polycarbonate spheres impacting on aluminum alloy 6061-T6 target (Impact velocity of 1.8 km/s)

Nishida et al., Proc. DYMAT, 2012

Summary

1. Ejecta mass and ejecta size distributions were examined in detail.
   - Material properties of targets
   - Impact velocity of projectiles
   - Material properties of projectiles
   - Impact angle of projectiles

2. Ejecta composition was proposed.

3. Scatter angle of ejecta depended on impact velocity.

4. Experimental formula of fragment size distribution were created.

5. Similarity rule was discussed for predicting ejecta size resulting from hypervelocity impacts of small projectile (<1mm).

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第5回スペースデブリワークショップ
Space Debris Workshop, Jan 22-23, 2013

Thank you for your kind attention

For further information contact : Masahiro Nishida
nishida.masahiro@nitech.ac.jp

Acknowledgments

This work was supported by the Space Plasma Laboratory, ISAS, JAXA.

The authors are greatly indebted to Mr. Nobuie Konishi of Nobby Tech. Ltd. for his help with taking images using high speed cameras.

This work was supported in part by a Grant-in-Aid for Scientific Research (C), KAKENHI (22560078), and (B), KAKENHI (24360351), from the Japan Society for the Promotion of Science (JSPS), and the Nitto Foundation.

E1

スペースデブリ接近評価－衝突リスク低減の経験－

Space Debris Conjunction Assessment
-- Collision Risk Mitigation Experience --

○成田兼章, 中村信一, 田島 徹, 染谷一徳, 阿部旬也（宇宙航空研究開発機構）
○Kaneaki Narita, Shinichi Nakamura, Toru Tajima, Kazunori Someya, Junya Abe (JAXA)

JAXA 統合追跡ネットワーク技術部では、2008 年から JAXA 衛星に接近する可能性のあるスペースデブリ（軌道上の物体）のスクリーニングと接近解析ツール（独自開発）を用いた接近評価作業を開始し、衝突回避の軌道制御要否判定につながる接近評価作業を続けている。
本資料では、JAXA における接近解析や衝突回避プロセスの概要、衝突回避の評価判断に関する知見や課題、各宇宙機関と協調して進めている標準化活動概要を報告する。

In 2008, JAXA Consolidated Space Tracking and Data Acquisition Department (CSTDAD) established the conjunction assessment capability to recognize possible space debris (space objects) approaching to JAXA satellites, when the debris screening engine and conjunction assessment tool became operational, and since then, we have been working on conjunction assessment which leads to judging the necessity for collision avoidance.
This presentation will introduce concept of JAXA conjunction assessment and collision avoidance process, lessons learned and issues for conjunction assessment, and summary of international standardization coordination under way in cooperation with other space agencies.

Space Debris Conjunction Assessment

- Collision Risk Mitigation Experiences -

#5 Space Debris Workshop
January 23, 2013

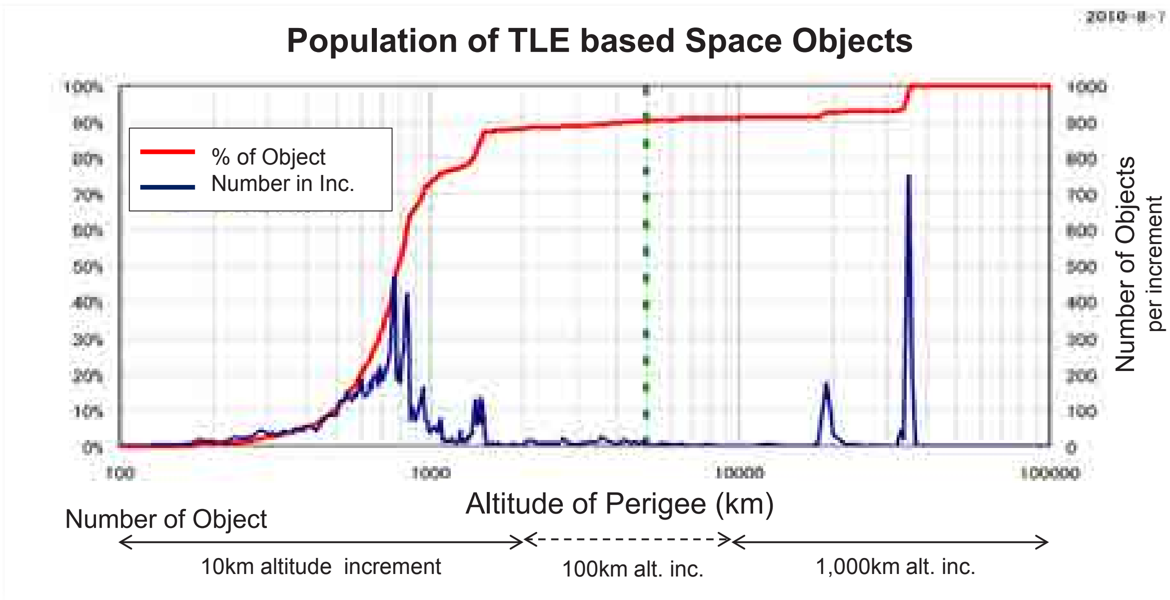
K. Narita, S. Nakamura, T. Tajima, K. Someya, J. Abe
Consolidated Space Tracking and Data Acquisition Department
JAXA

Introduction

- **UN COPUOS Space Debris Mitigation Guideline #3 (2007)**
  Limit the probability of accidental collision in orbit
  – *"If available orbital data indicate a potential collision, adjustment of the launch time or an on-orbit avoidance maneuver should be considered."*
- **Capability build**
  – In 2008, JAXA established conjunction assessment capability for JAXA satellite in LEO and GEO
  – Experienced 1st Collision Avoidance in 2009
- **Space Operation Experiences**
- **Conjunction information sharing standardization**
  – CCSDS, ISO TC20/SC13
  – Conjunction Summary Message (CSM)

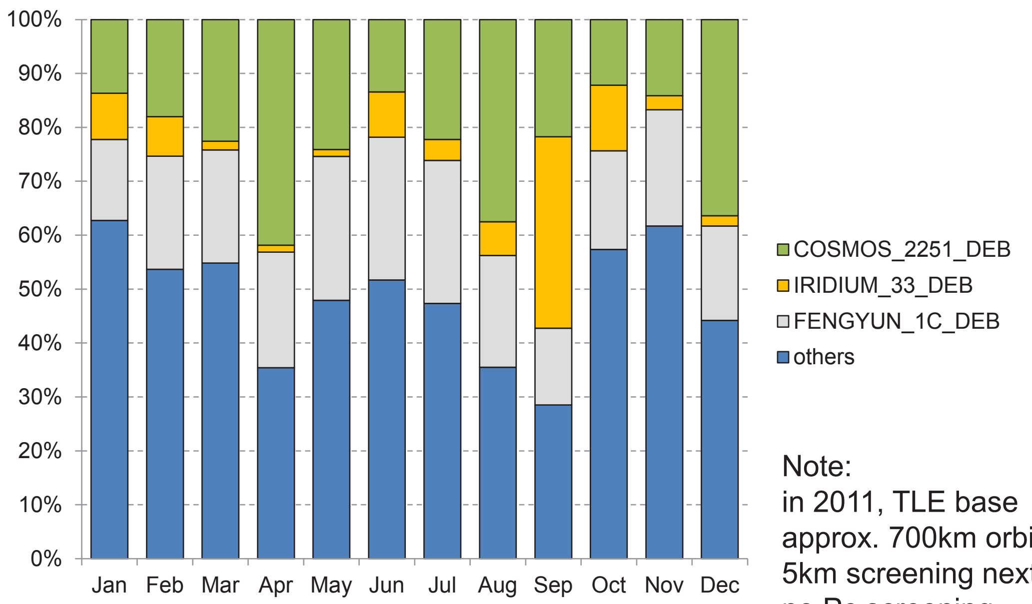
Population of Space Objects

- **U.S. cataloged objects in Earth orbit: approx. 16,000**
- **90% distributed in LEO region (2,000km alt. below)**



Congested Orbital Environment

- **Approaching space objects to LEO satellite**

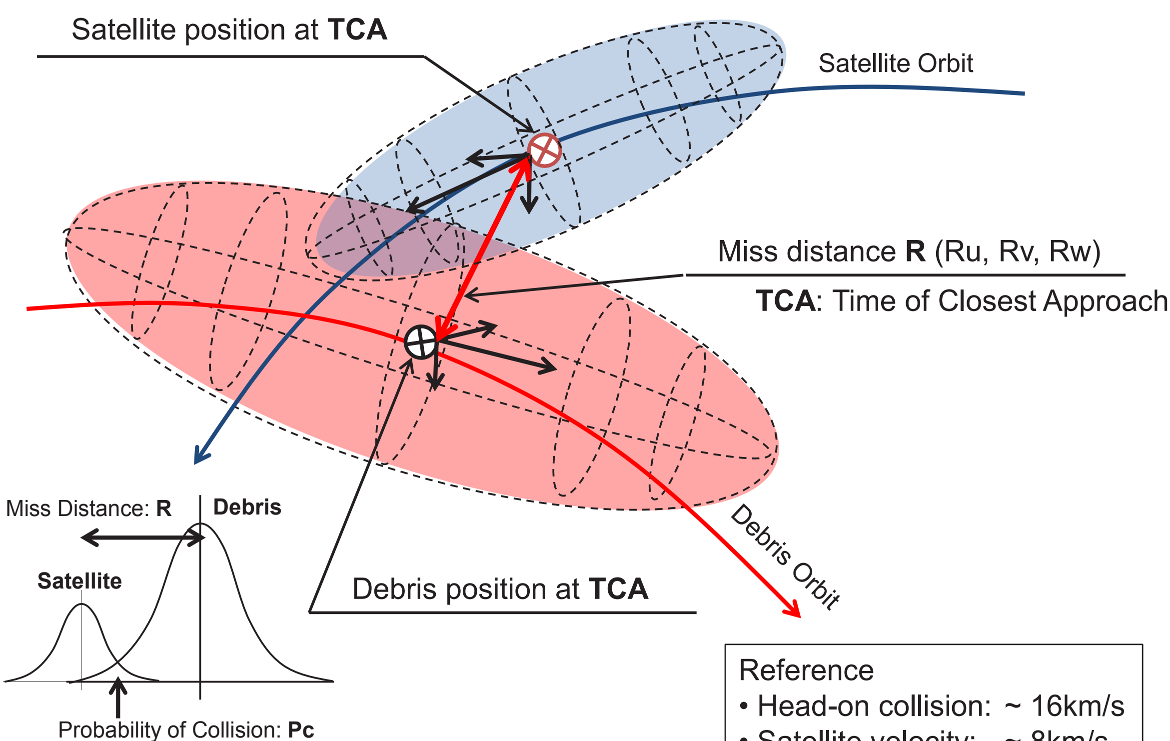


Note:
in 2011, TLE base
approx. 700km orbit satellite
5km screening next 7days
no Pc screening

Conjunction Assessment

- **Orbit Determination (OD) and conditions**
  - Covariance (radial, in-track, cross-tack)
  - Days since Epoch, Number of available data, etc.
  - Space Environment (short-term) concerning OD and Orbit Prediction
    - **Atmospheric drag, Solar radiation pressure**
- **Conjunction Assessment**
  - Probability of collision (Pc) will be calculated under some assumptions such as “dimensions (RCS)”
    - **“Pc” is not a single evaluation source**
    - **Miss distance**
    - **Credibility of OD and Orbit Prediction**
  - Satellite condition
    - **Regular maneuver plan**
    - **Fuel consumption, Recovery maneuver to mission orbit, etc.**
  - Concentrated work in a limited time is required (i.e. TCA-72h to -12h)

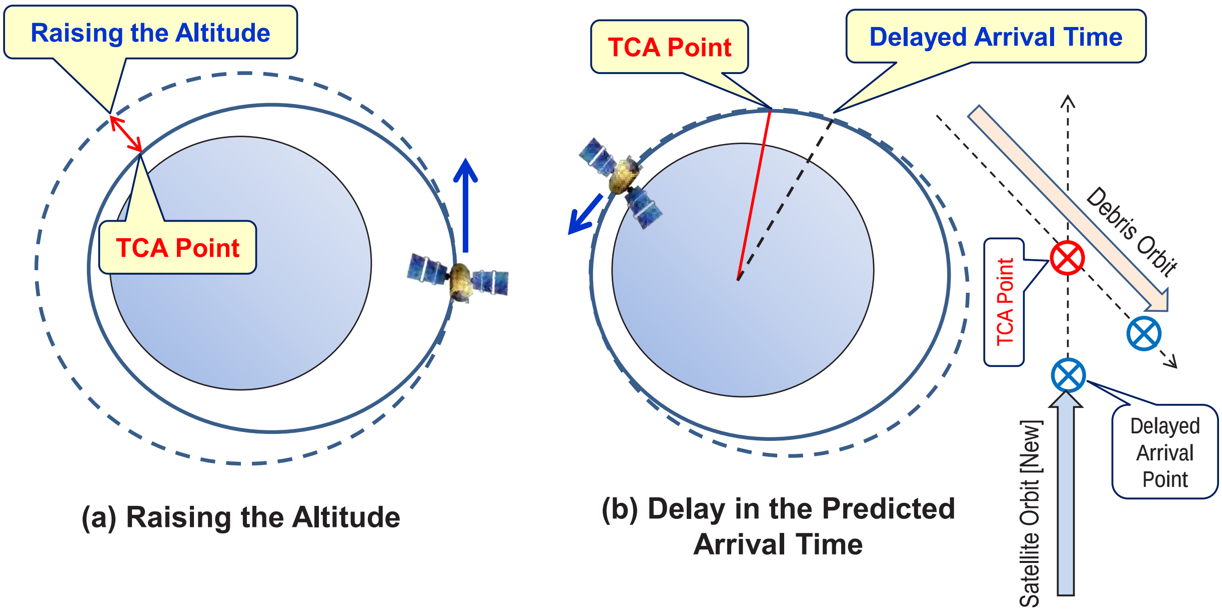
Conjunction Assessment View



Reference
- Head-on collision: ~ 16km/s
- Satellite velocity: ~ 8km/s

Collision Avoidance View

- **Useful regular satellite maneuver theory**



Space Operation Experiences

- **Characteristics of Orbital Flight Dynamics**
  – Space Environment (short-term) concerning OD and Orbit Prediction

- **Information sharing**
  – Direct communications with approaching satellite operator should be prepared, assuming s/c to s/c collision

  – Registration of Space object information
    - **State should provide registration information as soon as practicable to the Secretary-General to UN.**

  – Use a standard format when sharing orbital information on space objects
    - **Operators should use a common, internationally recognized standard formats to enable collaboration and information exchange.**

Standardization

- **Conjunction Summary Message (CSM)**
  - Standard message format for spacecraft conjunction information
  - Facilitate interoperability and enable warning and mitigation
  - CCSDS member agency demonstration will be in 2013 (CNES, DLR, ESA, JAXA, NASA, etc.)
  - CSM Example
    - **TCA (Time of Closest Approach), Miss distance, Relative position/velocity, and**
    - **State Vector, Covariance Matrix, etc.**

Conclusion

- **Conjunction Assessment**
  - Orbit Determination (OD) and conditions
  - “Pc” is not a single evaluation source
- **Collision Avoidance**
  - Useful regular satellite maneuver theory
  - (1) Rising the altitude, (2) Delay in the predicted arrival time
- **Space Operation Experiences**
  - Space Environment (short-term) concerning OD and Orbit Prediction
  - Information Sharing
- **Standardization**
  - Conjunction Summary Message (CSM)

E2

デブリに係わる損害保険

Non-life insurance related to Space debris

鈴木茂雄（あいおいニッセイ同和）
Shigeo Suzuki (Aioi Nissay Dowa Insurance Co., Ltd.)

(1)デブリに起因する損害について
　1)所有財物に関する損害
　2)第三者に与える損害
(2)現在の宇宙保険の種類について
　1)自社が所有・運用・管理するロケットもしくは人工衛星等財物の損害を補償するための保険として
　　①打上保険　②軌道上保険
　2)第三者への損害を補償するための保険として
　　①打上げに係る第三者賠償責任保険
　　②衛星の所有・運用・管理に係わる第三者賠償責任保険
(3)保険によるデブリに起因する損害の補償について
　1)現行の宇宙保険による補償
　　①打上保険および軌道上保険
　　②第三者賠償責任保険
　2)保険マーケットにおけるデブリのリスク認識と保険の普及度
(4) デブリ除去のための損害保険とその検討課題
　1)デブリ除去作業に考えられる保険
　2)保険契約者と被保険者
　3)保険金額（てん補限度額）の設定
　4)その他実際に保険手配する際の課題

(1)Loss or damage caused by debris
　1) To own property
　2) To third party
(2)Current Space Insurance
　1) Insurance for own property
　　①Launch Insurance ②In-Orbit Insurance
　2) Insurance for third party liability
　　①For launching ②For own satellite
(3)Indemnity of loss or damage caused by debris under insurance
　1) Under current space insurance policy
　　①Launch and In-Orbit insurance policy
　　②Third Party Liability insurance policy
　2) Assesment of risk of debris in the space insurance market
(4)Points to be considered for insurance coverage for debris removal works
　1) Insurance for debris removal works
　2) Insurance policy holder and insured
　3) Sum-Insured or limit of liability
　4) Others

デブリに係わる損害保険
Non-life Insurance related to Space Debris

鈴木　茂雄
Shigeo SUZUKI
あいおいニッセイ同和損害保険株式会社
Aioi Nissay Dowa Insurance Co.,Ltd.
MS&AD INSURANCE GROUP

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目次

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デブリに起因する損害について
Loss or Damage caused by Debris

- 所有財物に関する損害
- To own property

- 第三者に与える損害
- To third party

3

現在の宇宙保険の種類
Current Space Insurance

- 打上保険
- Launch Insurance

- 軌道上保険
- In-Orbit Insurance

- 第三者賠償責任保険
- Third Party Liability Insurance

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デブリに起因する損害の補償
Insurance coverage for loss or damage caused by debris

- 現行の宇宙保険による補償
- Under current space insurance

- 保険マーケットにおけるデブリのリスク認識と保険の普及度
- Assesment of risk of debris in the space insurance market

5

デブリ除去のための損害保険の考察
Consideration on insurance for debris removal works

- デブリ除去作業に考えられるリスクと保険
- Risks with debris removal works and insurance

- 保険契約者と被保険者
- Insurance policy holder and insured

- 保険金額(てん補限度額)の設定
- Sum Insured or limit of liability

- その他保険手配する際の課題
- Others

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E3

軌道上微小デブリ計測技術の研究開発 -JAXA 宇宙環境グループでの開発センサを中心に-

R&D on in-situ measurement MMOD sensors at JAXA

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Pauline Faure，赤星保浩（九州工大），服部真希（東大），花田俊也（九大），
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○Kitazawa, Y. (JAXA/IHI), Matsumoto, H., Okudaira, O. (JAXA), Faure, P. (Kyutech),
Akahoshi, Y. (Kyutech), Hattori, M. (The University of Tokyo), Hanada, T. (Kyushyu University),
Karaki, A. (IHI), Sakurai, A., Funakoshi, K., Yasaka, T. (iQPS)

軌道上微小デブリ（ダスト）計測の国内での研究開発を概観するとともにJAXA宇宙環境グループで開発中のアクティブセンサの開発状況について報告する。軌道上ダスト計測の研究開発は1980年代後半からメテオロイドの計測を目的として活発化した。アクティブ型の計測器は1990年の「ひてん」（Muses-A）に搭載されたMDC（Munich Dust Counter）が日本最初の搭載である。一方、パッシブ型の計測器は宇宙科学研究所で計画された彗星からのサンプルリターンミッション(SOCCOR 計画)での研究成果をベースに開発された「キャリブレーテッド・エアロジェル」を用いたダストコレクタが 1997 年にスペースシャトルに搭載されたのが最初である。その後、アクティブ型、パッシブ型とも多くの研究が行われてきている。JAXA 宇宙環境グループは諸外国で計測実績がなく、かつ、宇宙機への影響が懸念されるサイズ領域である大きさ100μm～数mmのデブリの存在量の計測を目的としたアクティブ型計測器を開発した。このセンサは２０１４年の「こうのとり」（HTV）に搭載され実装実証試験を行う予定である。

The history of Japanese R&D into in-situ sensors for micro-meteoroid and orbital debris (MMOD) measurements is neither particularly long nor short. Research into active sensors started for the meteoroid observation experiment on the HITEN (MUSES-A) satellite of ISAS/JAXA launched in 1990, which had MDC (Munich Dust Counter) on-board sensors for micro meteoroid measurement. This was a collaboration between Technische Universität München and ISAS/JAXA. The main purpose behind the start of passive sensor research was SOCCOR, a late 80's Japan-US mission that planned to capture cometary dust and return to the Earth. Although this mission was canceled, the research outcomes were employed in a JAXA micro debris sample return mission using calibrated aerogel involving the Space Shuttle and the International Space Station. There have been many other important activities apart from the above, and the knowledge generated from them has contributed to JAXA's development of a new type of active dust sensor. JAXA and its partners have been developing a simple in-situ active dust sensor of a new type to detect dust particles ranging from a hundred micrometers to several millimeters. The distribution and flux of the debris in the size range are not well understood and is difficult to measure using ground observations. However, it is important that the risk caused by such debris is assessed. In-situ measurement of debris in this size range is useful for 1) verifying meteoroid and debris environment models, 2) verifying meteoroid and debris environment evolution models, and 3) the real time detection of explosions, collisions and other unexpected orbital events. Multitudes of thin, conductive copper strips are formed at a fine pitch of 100 um on a film 12.5 um thick of nonconductive polyimide. An MMOD particle impact is detected when one or more strips are severed by being perforated by such an impact. This sensor is simple to produce and use and requires almost no calibration as it is essentially a digital system. Based on this sensor technology, the Kyushu Institute of Technology (KIT) has designed and developed an educational version of the sensor, which is currently on board the nano-satellite Horyu-II, which was built at KIT and launched on May 18, 2012 by JAXA. Although the sensor has a very small sensing area, sensor data were nonetheless successfully received. Moreover, a laboratory version of the sensor fitted on QSAT-EOS, a small satellite, will be launched in December 2012. This version was developed and manufactured by Japan's QPS Institute to evaluate the sensor's capability regarding hypervelocity impact experiments at JAXA. JAXA's flight version, to be employed on satellites and/or the ISS, will be ready soon and a flight demonstration will be conducted on KOUNOTORI (HTV) in 2014. This paper reports on the R&D into in-situ measurement MMOD sensors at JAXA.

軌道上微小デブリ計測技術の研究開発

−JAXA宇宙環境グループでの開発センサを中心に−

R&D activities on in-situ measurement MMOD sensors at JAXA

2013年1月23日
第5回スペースデブリワークショップ，調布市，東京

〇北澤幸人（IHI),松本晴久, 奥平修, 木本雄吾（JAXA）
Pauline Faure, 赤星 保浩（九州工大)，服部真季（東大)，花田俊也（九大）
唐木敦（IHI)，桜井晃，船越国広, 八坂哲夫（QPS研究所）

背景

宇宙の‘微小な固体粒子’（宇宙ダスト）の計測

宇宙でのダスト計測の目的／特徴

●メテオロイド（Meteoroid）：天然物
地球起源以外の物質の研究による太陽系生成過程の研究

●スペースデブリ(Space Debris)：人工物
宇宙‘ゴミ’の存在量とその変化、組成（発生源の情報）などの調査

宇宙ダストの軌道上計測方法

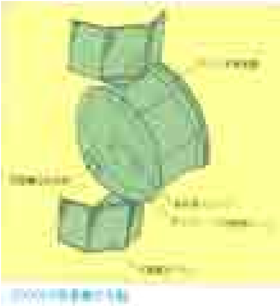
〇「パッシブ型センサ（ダストコレクタ）」
ダストを捕獲し、地上へのサンプルリターン（回収）

〇「アクティブ型センサ」
ダストの軌道情報や物性を軌道上で計測

2

始まりは「SOCCER計画」(1987年)

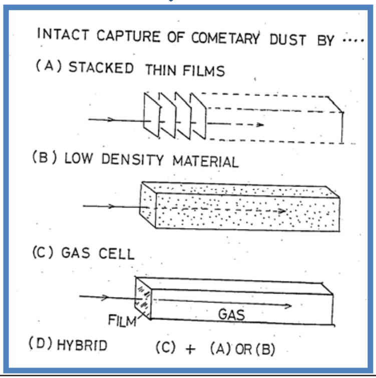
SOCCER:日米共同での彗星塵のサンプルリターン構想



(上杉,1991)

ミッション構想は米国の「STARDUST」へ

日本は「小惑星ランデブ探査計画」と併せ、「はやぶさ」へ(安部、2012)



ISAS藤原研究室の「ダストコレクタ」の研究

NASDA(現JAXA)材料Gr. での国産のダスト(微小デブリ)コレクタの開発へ

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パッシブ型センサ(ダストコレクタ)

主なコレクタ:シリカエアロジェルを利用

シリカエアロジェル(主成分:SiO_2)の特徴

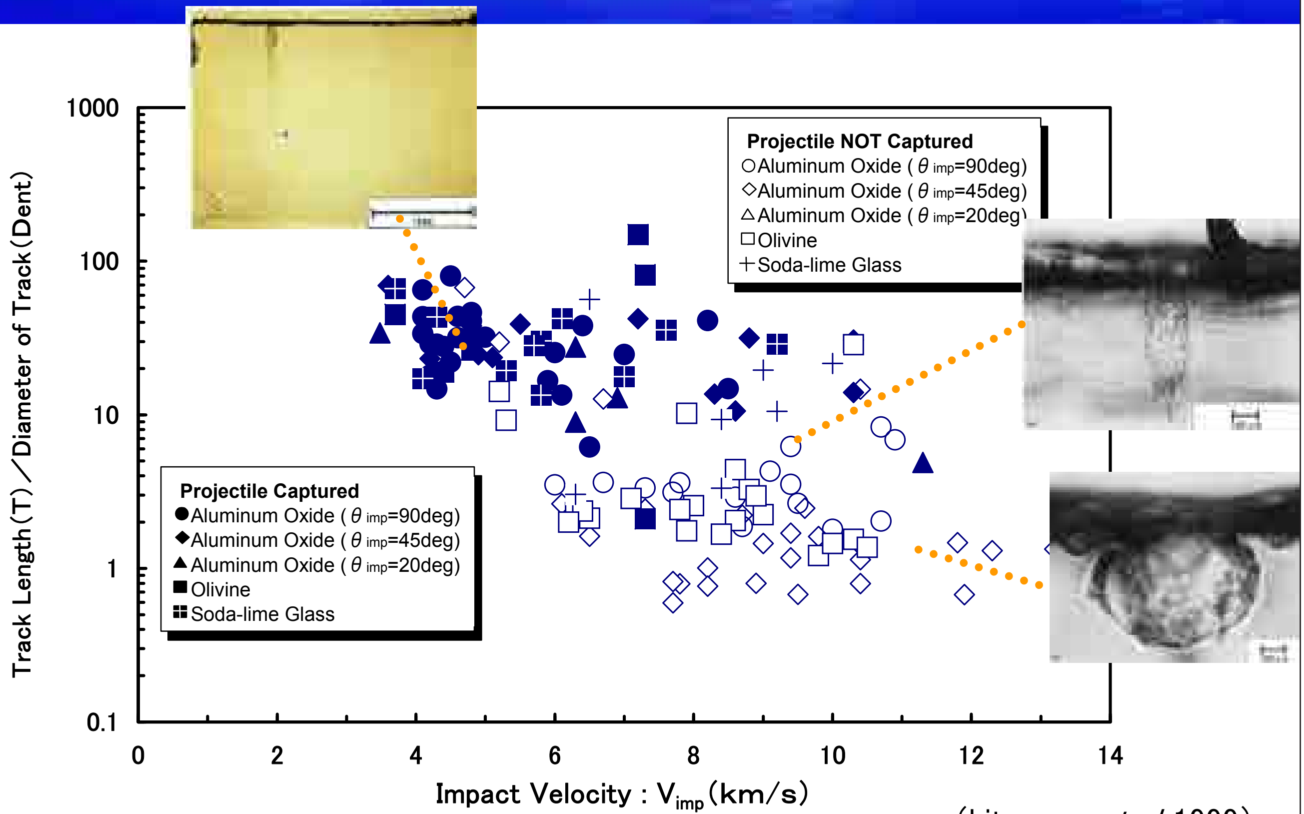
- ●**低密度**(〜0.03 g/cm^3)
  ⇨ ダストの非破壊捕獲に効果的
- ●**透明**
  ⇨ 捕獲したダストや衝突孔の確認が容易
- ●**宇宙環境に対し安定**
  ⇨ 曝露実験に好適

- **Status: Flight proven**

  List of on-board experiments
  - STS-85 (1997)
  - SM/ISS #1 (2001-2002)
  - SM/ISS #2 (2001-2004)
  - SM/ISS #3 (2001-2005)
  - JEM/ISS (2009-2010)

- **Feature of JAXA's sensor**
  - "Calibrated" silica aergel (density: 〜0.03 g/cm^3)
    Impact parameters can be estimated roughly from shape parameters of penetrations on aerogels.

Example of Calibration Experiments

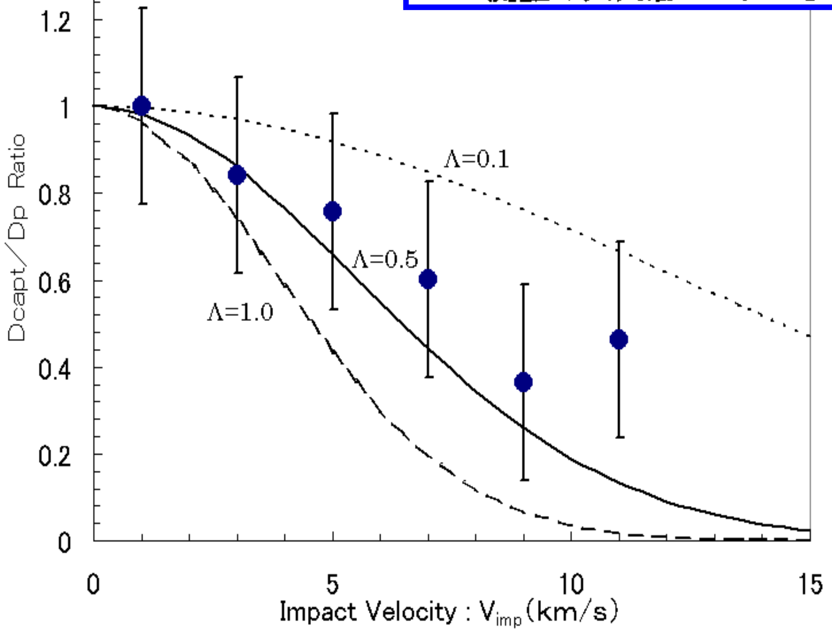


(kitazawa *et al.*,1999)

Relation of aspect ratio of the tracks (T/D_{ent}) with impact velocity

Example of Calibration Experiments

「ダストのエアロジェルへの突入」
「流星の大気層への突入」
同様の現象と仮定



$$m(t)\frac{dv(t)}{dt} = -\Gamma S \rho v^2 \qquad \cdots (1)$$

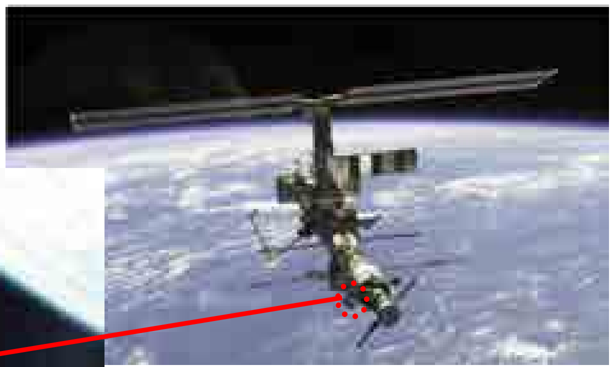
$$\frac{dm(t)}{dt} = -\Lambda \frac{S\rho v^3}{2Q} \qquad \cdots (2)$$

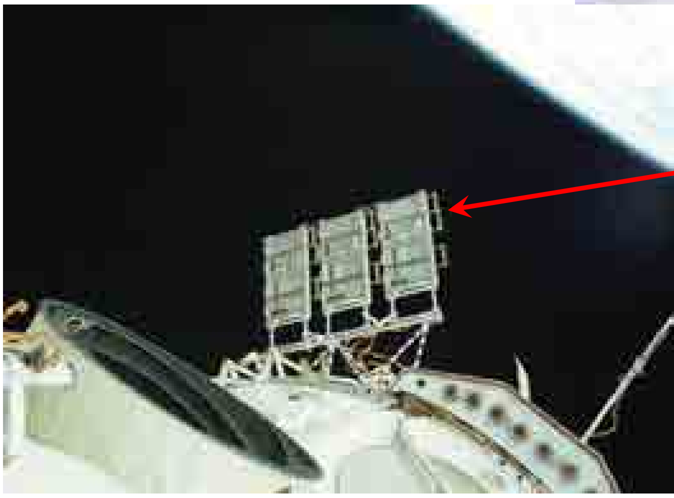
m(t)：ダストの質量
v(t)：ダストの速度
t：時間
Γ：抵抗係数（抗力係数）
S：ダストの断面積
ρ：捕獲材（＝エアロジェル）の密度
Λ：熱伝達係数（≦1）
Q：ダストの蒸発もしくは融解の潜熱

(Kitazawa *et al.*,1999)

国際宇宙ステーションに設置されたMPAC & SEED

Ⓒ RSC ENERGIA、Ⓒ NASA、Ⓒ JAXA





- 3式のMPAC&SEEDを設置（2001年10月）
- 1年毎に1式を地上へ回収し分析
- 3式の比較により、ダストの年変化の把握が可能

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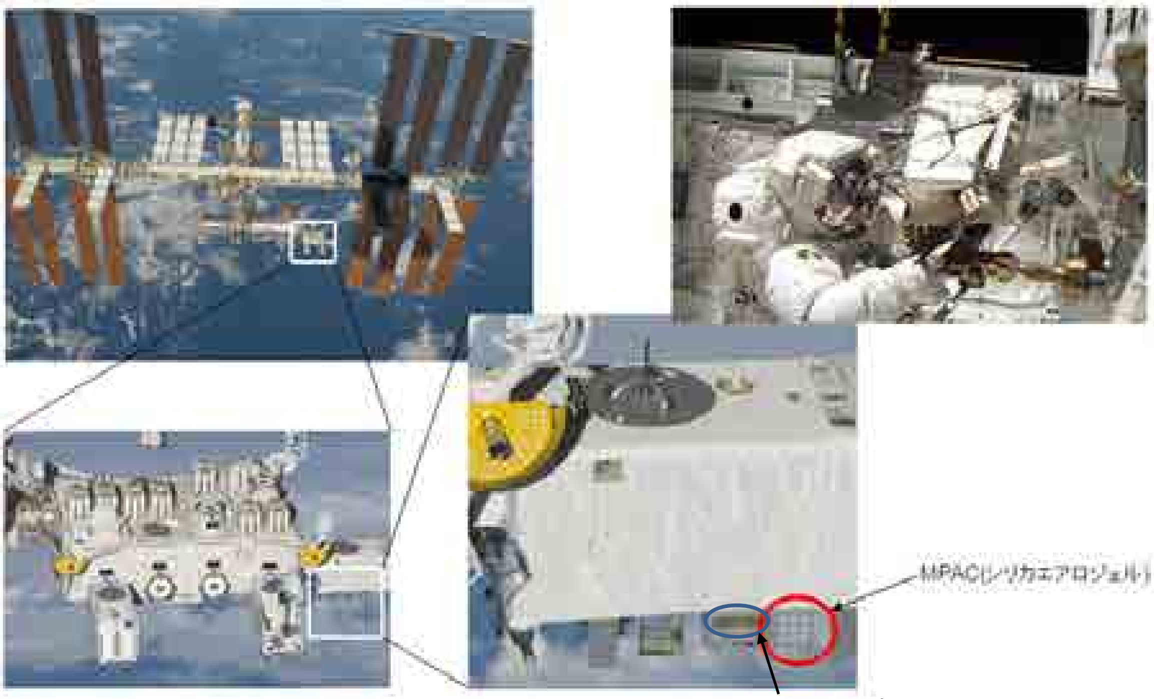
「きぼう」搭載MPAC

○「宇宙環境計測ミッション装置（SEDA-AP）」のミッション機器を構成



http://iss.jaxa.jp/kiboexp/news/images/120830_mpacseed_4_l.jpg ©JAXA

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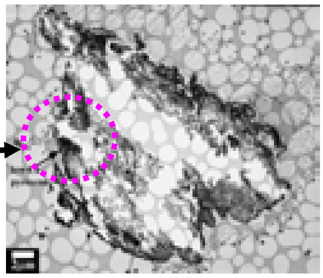
SM/MPACでの成果の例

○成果例１：Ejecta生成デブリの確認

天然物起因の粒子

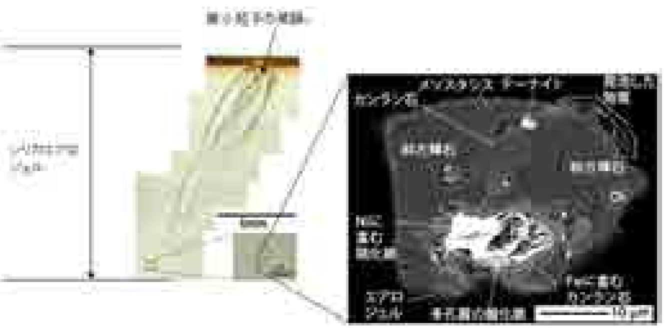


捕獲物(直径約20μmのデブリ)の切片のTEM画像

メテオロドが宇宙機外表面に衝突して発生した2次デブリと推定
（被衝突体は銀を含むペイント材の可能性）

*Noguchi et al. 2006*等による。

○成果例２：これまでにない鉱物学的特徴を持つ新種の地球外物質の発見



○茨城大・HP
http://www.ibaraki.ac.jp/news/2012/08/310959.html
○JAXA・HP
http://iss.jaxa.jp/kiboexp/news/120830_mpac_seed.html

T. Noguchi et al., A chondrule–like object captured by space–exposed aerogel on the international space station, Earth and Planetary Science Letters 309 (2011) 198–206

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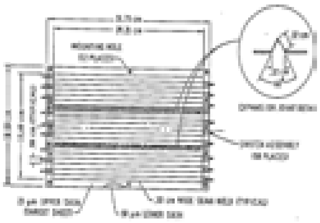
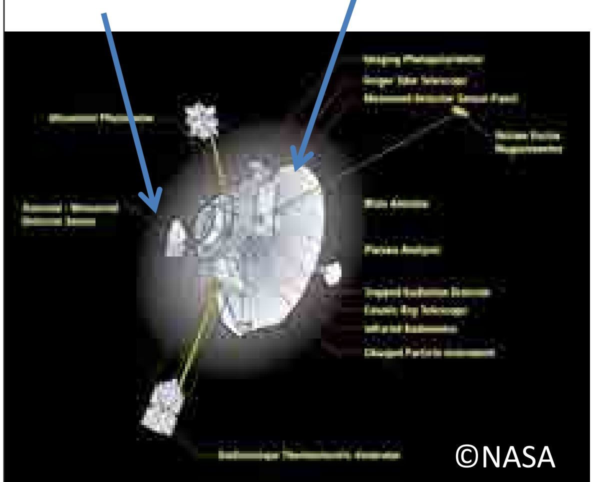
アクティブセンサの例

○パイオニア搭載センサ

Soberman et al.,1974



Humes et al.,1974



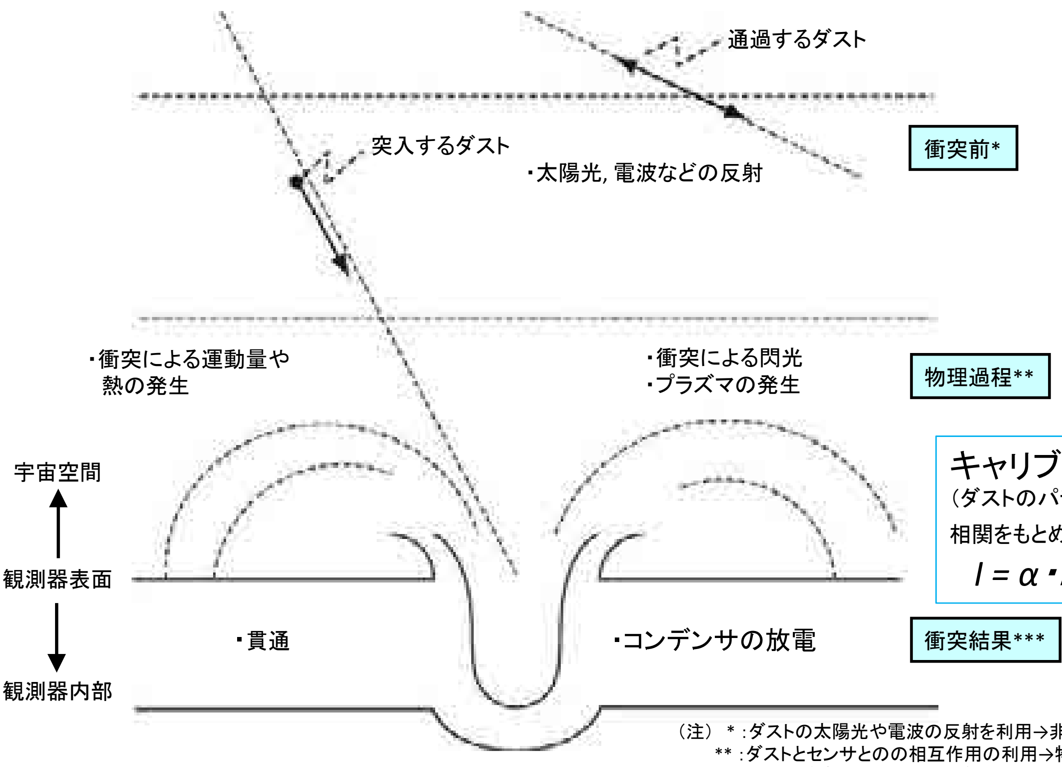
Pioneer　10号

○ESAのダストセンサ

Geostationary Orbit Impact Detector
(GORID)
計測面積：0.1 m².
（計測エリアの直径は43 cm）
（ESAによる）

微小デブリ計測器(アクティブ型センサ)の計測原理

Concepts of micro-debris detection techniques (McDonnel [1978]、山越 [1983]等)

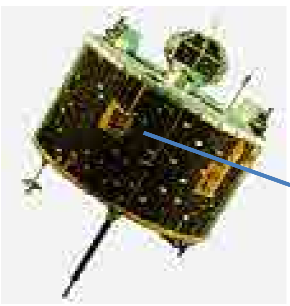


キャリブレーション試験
(ダストのパラメータと計測信号との相関をもとめる較正試験)**が必要**

$I = \alpha \cdot m^{\beta} \cdot v^{\gamma} \cdot f(\Theta)$

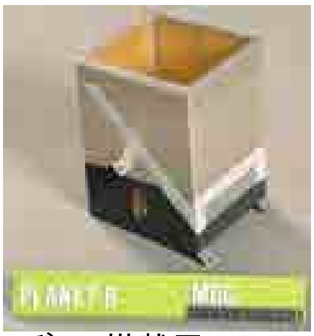
(注) * :ダストの太陽光や電波の反射を利用→非接触型
** :ダストとセンサとのの相互作用の利用→物理過程型
(微小デブリの運動エネルギーが他のエネルギーに置き換ることを利用)
* ** :残留物, 検出物資, 貫通孔等の利用→衝突型
(ダストがセンサに衝突した結果として生じるセンサの物性変化を利用)

国内でのアクティブセンサ例



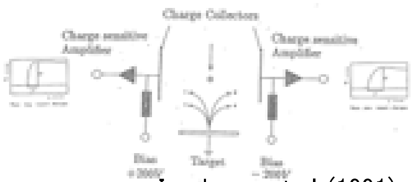
ひてん(MUSES-A)
(1990年打上げ)

Munich Dust Counter(MDC)
(故山越和雄教授提供)
開口面は約10cmx10m



「のぞみ」搭載用
Mars Dust Counter (MDC)
(佐々木、2007)
開口面は約10cmx10m

○MDCの原理



Igenbergs et al.,(1991)

衝突プラズマの波形からのダストの衝突速度・質量をもとめる

【最近の主要センサ】
○IKAROS搭載のPVDFセンサ(ALADDIN)
(例えば、Yano et al.,2012)

○水星探査機(BepiColombo)搭載用のPZT素子センサ(MDM)
(例えば,Nogami,et al.,2010, Hattori et al, 2012, , Hattori et al, 2013)

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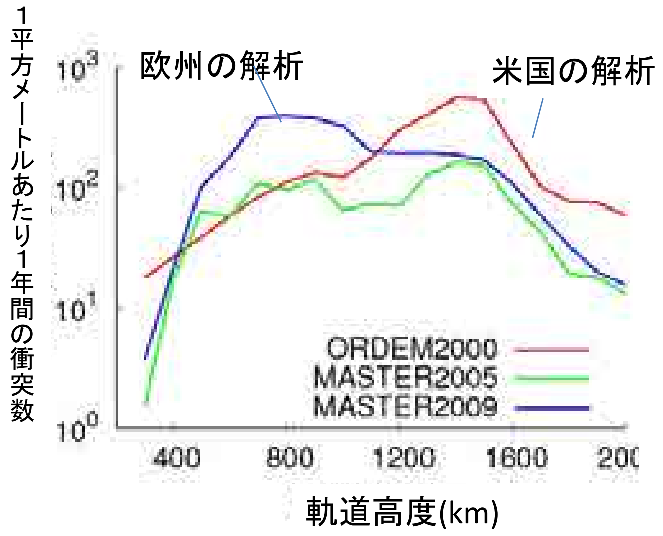
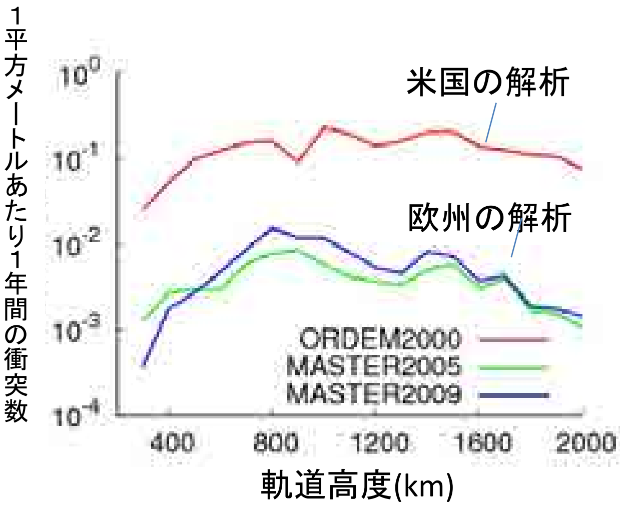
微小デブリ環境の問題点

デブリの大きさ:
約100 μm(=0.1mm)

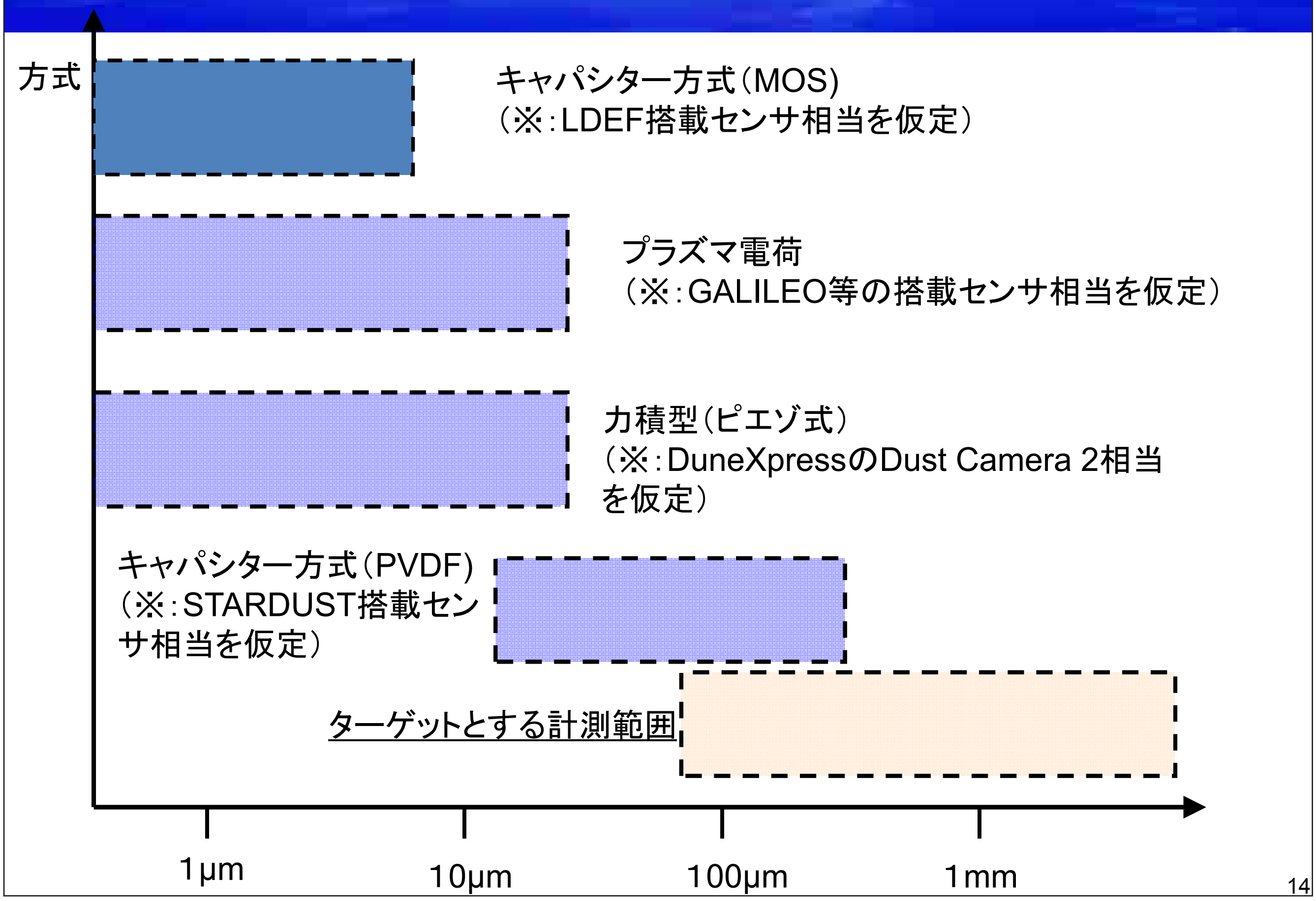
デブリの大きさ:
約1 mm





(Kanemitsu et al., 2012)

搭載実績のある方式の計測範囲と研究開発ターゲットとする範囲



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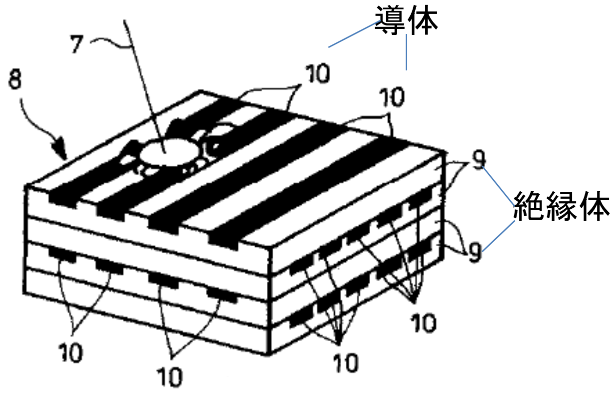
他と違うアイディアは？

○1990年度の実用新案から



森初男(1990)
IHI 出願実用新案 （実願平2-94558）

○絶縁性の薄板に、直線状の細長い導線のパターンを形成。積層構造

○導線の破断を電気的に検知することにより、ダストの衝突（貫通）を検知する。

○導線の破断数、破断層数から「衝突クレーター」の大きさを測定し、ダストの大きさ（質量）、速度、方向を推定

【アイディアとしての困難さ】
○「衝突クレーター」ではクレーターの大きさが、ダストの大きさ（質量）、速度、方向の関数となり、一意的に決定が困難
○キャリブレーション試験が膨大

【技術的困難さ】
○細い導線を細かいピッチで生成するのが困難
○特に導線の検出回路との接続が困難
○軽量で大面積なものがつくりにくい

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微小デブリセンサの計測原理 ＜アイディアのブレークスルー＞

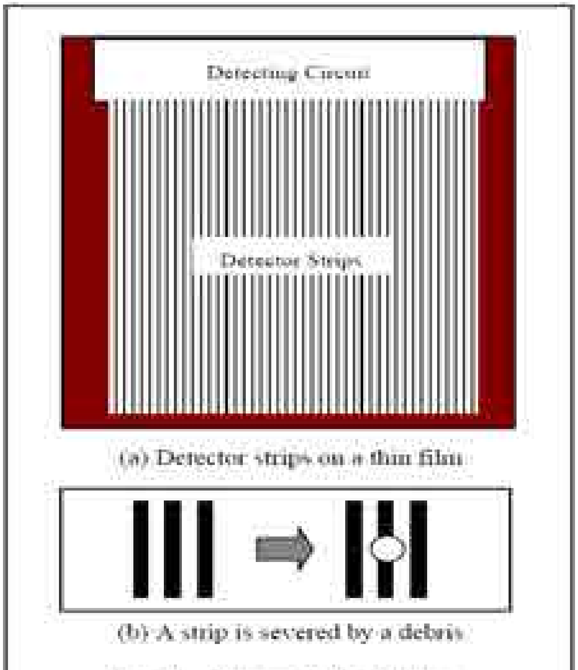

Fig. 1 Concept of the detector

QPS方式
（1）計測対象／計測項目
・計測対象：粒径100μm以上のダスト
・計測項目：デブリ（ダスト）粒径、衝突頻度

（2）基本原理
厚さ約10μm～20μm程度の絶縁性のフィルム上に、（空間周期）約100μm程度の直線状の細長い導線（太さ約50μm）のパターンを形成（図1(a)）。

検出線の破断を電気的に検知することにより、ダストの衝突（貫通）を検知する。

破断した導線の数、導線の幅、ピッチからダストのサイズを計測（図1(b)）。

［桜井(2008)による。(有)QPSとIHIで共同特許出願中］

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製造技術の発展
＜技術のブレークスルー＞

エッチング技術を用いセンサ面に導線を形成

はやぶさ衛星のターゲットマーカ、
80万人の名前を印字(Al微細エッチング法、
文字サイズ30μm、線幅5μm)

フレキシブルプリント基板製造技術を応用し、センサ部をプリント基板の一種として作成

フレキシブルプリント基板（フレキシブルプリントきばん）は、柔軟性があり大きく変形させることが可能なプリント基板。

厚み12μmから50μmのフィルム状の絶縁体（ベースフィルム）の上に導体箔を形成した構造

JAXA宇宙環境Grの開発センサ

（直径43 cm）

○欧州が開発したセンサの一例

- ・大きさ0.1㎜程度以下のデブリ計測用
- ・質量5kgと重く、信号処理も複雑。
- ・計測項目がデブリには十分過ぎる。（速度、質量、方向、基本組成、ダストの帯電等）
- ・キャリブレーション試験の量が膨大

⇒多種多様な衛星への搭載は困難

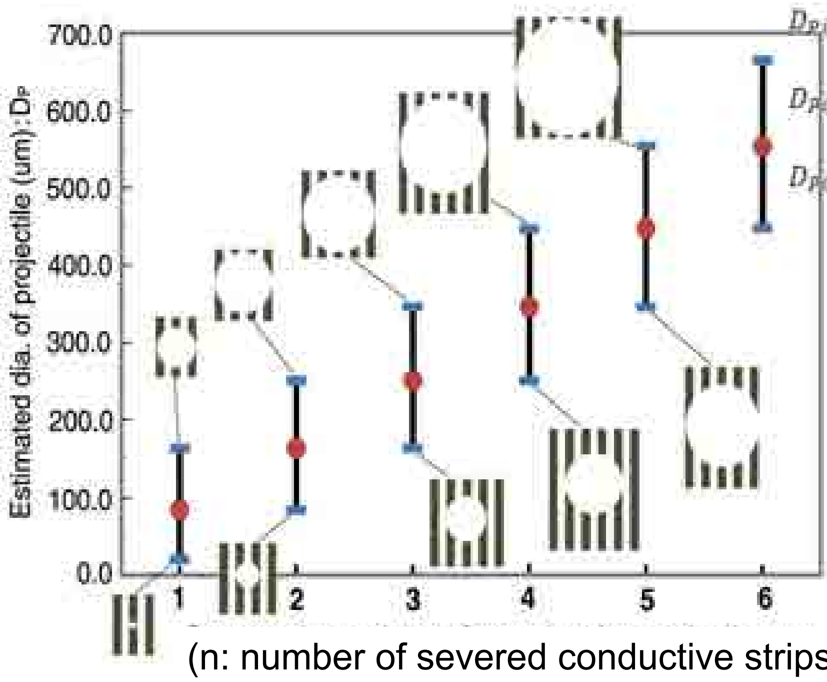
（35 cm（横） x 30 cm(縦)）

○JAXA宇宙環境Gr.開発センサ

- ・大きさ0.1㎜～数㎜のデブリの計測用
- ・質量0.2kg程度と軽く、信号処理も単純
- ・フィルム状（厚さ:0.025㎜）のため、形や大きさの調整が容易

⇒多種多様な衛星への搭載が可能

超高速度衝突試験によるセンサ性能評価
（検出線の破断本数に対するデブリ径）



(n: number of severed conductive strips)

$$D_{P(Maximum)} = 1.39\times10^{-1}(np+d+p)^{1.28}$$

$$D_{P(Nominal)} = 1.39\times10^{-1}(np+d)^{1.28}$$

$$D_{P(Minimum)} = 1.39\times10^{-1}(np+d-p)^{1.28}$$

計測項目
- ・貫通（検出線の破断）からデブリの通過
- ・検出線の破断本数からデブリの大きさ

Kitazawa et al., 2010

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QPS方式のセンサラインアップ

〇Educational　Model　（under Operation)

〇搭載機
高電圧技術実証衛星「鳳龍弐号」
〇打上げ
H24 年5月18日　H-ⅡA21号機　@種子島宇宙センター
〇特徴
IH/QPS研究所の特許及びJAXAの開発情報を元に九州工大で独自の開発・製作・搭載

〇Laboratory　Model (will be launched after December 2012)

〇搭載機
九州の『超小型地球観測システム実証衛星、(QSAT-EOSstration)』
〇打上げ
H24年12月(以降)ロシアのヤスネ基地
〇特徴
JAXAセンサ開発の委託業務の過程で(有)QPS研究所が製作した「研究室モデル」をQSAT-EOSチームが製作・搭載。

〇JAXA Flight Experiment　Model

〇搭載機
TBD
〇打上げ
TBD
〇特徴
フレキシブルプリント基板技術により大面積化を実現

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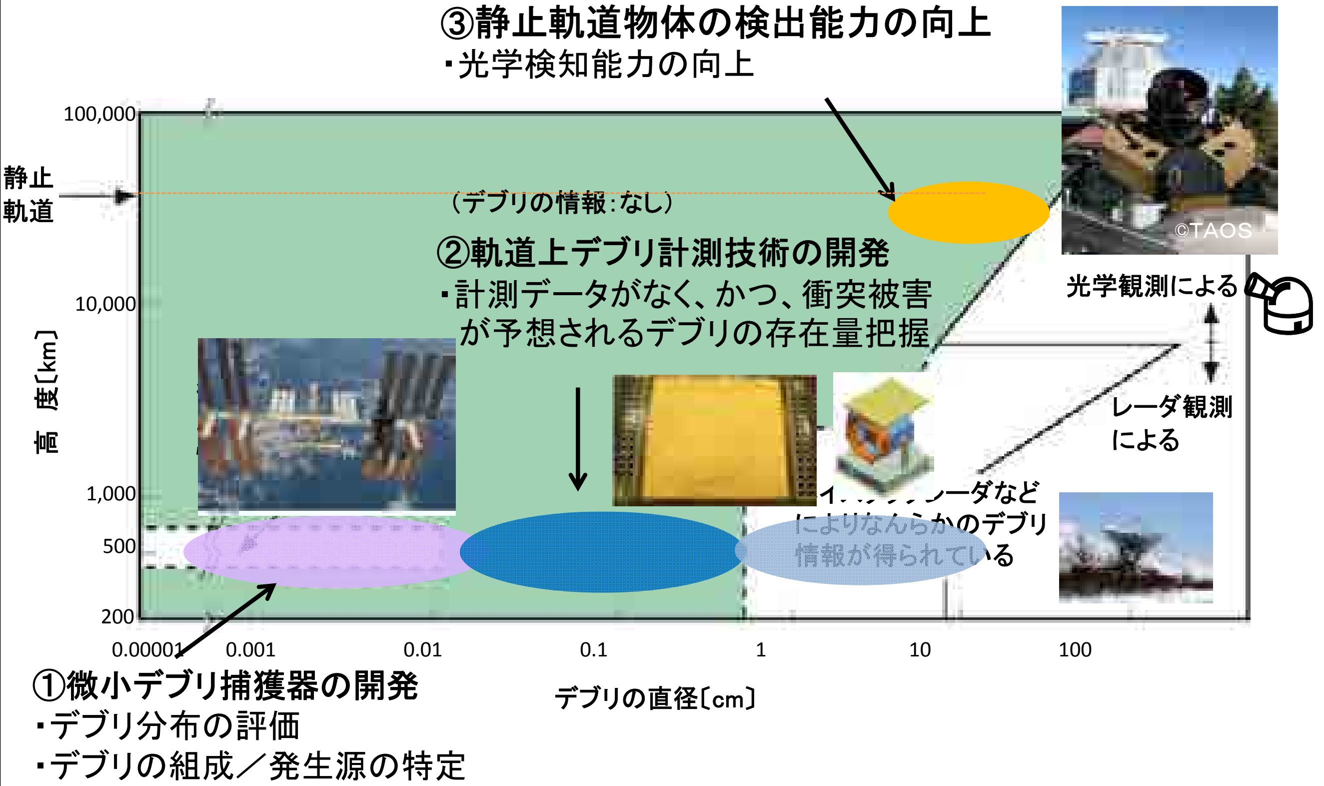
研究開発のフィールド



デブリの大きさ、軌道高度に対する計測可能範囲（北澤と上松,1995等による。）

今後の主要課題

○JAXAアクティブセンサの早期のフライト実証
○JAXAアクティブセンサの本格運用／ネットワーク化
　ex. 九大のIDEAの提案
　（環境変動の迅速な把握体制の整備）
○データ／技術アーカイブの整備・リスク評価への活用
○「環境モデル」構築

微小デブリ環境モニタリング計画 IDEA
（九州大学花田研究室による）
http://idea.aero.kyushu-u.ac.jp/

E4

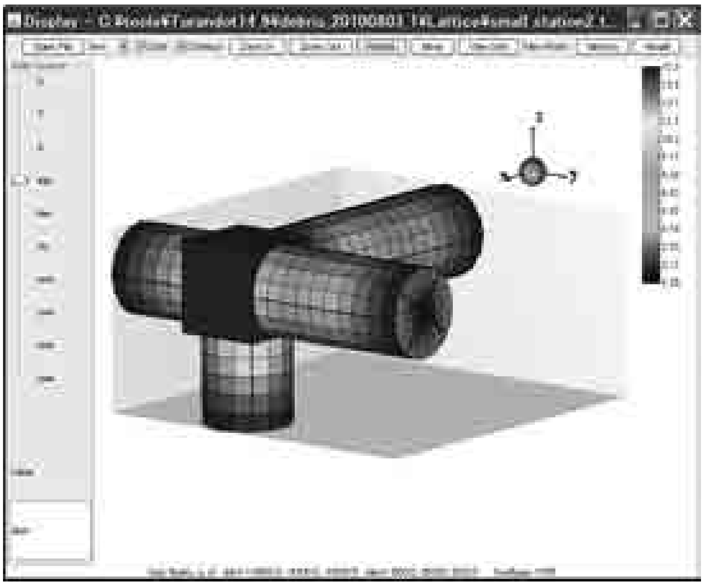
デブリ衝突損傷リスク解析ツール(TURANDOT)の機能拡張

Expansion of Tactical Utilities for Rapid ANalysis of Debris on Orbit Terrestrial

金 正浩, ○八田真児(MUSCAT スペース・エンジニアリング株式会社),
東出真澄, 河本聡美(JAXA 未踏技術研究センター)
Jeongho Kim, ○Shinji Hatta (MUSCAT Space Engineering Co., Ltd.),
Masumi Higashide, Satomi Kawamoto (JAXA/Innovative Technology Research Center)

デブリ衝突損傷リスク解析ツール(TURANDOT)は、2008年に開発を開始した宇宙機設計支援ソフトウェアである。本ツールは宇宙機表面を詳細な格子に分割し、衛星各部の遮蔽効果を考慮した上で、各部のデブリ衝突による損傷発生確率を推定する。軌道上デブリフラックスのデータベースとしては、当初、MASTER2005とORDEM2000を利用したが、現在ではMASTER2009も利用可能なように機能拡張を実施した。本ツールの概要を報告する。

Development of Tactical Utilities for Rapid Analysis of Debris on Orbit Terrestrial (TURANDOT) is started on 2008. The software is capable of prediction of spacecraft damage probability by collisional debris including shielding effect of the spacecraft itself. The tool initially makes use of MASTER-2005 and ORDEM2000 as database of debris flux. We conducted the expansion so that the tool can reference MASTER-2009 also. The report is of the schematic of the tool.



TURANDOT

Expansion of Tactical Utility for Rapid ANalysis of Debris on Orbit Terrestrial

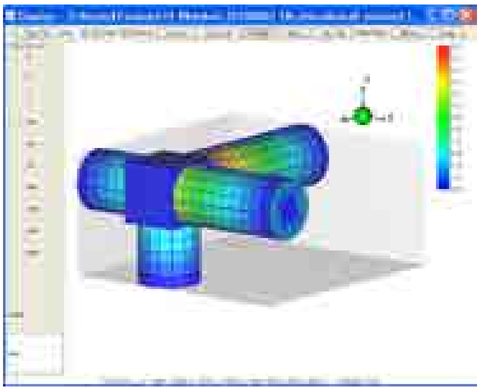
J. Kim (MUSCAT Space Engineering Co., Ltd.)
○ S. Hatta (MUSCAT Space Engineering Co., Ltd.)
M. Higashide (JAXA/Innovative Technology Research Center)
S. Kawamoto (JAXA/Innovative Technology Research Center)

5th Space Debris Workshop, 22~23, January, 2013
@ Chofu Aerospace Center

Contents

What is TURANDOT ?

- JAXA's Debris collision risk analysis tool
  - For each part of spacecraft system
  - Orbit, Attitude, Shape & Shielding Effect
  - Users' defined Damage Mode & Ballistic Limit Eq.

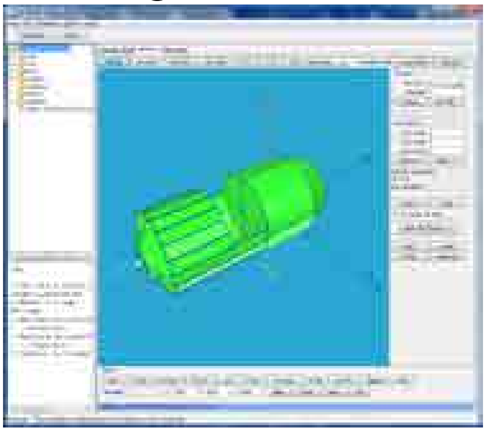


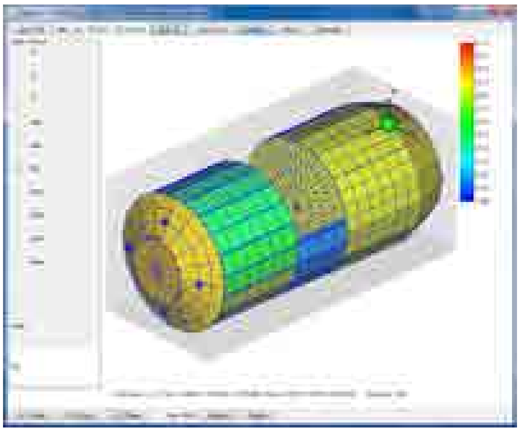
History

- April, 2007~Feb., 2009
  - "Collision Probability" Analysis Tool
- April, 2009~Feb., 2011
  - "Collisional Damage" Probability Analysis Tool
- April, 2011~Feb., 2012
  - Including "MASTER-2009"

Functions I

- GUI
  - Integrated Analysis Environment
  - Satellite modeling
  - Grid generation





Functions I

- GUI
  - Computation condition setting
  - Requirement from Databases (MASTER & ORDEM)

Functions II

- No Domestic Database!
  - MASTER-2005 & ORDEM2000
  - <u>MASTER-2009 & ORDEM2000</u>

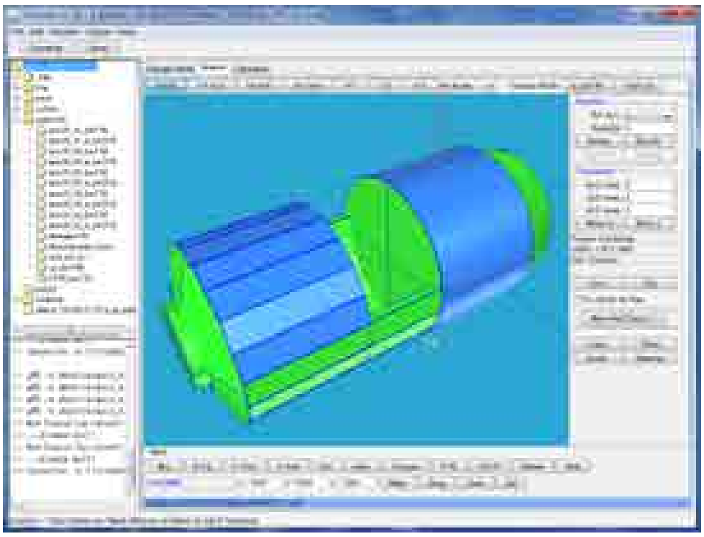
$$flux_{\mathrm{ORDEM}} = flux_{\mathrm{MASTER}} \cdot K \qquad if\ 1 < K$$

$$flux_{\mathrm{ORDEM}} = flux_{\mathrm{MASTER}} \qquad if\ K < 1$$

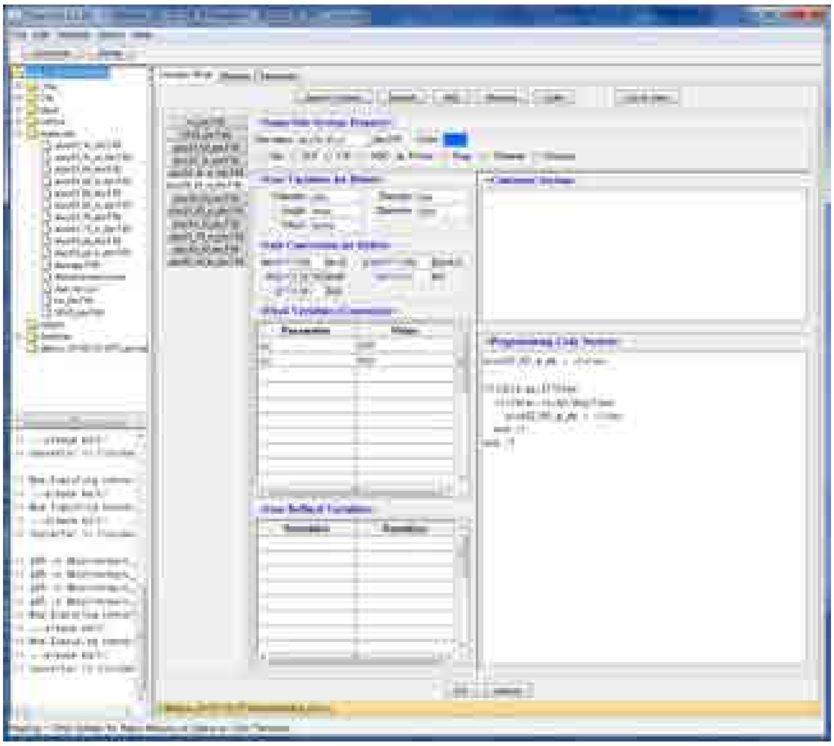
$$K = \frac{F_{\mathrm{ORDEM}}}{\int_{4\pi} f_{\mathrm{MASTER}} \cdot d\Omega}$$

Functions III

- Damage Probability
  - Users' Definition
  - Fortran 95 like



Functions III



Analytical Technic I

- Computation Cost
  - If an spacecraft has 1000 surface elements,

Shielding Elements

1000 x 1000 x 1000000 Shielding Effect Check !!

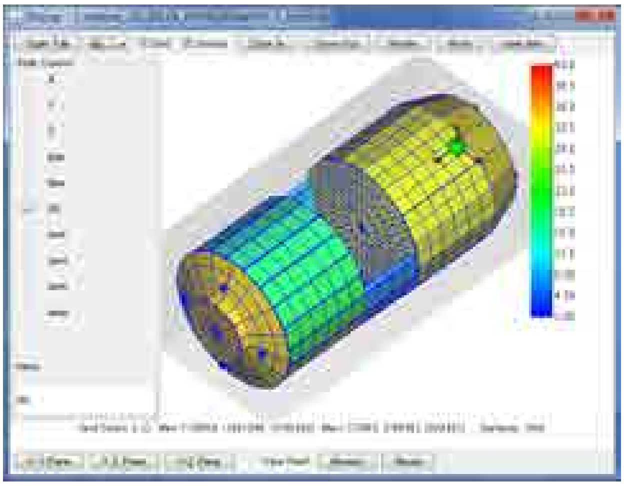
Surface Elements

MASTER Fluxes

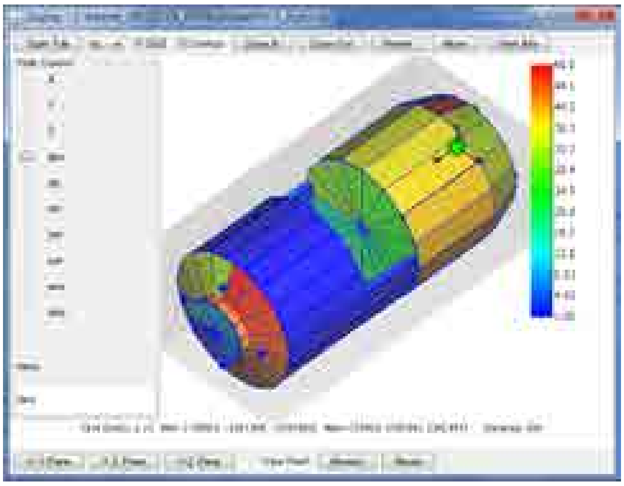
  - Long computation time.
  - Huge memories to Windows PC.
  - HD is too slow.

Analytical Technic II

- Reduce Shielding Elements



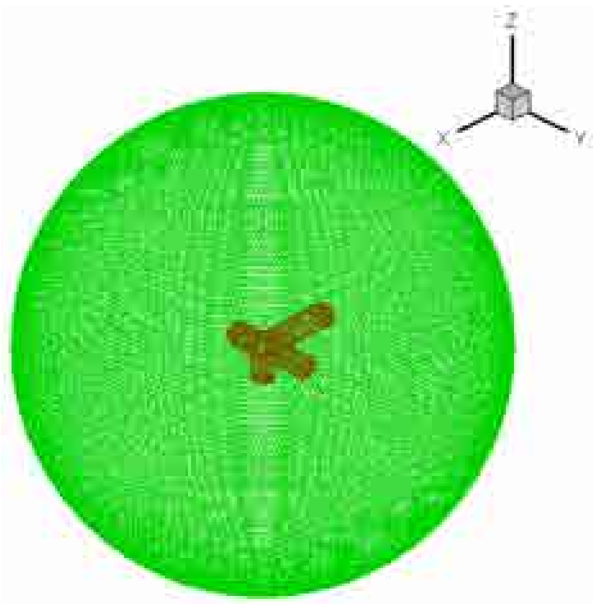
Shielded Element

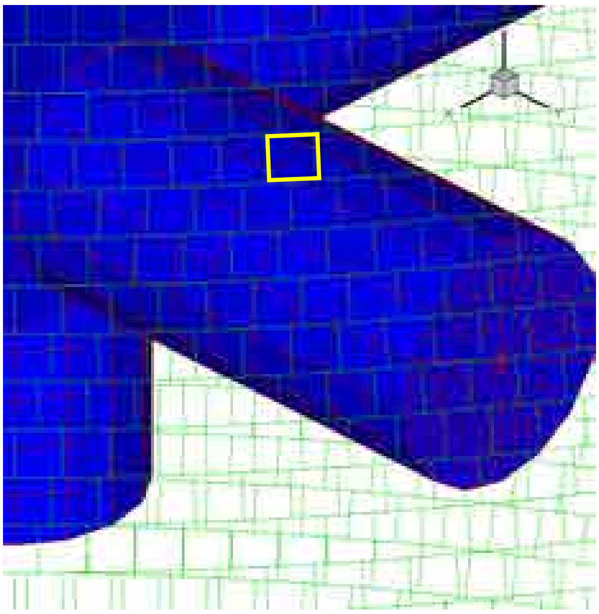


Shielding Element

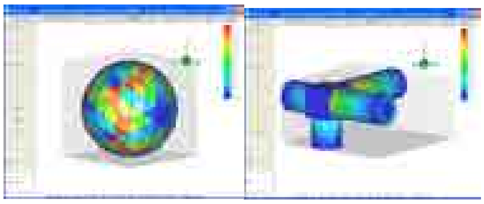
Analytical Technic III

- Reduce MASTER fluxes into solid angle

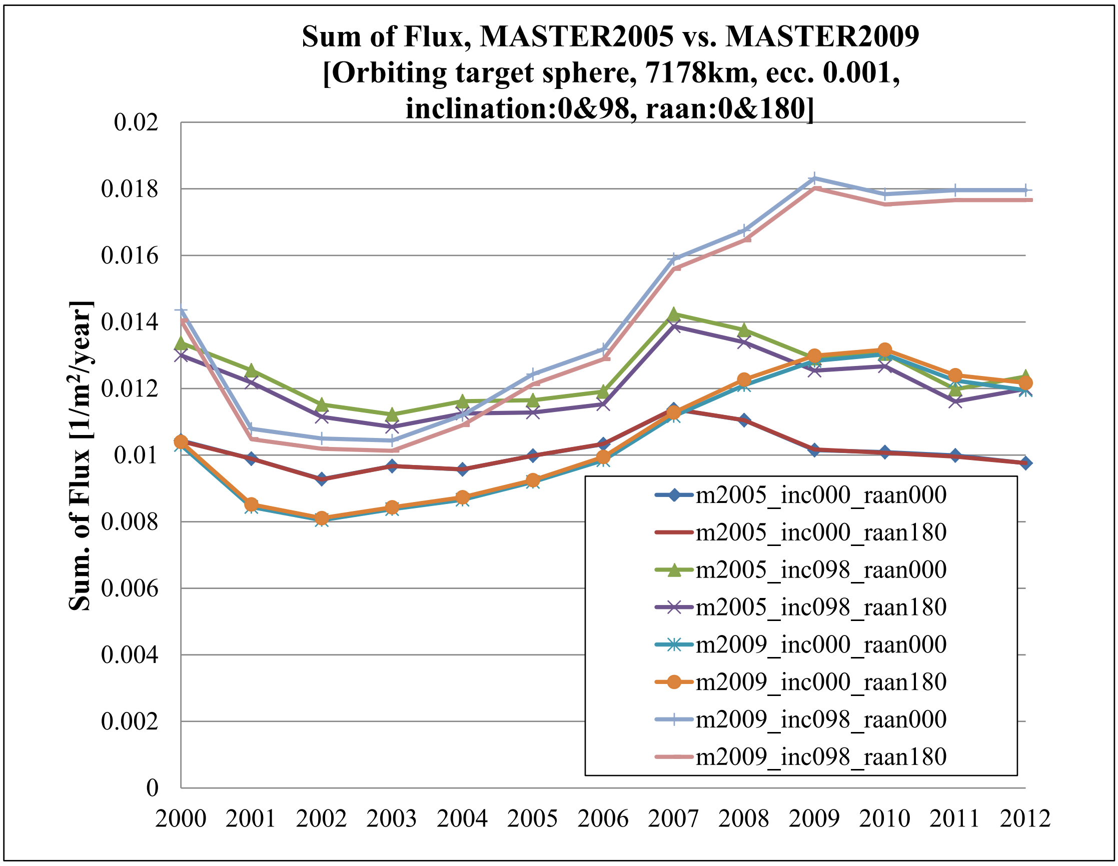




Validation

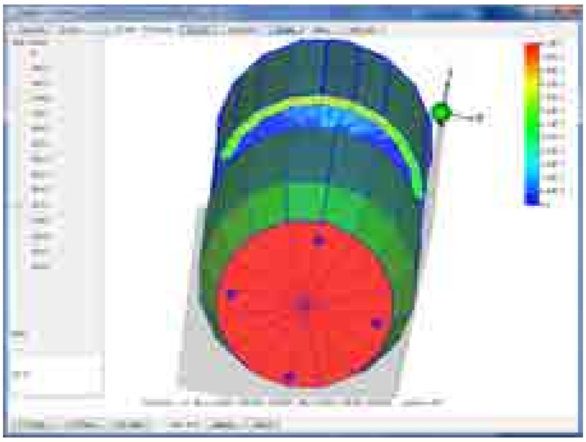
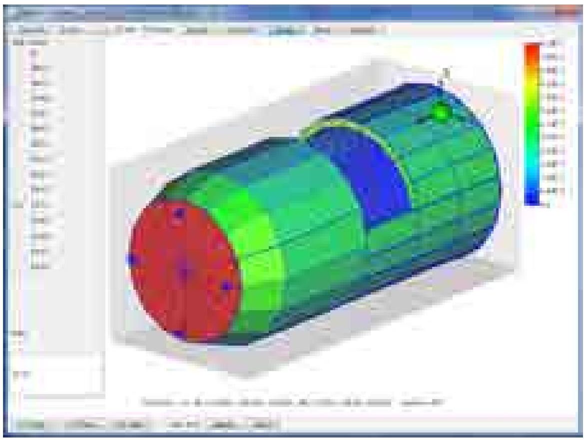


		Cube		Sphere		Small Station
		ORDEM2000/ MASTER2005	Turandot	Ordem2000/M ASTER2005	Turandot	Turandot
ORDEM2000 (+MASTER20 05)	D>0.1mm	-	2.25E+01	1.77E+01	1.60E+01	9.32E+01
	D>1.0cm	-	1.35E-05	2.16E-06	9.51E-06	5.44E-05
Master2005	D>0.1mm	6.14E+00	6.15E+00	4.65E+00	4.37E+00	2.55E+01
	D>1.0cm	1.36E-05	1.36E-05	1.04E-05	9.53E-06	5.45E-05



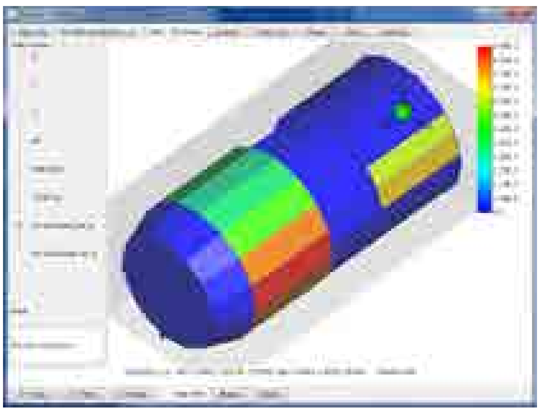
Example

- Collision Probability

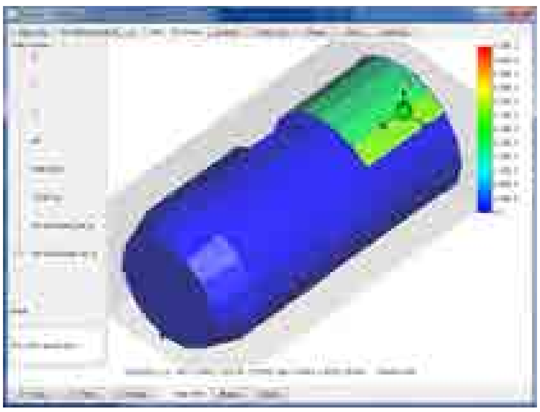



Example

- Damage Frequency



User defined SAP-1



User defined SAP-2

Conclusion

- Development April 2007~Feb.2012
- GUI
- Solver
- MASTER-2005/2009 & ORDEM2000
- Users' damage mode definition
- Tri-direction Spacecraft (Geo , Inertia & Helio)

References

- MASTER-2005/2009 Manuals
- ORDEM2000 Manual
- IADC Protection Manual
- Hastings & Garrett "Spacecraft Environment Interaction," Cambridge

FAQ “TURANDOT”

- Japanese E.T. legend “Kaguya” /”Taketori”
  - No “D” of debris, damage
  - No “C” of collision
- Oriental similar legend “Turandot”
  - François Pétis de la Croix, ”Les Mille et un Jours”

“Taketori”

“Turandot”

E5

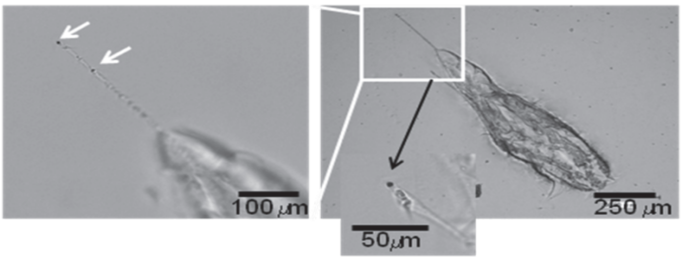
きぼう搭載微小粒子捕獲実験装置(MPAC)の観測結果について

KIBO/MPAC EXPERIMENT SUMMARY

木本雄吾（宇宙航空研究開発機構）, ○和気美幸（AES）
Yugo Kimoto (JAXA), ○Miyuki Waki (AES)

きぼう搭載微小粒子捕獲実験および材料曝露実験（JEM/MPAC&SEED 実験）装置は宇宙環境計測ミッション装置（SEDA-AP）の搭載装置の一部として、2009 年 7 月に STS-127（2J/A）に打ち上げられ、ISS に取り付けられた。JEM/MPAC&SEED 実験装置は宇宙空間に約 8.5 ヶ月曝露され、2010 年 4 月に地上へ回収された。この内MPAC 実験はスペースデブリ、マイクロメテオロイド等の宇宙空間に存在する微小粒子を捕獲し、その起源や分布量を把握する実験である。捕獲実験サンプルにはシリカエアロジェルと金プレートが用いられた。本発表において、衝突孔の速度分布、方向分布及び入射フラックス等の得られた観測結果について報告する。

JEM/MPAC&SEED experiments are composed of a Micro-Particles Capturer (MPAC) and Space Environment Exposure Device (SEED), which are installed in the outboard platform of “KIBO” in the ISS. KIBO/MPAC is an experiment to capture space debris or micro-meteoroids, and clarify the origin and amount of distribution. Silica-aerogels and Au-plates of MPAC samples were exposed to space for about 8.5 months. We presents the distribution of impact velocity, kinetic energy, and flux in impact holes confirmed with these samples.



An example of a Impact hole and capture particles on aerogel

KIBO/MPAC EXPERIMENT SUMMARY

Yugo Kimoto (JAXA)
Miyuki Waki (AES)

1

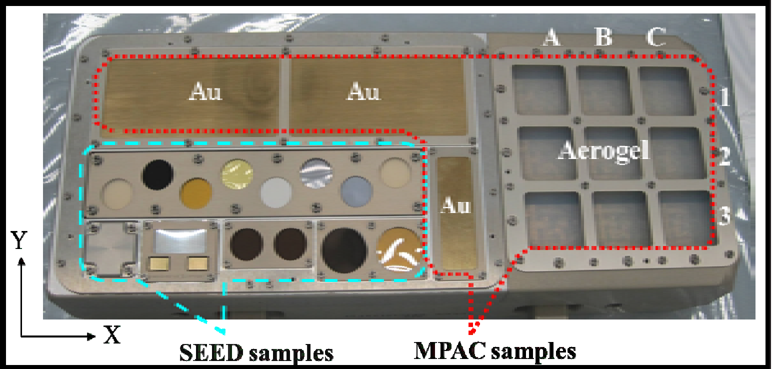
Over View

1. Introduction
2. Observation Method
3.Observation by CCD Scope
4. Distribution of Azimuth & Elevation
5. Presumption of Impact velocity
6. Flux
7. Summary
8. Future Prospects

2

1. Introduction

JEM/ MPAC&SEED (Japanese Experiment Module/Micro-Particles Capturer and Space Environment Exposure Device)



MPAC is an experiment to capture space debris or micro-meteoroids, and clarify the origin and amount of distribution.

MPAC&SEED structure was installed in the outboard platform of "KIBO" in the ISS.

Exposure period : 8.5months (259days)

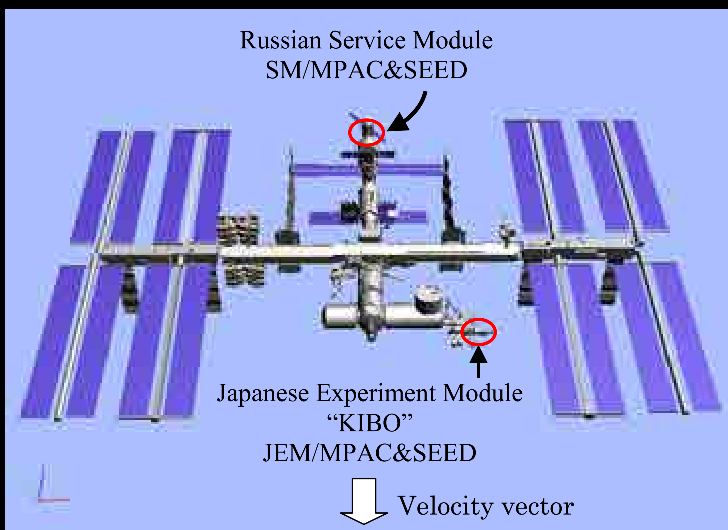
Aerogels : capture particles and estimate the impact parameters

Au-Plates : measure the number of impact holes and observe the shape.

3

Comparison the result of JEM/MPAC and SM/MPAC

SM/MPAC was the first debris capture experiment installed in the Service Module (SM) of Russia.



JEM/MPAC was installed at the front of the ISS, and the exposure side was only RAM (front face) .

SM/MPAC was installed behind the ISS, and the exposure side was RAM and WAKE (rear face)

We compare the collisional behavior of the micro-particles by the difference in the install position to ISS.

4

2. Observation Method

All the samples were observed by the CCD scope while searching for impact features with an overlapped view.

〈1〉 The feature had a crater-like rim and/or central peak.
〈2〉 The feature had radial cracks and/or ejecta.
〈3〉 The feature had a shape similar to those induced by hypervelocity impact experiments.

- Class I atisfied all 〈1〉 ~ 〈3〉 criteria.
- Class II satisfied one or two criteria.

→ Impact (It is possible that space debris and micrometeoroids are the origins.)

- Class III doesn't fulfill criteria

→ Track (signs of some impact are visible, possibiliy of secondary debris.)

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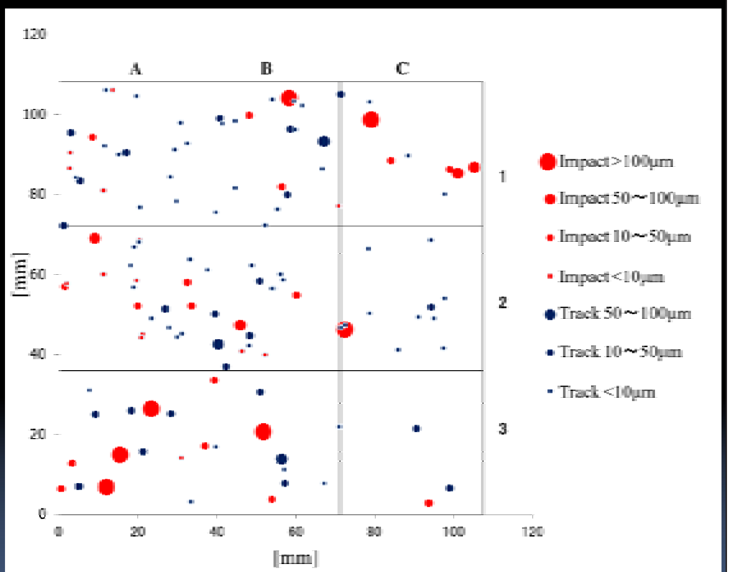
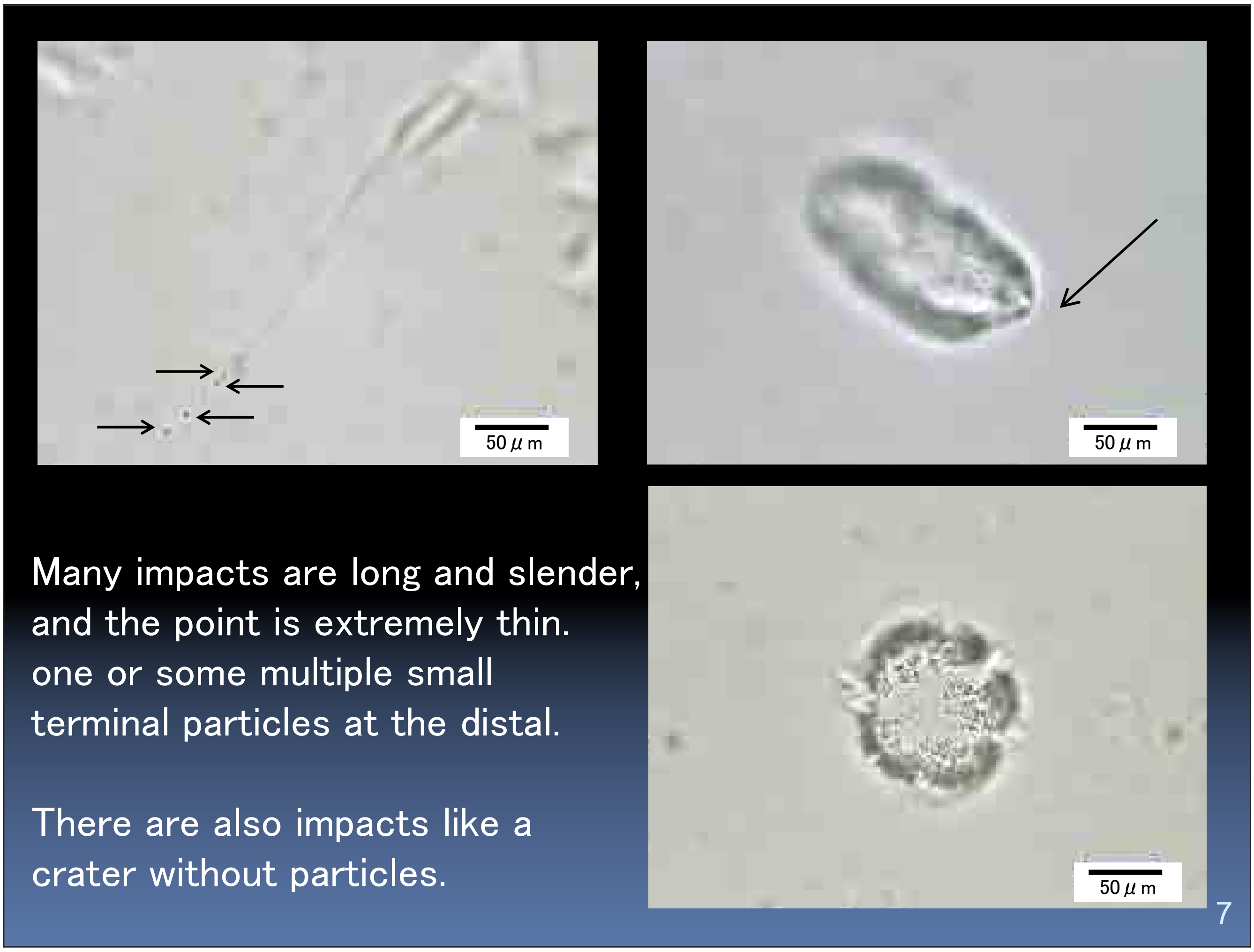
3. Observation by CCD Scope

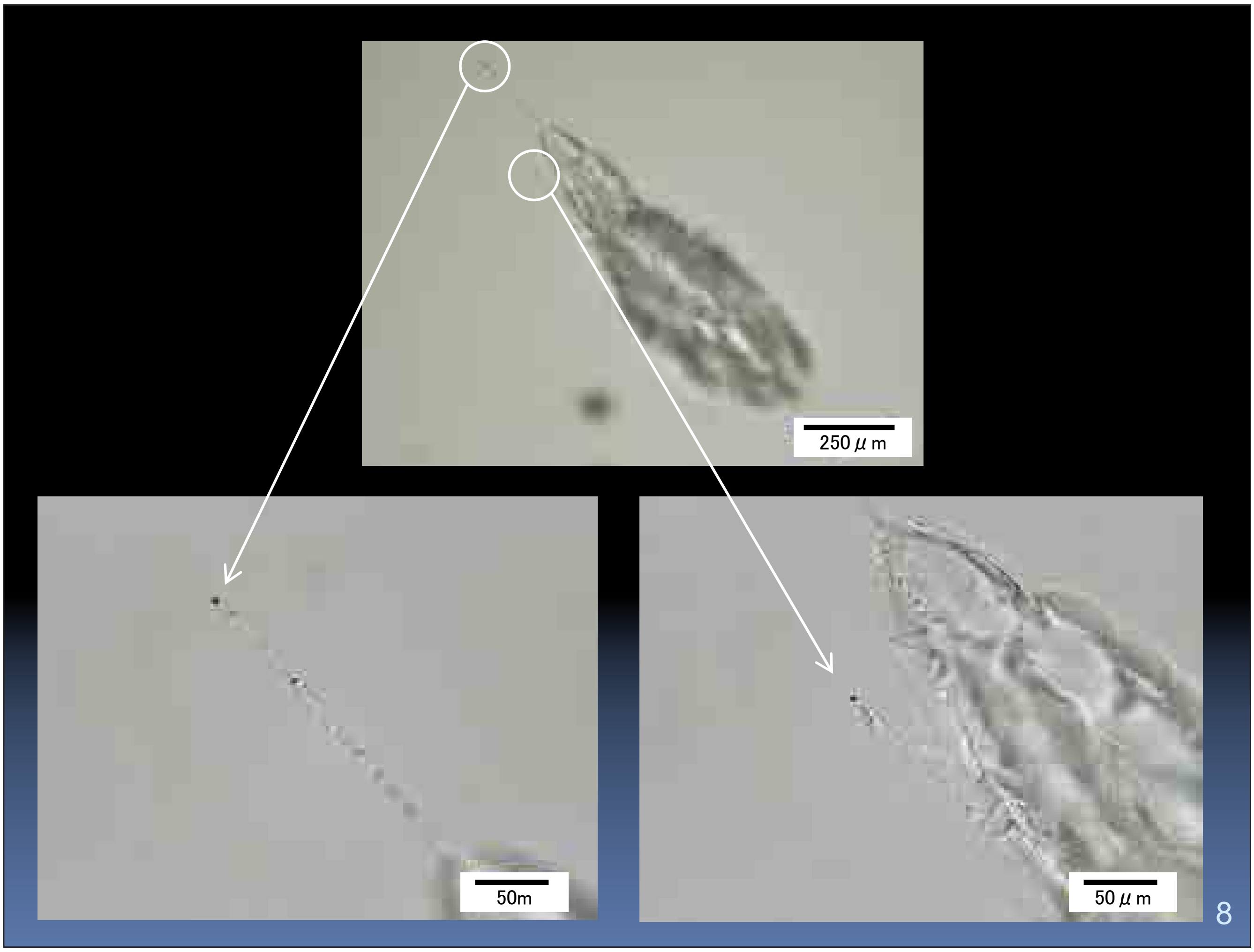
- Hardly any degradation and discoloration was observed on the surface of aerogels.
- 41 impact holes were found on the aerogels, and 83 tracks.
- In Au-plates, 15 impact holes were found.
- The density of the impact hole was about 3500/m².This means particles of about 5000/m²/year collided with the ISS in one year.

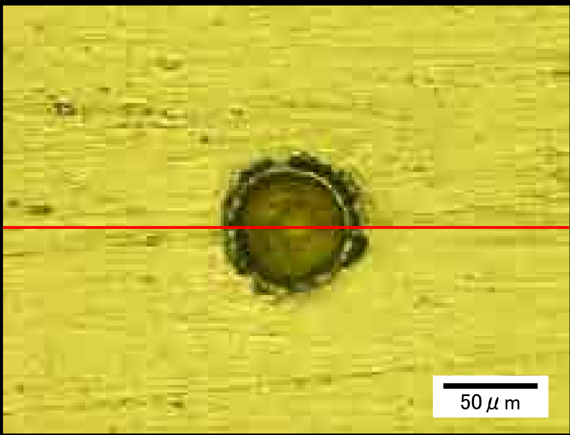


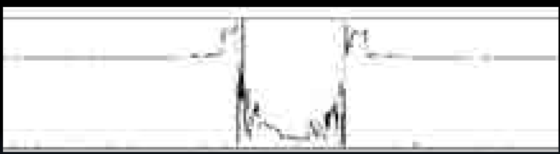
Distribution of impact holes and tracks on aerogels

6


50 μ m
50 μ m
Many impacts are long and slender, and the point is extremely thin.
one or some multiple small terminal particles at the distal.
There are also impacts like a crater without particles.
50 μ m
7

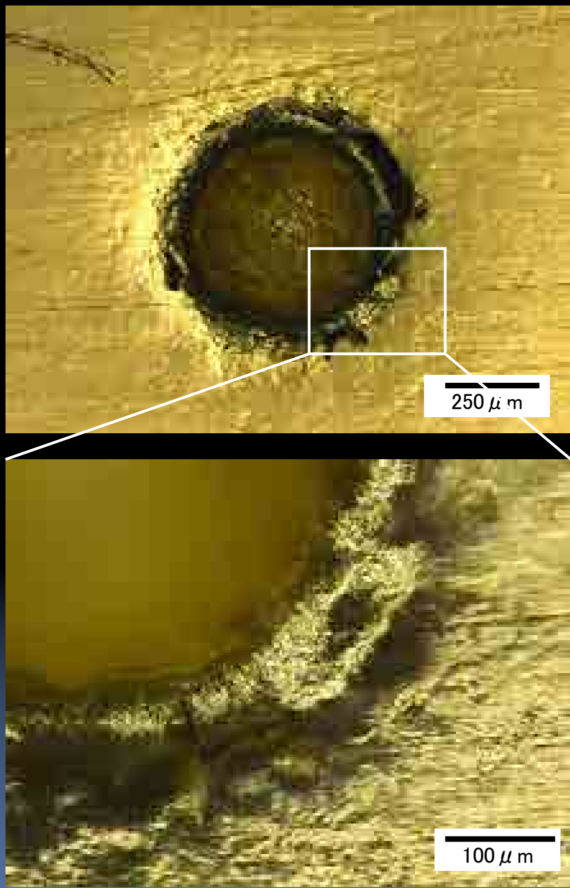

250 μ m
50m
50 μ m
8





Super-depth synthesis chart

Impacts on Au-plates were of the crater type. The rims were turned over and swelled out.



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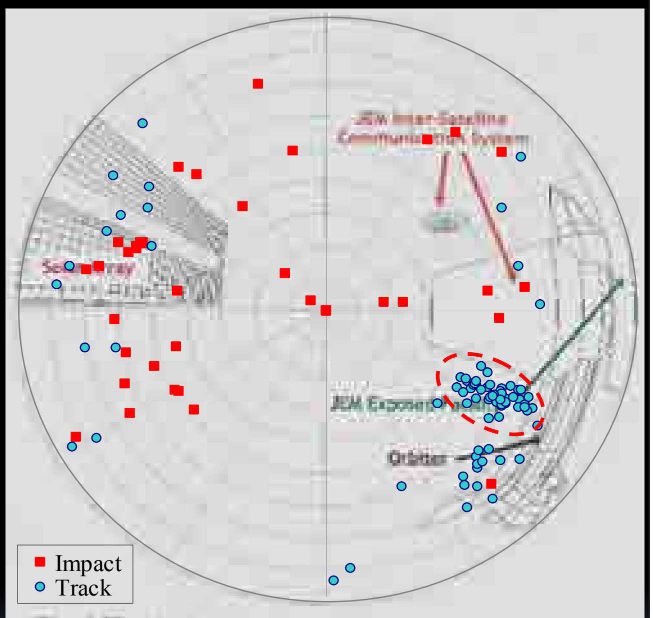
4. Distribution of Azimuth & Elevation

Many tracks were concentrated (α: 20～60, ε: 20～40)

➡ These were similar shapes, and may have been formed at the same time.

Their origins are JEM Inter-Satellite Communication System or the Orbiter ?



Hemispherical view from JEM/MPAC&SEED

- Orbiter thrusters may fire during docking/undocking operations

➡ Secondary debris occurred at this time.

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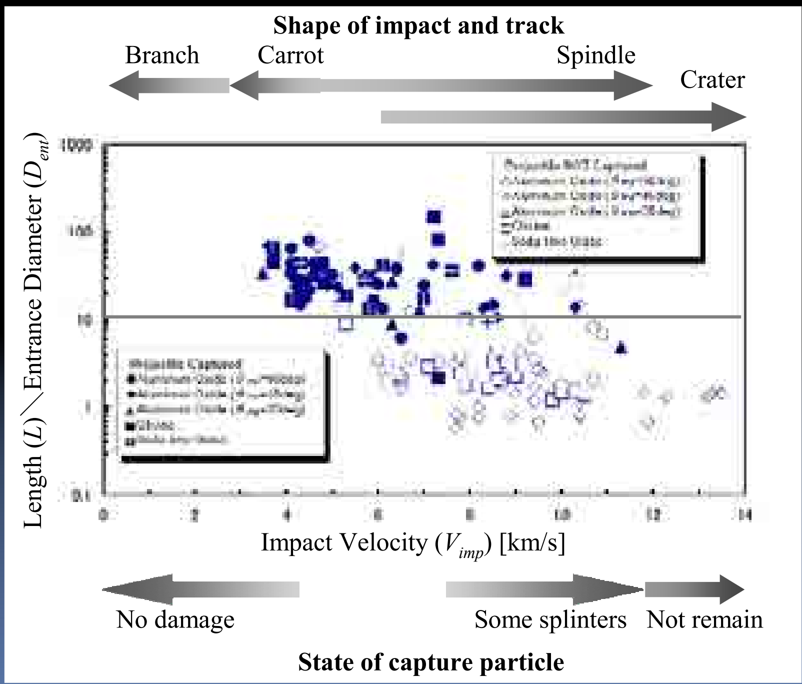
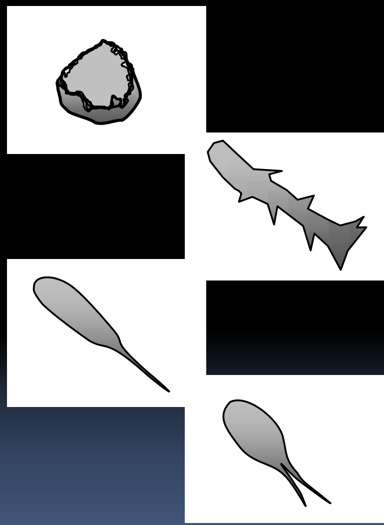
5. Presumption of Impact velocity

The Ground Hypervelocity Impact Experiment (Prof. of International Symposium on SM/MPAC&SEED Experiment, Kitazawa.et.al) : The experiment which made various size and material micro-particles collide aerogels.

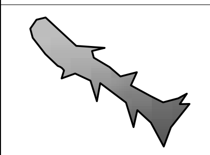
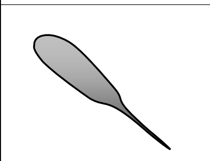
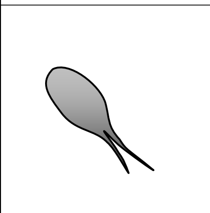
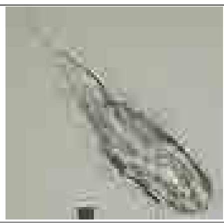
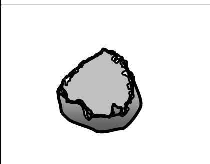
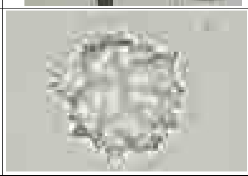




Relation of the aspect ratio of the impact hole (L/D_{ent}) with impact velocity (V_{imp})

11

Comparison of the result of the ground experiment and JEM/MPAC experiment.

	Shape	V_{imp}	JEM Observation Example
Branch		＜3km/s	
Carrot		3～5km/s	
Spindle		5～12km/s	
Crater		6km/s＜	

Many of impacts on JEM/MPAC aerogels are Crater type.

Impact velocity (V_{imp}) is more 6km/s. At impact without particles, more than 12km/s.

Many of tracks are L/D_{ent} =10～30, and Carrot or Branch type.

Impact velocity (V_{imp}) is 3～5km/s.

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6. Flux

6.1. ClassI

- The exposure period of JEM/MPAC experiment is shorter, and its area is also smaller than SM/MPAC experiment.
- Although, flux (ClassI) of JEM/MPAC is larger than SM/MPAC.

Comparison of JEM/MPAC with SM/MPAC

	JEM	SM
Exposure Period [day]	259	315
Area (RAM) [m^2]	1.12×10^{-2}	3.35×10^{-2}
Count [number]	13	2
Flux [number/m^2/year]	1500	350

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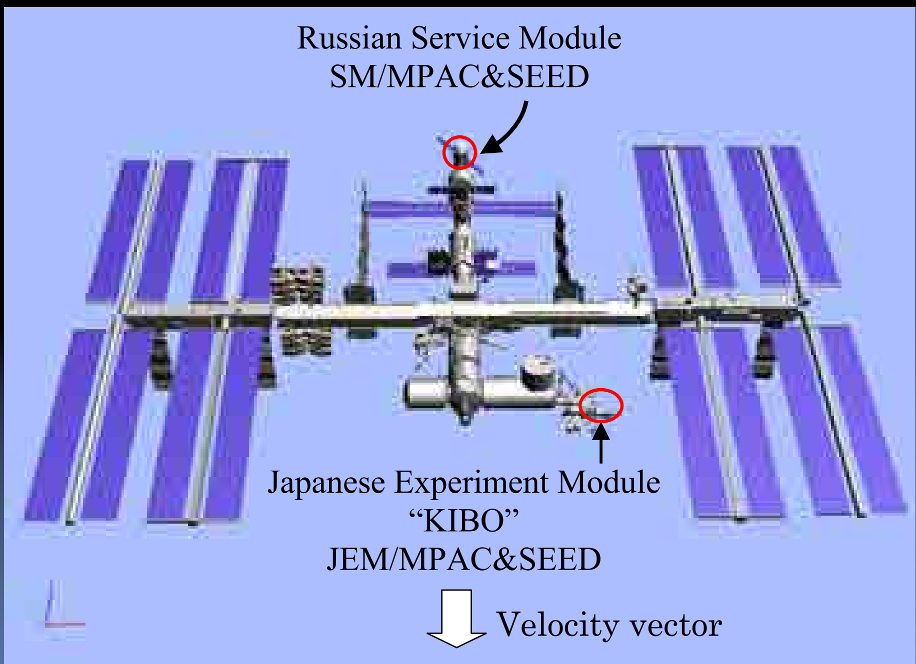
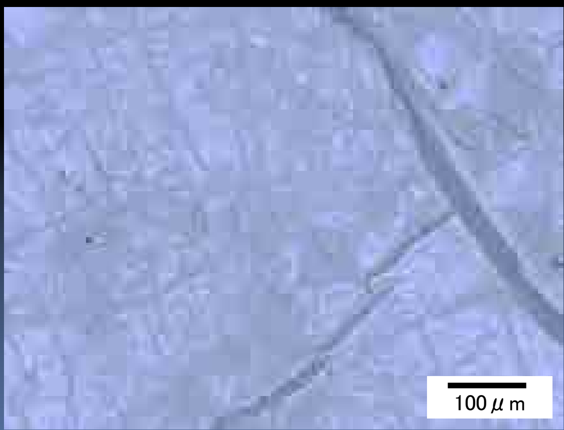
- This is a caused by the install position. With JEM/MPAC samples, since there is nothing that is interrupted at the front, it is thought that more particles collided for a short period of time compared with SM/MPAC samples.



14

- As for SM/MPAC aerogels, surface discoloration and crack were seen as the exposure period became long.
  → Discernment of class I impacts became difficult.
- As for JEM/MPAC aerogels, discoloration and crack are not almost.
  → Class I impacts remained without being erased.



SM/MPAC Aerogel

JEM/MPAC Aerogel

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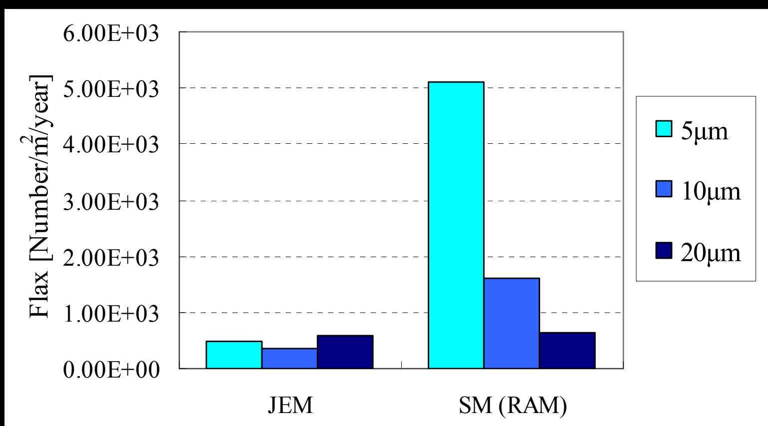
6. Flux

6.2. ClassI～III



Flux (classI～classIII)

- Contrary to the case of only the class I, all the flux containing class I ～ III of JEM/MPAC is less than SM/MPAC。

JEM/MPAC：Many of collision things are substance of space origin

SM/MPAC： substance of space origin＋secondary debris of ISS

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7. Summary

- Micro-particles that existed in space were captured, and their signs observed.
- There is a concentration region in angle distribution of tracks.

→ Influence by docking of an orbiter

- Impact Velocity（V_{imp}） Impacts : 6～12km/s　Tracks : 3～5km/s
- Flux （class I）　　JEM＞SM
- Flux （class I～III）　SM＞JEM

→ The difference in a install position is the cause
JEM/MPAC samples : substance of space origin
SM/MPAC samples : secondary debris of ISS

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8. Future Prospects

- We are conducting Raman spectroscopy analysis of captured particles in JEM/MPAC aerigels.

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- A future subject is establishing the method of analysis of buried particles (several microns in size) in aerogels.
- Micro particles forming micro-meteoroids were found in the SM aerogel . (pyroxene)
- There is also the potential for micro-meteoroids to be captured in the JEM aerogel. The result of future analysis is expected.

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E6

静止軌道周辺の破砕事象の観測とモデル化

Measurement and modeling of breakup events in the geostationary region

○上津原正彦，花田俊也（九大），柳沢俊史（JAXA），北澤幸人（IHI）
○Masahiko Uetsuhara, Toshiya Hanada (Kyushu University),
Toshifumi Yanagisawa (JAXA), Yukihito Kitazawa (IHI)

昨今活発に議論されているデブリの発生防止策・低減策の立案には，軌道上のデブリ環境を推定・予測した数値計算結果が積極的に用いられている．時々刻々と変化するデブリ環境に対して推定・予測結果の不確定性を抑えるためには観測・モデル化技術の向上が必要不可欠である．本研究の目的は，静止軌道周辺で発生した破砕事象の観測とモデル化である．運用中の人工衛星が約400機存在する重要な領域である静止軌道周辺では，未知デブリ(起源未同定のデブリ)がこれまでに数多く発見されている．未知デブリの起源は破砕を起こした宇宙機である可能性が高い．本発表では，観測における破砕事象の識別や未知デブリの起源同定方法，そして観測結果に基づく個々の破砕事象のモデル化方法について紹介する．

In this presentation we introduce measurement and modeling techniques applicable for spacecraft breakup events in the geostationary region. A large number of uncatalogued objects have been found in the geostationary region. Spacecraft breakup event is a possible cause of the population of uncatalogued objects. The techniques to be introduced may include observation planning for breakup fragments, origin identification of uncatalogued objects, and breakup event modeling based on the origin identification result. This research will contribute to space debris mitigation/remediation measures, whose effectiveness largely depends on our understandings of current space situation and its future prediction.

KYUSHU UNIVERSITY JAXA IHI

静止軌道周辺の破砕事象の観測とモデル化

Measurement and Modeling of Breakup Events in the Geostationary Region

UETSUHARA Masahiko[1], HANADA Toshiya[1], YANAGISAWA Toshifumi[2], KITAZAWA Yukihito[3]

[1] Kyushu University, Fukuoka, Japan
[2] Japan Aerospace Exploration Agency, Tokyo, Japan
[3] IHI Corporation, Tokyo, Japan

Objective

This research aims to establish a comprehensive method to understand and define the current orbital debris (OD) environment contributed by spacecraft breakup events

Breakup event is a major contributor to the catalogued in-orbit Earth satellite population

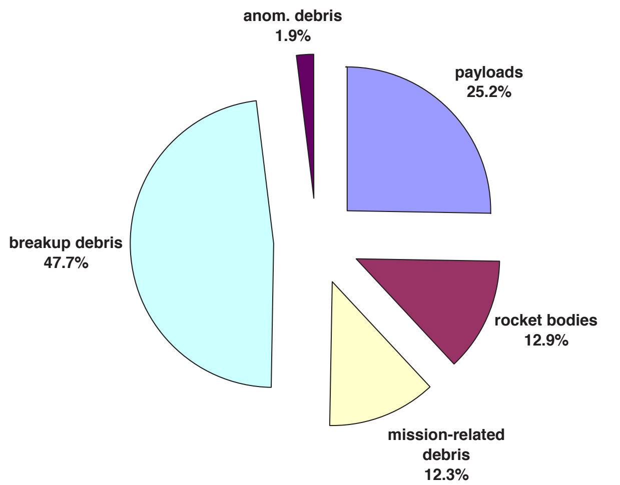
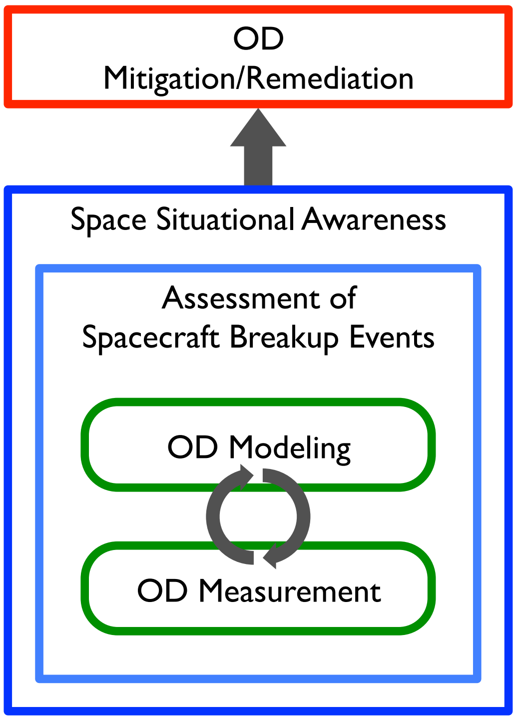


Figure 1.0-2. Relative segments of the cataloged *in-orbit* Earth satellite population.

Ref.) HISTORY OF ON-ORBIT SATELLITE FRAGMENTATIONS 14th Edition, NASA/TM–2008–214779 , 2008.

Approach and Contribution



- Objective
  - To estimate the characteristics of breakup events
  - To confirm the presence of unconfirmed breakup events
- Approach
  - To model the observable states of breakup events
  - To verify and revise the modeling results via optical measurements
- Contribution
  - To understand the current space situation and predict its future
  - To plan effective orbital debris mitigation/remediation measures

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R&D Roadmap

- Verification in GEO (2010-2013)
  - Development of the effective strategy applicable for breakup events in GEO
  - Confirmation of possible breakup events
  - Characterization of breakup events
- Application to LEO (2013-)
  - Establish the effective strategy applicable for breakup events in LEO

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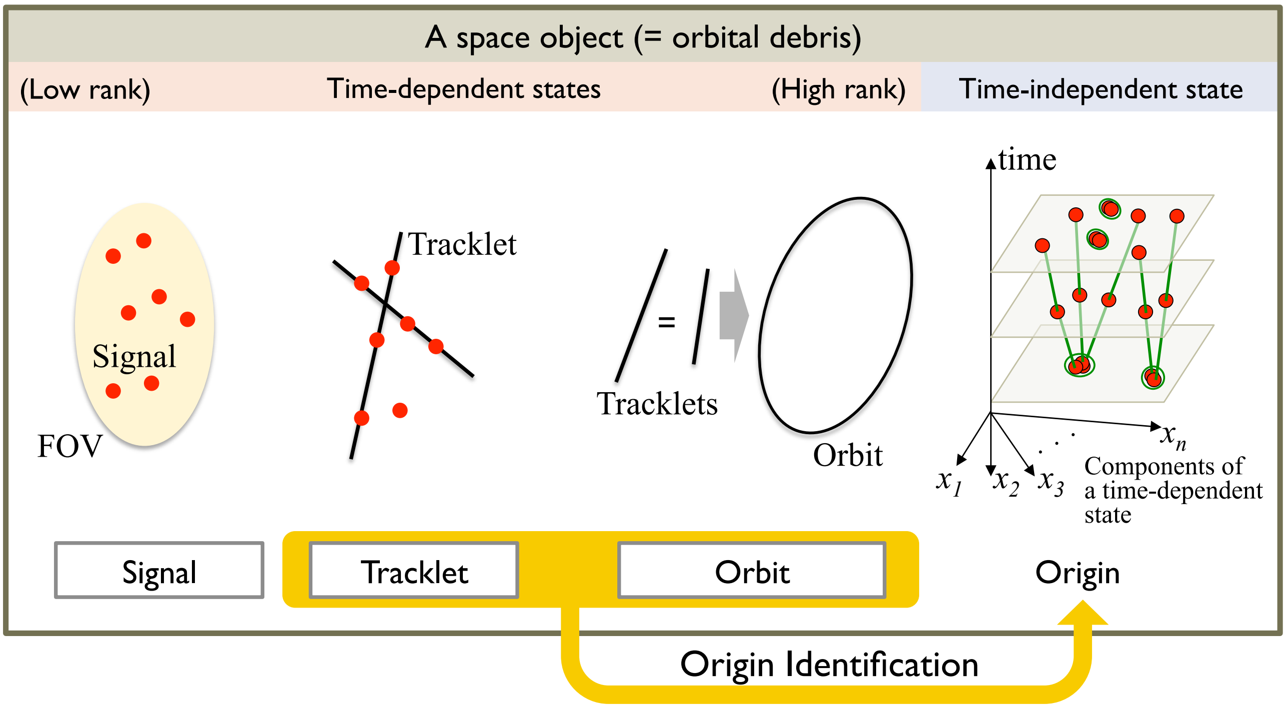
Breakup Events in GEO

Six rocket bodies (only Trastage!), four satellites, and two artificial events.
Two confirmed events (1968-081E and 1977-092A), and ten unconfirmed events.

ID	Cataloged name	Event epoch (YYDDD.dddd)
1966-053J	TITAN 3C TRANSTAGE R/B	87276.6882
1967-066G	TITAN 3C TRANSTAGE R/B	94045.4161
1968-081E	TITAN 3C TRANSTAGE R/B	92053.3745
1973-040B	TITAN 3C TRANSTAGE R/B	81067.2007
1975-117A	SATCOM 1	99257.6799
1975-118C	TITAN 3C TRANSTAGE R/B	87072.6430
1977-092A	EKRAN 2	78174.0000
1979-053C	TITAN 3C TRANSTAGE R/B	82309.0000
1979-087A	EKRAN 4	82157.7550
1988-018B	TELECOM 1C	02263.0000
(AE-02)	-	98180.0000
(AE-03)	-	92280.0000

(Oswald, 2008)

States of Orbital Debris



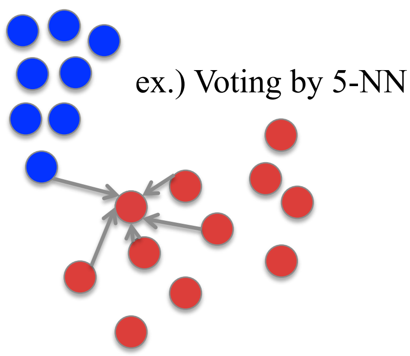
(To associate a time-dependent state with the time-independent state)

Origin Identification (1)

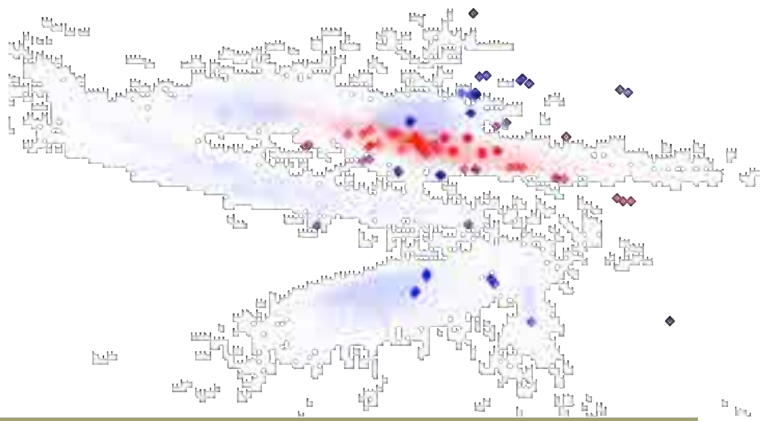
Tracklet

- Probabilistic assessment
  - To associate the tracklets with the predictions of breakup fragments in the angular velocity plane by using a k-NN (k nearest neighbor) algorithm

k-NN algorithm



Sample Result



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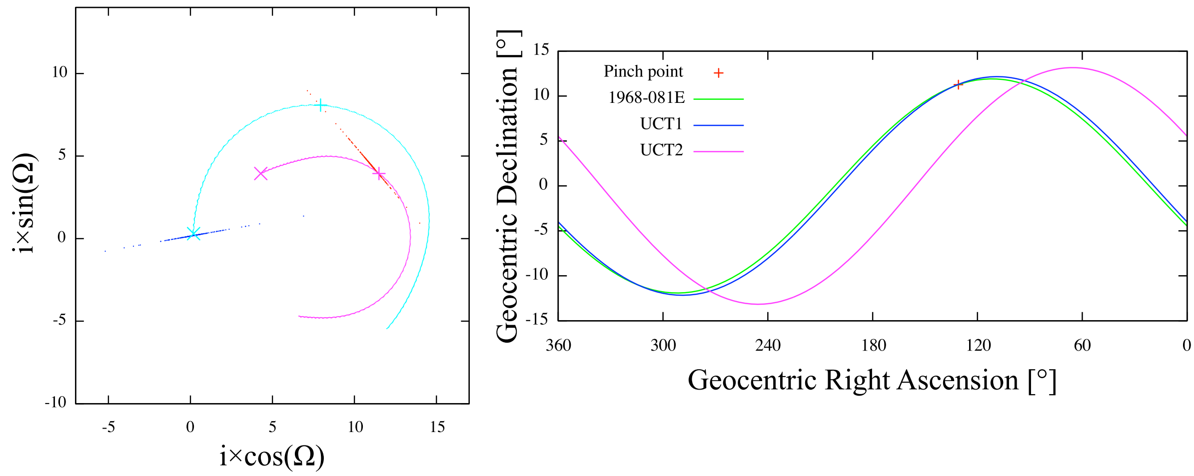
Origin Identification (2)

Orbit

- Deterministic assessment
  - Origins of breakup fragments can be identified in the parameter spaces related with orbital plane

Sample results from test cases (1968-081E, 1977-092A)



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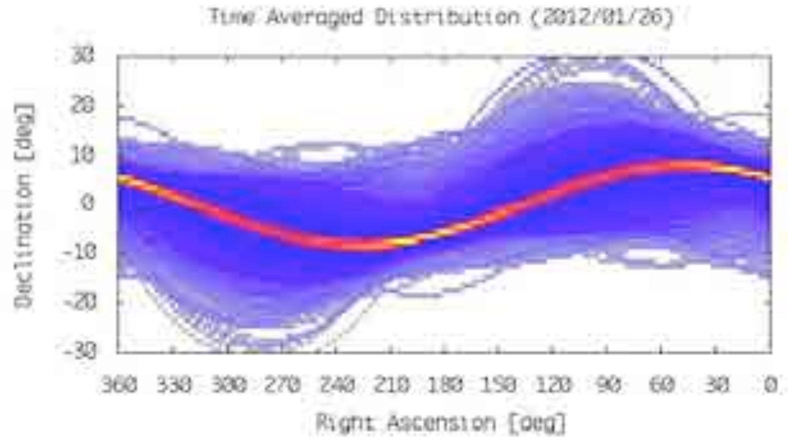
Event Identification

- To identify an orbital anomaly as a breakup event
- Problems to be solved
  1. How to plan survey observations of the possible breakup fragments
  2. How to identify the origin of observations with the possible breakup event, i.e., how to confirm the presence of the possible breakup event

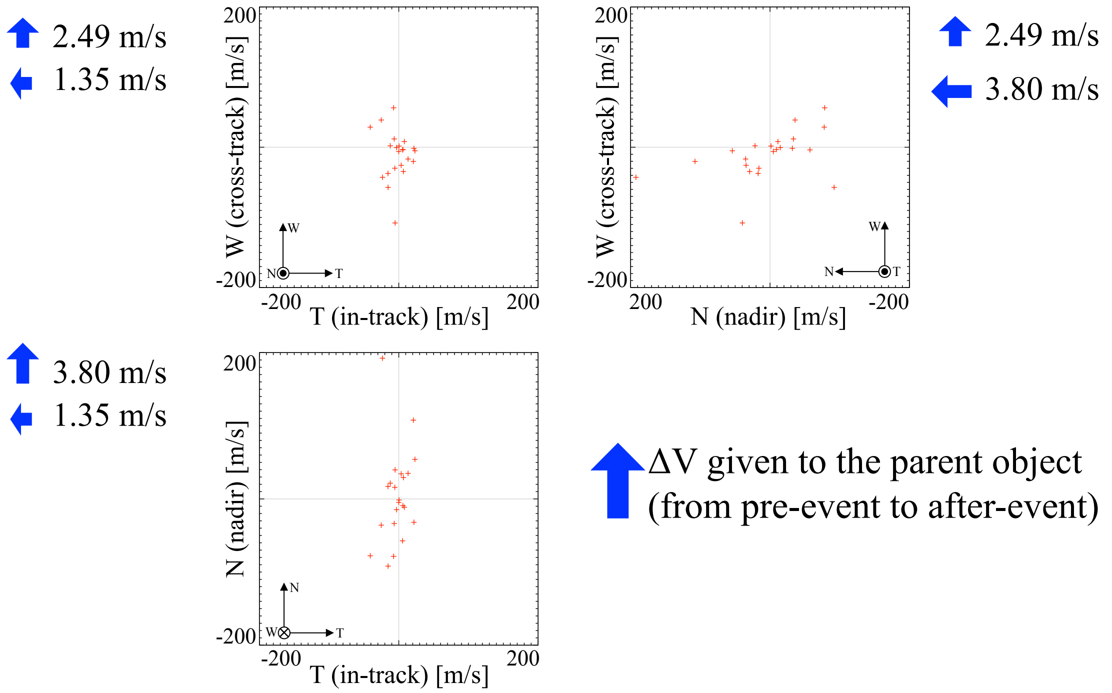
The evolution of possible fragments of 1967-066G



Suitable observation points can be determined even if there are uncertainties in the event epoch

Breakup Event Modeling (1)

- ΔV given to the 1968-081E fragments

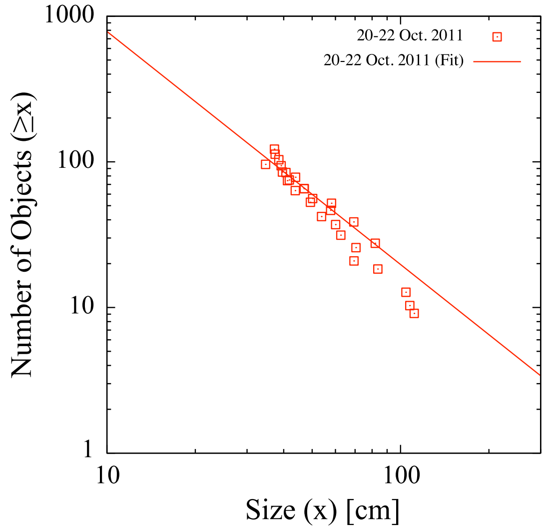


Breakup Event Modeling (2)

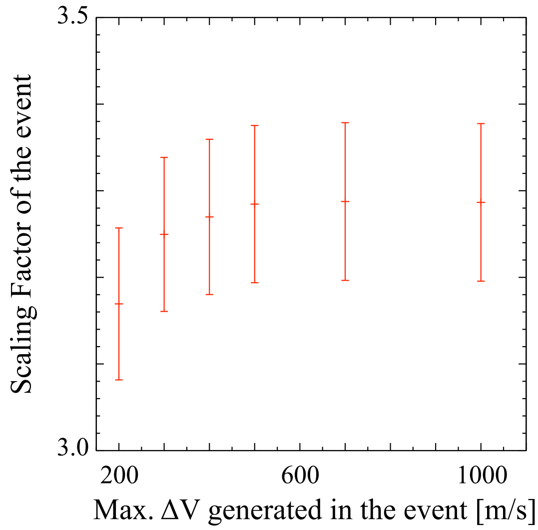
- Scaling factor (the term defined in the NASA's breakup model)

Results of the test case (1968-081E)

A size distribution estimated from the correlated observations



The scaling factor estimated for several hypotheses about max. ΔV of the event



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Conclusions

- To effectively combine the OD modeling and the OD measurement, we should select the right states to be handled
- Not only the deterministic assessments, but also the probabilistic assessments are necessary and helpful for characterizing breakup events

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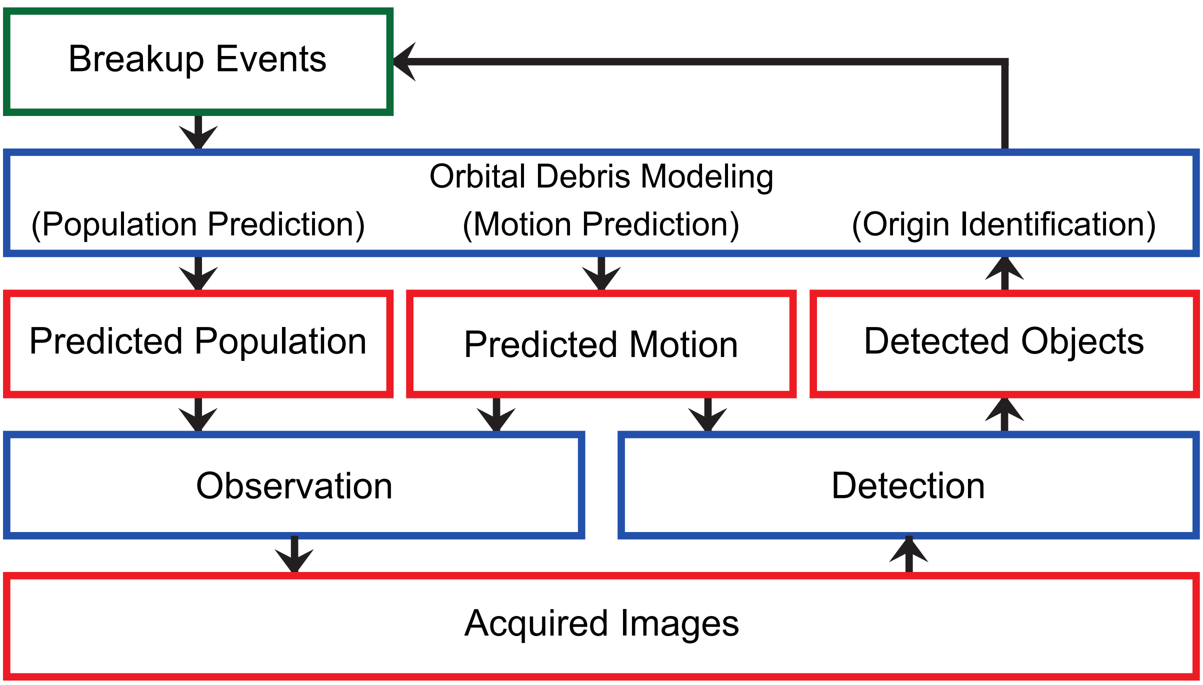
Acknowledgements

A part of this research is supported from Grant-in-Aid for JSPS Fellows Grant Number 243000.

IHI Corporation wishes to acknowledge US Air Force Office of Scientific Research (AFOSR) Asian Office of Aerospace Research and Development (AOARD) to support a part of this research under the grant No. FA2386-10-1-4136 (AOARD 104136).

BACKUP MATERIAL

The Effective Strategy applicable for Spacecraft Breakup Events



F1

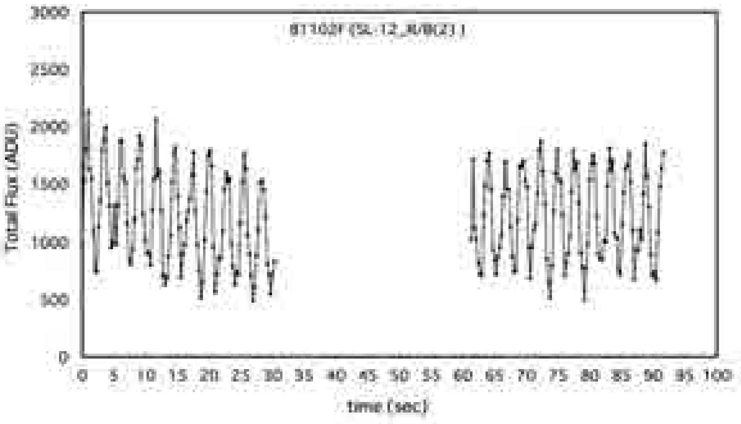
TDI モードを応用したデブリの短周期ライトカーブ観測

Short-period light-curve observations of space debris using TDI technique

○奥村真一郎，浦川聖太郎，西山広太，坂本 強，高橋典嗣（日本スペースガード協会），
吉川 真（JAXA/日本スペースガード協会）
○Shin-ichiro Okumura, Seitaro Urakawa, Kota Nishiyama, Tsuyoshi Sakamoto,
Noritsugu Takahashi (Japan Spacegaurd Association),
Makoto Yoshikawa (JAXA/Japan Spaceguard Association)

TDI(Time Delay Integration)モードを応用した、スペースデブリの短周期ライトカーブ観測の例を紹介する。TDI モードとはシャッターを開けた状態で電荷転送をするような CCD の読み出し手法であり、通常は視野の中で移動する物体を点状に撮像するために利用される。ここでは発想を転換し、スペースデブリの動きに合わせて望遠鏡を駆動させ、視野の中で止まった状態にして TDI で読み出すことにより電荷転送方向にのびた星像を人工的に作りだし、そのプロファイルから短時間における光度変化をとらえることを試みた。
81102F（ロケットボディ SL-12）の短時間ライトカーブ(図)など、デブリや運用中の衛星のライトカーブ観測結果について他の撮影手法と比較しながら紹介する。

I present the method and the examples of light-curve observations of space debris, using TDI (Time Delay Integration) technique. TDI mode is a readout technique of shifting the charge on the CCD while the shutter is open. It is usually applied to the moving objects with the expected motion, so that they appear as point sources. I tried to apply the TDI method to non-moving objects to derive their short-period light-curves. The advantage of the method and the result of the test observations will be presented here.



5th space debris workshop

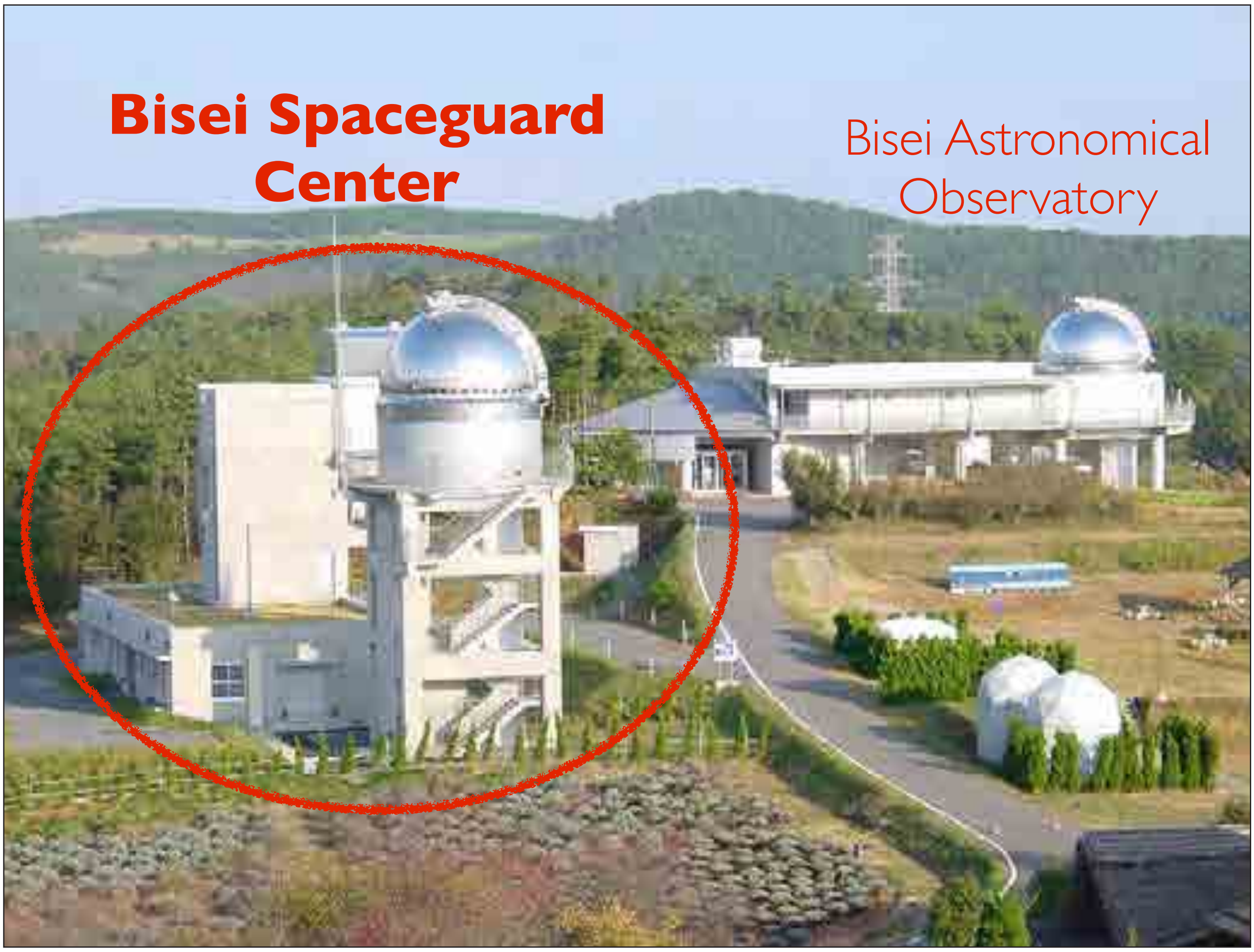
Short-period light-curve observations of space debris using TDI technique

Shin-ichiro Okumura, Seitaro Urakawa, Kota Nishiyama,
Tsuyoshi Sakamoto, Noritsugu Takahashi, and Makoto Yoshikawa
(Japan Spaceguard Association)

CONTENTS

- Introduction about Bisei Spaceguard Center and our Instruments
- about TDI mode
- Light-curve Observations using TDI mode and its advantages
- Examples of our observations


Okayama
prefecture
40km
倉吉
米子
鳥取県
真庭
津山
美作
新見
岡山県
高梁
赤磐
備前
総社
岡山
倉敷
福山
小豆島


Bisei Spaceguard
Center
Bisei Astronomical
Observatory

1m-telescope

- Equatorial fork mount
- Classical Cassegrain, focal length=3000mm (F/3), with five correcting lenses
- Field of view: 1.2°×2.3°

INSTRUMENT
(MOSAIC CCD CAMERA "VOLANTE")

- Detector : Hamamatsu 2k×4k back-illuminated, fully depleted CCD ×4
- Control : Mfront2 (front end), MESSIA-V (back end)
  (developed by National Astronomical Observatory of Japan)

we can customize its clock pattern
the camera is widely applicable
(usages such as TDI mode, etc., ,,,)

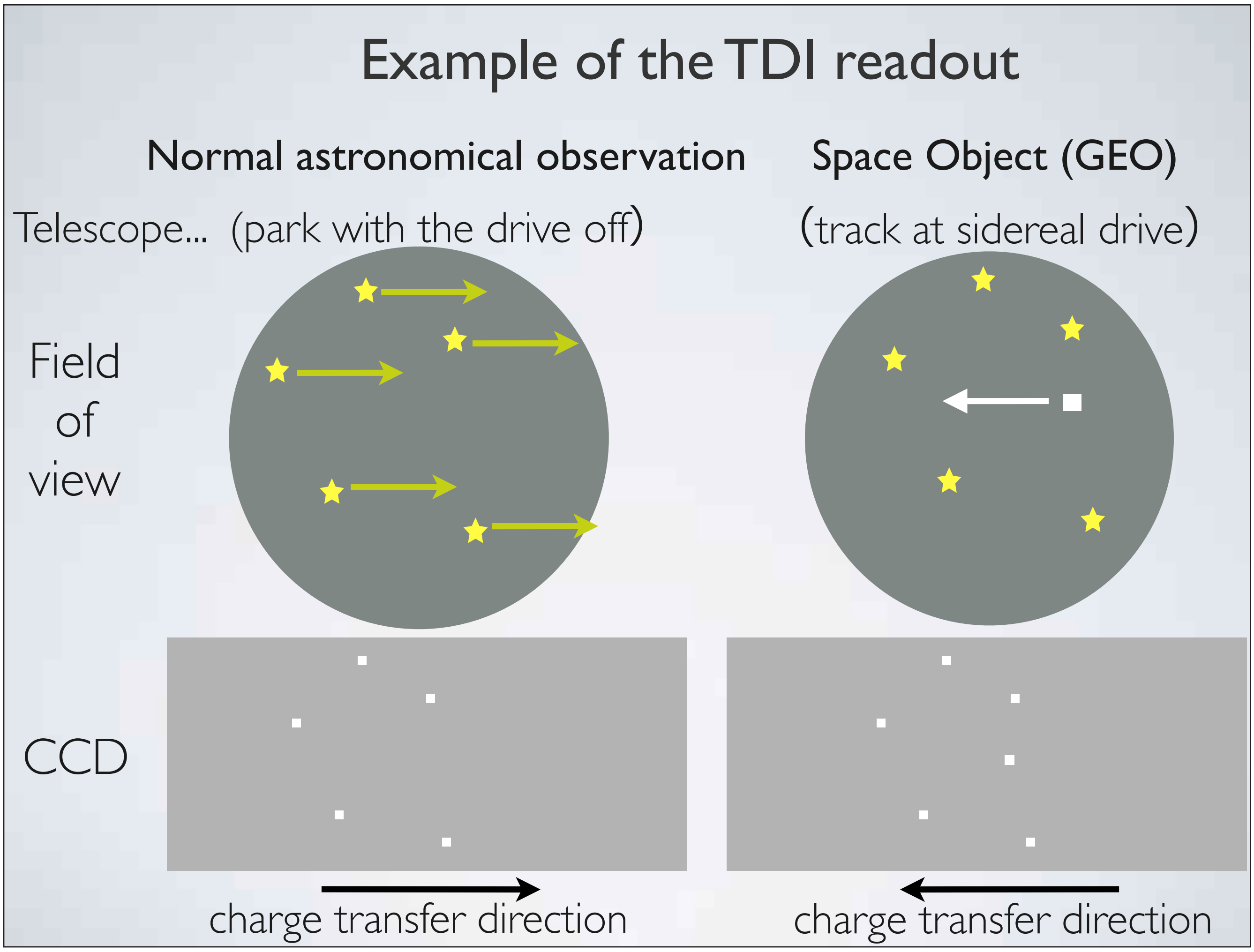
MAIN OBJECTS

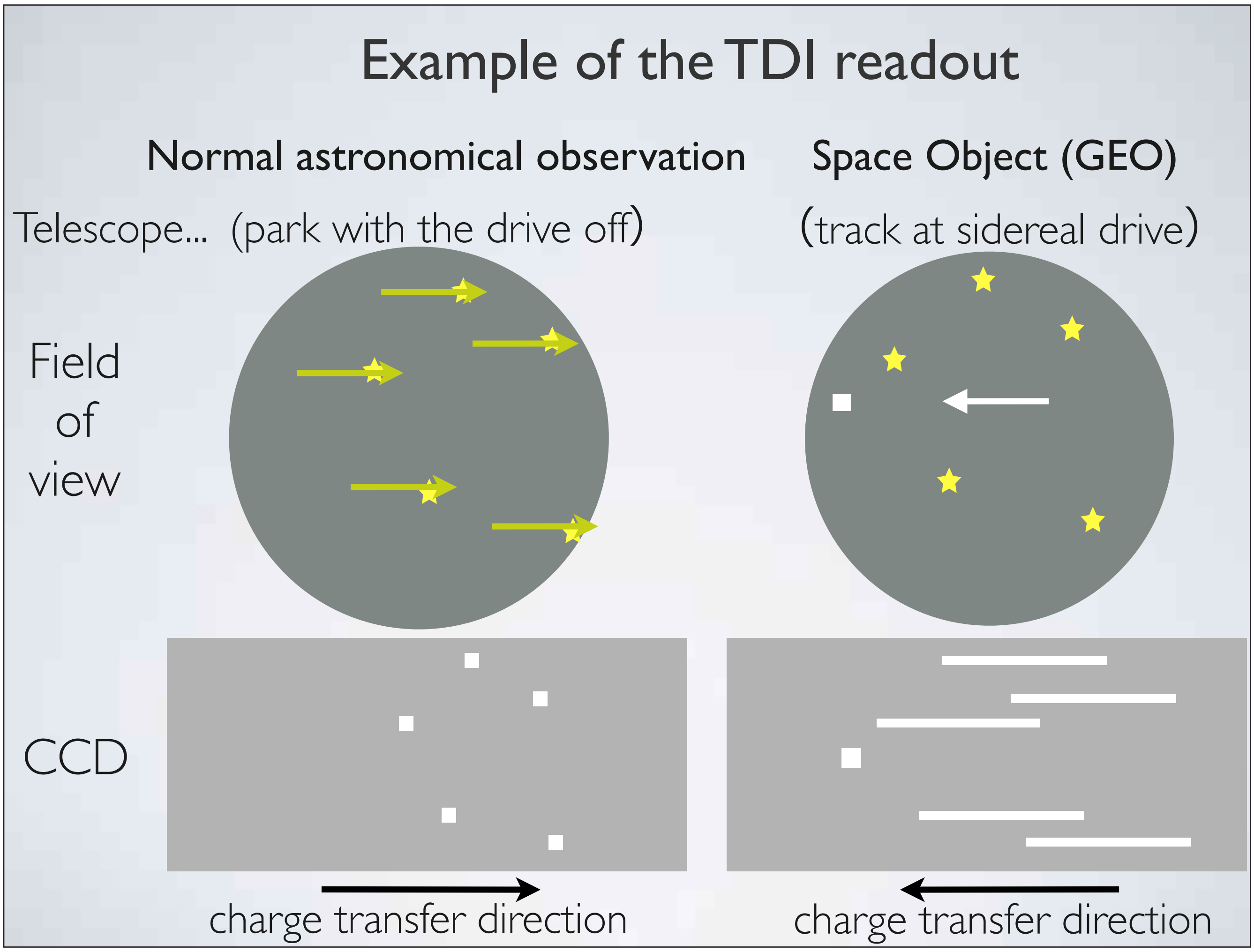
- Astrometry for space objects and space debris
- Discovery and confirmatory follow-up observations of Near Earth Objects
- Research observations of asteroids and space objects

TDI MODE

- Normal exposure on CCD
  …readout (charge transfer) after exposure
  (after shutter closing)
- TDI
  …shifting the charge on the CCD while the shutter is open

It is usually applied to the moving objects with the expected motion, so that they appear as point sources on the readout image


Example of the TDI readout
Normal astronomical observation
Space Object (GEO)
Telescope... (park with the drive off)
(track at sidereal drive)
Field of view
CCD
charge transfer direction
charge transfer direction

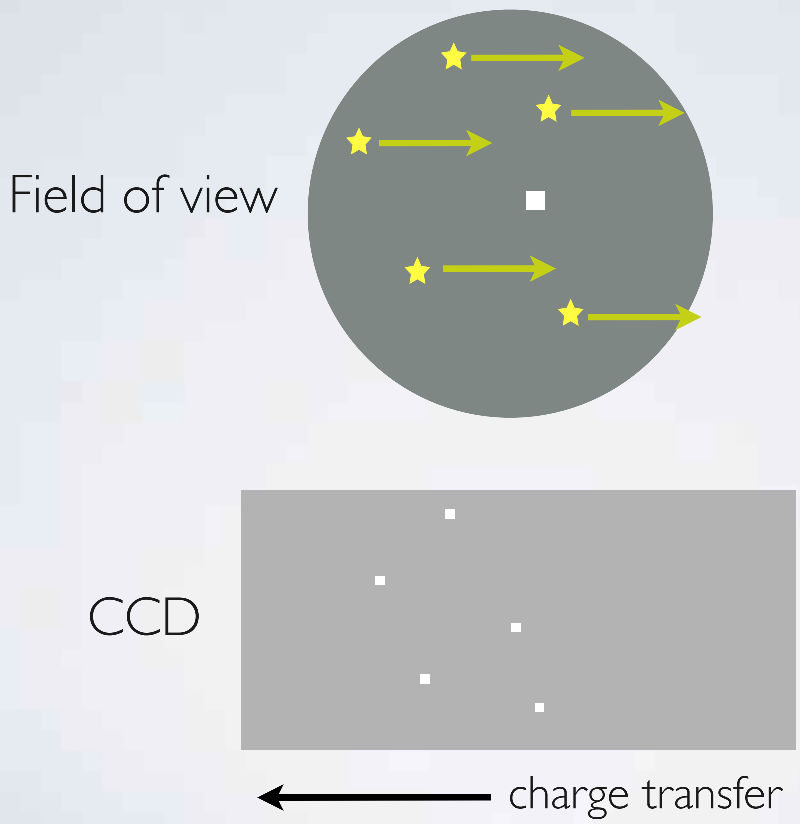

Example of the TDI readout
Normal astronomical observation
Space Object (GEO)
Telescope... (park with the drive off)
(track at sidereal drive)
Field of view
CCD
charge transfer direction
charge transfer direction

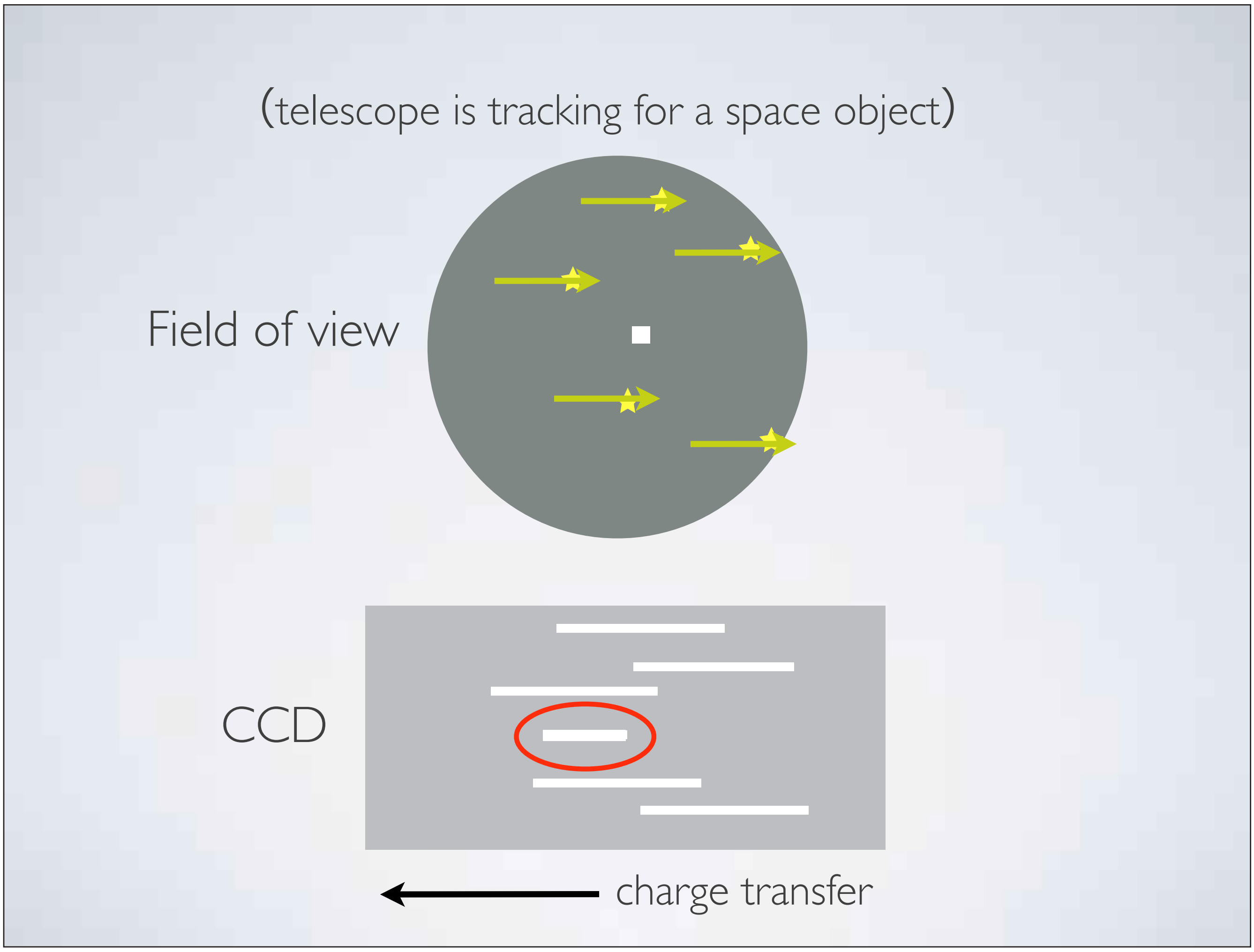
- TDI・・・a technique to image moving objects

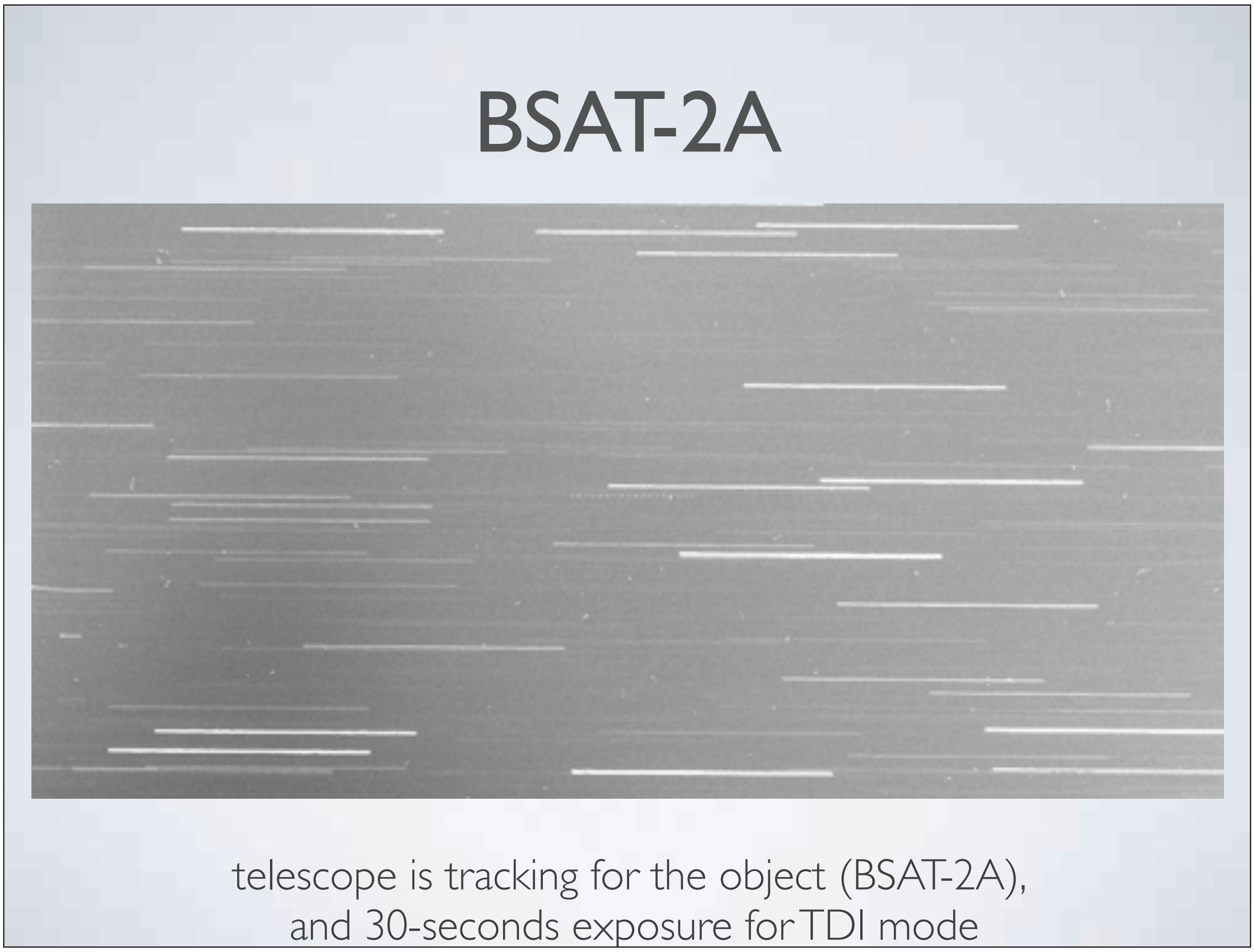
↓

Are there any advantages
in applying the technique for the objects which
stands still at a point in a field of view ??

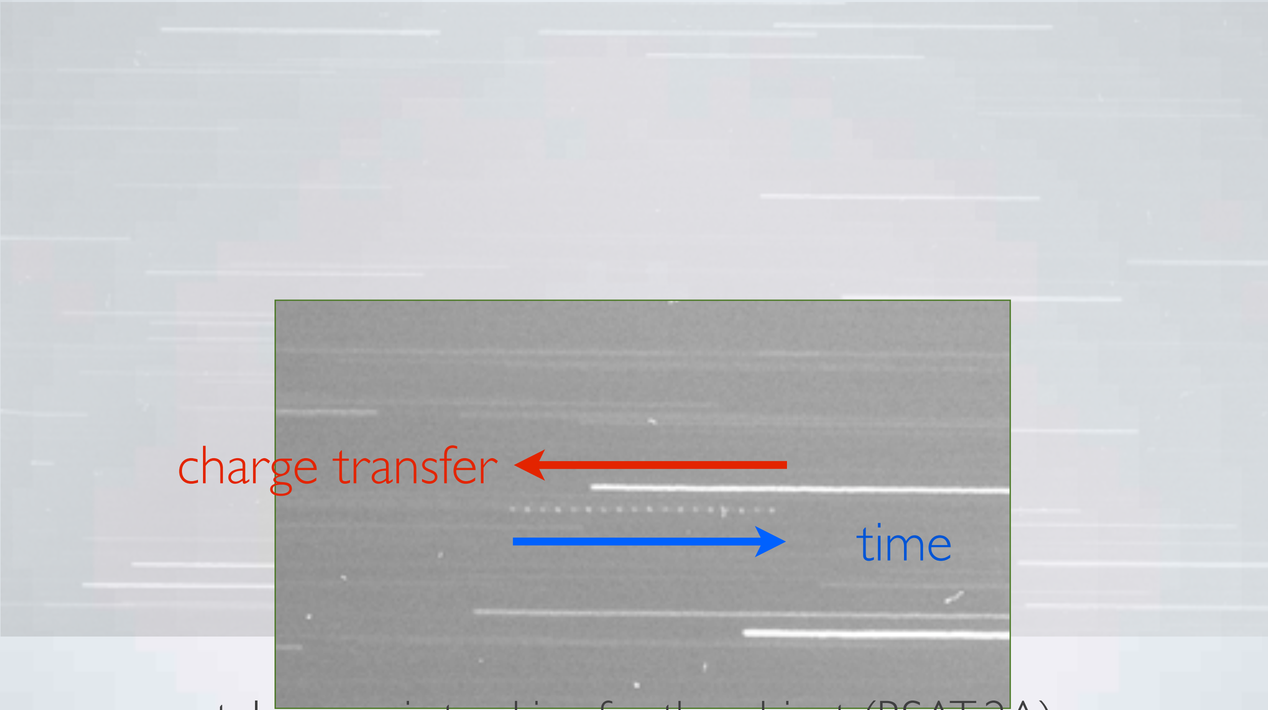
(telescope is tracking for a space object)




(telescope is tracking for a space object)
Field of view
CCD
charge transfer

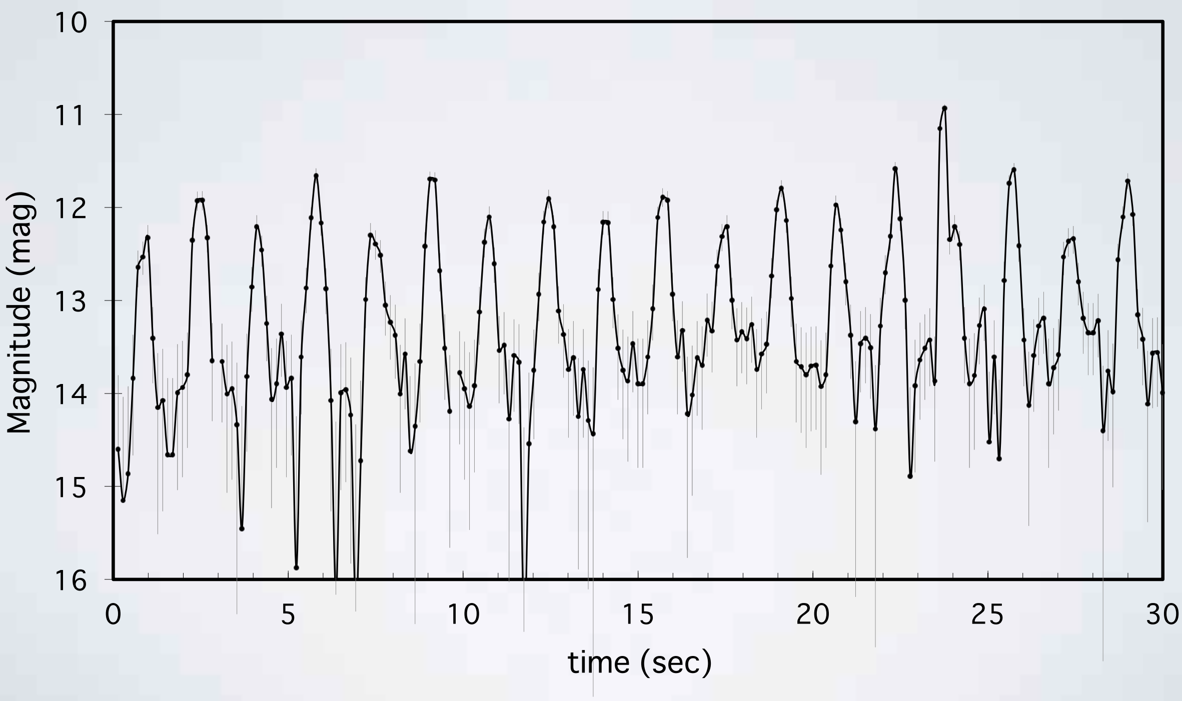

BSAT-2A
telescope is tracking for the object (BSAT-2A),
and 30-seconds exposure for TDI mode

BSAT-2A

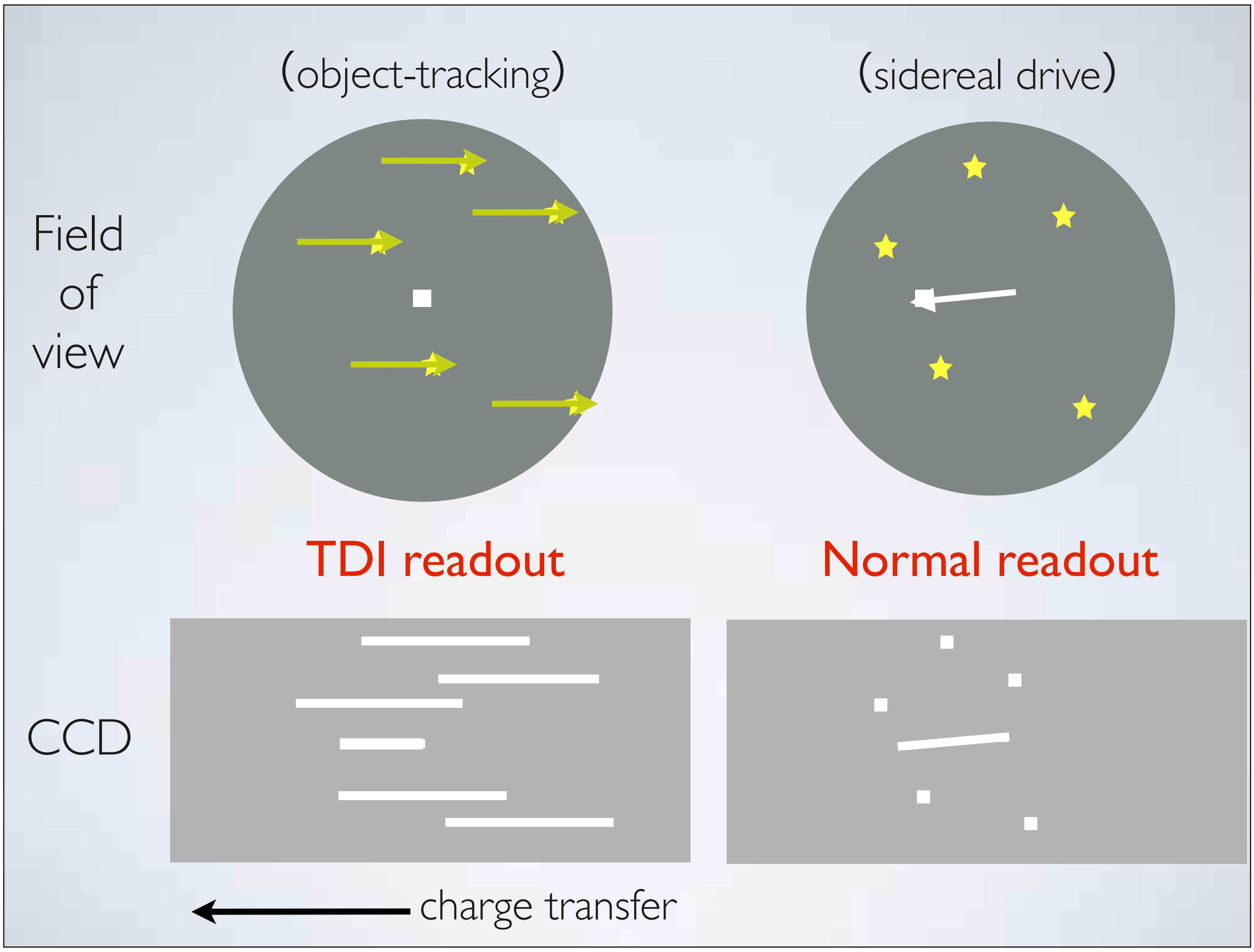


telescope is tracking for the object (BSAT-2A), and 30-seconds exposure for TDI mode

BSAT-2A



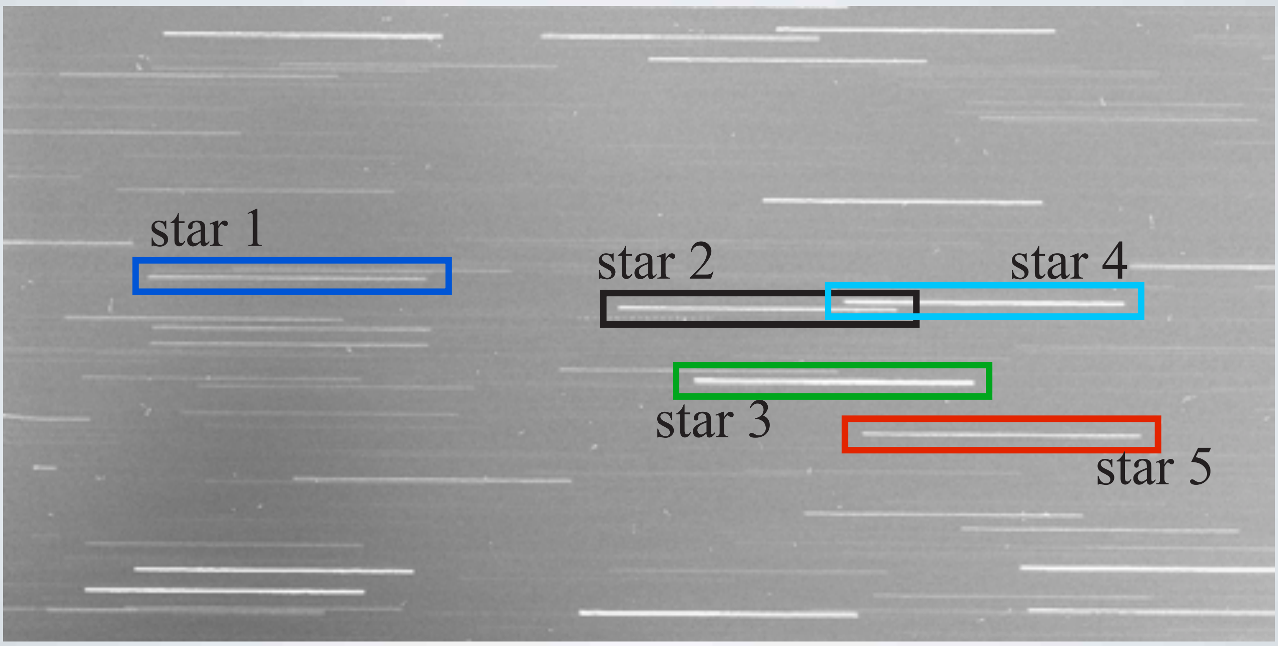
Comparison with other methods



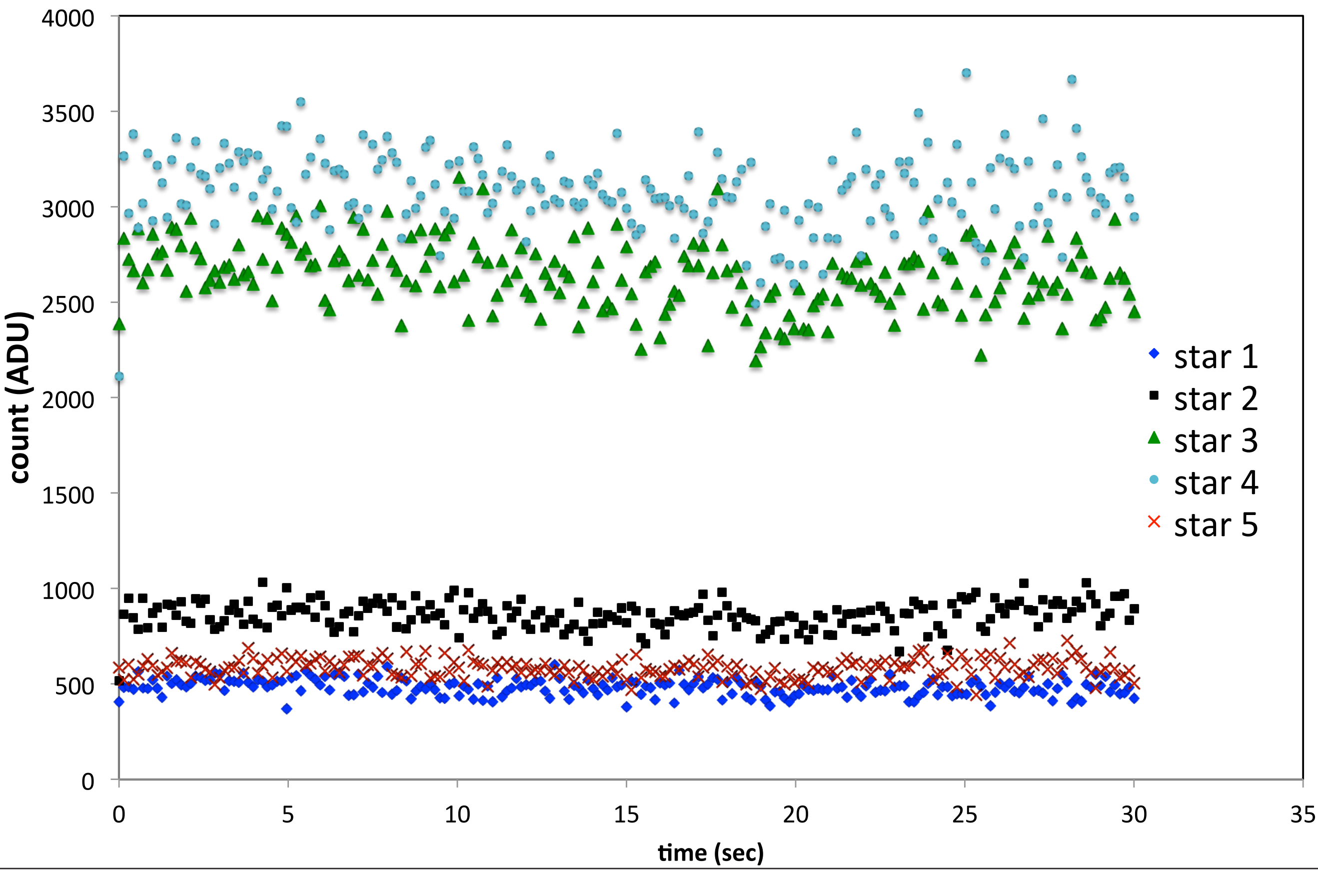
Advantages in using TDI mode
(compared with the sidereal-drive mode)

- variable sampling interval is available by the adjustment of charge transfer timing
- variability of atmospheric transmittance and photometric error can be estimated with referring the trailed image of background stars
- object is continuously in one field of view
- trailed image of the object always horizontally stretched on the CCD
- It can be applied to the observations of not only GEO objects, but Low Earth Orbit Objects, in case that the telescope can track the objects

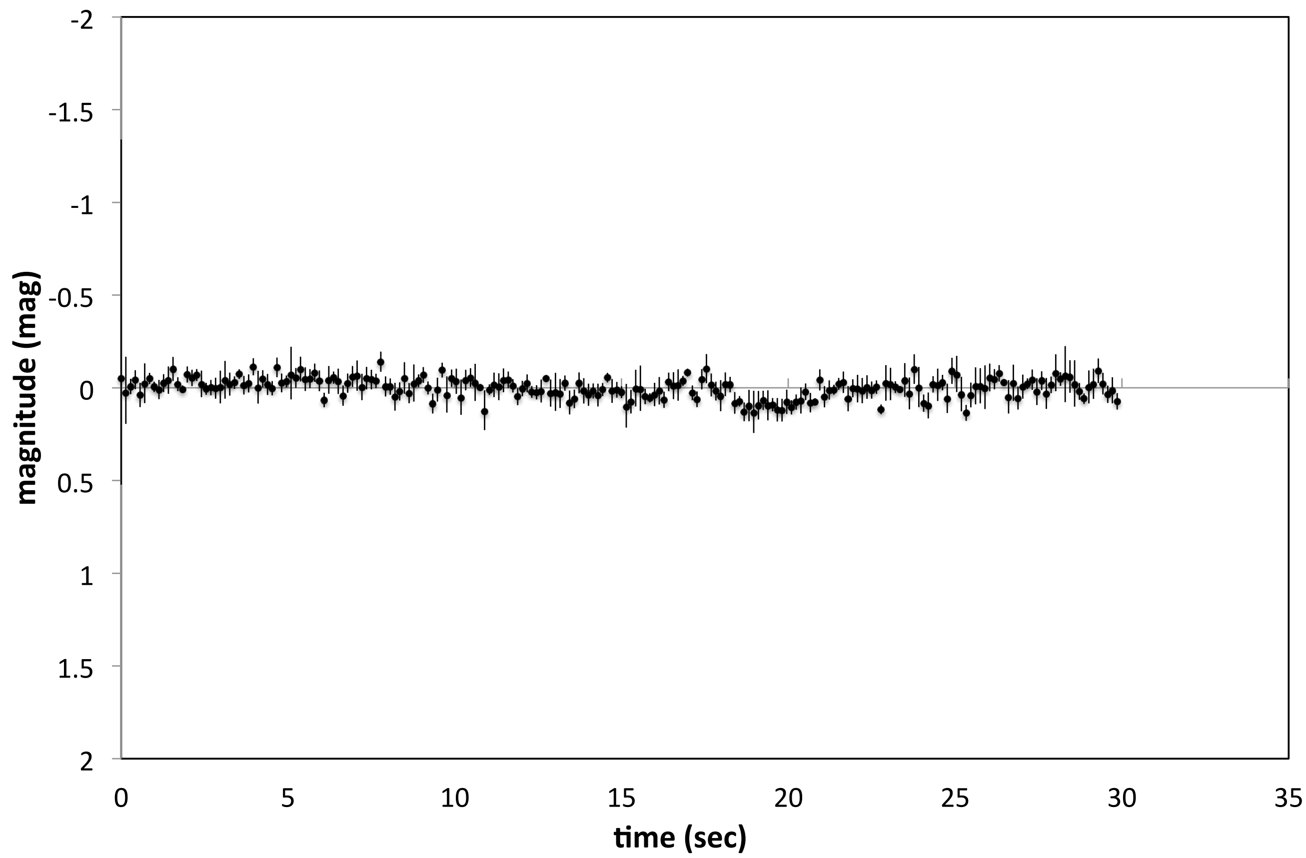
Estimation of the variability of atmospheric transmittance and photometric error



Flux variability of the reference stars



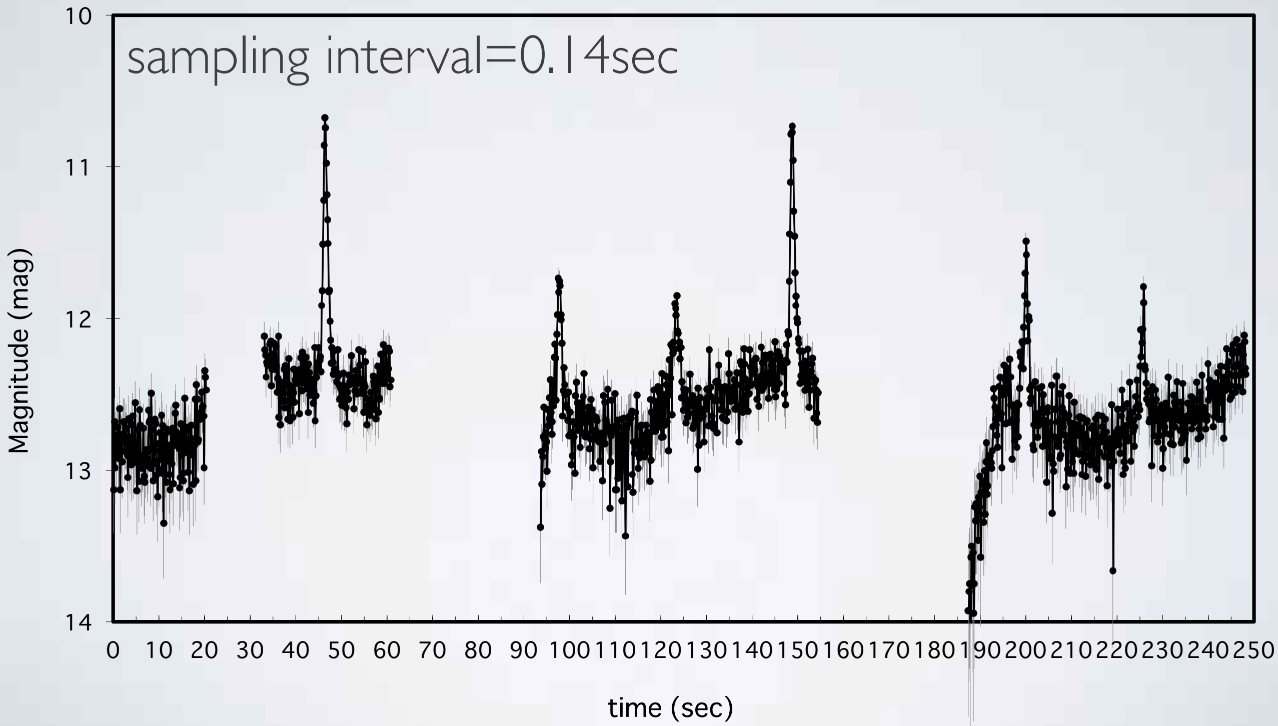
Flux variability and photometric error



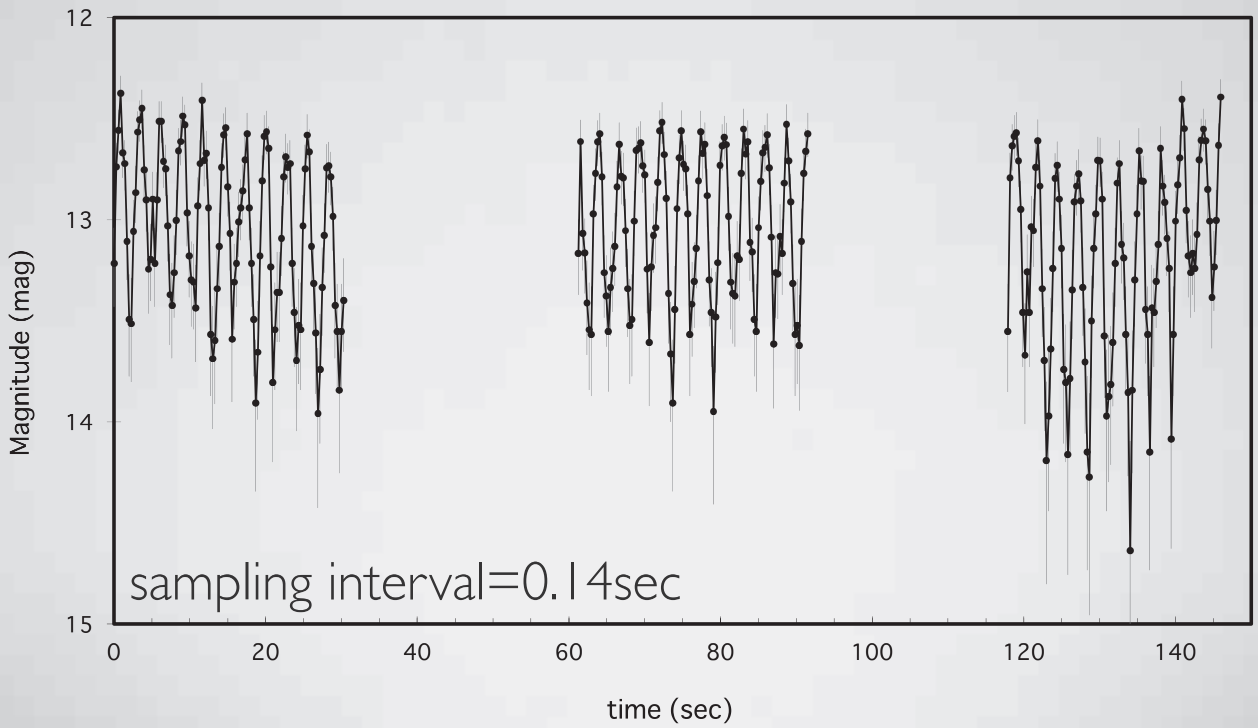
Limiting Magnitude
(BSGC 1m telescope, S/N=10)

exposure	sampling interval (charge-transfer timing)		
	1 sec	0.1415 sec	0.028 sec
30 sec	14.9 mag	12.8 mag	11.0 mag
5 sec	15.9 mag	13.8 mag	12.0 mag
1 sec	16.7 mag	14.6 mag	12.8 mag

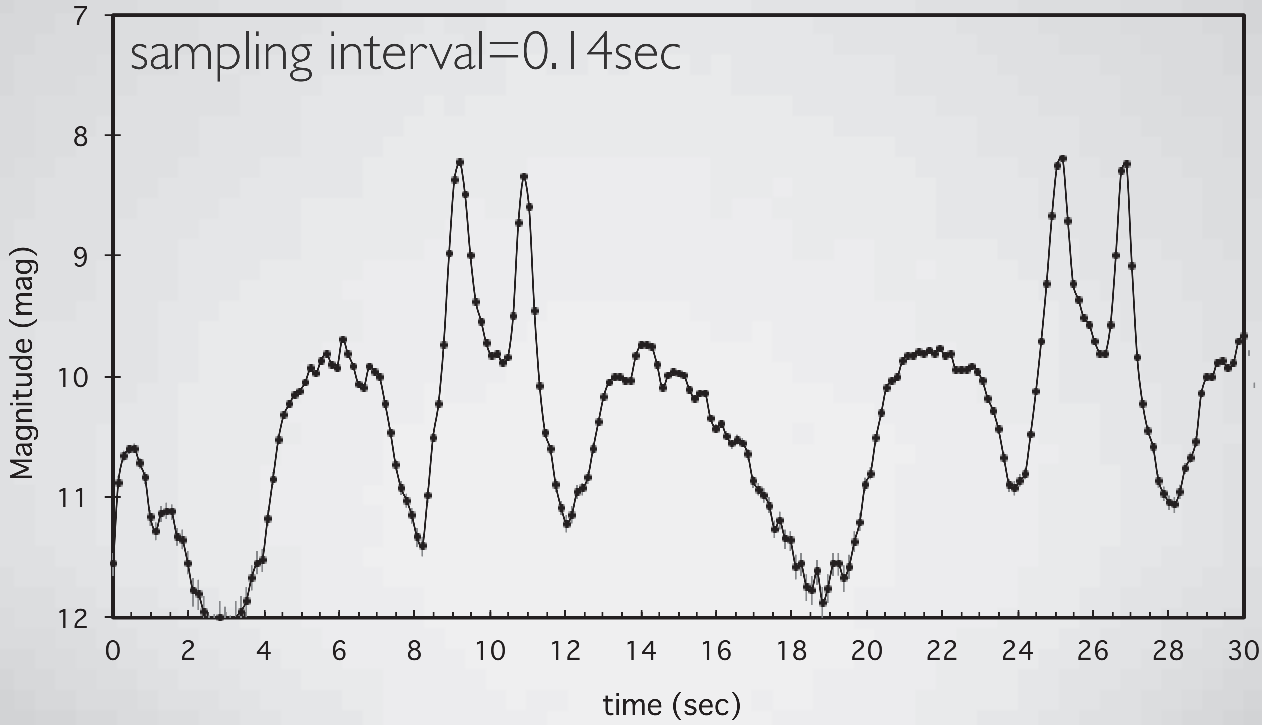
EXAMPLE：GORIZONT 33



EXAMPLE：
ROCKET BODY（SL-12_R/B(2)）



EXAMPLE:
H-2A R/B (WINDS/KIZUNA)



SUMMARY

★Details of theTDI-mode readout
and its applications to the observation of space objects, especially short-period light curve observations

★Advantages of the TDI mode
in short-period light curve observations

- variable timing sampling rate
- flux variability (atmospheric transmission) and photometric error can be corrected
- object is continuously in one field of view
- "trailed image" of the object always horizontally stretched
- applicable to the observations of not only GEO objects, but Low Earth Orbit objects

F2

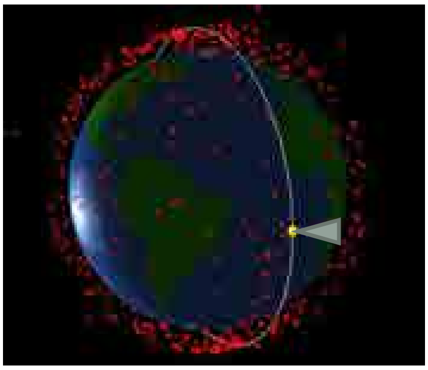
軌道上光学デブリ観測ミッションの検討

Feasibility study for Space-Based optical observation mission of space Debris

〇松本晴久，奥平 修，柳沢俊史（宇宙航空研究開発機構），
北澤幸人（IHI），田川 真（九大），黒崎裕久（JAXA）
〇Haruhisa Matsumoto, Osamu Okudaira, Toshifumi Yanagisawa (JAXA),
Yukihito Kitazawa (IHI Corporation), Makoto Tagawa (Kyushu University), Hirohisa Kurosaki (JAXA)

軌道上光学センサによる静止軌道デブリ観測は、既に実現され多くの成果をあげている。但し、デブリの密集している高度 800km 周辺の低軌道に関しては、観測の検討が報告されているものの実現に至ってはいない。
軌道上光学観測は、デブリに対して 0° に近い位相角(デブリへのセンサー視線方向と、太陽入射方向との角度)が取れる、大気の影響（例えば気象状況（雲と降水）、エアロゾルやローカルな光害）がない、長時間・広範囲のデブリ観測が可能である等、地上観測にはない利点がある。重要なのはこれらの利点を最大限に生かしたシステムをどのように構築するかである。
今回、軌道上観測の効率に影響を及ぼす要因としての衛星軌道、CCD のピクセル数、視野角、視野方向、バックグランドノイズ、センサシステムなどを検討した。
本報告では、新機軸を目指したこれらのミッション検討結果について報告する。

FEASIBILITY STUDY FOR SPACE-BASED OPTICAL OBSERVATION MISSION OF SPACE DEBRIS



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Outline

- **Objectives**
- Merit-demerit of space-based observation
- Observation method
- Debris Characteristics
  - radiation properties, Aungular velocity
- Environmental factors
  - Stray light, background light
- Study of sensor
- Data processing
  - Debris detection
  - Orbit determination
  - Catalog efficiency analyses
- Conclusion

Objectives

- Decide the orbit of the objects which seems to collide with the satellite exactly.
- When a crush accident happened, we survey an overall expanse.
- We create the catalogue of the objects (more than 1cm) in orbit of 600-800km that a lot of Japanese satellites are operated.
- The goal detects the 5% (TDB) of the whole in 1 year.

↓

Build structure of the cooperation with the ground observation.

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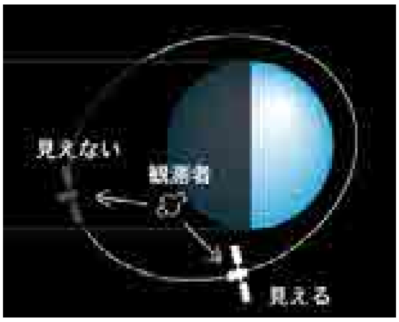
Merit of space-based observation(1/2)



- 24h/7h availability: No limitation e.g. by
  - Wheather (clouds, rain, aerosols, absorption)
  - Day/night cycle
  - Moon light, Light pollution
- Not a geographical limit
  - Location is an issue for the ground observation
- Flexibility of the operation
  - Most suitable observation strategy exists for various debris orbit.
  - Tracking of the time that is longer than ground observation is possible, and a cover range is wide.
- Fast detection of debris and high re detection to enable "Quasi-tracking"
  - To create a catalogue of unknown space debris.
  - To quick response to crushing accident, collision avoidance, etc..
  - Faster than ground-based observations high potential can detect.

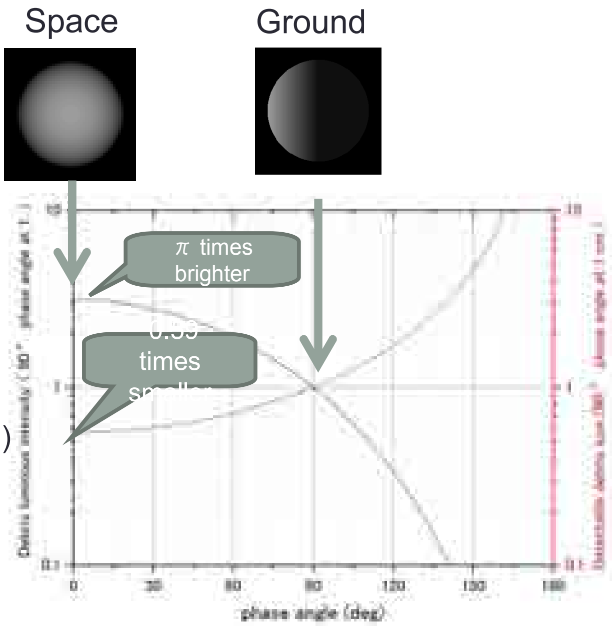
Merit-demerit of space-based observation(1/2)

Efficient debris detection and measurement accuracy

・Background noise reduction (no atmosphere)
→ increased sensitivity, detection of smaller objects possible

・Diffraction-limited optics (atmosphere degrade resolution)→ improvement of sensitivity and spatial resolution

・Debris brightness (brighter than on Earth if often)
-> Smaller pahse angle and short distance to the debris



The phase angle of 0°, can be observed π times brighter than the phase angle of 90°.
0.59 times as small debris can be seen.

Demerit of space-based observation

- Limits of the satellite mission life
- High costs (general recognition)
- Technical challenges, for example:
  - In a short period of time to determine the orbital debris.
  - Exact observation（time, satellite's altitude, pointing accuracy and stability）are required.
  - Need for a limited time, for near real-time downlink

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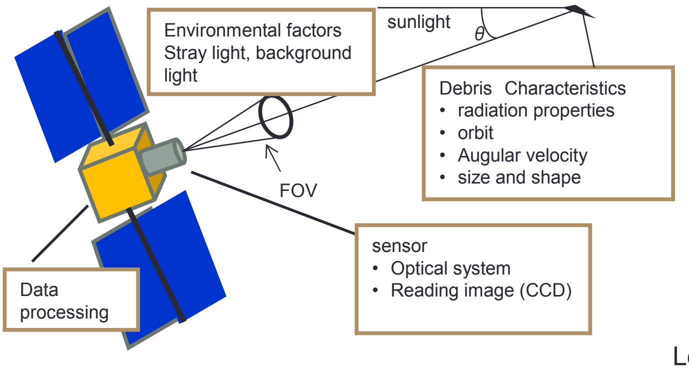
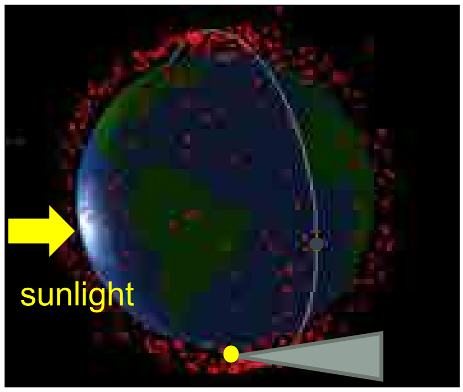
Observation method

The phase angle can be optimized, if the objects appear in the field of view of the sensor like full moons (phase angle = 0°), e.g. using sun-synchronous orbits in the vicinity of the day-night terminator and the line of sight directed anti-solar. Moreover, a satellite's orbit is 600 km altitude. (800 to 1000 km with high debris density is avoided.)





Low orbit debris observation satellite (draft) (STK)

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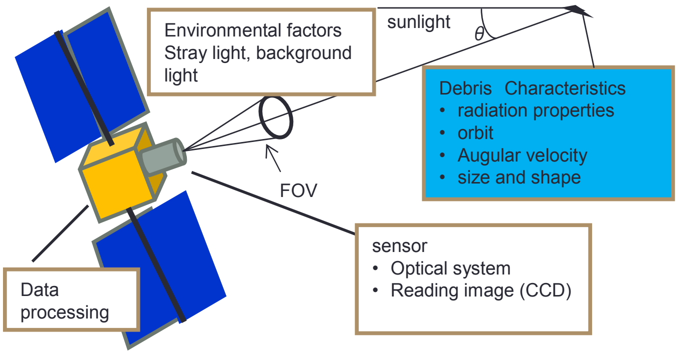

Debris Characteristics

- Debris apparent luminosity
- Condition: 1 AU solar luminosity is -26.74 magnitude
  phase angle: 0 °
  Albedo: 0.1
  Debris size: Lambertian balls 1 cm in diameter
- Luminous intensity in 1000 km away from debris will <u>17.7 mag. level.</u>
- Distance to the debris
- Angular velocity
  - Widely distributed to 0.02 degrees / second to 3 degrees / sec.
  - The median is 0.4 degrees / sec
  - If you are trying to shoot the image so as not to catch debris tail longer than 1 “, a fast-moving object angular velocity of 0.4 degrees / s, we must be shorter exposure time 0.7msec.

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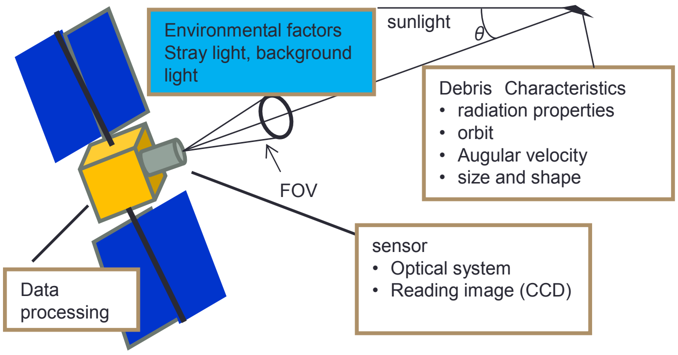
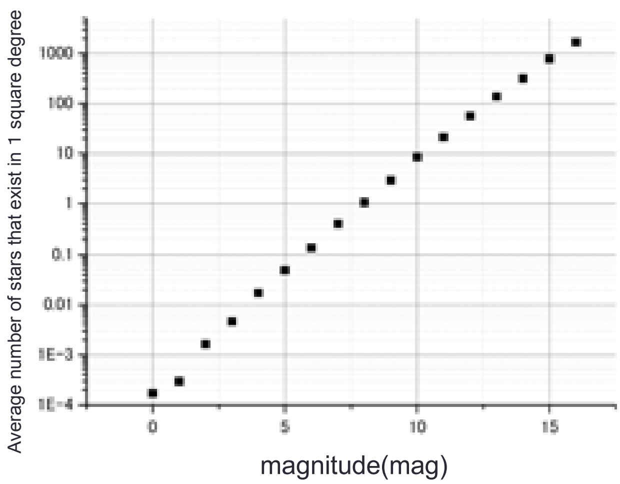


Background Noise

Scattered radiation from discrete sources (atmospheric reflections, zodiacal light, milky way, bright stars) and any stray light are background noise.

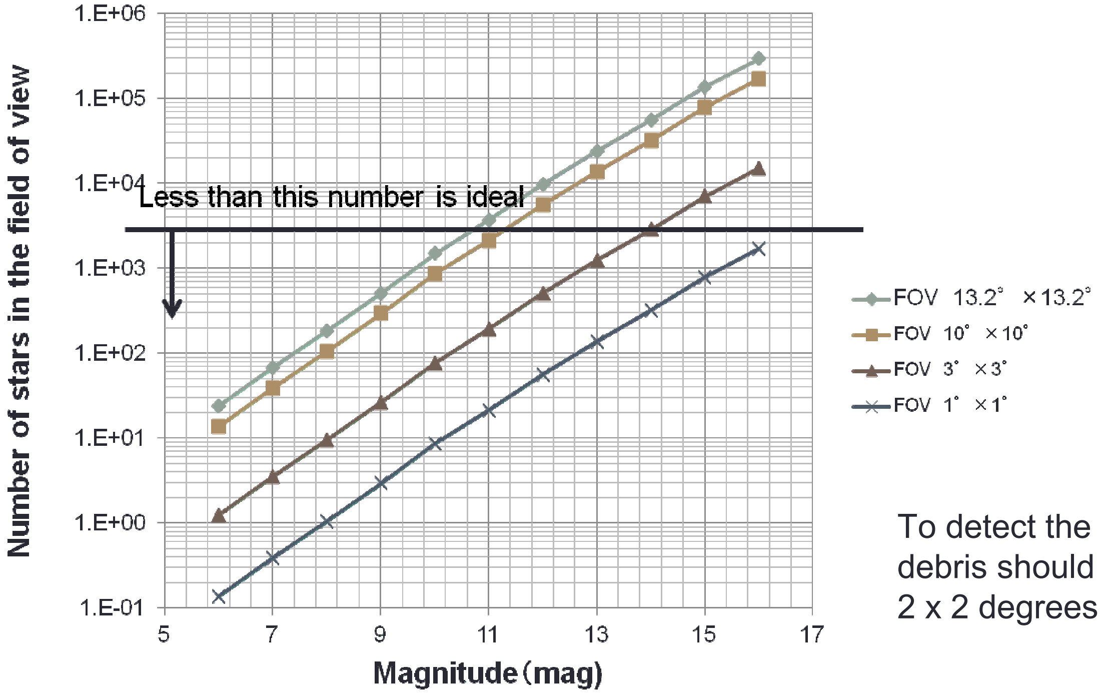
Number of stars within the field of view

- Estimate the number of stars into 1 square degree field of view.
- Values below the containing region of the milky way stars are concentrated.
- And according to chronological scientific tables, leaving about 20 degrees from the milky way, star will be approximately 1/2.



magnitude	Average number of stars in 1 square degree
9	2.9
10	8.5
11	21.2
12	56.0
13	136.6
14	317.1
15	780.5
16	1683

Number of stars within the field of view and viewing angles



To detect the small debris should about 2 x 2 degrees FOV.

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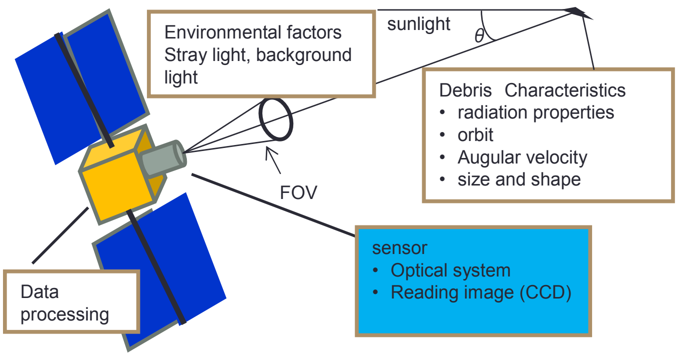

Optical sennsor review

-Debris detection ability is determined by what? -

	Item	Relationship between detection of debris diameter and each item				
		proportion	Proportion to the 1/2 power	Inverse proportion	Inverse proportion to the power of 1/2	a remarks column
Smaller is better	Range	○				
	Debris verosity		○			
	SN		○			
	Focal length		○			（Fn small things 1.2 is ideal）
Bigger is better	Aperture			○		
	debris object albedo				○	
	Exposure times of 1 pixel				○	
	Optical properties				○	
	Pixel size				○	（However, spatial resolution is worse）

Diameter of the light receiving optical system, as large as possible.
Proportional to 1/2 of the focal length of the light receiving optical system, the diameter of the debris which can be observed, increases in inverse proportion to the power of 1/2 of the pixel size of the detector. This is a derived from the integral time. Therefore, the focal length of the receiving optical system is as small as possible, the pixel size of the detector is as large as possible.
Optical system aperture size to as large as possible , and f-number （F = focal length / aperture）to as small as possible.

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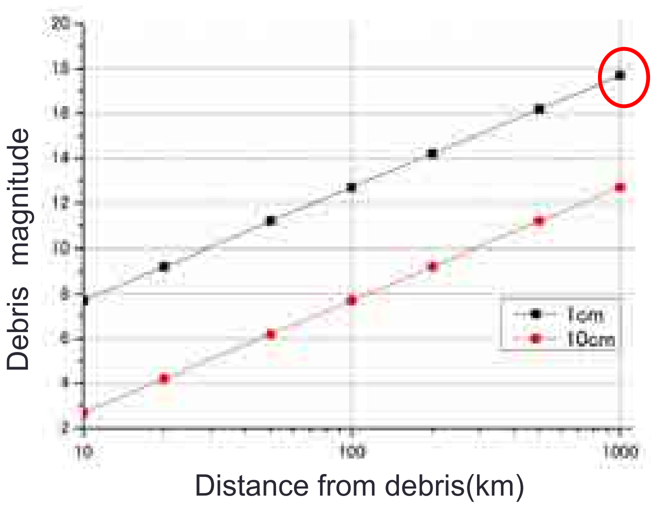
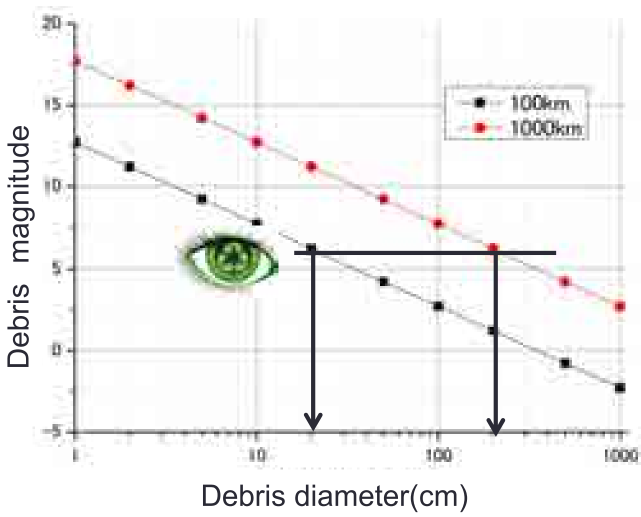
Relation to magnitude of debris by size and distance

-Lambertian ball, albedo=0.1 and phase angle=0° -



Relationship between magnitude and distance from the debris

Black:1cm、Red:10cm



Relationship between debris diameter and magnitude

Black：100km、Red:1000km

※ Nak is 0.85

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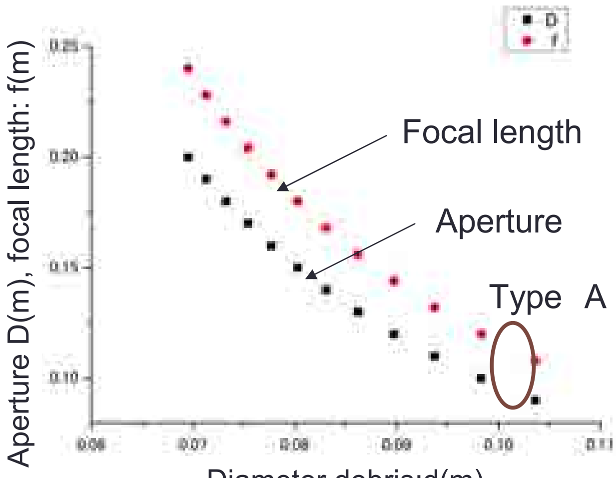
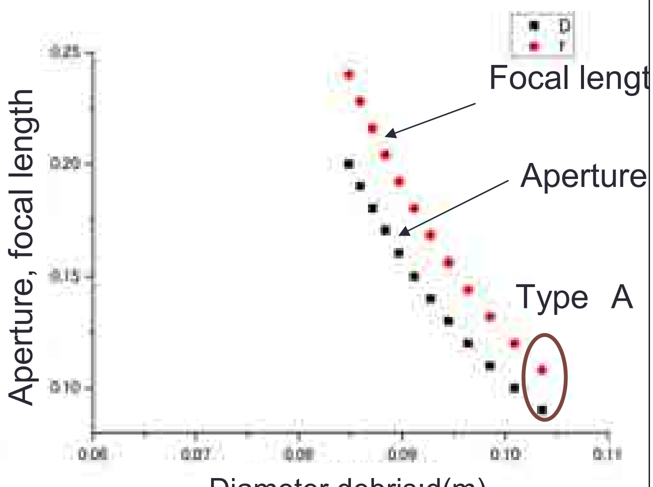
Relationship between debris size and focal length detection, diameter

- F number is fixed to 1.2:　Type A　Camera(Next page)-



Unchanging image degradation rate



Consider the focal image degradation rate

Camera specification (draft)

Lambertian ball , Range 1000km, albeo 0.1
phase angle=0°, Debris velocity 0.4°/sec,
4×4Binning

Item	Lens		Reflector	
	Type A	Type B	Type C	Type D
Detector	24μm×24μm 2048×2048　CCD	←	←	←
Focal length (f) (mm)	106.5	100	183.4	600
F number (Fn)	1.2	1.4	1.2	3
Full-width（FOV)	13.3°×13.3°	14.2°×14.2°	7.7°×7.7°	2.3×2.3°
Effective aperture (D)(mm)	88.7	71.4	152.0	200
Wavelength range（⊿λ）	0.2μm（450~650nm, standard wavelength :550nm）	←	0.3μm（400~700nm,standard wavelength:550nm）	←
Optical properties	0.215	0.222	0.3	0.188
S/N（dB）	5（goal　2）	←	←	←
read　noise	10e-　(goal　5e-)	←	←	←
Detect size (cm) ( ) in stacking method	10.4（6.6)	12.3(7.8)	5.5(3.4)	9.6(6.08)
Priority	2	4	1	3

Comparison of image sensor

	CCD	EMCCD	CMOS	I. I.+CCD(CMOSD)
Number of pixels	△	◎	◎	same CCD or CMOS
Structure(Simplicity)	△	◎	◎	as above
Power consumption	×	◎	◎	as above
Image quality	◎	△	△	as above
Quantum efficiency	◎	△	△	as above
Electronic shutter	◎	△	△	as above
Blooming	×	◎	◎	as above
Linearity	◎	×	◎	×
Life	—	—	—	Vulnerable to bright light
Reading speed (rt)	>0.1sec	>0.1sec	0.03～0.01sec	10ns～ms
Low-noise (high SN)	◎	◎	◎	Photon counting
Evaluation results	◎(rt>0.1sec)	×	◎(rt<0.1)	◎(Protection against bright ligh)

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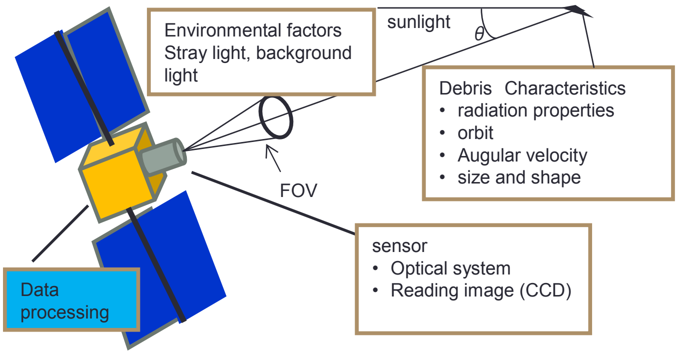


Data processing

- **Method for observation of space debris**

（1）observation, fixed in inertial space

（2）observation, tracking and space debris

- **Observation data processing in inertial space-fixed view**

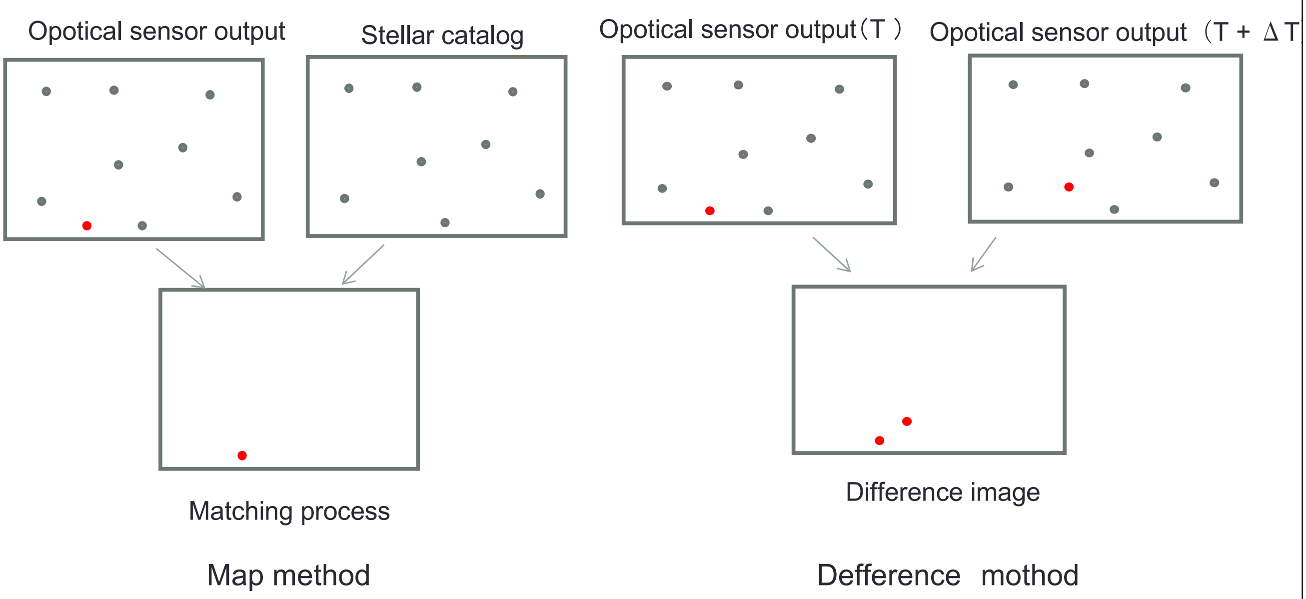
Need to catch the debris moves through the stars in a fixed field of view relative to.

Following two as possible and how.

（1）to detect debris, compared to stellar catalog(map method)

（2）Motion detection, frames before and after diff as debris (defference　mothod)

Data processing



Trade-offs of mapping method and difference method

Not work well either way darker than the marginal magnitude of optical sensor debris detection.

So many stellar, map method is unavailable in this case.

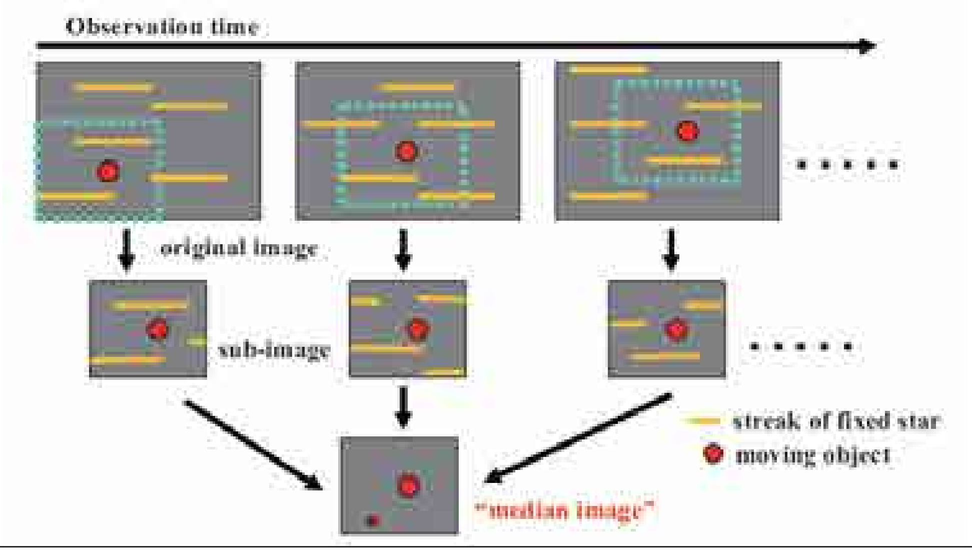
Adopt a finite-difference method.

In addition, do not acquire only debris, and the degree that can decide a field of view direction is necessary for the fixed stellar data.

If is type A; I think and should be set threshold 4 magnitude level (TBD) from the number of stars in the field of view.

Stacking method

- The stacking method, using multiple CCD images to detect very faint objects that are undetectable on a single CCD image. Can to recognize dark object about 6 times with 30 pieces of CCD image.



Data processing

Onboard processing

- ☐Pre-treatment: background noise processing, image enhancement & shaping, Centroid processing
- ☐Improved detection sensitivity: Stacking method

Ground processing

- ☐Catalog object identification and labeling
- ☐Selection analysis of debris
- ☐Orbit determination

Orbit determination

- Determine the debris orbit in the conditions that can be observed several times the same debris within three days.
- After orbit determination, update the orbit data once a few days on the ground system　(cataloged).

- Subject of future investigation
  - Ability of ground-based observations after the orbit decision. If the orbit is identified, tracking how much large debris until systems is possible?
  - Required number of ground-based observations.

Catalog efficiency analyses

Simulation conditions

Satellite: sun-synchronous orbits in the vicinity of in the day-night trminator and the line of sight directed anti-solar. 600 km altitude.

Objects: 600 to 800 km altitude, eccentricity 0.002 choosing 967 objects

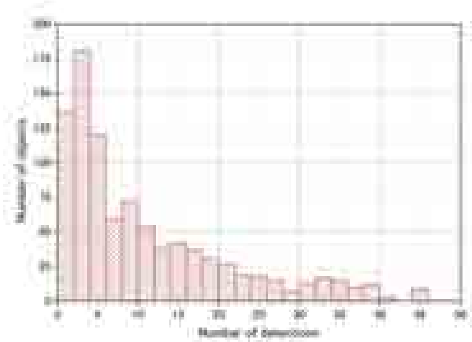
Period: 01/15/2013 ~ 01/25/2013

Optical sensor : 15.8 ° × 15.8 ° FOV

Exposure time 1sec

To count up newly detected objects in the CCD.

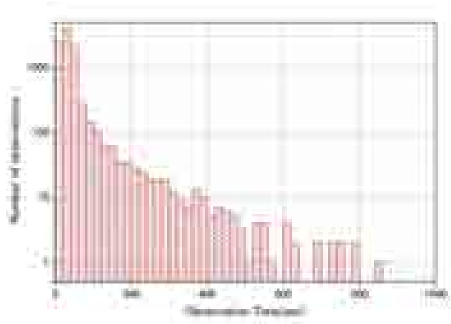
Result(1/2)



Number of detections of three days from 2013/01/15. 315 (32.6%)individual objects can be observed continuously for 3 days.

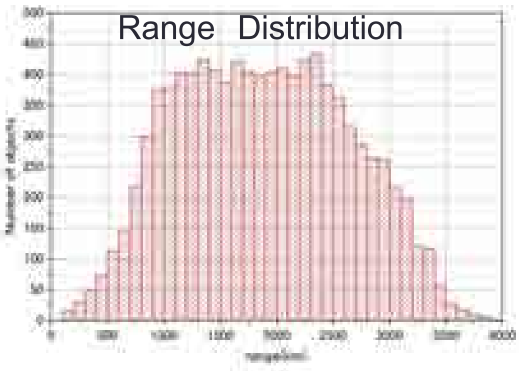
Detection objects in the number of in different times

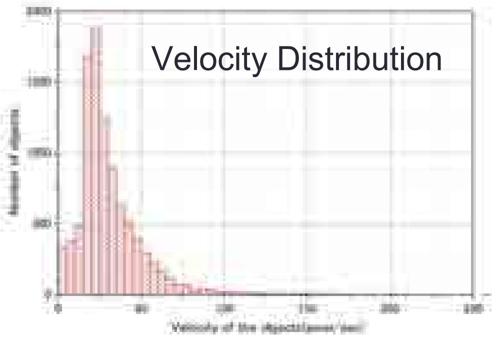
Detection time	Number of objects	Percentage
1day	585	60.5%
2days	792	81.9%
3days	855	88.4%
4days	883	91.3%
10days	937	96.9%

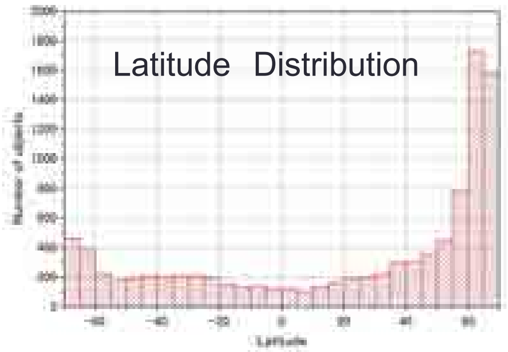


Observation time of object(3 days)

Result(2/2)







Conclusion

- Presented a feasibility study on space based optical observation mission.
- Space observations have many advantages.
- In the future, we consider error factor (satellite altitude, a sensor field of vision direction, the satellite time) for orbit determination and realization of satellite.

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軌道上光学センサによる LEO デブリ観測

Low Earth orbit debris observation using space-based optical sensors

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○Makoto Tagawa, Toshiya Hanada (Kyushu Univ.), Toshifumi Yanagisawa,
Haruhisa Matsumoto (JAXA), Yukihito Kitazawa (IHI Corp.)

スペースデブリの存在は持続的な宇宙開発利用に対する大きな脅威である．特に地球低軌道（LEO）には追跡されている宇宙機のおよそ 7 割が集中しており，衝突による破砕リスクが高いため早急な対策が必要である．衝突による破砕を防止するために有効な手段の一つが，軌道上物体の高精度な追跡情報に基づく衝突回避運用である．現状で，LEO において定常的に追跡されている物体サイズの下限はおよそ 10cm である．本研究では，LEO に配置した光学センサによって観測能力を向上させることを提案する．効果的なシステム提案を行うためには，LEO 同士の観測における能力評価を適切に行う必要がある．著者らは能力評価のツールとして軌道上観測シミュレータの開発を進めている．また軌道上観測結果に対する初期軌道推定手法やフィルタの検討も行なっている．それらツール開発や検討結果の現状とあわせて技術的課題などについて報告を行う．

Space-debris related issues are major threats for sustainable space development and utilization. Urgent countermeasure for satellite breakup due to collision is required especially for Low Earth Region because approximately 70 percent of tracked objects are concentrated to the region. Collision avoidance maneuver based on precise tracking information is one of effective measure to prevent collision. Current size limitation of steady tracking operation for LEO region is about 10 cm in diameter. We propose space-based optical sensor for debris placed in LEO region as a tracking capability improvement method. Proper capability assessment for LEO to LEO observation geometry is required to propose effective system. We develop space-based observation simulator as an assessment tool and consider suitable algorithms of initial orbit determination, correlation and filter. Current status of the simulator and algorithms consideration results, and technical problems are reported.

Low Earth orbit debris observation using space-based optical sensors

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([1]Kyushu University, [2]JAXA, [3]IHI Corporation)

Objectives

- Track small debris in Low Earth Orbit (LEO)
  - Smaller than 10 cm
  - We propose a “space-based” optical system for this mission
    - All-day observation, No atmospheric disturbances, Close to LEO objects (i.e. brighter)
- Clarify capabilities and technical problems through feasibility studies

2013/1/23　第5回スペースデブリワークショップ　2

Our approaches (1)

- Space-based observatory simulator
  - Input
    - Observatory orbit
    - Optical system specifications
    - Small LEO debris catalog
    - Mission duration
  - Output
    - Density distribution of observation points
    - Target’s motion in Field Of View (FOV)
    - Detected objects number and their observation interval
    - Target’s apparent magnitude

Our approaches (2)

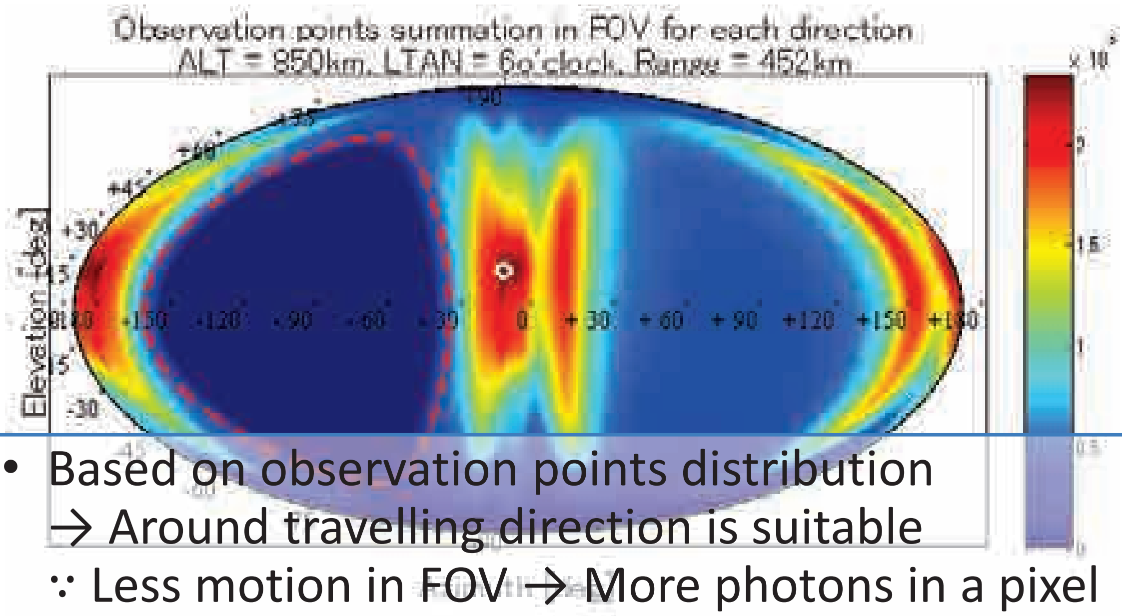
- Orbit Determination (OD)
  - Angles only
    - Typical optical observation only provides angles and their time derivatives ($\alpha, \dot{\alpha}, \delta, \dot{\delta}$)
    - Initial Orbit Determination (IOD) and correlation
    - Gaussian, Admissible region, Circular assumed IOD
  - Ranging
    - Range measurement by two optical observatories
      - Triangulation
  - Batch least square
- Collaborative observation with ground telescope

Optical system

- Specification assumptions
  - 2k2k cooled CCD camera
  - F2 f=135mm single focus lens

- $N_t = \sqrt{N_{sys}^2 + N_{dc}^2 + N_{shot}^2 + N_{sky}^2}$
  - Assumed noise component
- Signal to Noise Ratio requirement
  → 5

Space-based observatory simulator: Observation points distribution



- Based on observation points distribution
  → Around travelling direction is suitable
  ∵ Less motion in FOV → More photons in a pixel

Space-based observatory simulator: Observed objects number

- Small debris (1 ~ 10 cm in diameter)
  - Observed 0.2 % in a year
    - Travelling direction observation
    - Observed objects in almost same altitude of observatory
    - Observable orbit period and drift rate (RAAN) is limited
      - RAAN: Right ascension of the ascending node
  - Needs improvement

Correlation: Test case (Angles only, Travelling direction)

- Tracklets in different epochs
  - Object identification
- FOV is assumed as travelling direction
  - Virtual observation data (Error 0.01[deg]:1σ)
  - Correlation based on degree of similarity in orbital elements (Admissible Region method)
- Failed
  - Different objects are correlated
  - Same object's tracklets are not correlated

Causes for correlation failure

- Angles only observation
  - Range cannot be determined
    - Far and fast, close and slow → same apparent motion
  - Travelling direction observation
    - Less motion in FOV → less information
    - Unable to identify different objects
- Brief summary
  - Travelling direction FOV is suitable from a view point of sensitivity
  - However, less information in FOV causes negative effect in correlation

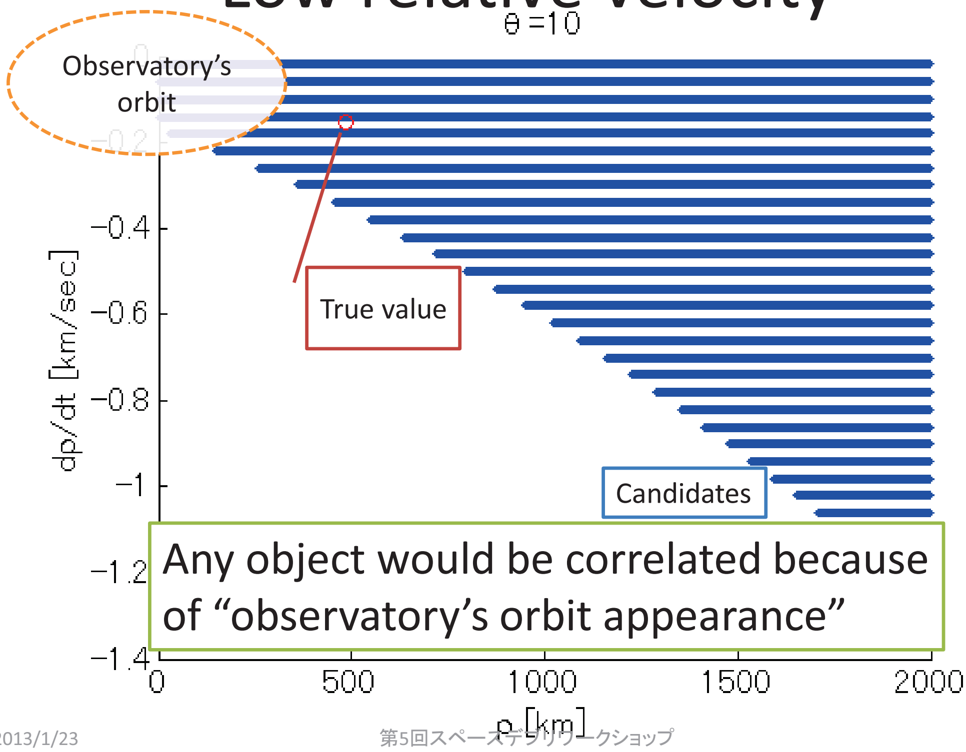
Solutions

- Sweep observation for higher or lower altitude
  - Tilt FOV from travelling direction
- Ranging

Sweep observation, Tilt FOV from travelling direction

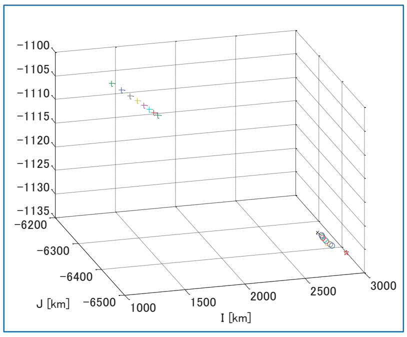
- Put observatory into lower (or higher) orbit than observation target region (e.g. 800 - 900 km)
  - Difference in orbital period, RAAN drift rate
  - Whole target region (shell like shape) can be observed
  - For example, 4.3% (approx. 12000) of LEO small debris can be swept
- Tilt optical axis from travelling direction
  - High relative velocity → cannot be observed
  - Low relative velocity → can be observed
    - However, problem in correlation remains (AR method)

Low relative velocity



Typical OD, (Angles only)

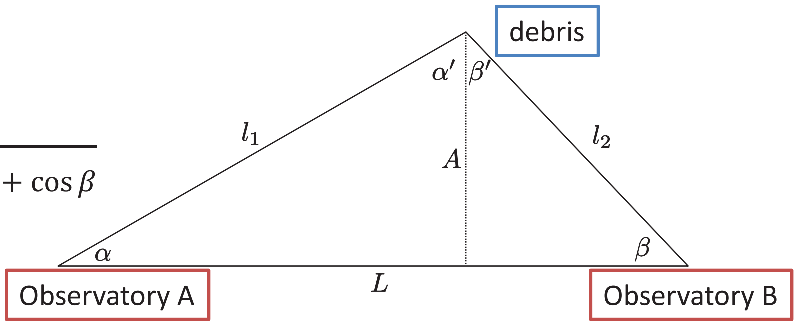
- Low relative velocity gives longer duration of observations
- IOD by Gaussian and circular orbit assumption
  - Gaussian : Poor accuracy
  - Circular : Better but still poor
- Refine by batch least square
  - Does not converge
  - Extremely short arc



Ranging

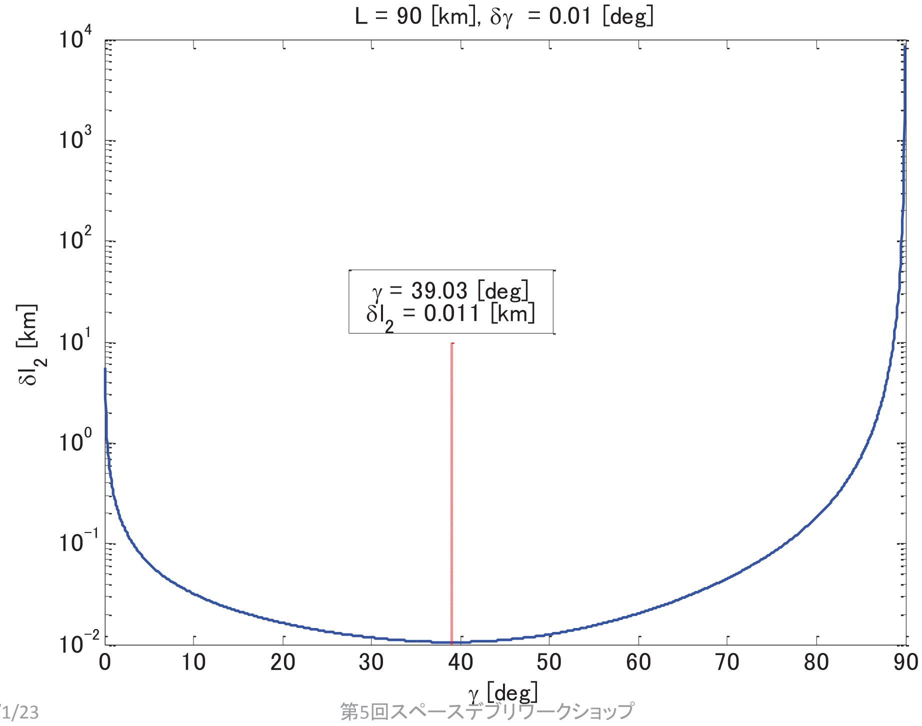
- Range information determines unique position vectors from angles data
- Triangulation

$$l_2 = \frac{L}{\frac{\sin\beta}{\sin\alpha}\cos\alpha + \cos\beta}$$



- Proper configuration provides 10m accuracy
  - 0.01[deg] angles error

FOV tilt angle and range accuracy



OD using triangulation: Test case

- Observe object in 800km altitude
- From observatory in 700km altitude
- Angles error 0.01[deg] (1σ)
- OD result accuracy
  - Position ~100m
  - Velocity ~4m/s
- High accuracy estimation is available
  - However, sweep observation is not suitable for periodic data update

Collaborative observation concept

- Space-based observatory
  - Sweep, Triangulation
  - Less than 100m accuracy
  - Not suitable for frequent observation
- Ground-based observatory
  - Small debris are too dark to detect
  - OD result provided by space-based system enables target motion estimation
  - Then TDI (Time Delayed Integration) or image stacking method are available
  - Periodic data update

2013/1/23 第5回スペースデブリワークショップ 17

Summary

- Travelling direction is suitable for observation in terms of photon criteria
- However, this direction has negative effects in correlation and observation efficiency
- Tilted FOV enables sweep observation
  - 4.3 % of LEO debris
    → potentially observable (800 – 900km)
- It is hard to determine target’s orbit from space-based angles only observation
- Triangulation by two satellites provides precise range information
- Target’s orbit can be determined less than 100m accuracy with triangulation

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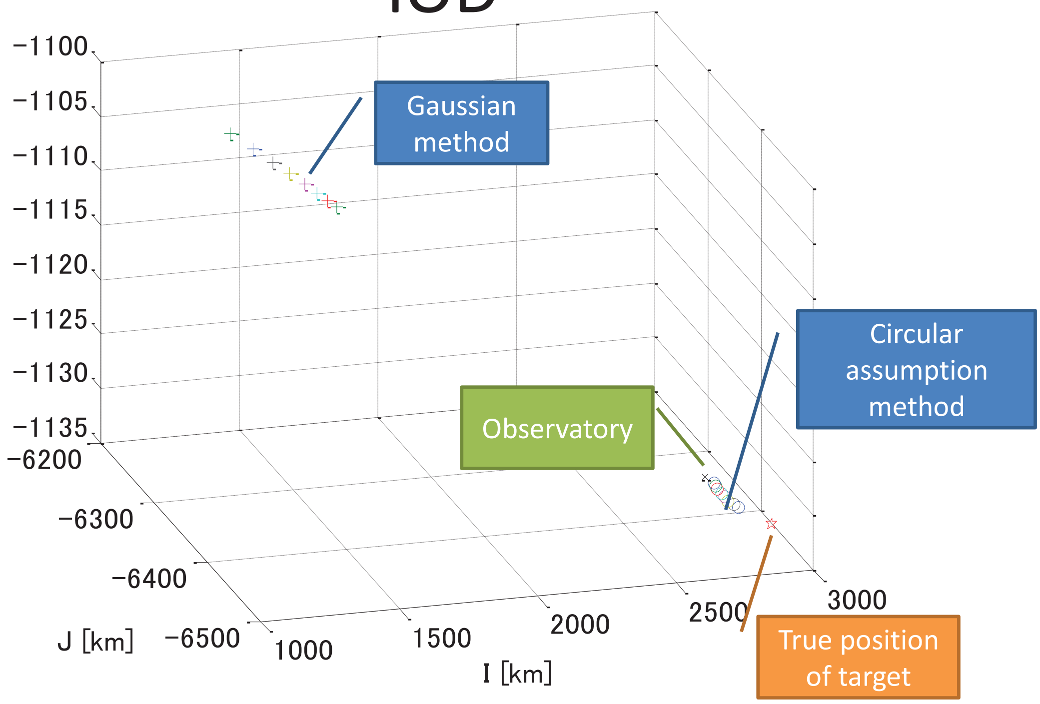
Future tasks

- Improvement of space-based observatory simulator
- Detailed study of collaborative observation between space-based and ground telescope
- Review optical system (CCD, CMOS, EMCCD)
- Feasibility study of triangulation ranging
  - Object identification

IOD



F4

再突入物体のレーダ観測及び予測解析

Observation and Prediction for Re-entry Objects

○染谷一徳, 阿部旬也, 田島 徹（宇宙航空研究開発機構）,
足立 学, 亀山雅也（富士通株式会社）
○Kazunori Someya, Junya Abe, Toru Tajima (JAXA),
Gaku Adachi, and Masaya Kameyama (FUJITSU LIMITED)

低軌道のスペースデブリは、大気抵抗による減速効果で高度が下がり、いずれ大気圏に再突入する。大気圏再突入の時期やその位置を予測することは重要である。JAXA では、上齋原スペースガードセンターに設置されたレーダを用いた観測及び米国が公開している軌道情報（Two-Line Elements）を用いて、軌道把握と再突入予測解析を行っている。再突入間際のレーダ観測においては、低高度であるがゆえに、大気抵抗の予測誤差、大気密度モデル誤差の増大、及び質量面積比の不確定性などにより、観測が困難となる。そのため、多段観測と呼ぶ観測手法を確立させ、再突入直前までの観測を可能とした。
本講演においては、2011 年度に実施した 3 物体の再突入予測解析について、レーダ観測及び再突入予測解析の結果を示すとともに、得られた知見と、今度の予測精度向上に向けた取り組みを発表する。

Uncontrolled space debris re-enters atmosphere due to atmospheric drag in low altitude. The prediction of re-entry point and time window are important for space debris issues. Orbits of re-entering objects are observed by radar and also estimated using Two-Line Elements obtained from a web site for re-entry prediction analysis. However, accurate observation by radar just before re-entry is difficult due to errors in atmospheric drag prediction. We therefore established a method called the Multi-Stage Observation to solve this problem, and made much progress in observing the objects in the last hours of re-entry in visible paths.
This paper presents recent activities of space debris observation and re-entry prediction and their results obtained from three targeted satellites which re-entered in JFY 2011. In addition, means for improving prediction accuracy is further discussed.

The 5th Space Debris Workshop

再突入物体のレーダ観測及び予測解析

Observation and Prediction of Re-entry Objects

23, January, 2013
Tokyo, Japan

Kazunori Someya, Junya Abe, Toru Tajima（JAXA）
Gaku Adachi and Masaya Kameyama（FUJITSU Ltd.）

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1. Introduction
2. Method of Orbit estimation
   – Radar observation
   – Using multi-TLEs
3. Reentry prediction
   – Case1: UARS
   – Case2 : ROSAT
   – Case3 : Phobos-Grunt(P-G)
   – Evaluations
4. Conclusion


UARS

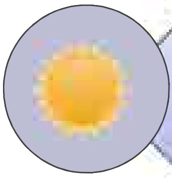

ROSAT


Phobos-Grunt

1. Introduction (1/2)

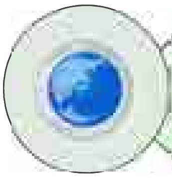
JAXA FUJITSU

- Orbit of uncontrolled space debris is difficult to predict due to errors in atmospheric drag prediction.
- 自然落下するデブリの軌道は、大気抵抗に大きく左右され、予測が難しい。



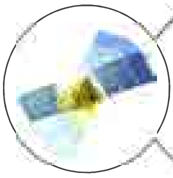
太陽活動の将来予測の不確定性
（大気密度の変化の不確定性）

(Uncertainty 1:
Prediction of solar activity)



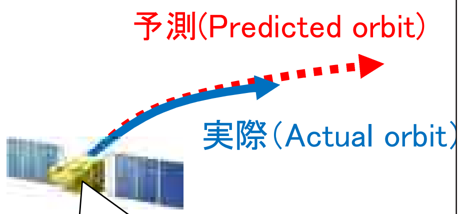
低高度（100～200km前後）領域における大気密度モデルの不確定性

(Uncertainty 2: Errors in atmospheric model in low attitude)



再突入物体の姿勢変動による弾道係数の変動状況の不確定性

(Uncertainty 3: Ballistic coefficient)



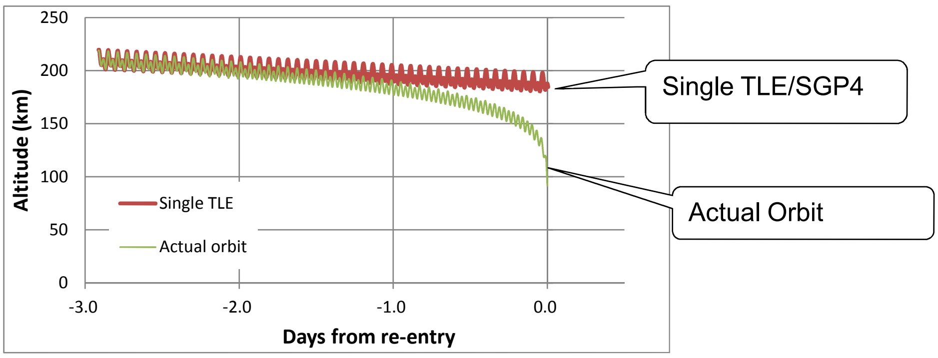
Most errors occur in the direction of travel of the predicted orbit.
誤差は主として軌道の進行方向に生じる

1. Introduction (2/2)

JAXA FUJITSU

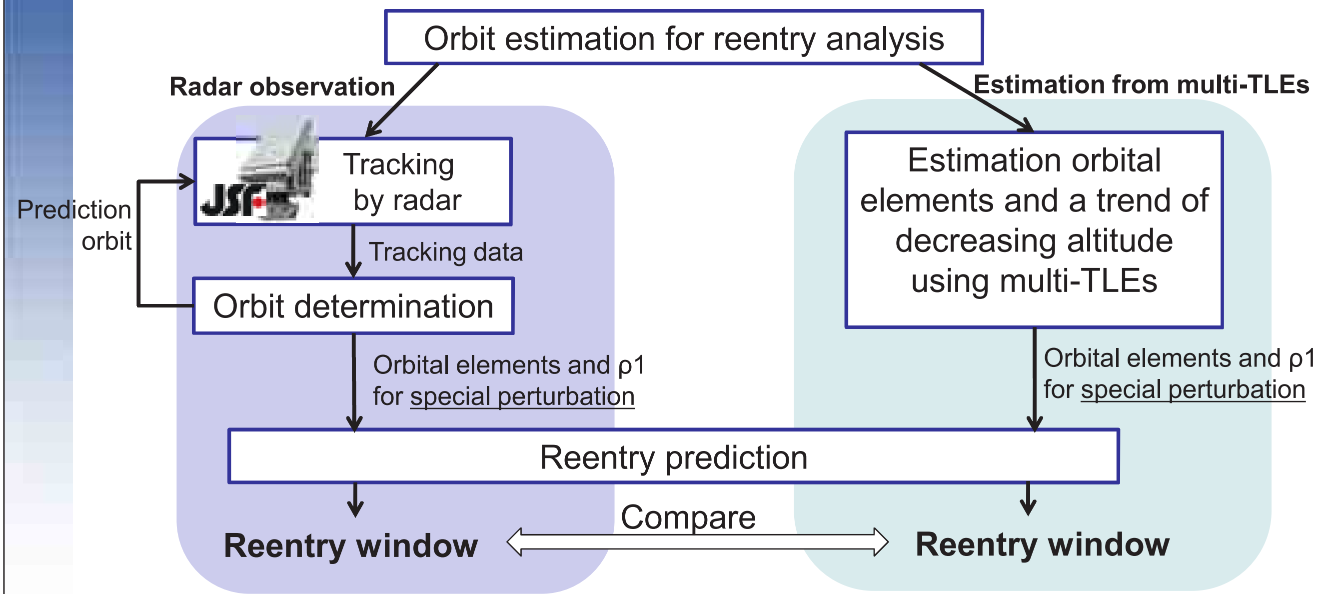
- As a first step, orbit of reentry object gets Two-line elements (TLE) from Space-Track.org.)
- However, prediction accuracy has a large error using only single TLE.
- We therefore performed observation by radar and orbit estimation using the multi-TLEs in order to improve accuracy.

- 再突入物体は、まずSpace-TrackのTLEを用いて軌道を把握する。
- しかし、TLE単体では、再突入予測の精度が満たせない。
- 「レーダー観測」と「複数のTLEsから軌道を求める」ことで再突入予測で使用できる軌道精度向上を図っている。



2. *Method of orbit estimation*

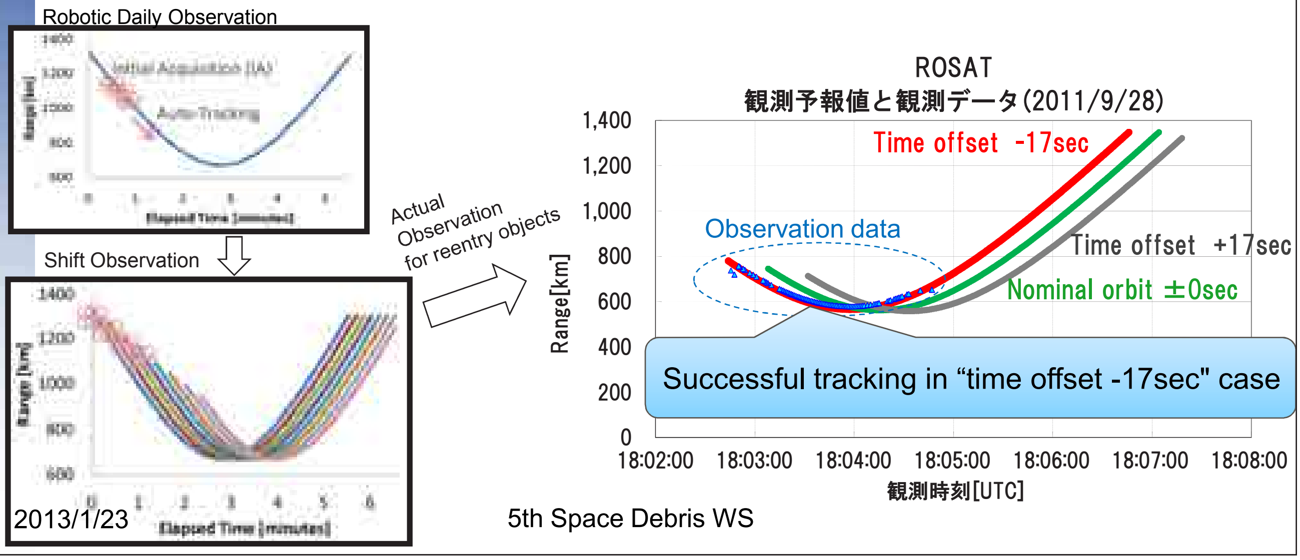
- Accuracy in orbit prediction is improved using special perturbation method.
  - Reentry objects are observed for orbit determination by KSGC radar using TLE.
  - On the other hand, orbital elements are also estimate from multi-TLEs.



2013/1/23 ρ1：大気抵抗係数調整パラメータ 5th Space Debris WS

2.1. *Radar observation*

- Accurate observation by radar just before re-entry is difficult due to errors in atmospheric drag prediction.
- A prediction error is covered only 3 seconds if a method of robotic daily observation use.
- We therefore established a method called the Shift Observation to extend covering error span more than 20 seconds.



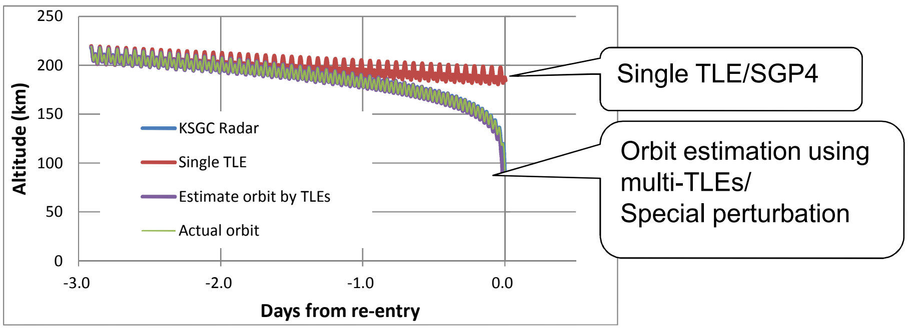
2013/1/23 5th Space Debris WS

2.2. Orbit estimation using multi-TLEs

- A propagate of TLE is used general perturbation such as SGP4.
- A prediction accuracy has a large error using SGP4. It isn't available to use reentry prediction.

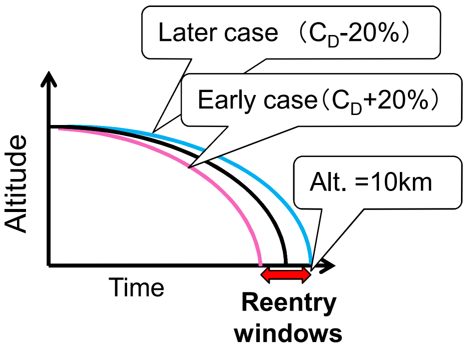
⇩

- Improved orbital elements and a trend of altitude decreasing rate are estimated using multi-TLEs for several days.
- Accuracy in prediction orbit is improved using special perturbation after estimation from multi-TLEs.



3. Re-entry analysis condition

- 大気密度モデル:
  （Atmospheric density models）
  - Jacchia-Roberts（Alt. ≧90km）
  - US. Standard（Alt.＜90km）
- 再突入予測範囲:
  （Reentry windows）
  - 大気抵抗係数(C_D) ±20%
  - 過去の実績及び経験則から設定
    （Based on past results and heuristics）

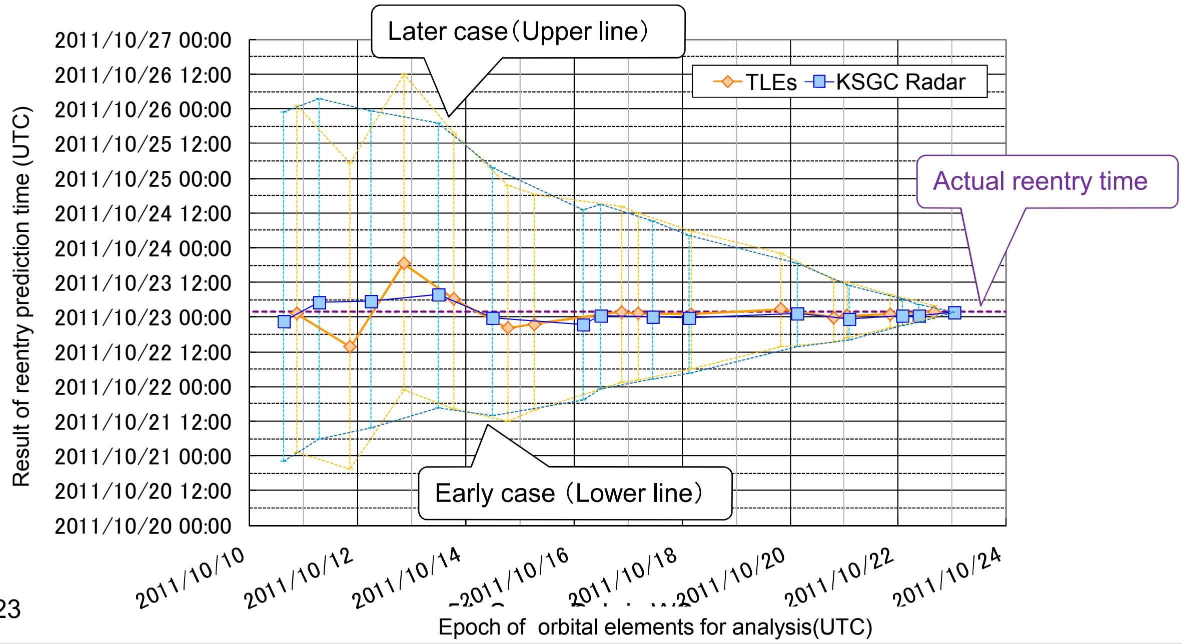


- Analysis targets (satellites)

ROSAT  UARS  Phobos-Grunt (P-G) 

3.1. Result of reentry prediction for ROSAT

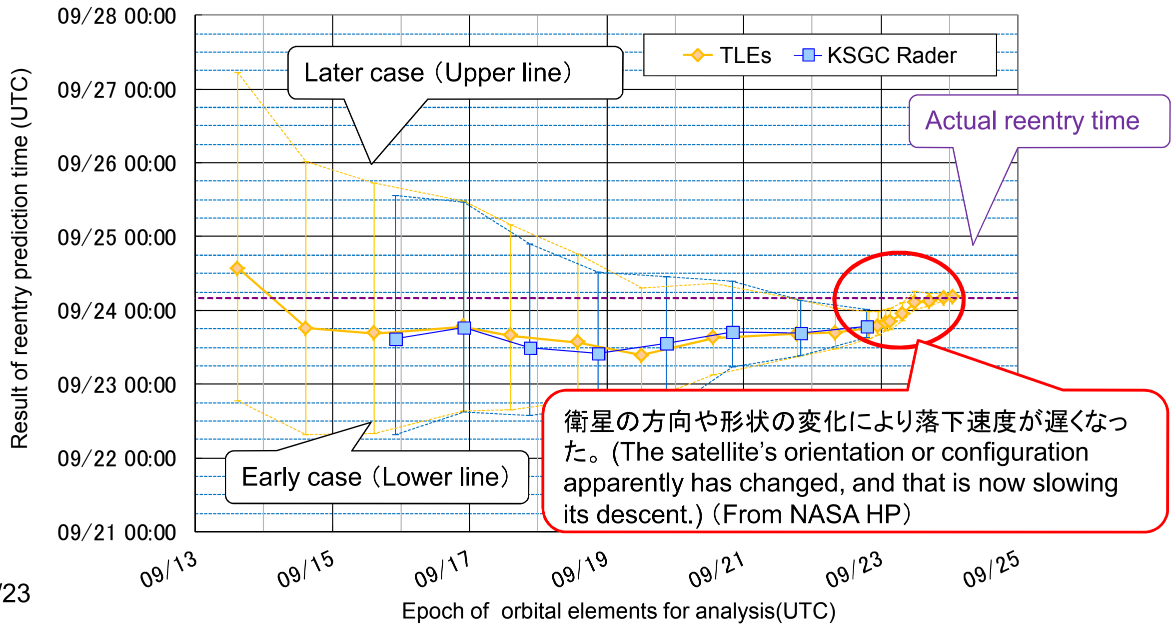
- There is no significant difference between case of orbit estimation from multi-TLEs and case of KSGC radar.
- This analysis is shown good results because of ideal convergence.



2013/1/23

3.2. Result of reentry prediction for UARS

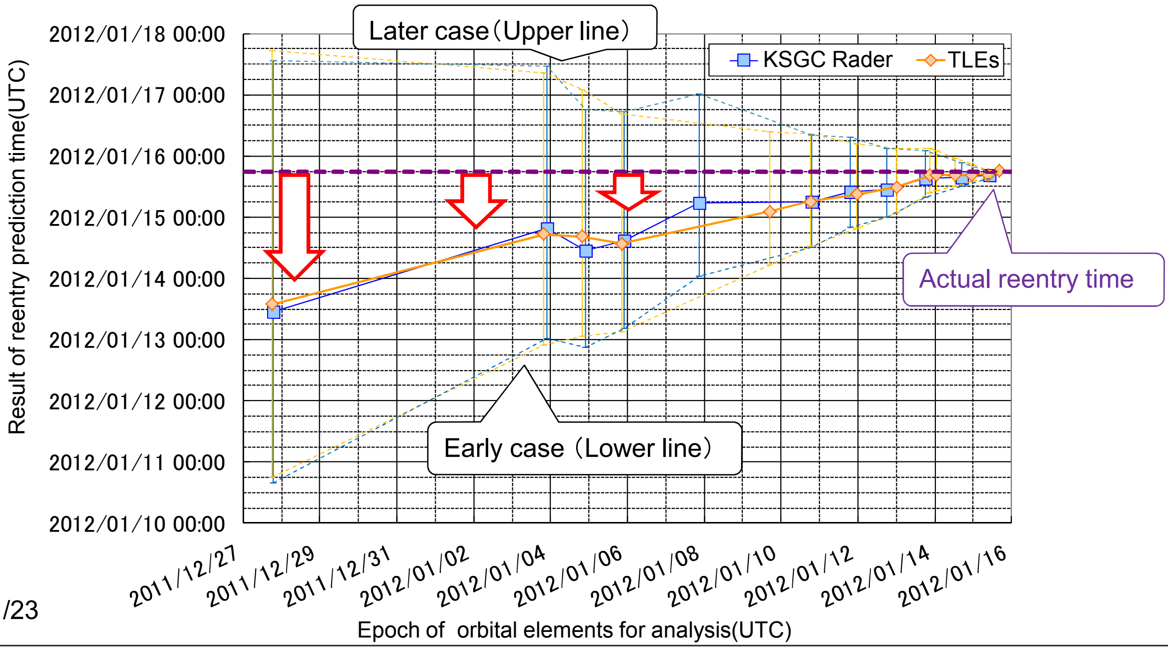
- Change in the satellite’s orientation or configuration is apparently slowing its descent before one day from reentry.
- There is shown to be associated uncertainty 3 such as Ballistic coefficient .



2013/1/23

3.3. Result of reentry prediction for P-G

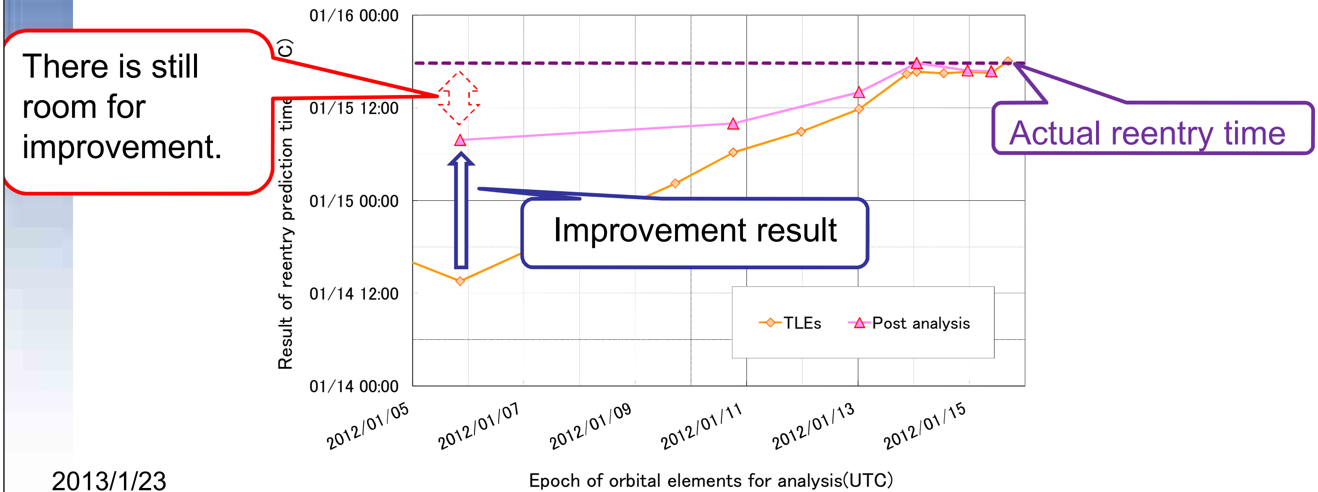
- Most results were earlier than reference reentry time.
- There are one of the factors that effects of prediction of solar activity. (Relation with uncertainty 1)



2013/1/23

3.4. Effects of prediction of solar activity

- Prediction of solar activity refers solar flux (F10.7cm) and geomagnetic index value from NOAA site.
- The solar activity is updated from perdition to actual value several days later.
- Post analysis : conducted by replacing the solar activity prediction to its actual value.



2013/1/23

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5. Conclusion

- We were successful in continual prediction of reentry window through establishing the method of initial acquisition for radar observation and orbit estimation based on multi-TLEs for accuracy improvement.
- We performed estimation of orbits and prediction of reentry windows for three satellites in FY2011. The errors in these results were almost within 20 percent, as we had expected.

- レーダー観測における捕捉方法の確立、複数TLEからの精度向上を行うことで、継続的な再突入予測解析が実施できた。
- 2011年度に再突入した3衛星について、再突入予測解析を行い、概ね誤差20%の予測範囲内の結果であった。

Future Works(今後の課題)

- We will further study the physics of a situation just before re-entry, in order to improve the accuracy of prediction.)
- 再突入物体の挙動から物理的現象の分析を深掘りし、精度向上に向けた研究を実施していきたい。

2013/1/23 5th Space Debris WS

ご清聴ありがとうございました。
Thank you for your attention!

2013/1/23 5th Space Debris WS

F5

鹿島 35cm 望遠鏡を用いた人工衛星の観測

Observations of Artificial Satellites with Kashima 35cm Optical Telescopes

○布施哲治（NICT 鹿島）
○Tetsuharu Fuse (NICT Kashima)

情報通信研究機構 (NICT) では、企業・大学と共同開発中の超小型衛星に光通信用レーザ発振器およびコリメーターを搭載し、地上局との光通信実験を計画している。一般的に、低軌道を周回する超小型衛星は、自ら発光していない限り地上から見える可能性は低いが、光通信用の近赤外線を発している同衛星では地上望遠鏡による位置観測および軌道決定ができる可能性がある。鹿島宇宙技術センターの口径 35cm 光学望遠鏡は静止衛星専用であったが、低軌道衛星をも観測できるように改修作業を行っている。本発表では、現在の観測システムの状況を報告する。

鹿島35cm望遠鏡を用いた人工衛星の観測

情報通信研究機構 鹿島宇宙技術センター
布施 哲治

1. 鹿島センターと立地条件
2. 望遠鏡： 1997/2002年～2005年
3. 望遠鏡： 2005年～2011年
4. 新しい研究対象
5. 望遠鏡： 現在～

1

1. 鹿島宇宙技術センターと立地条件

情報通信研究機構 (NICT) の施設


鹿島宇宙技術センター
Kashima Space Research Center


口径 34m アンテナ
口径 13m アンテナ
（左：放送衛星、右：通信衛星）
口径 35cm望遠鏡
可動基線電波干渉計

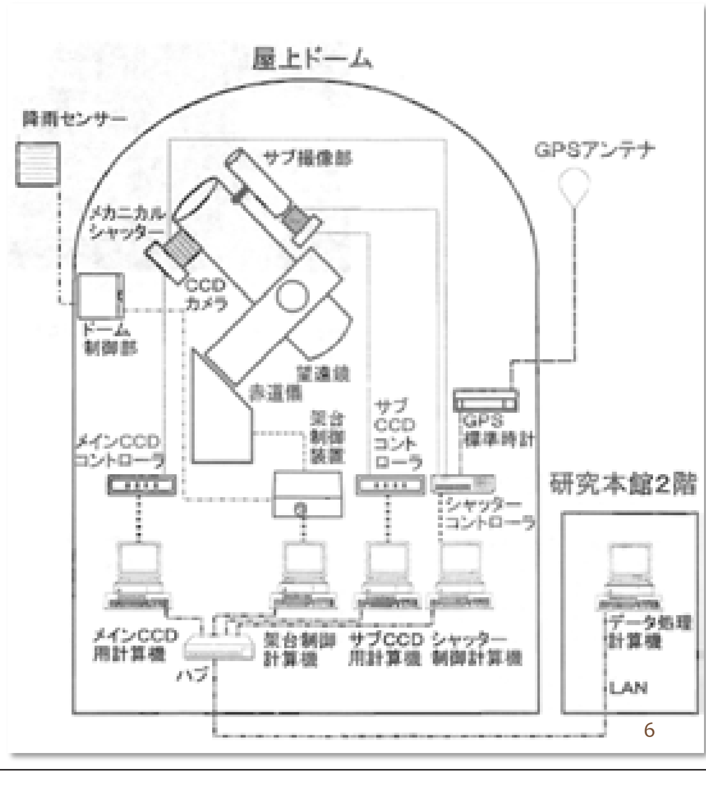
1. 鹿島宇宙技術センターと立地条件

- 太平洋まで東に 2kmほど
- 南東に製鉄所・化学工場など
- 近隣に娯楽・商業施設、住宅
- 南西約30kmに成田空港

→ 観測環境は非常に悪い

2. 望遠鏡：1997/2002年～2005年

- 静止衛星の撮像および軌道決定を目的に2台を建設
  - 望遠鏡：タカハシ ε-350 (口径35cm)、焦点距離 1,248mm
  - 架台： SHOWA (耐荷重 60kg)
  - 視野： 1度×1度
  - シャッター、カメラ、架台の制御 PCが各3台
  - 研究室から Windows のリモートデスクトップでコントロール



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3. 望遠鏡: 2005年～2011年

- 2005年のトラブル後に改修
  - 望遠鏡:タカハシε-350（口径35cm）、焦点距離 1,248mm
  - 架台: SHOWA（中身は住金金属系列会社作成？）
  - カメラ: BITRAN BT214E　1,024×1,024 pix　24μm
  - 視野:　1度×1度
  - シャッター精度: UTC＜0.01秒
  - 位置測定精度: 1/1,000度（＝3.6秒角、静止軌道上で約700m）

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3. 望遠鏡: 2005年～2011年

- 位置測定の**精度が低い**（1/1000度＝3.6秒角 → 1ピクセル？）
  - 使っている星表カタログが Guide Star Catalogue 1.1
  - CCDカメラのピクセルスケールが大きい（24μm）
- 非恒星追尾はもちろん、**恒星追尾もできなかった**
- その後のできごと
  - 2011年度で静止衛星監視の**電波利用料が終了**
  - 研究室の方向性 → **低軌道衛星による光通信実験**
- そこで、どうしたか

1:「**光通信中の低軌道衛星を光学的に位置観測→軌道決定**」を目標に

2: 普通の赤道儀に戻して、**普通の天体望遠鏡**にする（昨年度）

3: **低軌道衛星**の軌道決定向けにカメラ周辺を改修（昨年度＋今年度）

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4. 新しい研究対象

- 低軌道衛星 ： 高度628km、重さ50kg
  - 宇宙光通信技術実証衛星SOCRATES by AES： H25年度打上げ（ALOS-2の相乗り）

http://www.aes.co.jp/product/pdf/socrates_hp_j.pdf

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4. 新しい研究対象

- SOCRATES by AES： H25年度打上げ予定
  - SOTA (Small Optical Transponder):
    小型衛星へ搭載できるよう小さくデザインされた光通信装置

SOTA Proto-flight Model (PFM). 光学部（左）および 電気回路部（右）.

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4. 新しい研究対象

- SOCRATES by AES：H25年度打上げ予定
  - SOTA (Small Optical Transponder):
    小型衛星へ搭載できるよう小さくデザインされた光通信装置

表１ SOTA BBM の主な仕様

Mass	5.3 kg(including both the optical part and the electric part)
Power	22.8 Watt
Gimbal angular range	Az: >±10deg. El: >±10deg
Link range	1000km
Wavelength	TX 1: 975nm
	TX 2 & 3 : 800nm-band
	TX 4 : 1550nm
	RX: 1064nm
Data Rate	10Mbps

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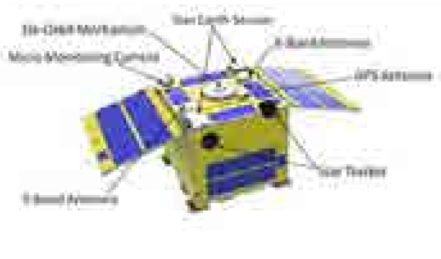
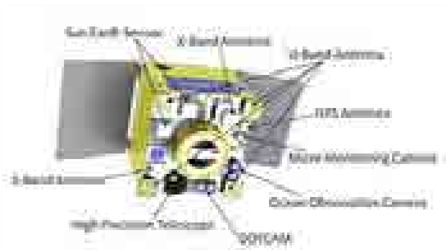
4. 新しい研究対象

- 低軌道衛星 ： 高度500−900km、重さ50kg
  - ほどよし2号 (RISESAT: Rapid International Scientific Experiment Satellite) by 東北大学 ： H25年度打上げ





http://park.itc.u-tokyo.ac.jp/nsat/hodo2.html

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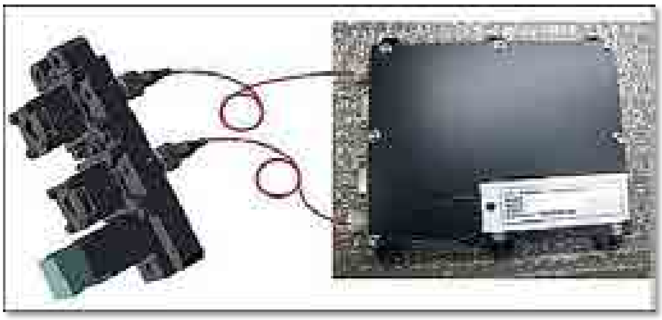
4. 新しい研究対象

- ほどよし2号 by 東北大学 : H25年度打上げ
  - VSOTA (Very Small Optical Transponder):
    SOTA の機能限定版の光通信装置 (100kbps with 980nm/1540nm)



https://directory.eoportal.org/

http://www.nict.go.jp/

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4. 新しい研究対象

- 低軌道衛星の位置観測について
  - 光通信実験中の低軌道衛星は 0.8/0.98/1.54 μm で**明るい**
    → **夜間はいつでも OK** （通常の LEO は日の出前・日没後のみ）

波長 0.8 μm

2006年3月29日

「きらり」(OICETS)
610km の円軌道

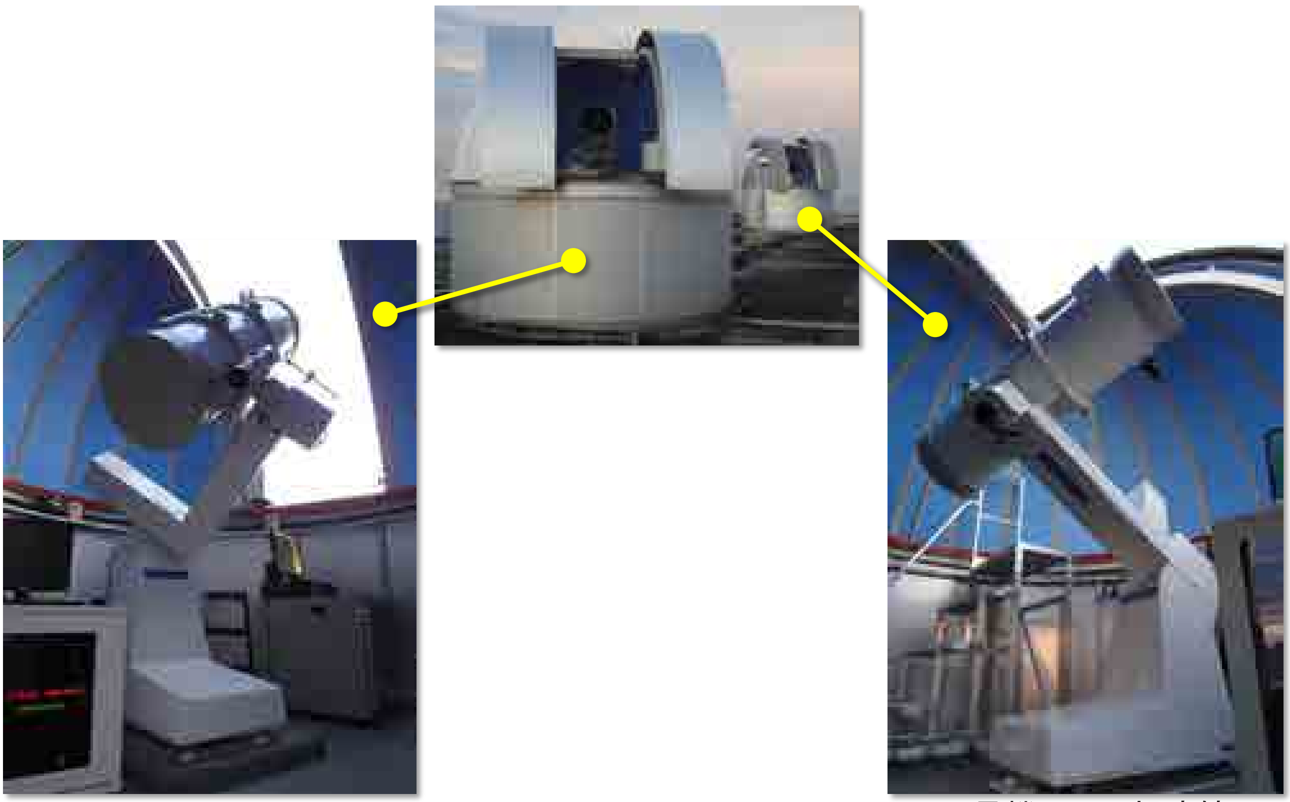
4. 新しい研究対象

- 低軌道衛星の位置観測について
  - GPSによる軌道決定とは**独立した物理量**から軌道を求める
  - **おおよその軌道**がわかっている、**明るい衛星**を対象とする
  - **恒星追尾**をして、視野内を**横切る衛星**を捉える（＝**流星**）
  - 恒星は点状
  - 線状に伸びた衛星像の位置を測定

    → GPS時計を用いた時刻制御

    → シャッターの開閉が高精度に時刻管理されたカメラ
  - **時刻制御精度が軌道決定精度を決める** → ～50μs

5. 望遠鏡： 現在～



1号機：低軌道用望遠鏡

2号機：汎用望遠鏡

5. 望遠鏡： 現在～

- 低軌道衛星用望遠鏡（1号機）
  - 鏡筒は過去と同じ：タカハシε-350（口径35cm）、焦点距離1,248mm、視野 1度 x 1度
  - 架台・西村製作所製（耐荷重100kg）
  - カメラ：BITRAN BQ－82 （1600万画素）＋ I band フィルター
    シャッター時刻管理精度 ～50μsec

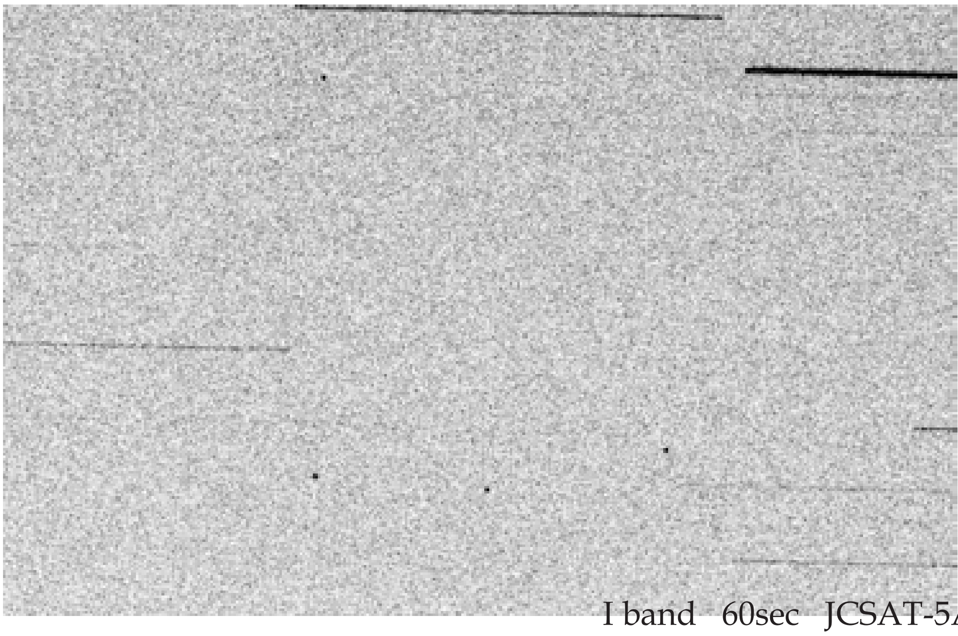
5. 望遠鏡： 現在～

- 低軌道衛星用望遠鏡（1号機）

BITRAN BQ-82M
4872×3248pix（1600万画素） 7.4μm

5. 望遠鏡： 現在～

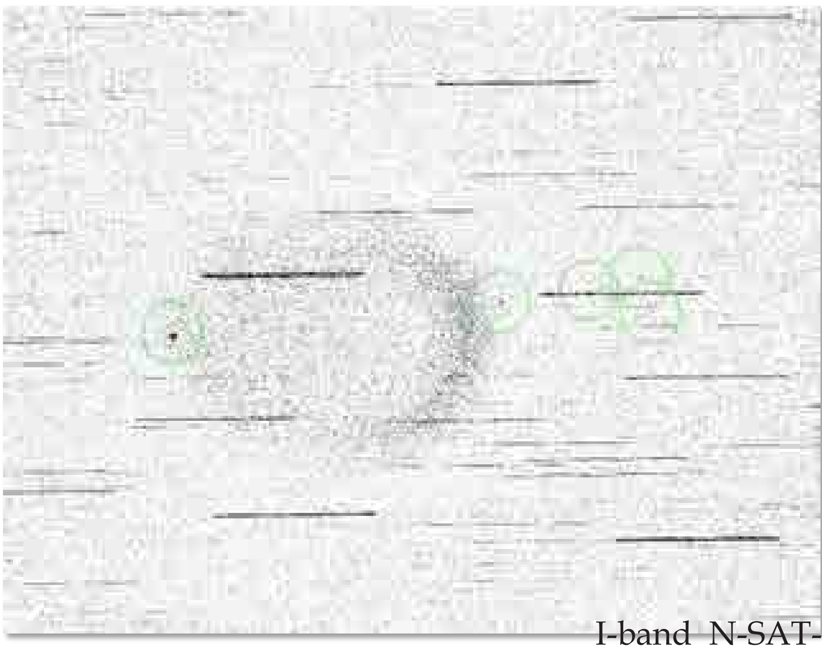
- 低軌道衛星用望遠鏡（1号機）
  - 静止衛星の観測 ＝**追尾を止めると**衛星が点状



I band 60sec JCSAT-5A E135deg

5. 望遠鏡： 現在～

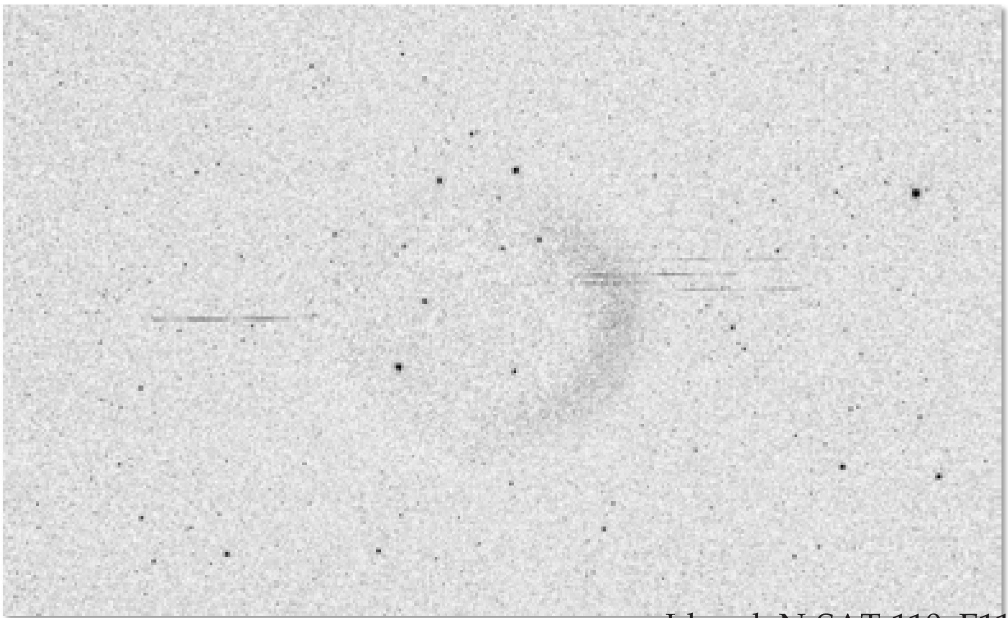
- 低軌道衛星用望遠鏡（1号機）
  - 静止衛星の観測 ＝**追尾を止めると**衛星が点状



I-band N-SAT-110 E110deg

5. 望遠鏡： 現在～

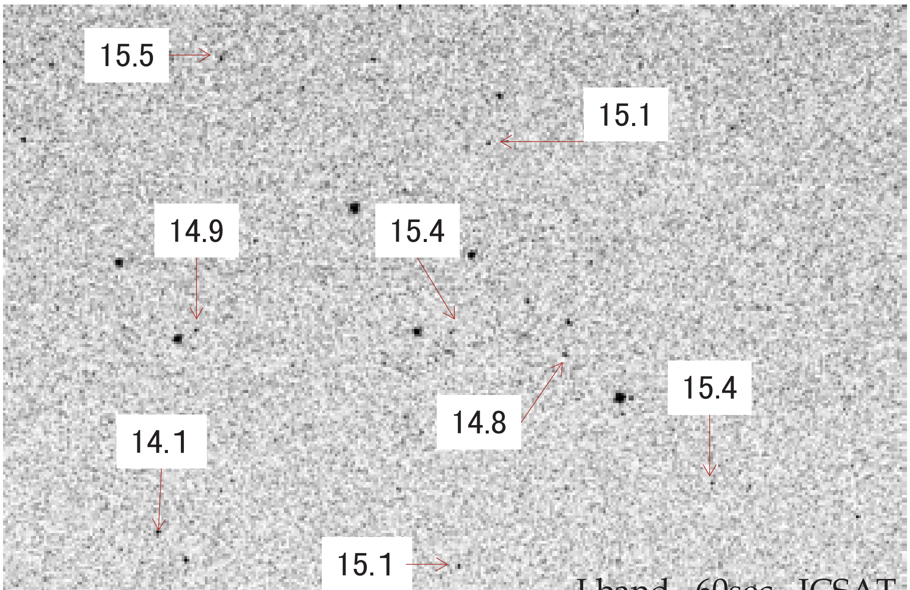
- 低軌道衛星用望遠鏡（1号機）
  - 静止衛星の観測 ： **恒星追尾** ≒ 低軌道衛星の観測



I-band N-SAT-110 E110deg

5. 望遠鏡： 現在～

- 低軌道衛星用望遠鏡（1号機）
  - 静止衛星の観測 ： **恒星追尾** ≒ 低軌道衛星の観測



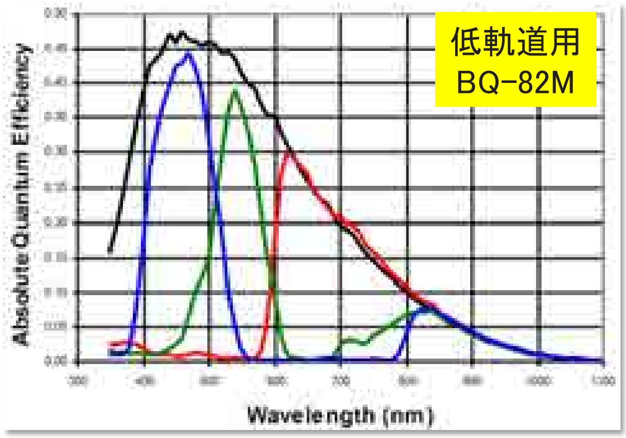
I band 60sec JCSAT-5A E135deg

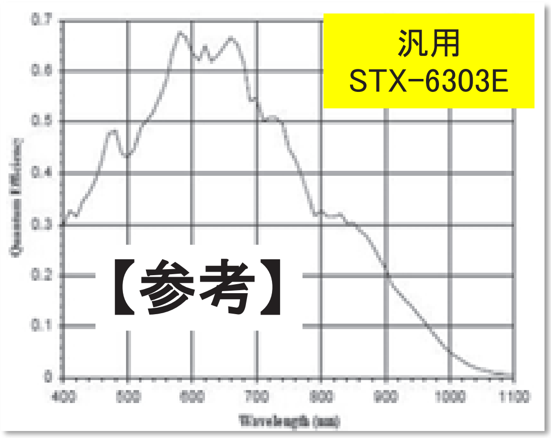
5. 望遠鏡: 現在～

- 汎用望遠鏡（2号機）
  - 鏡筒、架台、架台まわりは1号機と同一
  - CCDカメラ: SBIG STX-6303E 3072×2048 pix （630画素） 9μm
  - 眼視向けに巨大脚立を導入: 中学生の職場体験などに利用

5. 望遠鏡: 現在～

- これから、やるべきこと、やっていること
  - 0.8 μmの QE は 10% だが、位置観測は可能
  - 0.98 μm を放つ衛星の位置観測も、現システムで可能な見込み





  - 1.54 μm を放つ衛星の位置観測の可能性は調査中
  - **低軌道衛星の追尾**のため、ドームモータの交換済み。架台制御プログラムは改修中

まとめ

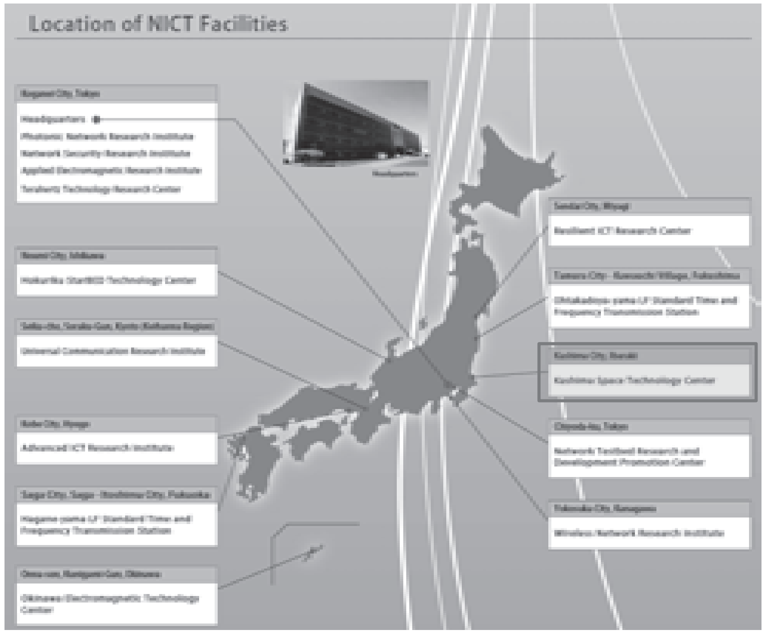
- 低軌道衛星用望遠鏡（1号機）
  - 静止衛星・デブリの位置観測（追尾なし＝衛星追尾）
    限界等級 15.5mag @ 10秒露出
  - 低軌道衛星の位置観測（恒星追尾で待ち伏せ、明るい衛星）
  - 低軌道衛星の追尾（今年度ハード・ソフト対応）

- 汎用望遠鏡（2号機）
  - 静止衛星・デブリの位置観測（追尾なし＝衛星追尾）
  - 低軌道衛星の追尾（今年度ハード・ソフト対応、ドーム改修必要）
  - 昼間に眼視による観望会

Observations of Artificial Satellites with Kashima 35cm Optical Telescopes

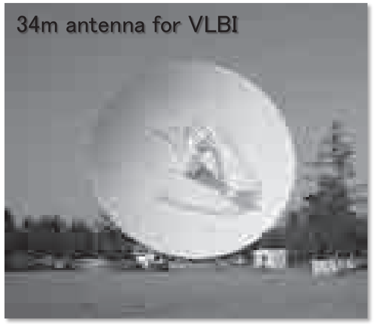
Tetsuharu Fuse
Kashima Space Technology Center
National Institute of Information and Communications Technology

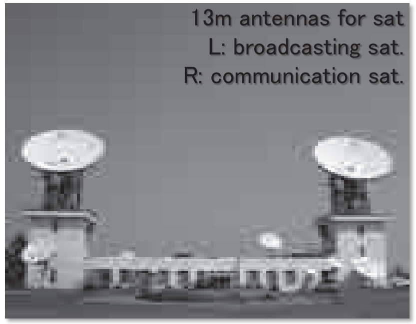
1

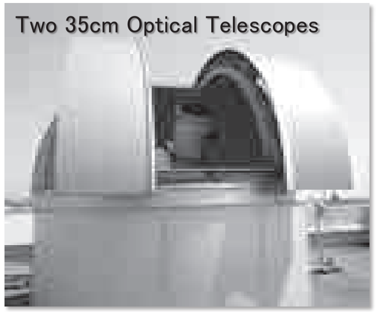


2

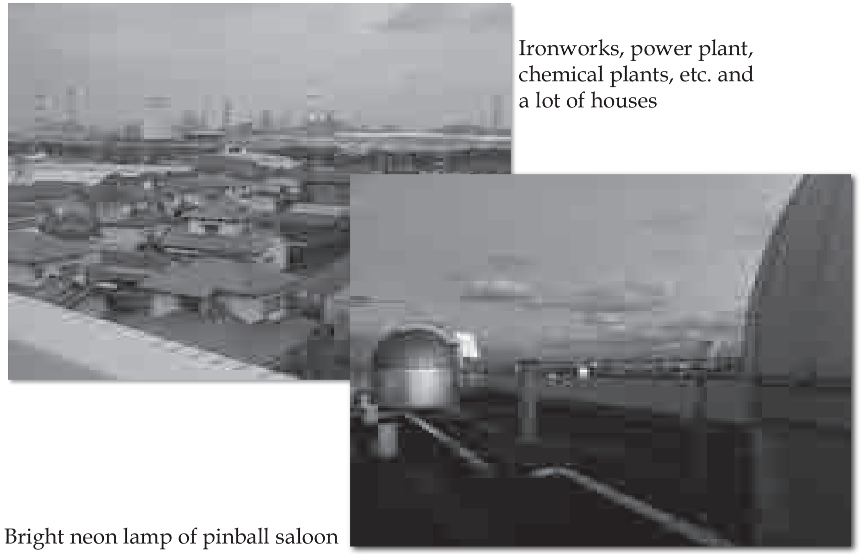
Kashima Center in Kashima City







Environment around Kashima Center

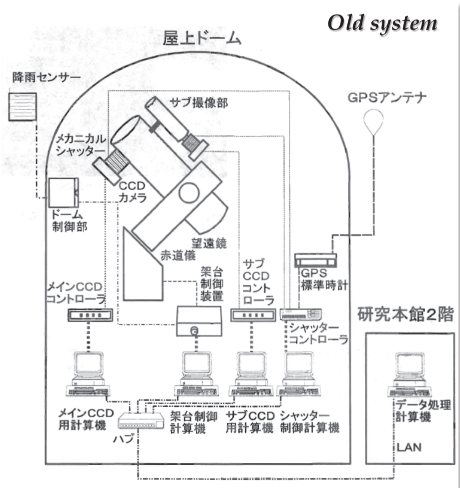


Ironworks, power plant, chemical plants, etc. and a lot of houses

Bright neon lamp of pinball saloon

History of Kashima Telescopes

- The old systems could only measure geostationary satellite positions to determine their orbits around the earth; this was because the old telescope mount functions were limited.
- After the 2011's huge earthquakes, the mounts were replaced and any objects can be observed now.



6

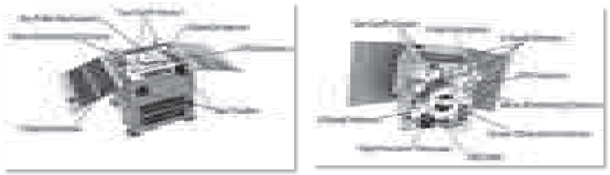
Two Microsatellite Missions with NICT's Optical Component

- A LEO microsatellite SOCRATES, alt 628km and mass 50kg, developed by Advanced Engineering Services Co., Ltd. will be launched in 2013.
- NICT's on board component SOTA (Small Optical Transponder) emits 800, 980, and 1550nm near-infrared lights for optical communications.

7

Two Microsatellite Missions with NICT's Optical Component

- HODOYOSHI-2, a LEO microsatellite of alt 500–900km and mass 50kg, developed by Tohoku University, will also be launched in 2013.
- NICT's on board component VSOTA (Very Small Optical Transponder) emits 980 and 1540nm near-infrared lights for optical communications.



8

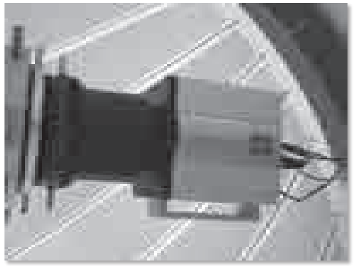
Two Microsatellite Missions with NICT’s Optical Component

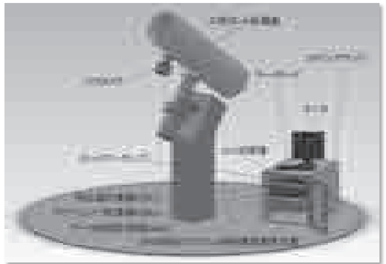
- Orbital determination of LEO satellites on boarded optical component
  - If a LEO satellite emits (near–infrared) light, the streak light and background star light can be detected simultaneously in night; the satellite’s relative positions to the stars give us their orbital elements.
  - This is a similar method to a meteor observation.
  - Kashima telescopes are currently under development for the LEO satellite positional observations.

meteor

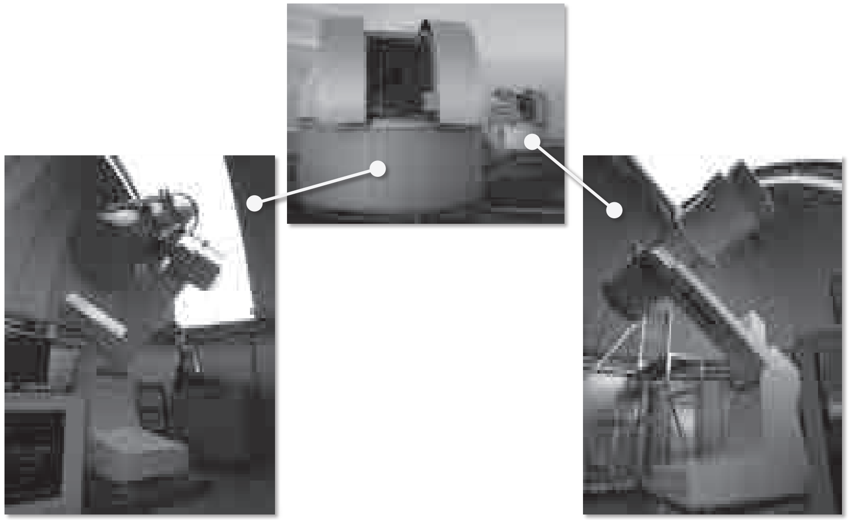
New Kashima Telescope Systems

- Telescope–1
  - Telescope: Takahashi ε –350 (Dia 35cm), f = 1,248mm
  - Mount: Nishimura ← New!
  - CCD Camera BITRAN BQ－82 (1600M pix) ← New!





New Kashima Telescope Systems

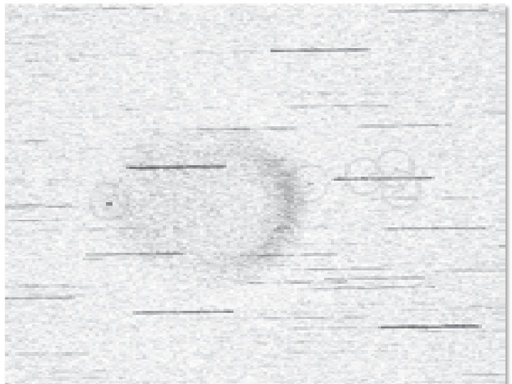


Telescope-1

Telescope-2

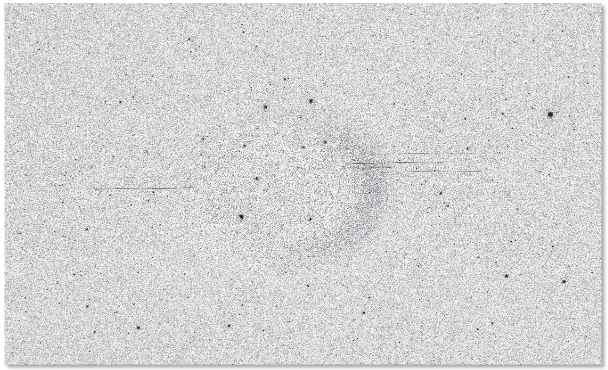
New Kashima Telescope Systems

- Telescope–1
  - A sample image of gestational satellites with no tracking



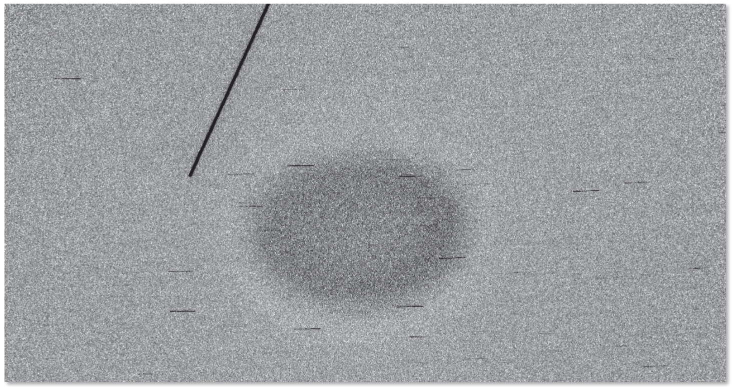
New Kashima Telescope Systems

- Telescope-1
  - A sample image of gestational satellites with the sidereal tracking



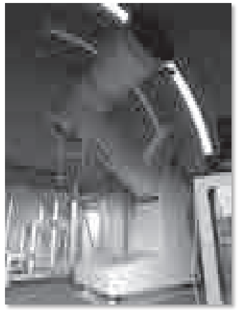
New Kashima Telescope Systems

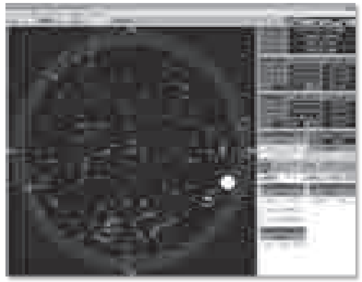
- Telescope-1
  - A sample image of ISS with the sidereal tracking



New Kashima Telescope Systems

- Telescope-2
  - Telescope: Takahashi ε -350 (Dia 35cm), f = 1,248mm
  - Mount: Nishimura ← New!
  - CCD Camera: SBIG STX-6303E (630M pix) ← New!
  - Eyepieces can also be used for educational purpose.





F6

軌道シミュレーションを用いた静止軌道上物体の複数地点観測の有効性評価

Evaluation of multi-site observation of GEO objects by simulation

○樋川 治, 泉山 卓, 大塚健功（IHI）
○Osamu Hikawa, Taku Izumiyama, Takenori Otsuka (IHI)

（静止）軌道上物体に対する複数地点からの観測は、三角測量からの類推から軌道決定精度の向上が期待される。本検討では、IHI富岡事業所を基準として、緯度・経度が異なる日本国内および海外の観測地点を設定して複数地点での光学観測での軌道決定精度（6要素）の比較と瞬時の軌道上物体の位置測定精度を軌道シミュレーションにより作成したデータを使用して比較評価を行った。実際の観測データには観測誤差が含まれるため、シミュレーションデータには観測誤差相当を白色雑音として加えている。また、複数地点で観測時刻が異なる場合についてもその影響を評価した。

Doc.#:JGM1-13 0024

5th Space Debris Workshop

EVALUATION OF MULTI-SITE OBSERVATION OF GEO OBJECTS BY SIMULATION =SUMMARY=

O. Hikawa, T. Izumiyama, T. Ootsuka

IHI
Realize your dreams

I H I Corporation

1. Introduction

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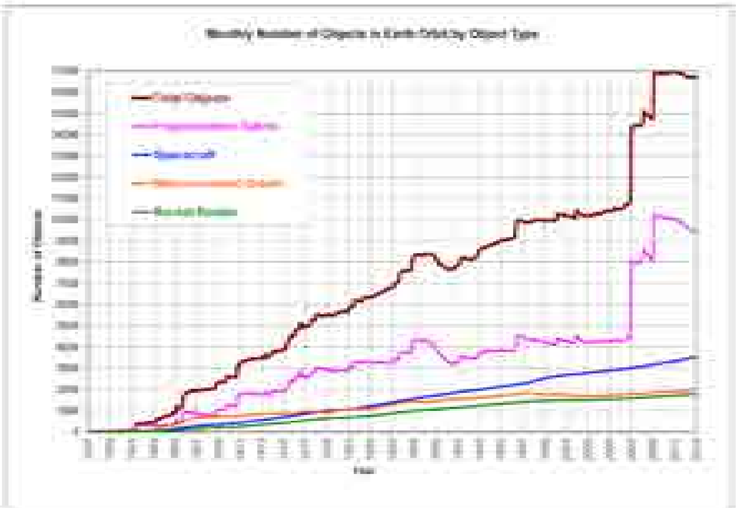
- There exists **more than 16,000**※1 objects, not only active satellites but also inactive satellite and upper stage of launcher, fragments from those space systems on Earth orbit.
- It become appear that even the latest upper stage of launcher might be the cause of many on-orbit fragments, space debris, through Briz-M explosion on October 2012.
- Orbital Objects on GEO: **1,557**※2
  - Active satellites: 404
  - Fragments, etc: 378 (20※3)
- GEO is a unique, one and only orbit for many applications satellites, therefore it is most important topics to prevent debris generation due to collisions.



Ref.: NASA Orbital Debris Program Office, "Orbital Debris Quarterly News," Volume 17, Issue 1, January 2013

※1.: 2013年1月14日現在、米空軍が識別している軌道上物体は16,897個(SpaceTrack.org, "Satellite Situtation Report," January 14, 2013

※2: 2011年初期の時点。 V. Agapov, "Results of GEO and HEO space debris population research and asteroids study within the framework of ISON international project in 2011," 49th session of STSC of COUPUOS, 6-17 February 2012による。同時期に米空軍カタログでは、1016個。

※3: 米空軍のカタログに記載された個数。 出典は※2。

1. Introduction

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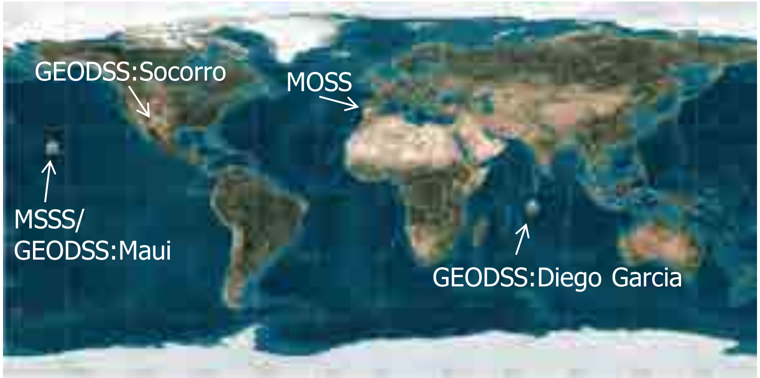
Space Situational Awareness on GEO regions is necessary for sustainable space utilization/GEO application.

- Orbital determination of the satellite around geo-stationary orbit is conducted by optically observed data.
  - Optical Observation Site of the US Space Surveillance Network: 4 sites



US Space Surveillance Network (SSN): Optical Site

From the analogy of triangulation, it is supposed that the use of data observed from multiple sites give some advantages to improve the accuracy of orbit determination.

Multi-site observation by small optical equipment might give comparable accuracies of orbital determination by large optical equipment on one site.

2. Assumptions

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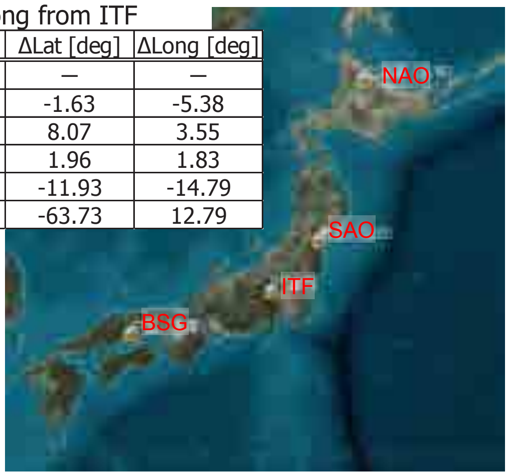
- Site Location:

Site		Lat. [deg]	Long. [deg]	Alt. [m]
IHI-Tomioka	ITF	36.2993	138.928	205
Bisei	BSG	34.6727	133.545	420
Hokkaido	NAO	44.3736	142.482	142
Sendai	SAO	38.2569	140.755	164
Okinawa	IAO	24.3736	124.140	176
Eastern Australia	QRO	-27.4333	151.717	400

Difference in Lat and long from ITF

Site		ΔLat [deg]	ΔLong [deg]
ITF		–	–
BSG		-1.63	-5.38
NAO		8.07	3.55
SAO		1.96	1.83
IAO		-11.93	-14.79
QRO		-63.73	12.79



2. Assumptions

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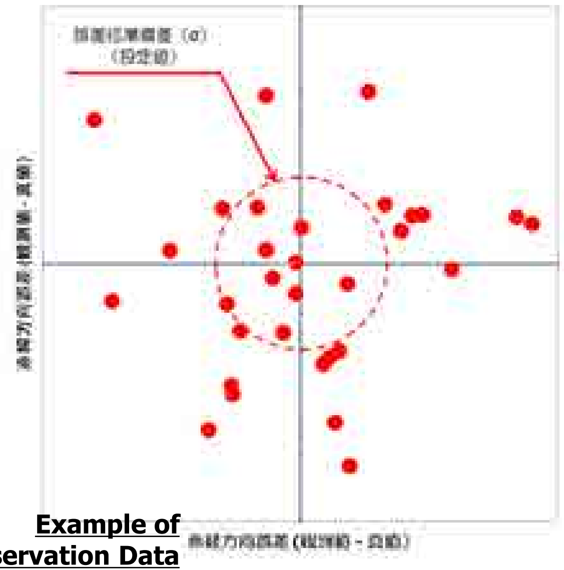
- Orbital Object to be observed:
  - Existing geo-stationary satellite was assumes for simulation.
    - NSS-6: TLE as follows。

      1 27603U 02057A   13010.45190851 .00000000 00000-0 10000-3 0 6205

      2 27603   0.0369 351.5205 0002994 296.6192 79.6083 1.00264833 36939
- Observation Data Generation:
  - 衛星軌道シミュレーションにより各観測拠点から各時刻での衛星方向を算出
  - 観測誤差は2変数（赤経・赤緯方向）正規分布すると仮定。
  - シミュレーションにより得られた方向に観測誤差を加えた値を、観測システムの分解能で離散化して観測データを算出。

  （観測誤差・分解能は小型望遠鏡相当を仮定）
  - Observation duration: 5 min/cycle
  - Data (image) sampling rate: 10 sec/data
  - Number of data (images): 31 data/cycle



Example of Observation Data

3. Simulation Results:

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3.1. Observation from Single site with interval

Two observation from single site with interval

- Site: IHI Tomioka (ITF)

	1st observation (UTC)	2nd observation (UTC)
Short duration (1 cyc)	2013/01/10 13:00～13:05	―
30 min interval	2013/01/10 13:00～13:05	2013/01/10 13:30～13:35
4 hour interval	2013/01/10 13:00～13:05	2013/01/10 17:00～17:05
24 hour interval	2013/01/10 13:00～13:05	2013/01/11 13:00～13:05

3. Simulation Results:

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3.1. Observation from Single site with interval

- Orbit determination (epoch: 2013/01/10 13:00:00)
  - No determination of orbit for 24 hours interval case
  - No valid result for observation with short duration(1 cycle of 5min)

		Short (1 cycle)	30m interval	4h interval	TLE
		ITF	ITF	ITF	
Result	Semi-major Axis (km)	-49,389.168	41,907.248	42,185.046	42,167.785
	Eccentricity	2.212463	0.005116	0.000099	0.000289
	Inclination (deg)	1.9475	0.1106	0.0975	0.0972
	RAAN (deg)	103.7830	46.9480	53.6280	53.3550
	Arg of Perigee (deg)	310.1164	153.7935	40.4848	241.6128
	True Anomaly (deg)	344.4558	199.2957	305.9146	105.0615
	Mean Anomaly (deg)	344.4558	199.4901	305.9238	105.0296
Error	Semi-major Axis (km)	-91,556.952	-260.537	17.261	
	Eccentricity	2.212174	0.004827	-0.000190	
	Inclination (deg)	1.850	0.013	0.000	
	RAAN (deg)	50.428	-6.407	0.273	
	Arg of Perigee (deg)	68.504	-87.819	-201.128	
	True Anomaly (deg)	239.394	94.234	200.853	
	Mean Anomaly (deg)	239.426	94.461	200.894	
Error(%)	Semi-major Axis (km)	-217.13%	-0.62%	0.04%	
	Eccentricity	766253.48%	1672.12%	-65.64%	
	Inclination (deg)	1903.60%	13.79%	0.31%	
	RAAN (deg)	94.51%	-12.01%	0.51%	
	Arg of Perigee (deg)	28.35%	-36.35%	-83.24%	
	True Anomaly (deg)	227.86%	89.69%	191.18%	
	Mean Anomaly (deg)	227.96%	89.94%	191.27%	

3. Simulation Results:

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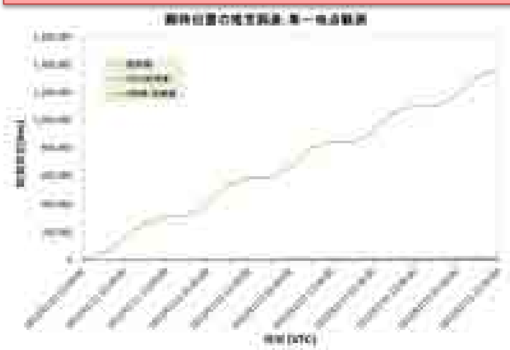
3.1. Observation from Single site with interval

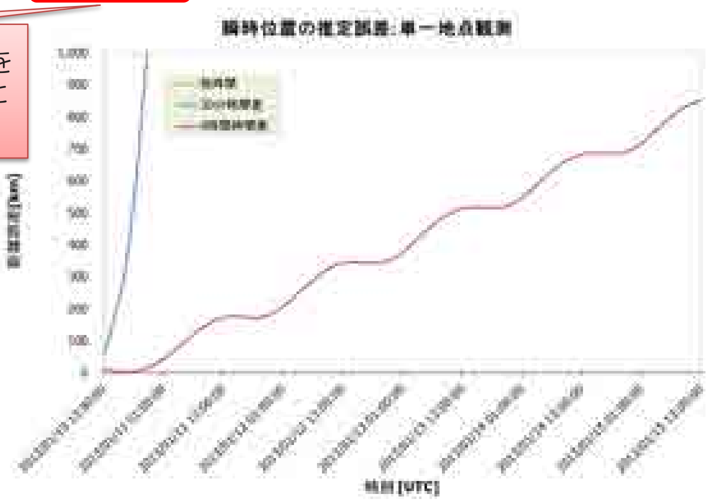
衛星／宇宙デブリの衝突リスク評価には、瞬時の軌道上物体位置を正確に推定することが必要

- Position errors at time (Epoch: 2013/01/10 13:00:00)

		瞬時位置誤差[km]				
		元期	観測終了時	観測終了時刻[UTC]	最小値	観測終了時刻[UTC]
短時間観測	富岡	19,377.747	19,130.584	2013/01/10 13:05:00	17,779.719	2013/01/10 14:00:45
30分 時間差観測	富岡	62.067	77.242	2013/01/10 13:35:00	62.067	2013/01/10 13:00:00
4時間 時間差観測	富岡	11.725	3.566	2013/01/10 17:05:00	3.101	2013/01/10 17:47:55

観測終了直後では、軌道上物体（衛星）位置を半径4km以内に推定できているが、時間経過とともに、真の物体位置と推定値の差は拡大。





3. Simulation Results:

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3.2. Two sites Observation

– Two sites observations with simultaneous or time interval

	IHI Tomioka (UTC)	Other (UTC)
Simultaneous	2013/01/10 13:00～13:05	2013/01/10 13:00～13:05
30 min interval	2013/01/10 13:00～13:05	2013/01/10 13:30～13:35
4 hour interval	2013/01/10 13:00～13:05	2013/01/10 17:00～17:05

3. Simulation Results:

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3.2. Two sites Observation

• Orbit determination (epoch: 2013/01/10 13:00:00)

		Short (1 cycle)	Simultaneous					TLE
		ITF	ITF-NAO	ITF-SAO	ITF-BSG	ITF-IAO	ITF-QRO	
Result	Semi-major Axis (km)	-49,389.168	43,233.631	42,692.849	43,310.970	42,046.325	42,108.172	42,167.785
	Eccentricity	2.212463	0.087270	0.043129	0.092687	0.014870	0.006915	0.000289
	Inclination (deg)	1.9475	0.6238	0.3578	0.6011	0.0342	0.1012	0.0972
	RAAN (deg)	103.7830	42.8970	44.8730	42.9340	77.5450	52.4080	53.3550
	Arg of Perigee (deg)	310.1164	76.7504	73.1702	76.7938	220.5947	245.0958	241.6128
	True Anomaly (deg)	344.4558	280.3736	281.9780	280.2926	101.8897	102.5252	105.0615
	Mean Anomaly (deg)	344.4558	290.0839	286.7789	290.6002	100.2185	101.7508	105.0296
Error	Semi-major Axis (km)	-91,556.952	1,065.846	525.065	1,143.185	-121.460	-59.613	
	Eccentricity	2.212174	0.086982	0.042840	0.092398	0.014582	0.006626	
	Inclination (deg)	1.850	0.527	0.261	0.504	-0.063	0.004	
	RAAN (deg)	50.428	-10.458	-8.482	-10.421	24.190	-0.947	
	Arg of Perigee (deg)	68.504	-164.862	-168.443	-164.819	-21.018	3.483	
	True Anomaly (deg)	239.394	175.312	176.917	175.231	-3.172	-2.536	
	Mean Anomaly (deg)	239.426	185.054	181.749	185.571	-4.811	-3.279	
Error(%)	Semi-major Axis (km)	-217.13%	2.53%	1.25%	2.71%	-0.29%	-0.14%	
	Eccentricity	766253.48%	30128.75%	14839.04%	32004.99%	5050.81%	2295.08%	
	Inclination (deg)	1903.60%	541.77%	268.11%	518.42%	-64.81%	4.12%	
	RAAN (deg)	94.51%	-19.60%	-15.90%	-19.53%	45.34%	-1.77%	
	Arg of Perigee (deg)	28.35%	-68.23%	-69.72%	-68.22%	-8.70%	1.44%	
	True Anomaly (deg)	227.86%	166.87%	168.39%	166.79%	-3.02%	-2.41%	
	Mean Anomaly (deg)	227.96%	176.19%	173.05%	176.68%	-4.58%	-3.12%	

3. Simulation Results:

IHI Realize your dreams

3.2. Two sites Observation

• Orbit determination (epoch: 2013/01/10 13:00:00)

		30m interval	30 min interval					TLE
		ITF	ITF-NAO	ITF-SAO	ITF-BSG	ITF-IAO	ITF-QRO	
Result	Semi-major Axis (km)	41,907.248	41,417.968	40,586.117	42,018.916	42,338.270	42,288.962	42,167.785
	Eccentricity	0.005116	0.014057	0.029110	0.002826	0.002954	0.004352	0.000289
	Inclination (deg)	0.1106	0.1545	0.1432	0.1007	0.1097	0.1401	0.0972
	RAAN (deg)	46.9480	39.2940	27.0040	49.7850	54.3490	51.0810	53.3550
	Arg of Perigee (deg)	153.7935	170.8230	190.5481	168.1641	347.3979	53.9015	241.6128
	True Anomaly (deg)	199.2957	189.9354	182.5282	182.0844	358.2764	295.0418	105.0615
	Mean Anomaly (deg)	199.4901	190.2163	182.6786	182.0962	358.2865	295.4930	105.0296
Error	Semi-major Axis (km)	-260.537	-749.817	-1,581.668	-148.869	170.485	121.177	
	Eccentricity	0.004827	0.013768	0.028821	0.002537	0.002665	0.004063	
	Inclination (deg)	0.013	0.057	0.046	0.004	0.013	0.043	
	RAAN (deg)	-6.407	-14.061	-26.351	-3.570	0.994	-2.274	
	Arg of Perigee (deg)	-87.819	-70.790	-51.065	-73.449	105.785	-187.711	
	True Anomaly (deg)	94.234	84.874	77.467	77.023	253.215	189.980	
	Mean Anomaly (deg)	94.461	85.187	77.649	77.067	253.257	190.463	
Error(%)	Semi-major Axis (km)	-0.62%	-1.78%	-3.75%	-0.35%	0.40%	0.29%	
	Eccentricity	1672.12%	4768.96%	9982.96%	878.73%	923.24%	1407.45%	
	Inclination (deg)	13.79%	58.95%	47.33%	3.60%	12.86%	44.14%	
	RAAN (deg)	-12.01%	-26.35%	-49.39%	-6.69%	1.86%	-4.26%	
	Arg of Perigee (deg)	-36.35%	-29.30%	-21.13%	-30.40%	43.78%	-77.69%	
	True Anomaly (deg)	89.69%	80.78%	73.73%	73.31%	241.02%	180.83%	
	Mean Anomaly (deg)	89.94%	81.11%	73.93%	73.38%	241.13%	181.34%	

3. Simulation Results:

IHI Realize your dreams

3.2. Two sites Observation

• Orbit determination (epoch: 2013/01/10 13:00:00)

		4h interval	4 hr interval					TLE
		ITF	ITF-NAO	ITF-SAO	ITF-BSG	ITF-IAO	ITF-QRO	
Result	Semi-major Axis (km)	42,185.046	42,334.080	42,106.381	42,106.605	42,290.343	42,284.773	42,167.785
	Eccentricity	0.000099	0.002865	0.001446	0.001445	0.002061	0.001925	0.000289
	Inclination (deg)	0.0975	0.0915	0.1012	0.1005	0.0953	0.1056	0.0972
	RAAN (deg)	53.6280	57.8650	51.9030	52.0030	56.1040	54.6590	53.3550
	Arg of Perigee (deg)	40.4848	4.8094	179.3346	178.5361	5.6788	9.6171	241.6128
	True Anomaly (deg)	305.9146	337.3481	168.7925	169.4903	338.2416	335.7479	105.0615
	Mean Anomaly (deg)	305.9238	337.4743	168.7603	169.4601	338.3291	335.8384	105.0296
Error	Semi-major Axis (km)	17.261	166.295	-61.404	-61.179	122.558	116.988	
	Eccentricity	-0.000190	0.002577	0.001157	0.001157	0.001772	0.001636	
	Inclination (deg)	0.000	-0.006	0.004	0.003	-0.002	0.008	
	RAAN (deg)	0.273	4.510	-1.452	-1.352	2.749	1.304	
	Arg of Perigee (deg)	-201.128	-236.803	-62.278	-63.077	-235.934	-231.996	
	True Anomaly (deg)	200.853	232.287	63.731	64.429	233.180	230.686	
	Mean Anomaly (deg)	200.894	232.445	63.731	64.431	233.300	230.809	
Error(%)	Semi-major Axis (km)	0.04%	0.39%	-0.15%	-0.15%	0.29%	0.28%	
	Eccentricity	-65.64%	892.48%	400.87%	400.66%	613.89%	566.68%	
	Inclination (deg)	0.31%	-5.86%	4.12%	3.40%	-1.95%	8.64%	
	RAAN (deg)	0.51%	8.45%	-2.72%	-2.53%	5.15%	2.44%	
	Arg of Perigee (deg)	-83.24%	-98.01%	-25.78%	-26.11%	-97.65%	-96.02%	
	True Anomaly (deg)	191.18%	221.10%	60.66%	61.32%	221.95%	219.57%	
	Mean Anomaly (deg)	191.27%	221.31%	60.68%	61.35%	222.13%	219.76%	

3. Simulation Results:

IHI
Realize your dreams

3.2. Two sites Observation

• Position errors at time (Epoch: 2013/01/10 13:00:00)

		瞬時位置誤差[km]				
		元期	観測終了時	観測終了時刻[UTC]	最小値	観測終了時刻[UTC]
短時間観測（１地点）	富岡	19,377.747	19,130.584	2013/01/10 13:05:00	17,779.719	2013/01/10 14:00:45
２地点同時観測	富岡-名寄	70.212	9.199	2013/01/10 13:05:00	1.178	2013/01/10 13:04:25
	富岡-仙台	64.971	25.792	2013/01/10 13:05:00	1.267	2013/01/10 13:08:17
	富岡-美星	68.954	15.221	2013/01/10 13:05:00	0.878	2013/01/10 13:04:06
	富岡-石垣	4.875	8.542	2013/01/10 13:05:00	0.873	2013/01/10 13:01:48
	富岡-豪州	1.653	4.546	2013/01/10 13:05:00	0.664	2013/01/10 13:01:16
30分 時間差観測（１地点）	富岡	62.067	77.242	2013/01/10 13:35:00	62.067	2013/01/10 13:00:00
２地点時間差(30m)観測	富岡-名寄	181.425	206.293	2013/01/10 13:35:00	181.425	2013/01/10 13:00:00
	富岡-仙台	408.326	433.496	2013/01/10 13:35:00	408.326	2013/01/10 13:00:00
	富岡-美星	33.734	37.526	2013/01/10 13:35:00	33.734	2013/01/10 13:00:00
	富岡-石垣	42.665	41.674	2013/01/10 13:35:00	41.629	2013/01/10 13:29:02
	富岡-豪州	39.764	13.600	2013/01/10 13:35:00	4.380	2013/01/10 13:52:17
4時間 時間差観測（１地点）	富岡	11.725	3.566	2013/01/10 17:05:00	3.101	2013/01/10 17:47:55
２地点時間差(4h)観測	富岡-名寄	51.540	61.502	2013/01/10 17:05:00	38.069	2013/01/10 14:48:10
	富岡-仙台	4.989	33.680	2013/01/10 17:05:00	4.989	2013/01/10 13:00:45
	富岡-美星	4.654	33.995	2013/01/10 17:05:00	4.654	2013/01/10 13:00:00
	富岡-石垣	38.716	44.948	2013/01/10 17:05:00	28.183	2013/01/10 14:51:34
	富岡-豪州	39.904	42.100	2013/01/10 17:05:00	28.123	2013/01/10 15:01:34

- IHI富岡-豪州での２地点同時観測では、軌道上物体（衛星）位置を半径4km以内に推定可能。
- 他のケースは、推定位置誤差は安定しない。

⇒ 時間経過とともに、位置誤差が拡大

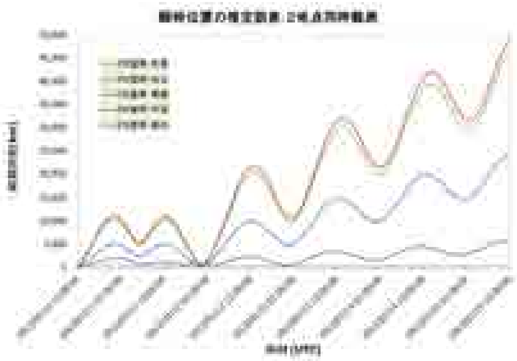
- ２地点観測により、瞬時位置の推定精度が向上するわけではない（時間差による誤差の影響の方が大きい）

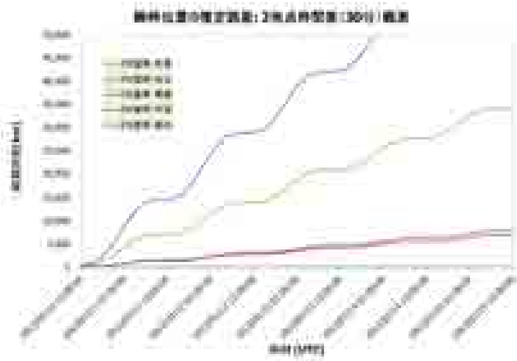
3. Simulation Results:

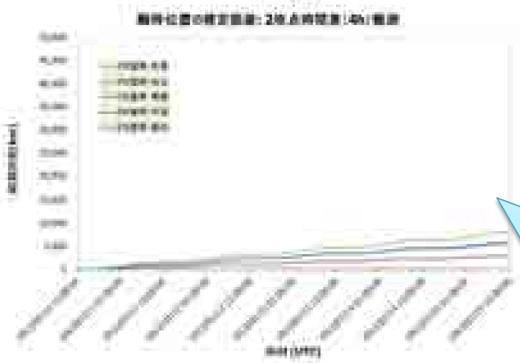
IHI
Realize your dreams

3.2. Two sites Observation

• Position errors at time (Epoch: 2013/01/10 13:00:00)







- 4時間差２地点観測では、
  - 瞬時の軌道上物体の位置は、他のケースが推定精度が良くなる場合があるが、
  - 時間差により軌道力学的考慮が加わるため、時間経過に伴う推定位置誤差の拡大を抑制可能。

3. Simulation Results:

IHI Realize your dreams

3.3. Three sites Observation

– Three sites observations with simultaneous or time interval

	IHI Tomioka (UTC)	IAO	QRO(UTC)
Simultaneous	2013/01/10 13:00～13:05	2013/01/10 13:00～13:05	2013/01/10 13:00～13:05
30 min interval	2013/01/10 13:00～13:05	2013/01/10 13:00～13:05	2013/01/10 13:30～13:35
4 hour interval	2013/01/10 13:00～13:05	2013/01/10 13:30～13:35	2013/01/10 17:00～17:05

3. Simulation Results:

IHI Realize your dreams

3.3. Three sites Observation

• Orbit determination (epoch: 2013/01/10 13:00:00)

		4h interval	Simul	30 min interval	4 hr interval	TLE
		ITF	ITF-IAO-QRO	ITF-IAO-QRO	ITF-IAO-QRO	
Result	Semi-major Axis (km)	42,185.046	42,131.900	42,183.516	42,202.023	42,167.785
	Eccentricity	0.000099	0.004273	0.001854	0.000502	0.000289
	Inclination (deg)	0.0975	0.0834	0.0930	0.0998	0.0972
	RAAN (deg)	53.6280	54.9110	53.7830	53.2120	53.3550
	Arg of Perigee (deg)	40.4848	242.2422	73.0761	336.1926	241.6128
	True Anomaly (deg)	305.9146	102.8756	273.1687	10.6228	105.0615
	Mean Anomaly (deg)	305.9238	102.3979	273.3808	10.6122	105.0296
Error	Semi-major Axis (km)	17.261	-35.885	15.731	34.238	
	Eccentricity	-0.000190	0.003984	0.001565	0.000214	
	Inclination (deg)	0.000	-0.014	-0.004	0.003	
	RAAN (deg)	0.273	1.556	0.428	-0.143	
	Arg of Perigee (deg)	-201.128	0.629	-168.537	94.580	
	True Anomaly (deg)	200.853	-2.186	168.107	-94.439	
	Mean Anomaly (deg)	200.894	-2.632	168.351	-94.417	
Error(%)	Semi-major Axis (km)	0.04%	-0.09%	0.04%	0.08%	
	Eccentricity	-65.64%	1380.08%	→ 542.15%	→ 73.99%	
	Inclination (deg)	0.31%	-14.20%	-4.32%	2.67%	
	RAAN (deg)	0.51%	2.92%	0.80%	-0.27%	
	Arg of Perigee (deg)	-83.24%	0.26%	-69.75%	39.15%	
	True Anomaly (deg)	191.18%	-2.08%	160.01%	-89.89%	
	Mean Anomaly (deg)	191.27%	-2.51%	160.29%	-89.90%	

3. Simulation Results:

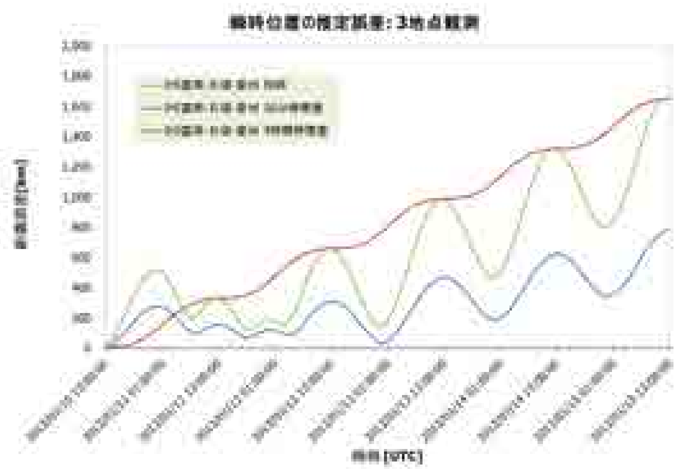
IHI
Realize your dreams

3.3. Three sites Observation

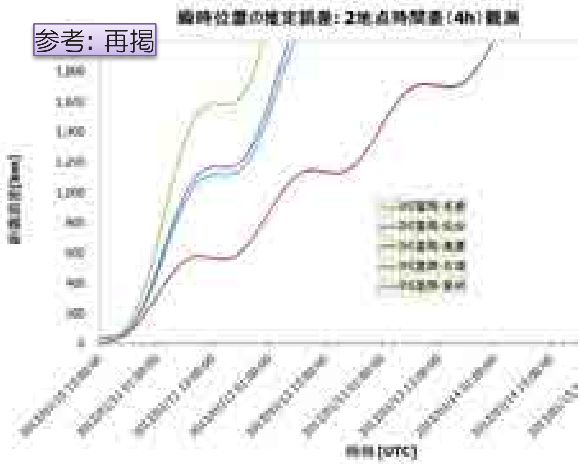
• Position errors at time (Epoch: 2013/01/10 13:00:00)

		瞬時位置誤差[km]				
		元期	観測終了時	観測終了時刻[UTC]	最小値	観測終了時刻[UTC]
3地点同時観測	富岡-石垣-豪州	0.951	4.075	2013/01/10 13:05:00	0.951	2013/01/10 13:00:00
	富岡-石垣-豪州	8.178	5.513	2013/01/10 13:35:00	1.068	2013/01/10 13:21:00
	富岡-石垣-豪州	10.327	21.039	2013/01/10 17:35:00	9.165	2013/01/10 14:09:27

- 3地点観測により瞬時位置の推定精度は向上する。
- 時間経過に伴う推定位置誤差の拡大も抑制（２地点観測と比較して）



参考：再掲



3. Simulation Results: (Summary: cases of QRO)

IHI
Realize your dreams

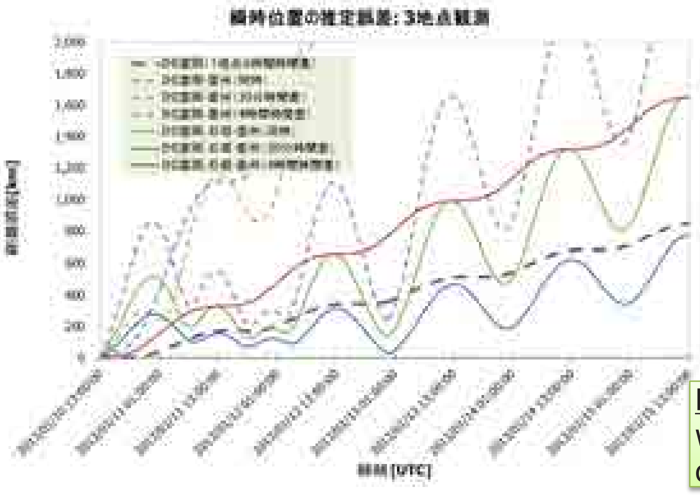
			Two-sites			Three-sites			
		4h interval	Simul	30min interval	4h interval	Simul	30 min interval	4 hr interval	TLE
		ITF	ITF-QRO	ITF-QRO	ITF-QRO	ITF-IAO-QRO	ITF-IAO-QRO	ITF-IAO-QRO	
Result	Semi-major Axis (km)	42,185.046	42,108.172	42,288.962	42,284.773	42,131.900	42,183.516	42,202.023	42,167.785
	Eccentricity	0.000099	0.006915	0.004352	0.001925	0.004273	0.001854	0.000502	0.000289
	Inclination (deg)	0.0975	0.1012	0.1401	0.1056	0.0834	0.0930	0.0998	0.0972
	RAAN (deg)	53.6280	52.4080	51.0810	54.6590	54.9110	53.7830	53.2120	53.3550
	Arg of Perigee (deg)	40.4848	245.0958	53.9015	9.6171	242.2422	73.0761	336.1926	241.6128
	True Anomaly (deg)	305.9146	102.5252	295.0418	335.7479	102.8756	273.1687	10.6228	105.0615
	Mean Anomaly (deg)	305.9238	101.7508	295.4930	335.8384	102.3979	273.3808	10.6122	105.0296
Error	Semi-major Axis (km)	17.261	-59.613	121.177	116.988	-35.885	15.731	34.238	
	Eccentricity	-0.000190	0.006626	0.004063	0.001636	0.003984	0.001565	0.000214	
	Inclination (deg)	0.000	0.004	0.043	0.008	-0.014	-0.004	0.003	
	RAAN (deg)	0.273	-0.947	-2.274	1.304	1.556	0.428	-0.143	
	Arg of Perigee (deg)	-201.128	3.483	-187.711	-231.996	0.629	-168.537	94.580	
	True Anomaly (deg)	200.853	-2.536	189.980	230.686	-2.186	168.107	-94.439	
	Mean Anomaly (deg)	200.894	-3.279	190.463	230.809	-2.632	168.351	-94.417	
Error(%)	Semi-major Axis (km)	0.04%	-0.14%	0.29%	0.28%	-0.09%	0.04%	0.08%	
	Eccentricity	-65.64%	2295.08%	1407.45%	566.68%	1380.08%	542.15%	73.99%	
	Inclination (deg)	0.31%	4.12%	44.14%	8.64%	-14.20%	-4.32%	2.67%	
	RAAN (deg)	0.51%	-1.77%	-4.26%	2.44%	2.92%	0.80%	-0.27%	
	Arg of Perigee (deg)	-83.24%	1.44%	-77.69%	-96.02%	0.26%	-69.75%	39.15%	
	True Anomaly (deg)	191.18%	-2.41%	180.83%	219.57%	-2.08%	160.01%	-89.89%	
	Mean Anomaly (deg)	191.27%	-3.12%	181.34%	219.76%	-2.51%	160.29%	-89.90%	

3. Simulation Results: (Summary: cases of QRO)

IHI Realize your dreams

- Position errors at time (Epoch: 2013/01/10 13:00:00)

			瞬時位置誤差[km]				
			元期	観測終了時	観測終了時刻[UTC]	最小値	観測終了時刻[UTC]
時間差観測(4h後)	富岡	n04_itf_04	11.725	3.566	2013/01/10 17:05:00	3.101	2013/01/10 17:47:55
２地点同時観測	富岡-豪州	n10_qro_00	1.653	4.546	2013/01/10 13:05:00	0.664	2013/01/10 13:01:16
２地点時間差(30m)観測	富岡-豪州	n15_qro_hf	39.764	13.600	2013/01/10 13:35:00	4.380	2013/01/10 13:52:17
２地点時間差(4h)観測	富岡-豪州	n20_qro_04	39.904	42.100	2013/01/10 17:05:00	28.123	2013/01/10 15:01:34
３地点同時観測	富岡-石垣-豪州	n21_iao_qro_00	0.951	4.075	2013/01/10 13:05:00	0.951	2013/01/10 13:00:00
	富岡-石垣-豪州	n22_iao_00_qro_hf	8.178	5.513	2013/01/10 13:35:00	1.068	2013/01/10 13:21:00
	富岡-石垣-豪州	n23_iao_hf_qro_04	10.327	21.039	2013/01/10 17:35:00	9.165	2013/01/10 14:09:27



=Conclusion=
- (Multi-sites)Simultaneous observation give good estimation of positions
- Long interval of observation cycle improve eccentricity

Proposed observation strategy:
- Good position estimation
  ⇒ (Multi-sites) simul. observation
- Improvement of eccentricity/orbit shape estimation
  ⇒ Observation with Long interval

Expectation of fine orbit determination with two-sites simultaneous & time interval observation using minimal facility and time.

3. Simulation Results:

IHI Realize your dreams

3.4. Two sites Simultaneous and time interval observation

– 4hr time interval is assumed

	IHI Tomika (UTC)	Australia (UTC)
Case 1: Time interval observation conducted at one site	2013/01/10 13:00～13:05 2013/01/10 17:00～17:05	2013/01/10 13:00～13:05
Case 2: Both site conduct time interval observation	2013/01/10 13:00～13:05 2013/01/10 17:00～17:05	2013/01/10 13:00～13:05 2013/01/10 17:00～17:05

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3. Simulation Results:

IHI Realize your dreams

3.4. Two sites Simultaneous and time interval observation

- Orbit determination (epoch: 2013/01/10 13:00:00)

		4h interval	Case 1:Simul. +4 hr int	Case 2:Simul. +4 hr int	TLE
		ITF	ITF-QRO	ITF-QRO	
Result	Semi-major Axis (km)	42,185.046	42,167.248	42,162.962	42,167.785
	Eccentricity	0.000099	0.000307	0.000350	0.000289
	Inclination (deg)	0.0975	0.0966	0.0970	0.0972
	RAAN (deg)	53.6280	52.9620	52.9180	53.3550
	Arg of Perigee (deg)	40.4848	233.3355	217.2941	241.6128
	True Anomaly (deg)	305.9146	113.7308	129.8164	105.0615
	Mean Anomaly (deg)	305.9238	113.6986	129.7857	105.0296
Error	Semi-major Axis (km)	17.261	-0.537	-4.823	
	Eccentricity	-0.000190	0.000018	0.000061	
	Inclination (deg)	0.000	-0.001	-0.000	
	RAAN (deg)	0.273	-0.393	-0.437	
	Arg of Perigee (deg)	-201.128	-8.277	-24.319	
	True Anomaly (deg)	200.853	8.669	24.755	
	Mean Anomaly (deg)	200.894	8.669	24.756	
Error(%)	Semi-major Axis (km)	0.04%	0.00%	-0.01%	
	Eccentricity	-65.64%	6.30%	21.16%	
	Inclination (deg)	0.31%	-0.62%	-0.21%	
	RAAN (deg)	0.51%	-0.74%	-0.82%	
	Arg of Perigee (deg)	-83.24%	-3.43%	-10.07%	
	True Anomaly (deg)	191.18%	8.25%	23.56%	
	Mean Anomaly (deg)	191.27%	8.25%	23.57%	

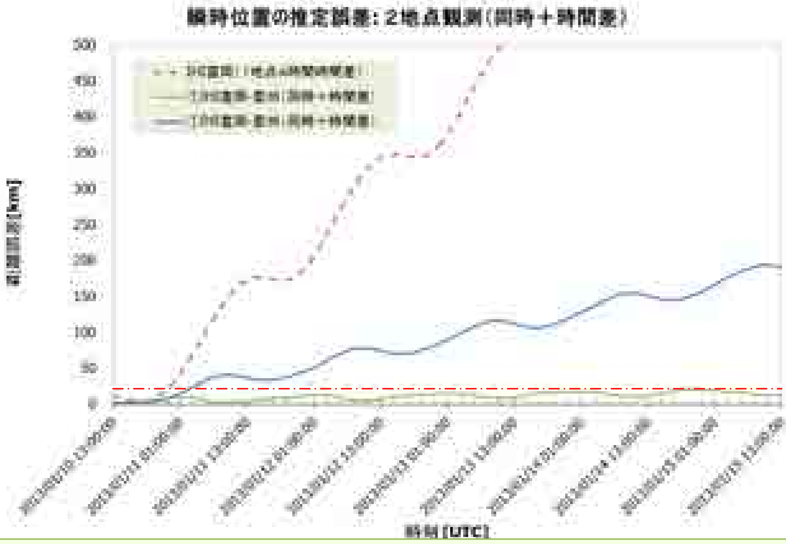
3. Simulation Results:

IHI Realize your dreams

3.4. Two sites Simultaneous and time interval observation

- Position errors at time (Epoch: 2013/01/10 13:00:00)

			瞬時位置誤差[km]				
			元期	観測終了時	観測終了時刻[UTC]	最小値	観測終了時刻[UTC]
時間差観測(4h後)	富岡	IHI富岡（１地点４時間時間差）	11.725	3.566	2013/01/10 17:05:00	3.101	2013/01/10 17:47:55
２地点観測(同時＋4h後単独)	富岡-豪州	①IHI富岡-豪州（同時＋時間差）	1.716	3.192	2013/01/10 17:05:00	1.716	2013/01/10 13:00:00
２地点観測(同時＋4h後同時)	富岡-豪州	①IHI富岡-豪州（同時＋時間差）	1.662	3.207	2013/01/10 17:05:00	1.662	2013/01/10 13:00:00



"Two sites Simultaneous and time interval observation" can provide fine orbit determination within short period of observation.

4. Conclusion

IHI Realize your dreams

- Effectiveness of multi-site observation is evaluated using virtual observation data generated by orbit simulation considering influence of observation errors /resolutions
- Multi(two or three) sites observation with time interval may not improve accuracy of estimated orbit due to error associated with different observation time (errors due to orbit propagation)
  - ➢Depend on observation error and time interval (propagation error)
- Multi-site simultaneous observation improve position estimation of on-orbit object.
- Propose observation strategy and scenario for orbital object in GEO region using minimal asset and short period of observation
  - ➢At **two sites** far from each other(ex. IHI tomioka-Australia), (1) simultaneous observation(5 min), after that, (2) re-observation with appropriate time interval(5 min after 4 hr interval) provide fine orbital determination.

◆ Only one scenario was evaluated in this study. It is necessary to evaluate this proposed observation strategy with some other cases.

F7

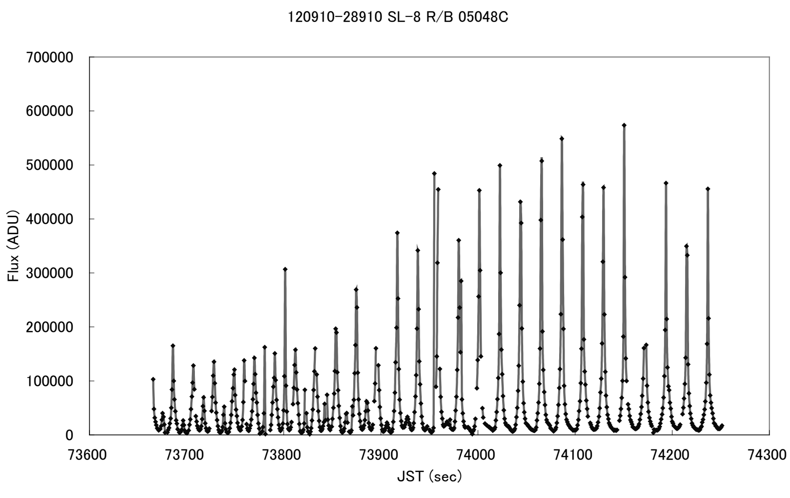
低軌道デブリのライトカーブ観測

Light curve observations of LEO debris

○黒崎裕久，柳沢俊史（宇宙航空研究開発機構）
○Hirohisa Kurosaki and Toshifumi Yanagisawa (JAXA)

多くの宇宙物体（人工衛星、ロケット、デブリなど）が地球を回っている。これらの軌道は光学観測やレーダー観測によって常時観測されているが、物体の姿勢状態はあまり知られていない。光学観測による光度変化を見ると、スピン衛星や異なる反射面を持つ物体が回転している場合には、周期的な明るさの変化がみられる。
将来のデブリ除去では対象の回転状態によって捕獲方法を検討する必要がある。
我々はとくに SL-8 R/B の光度変化を調べている。これはロシアの COSMOS-3M ロケットの 2 段目である。ロケットボディは軌道上では安定しているという1説もあるが、観測すると光度変化しているロケットボディもいくつかある。ここでは低軌道の SL-8 R/B の光度変化の観測結果について報告する。

Many space objects (space satellite, rocket, and debris, etc.) are orbiting the earth. As for these, the orbit is always observed by the optical observation and the radar observation. However, the state of attitude of the object is not known so much. As for the change in brightness, when the object on a spinning satellite and a different reflection side rotates, the periodic change is seen. In the debris removal in the future, it is necessary to examine the capture method according to the rotating state of the object.
We are especially examining the change in the brightness of SL-8 R/B. This is the second stage of the COSMOS-3M rocket of Russia.
In one theory, it is said that the rocket body is steady on the orbit. However, there are some things that brightness has changed if the rocket body is observed. It reports on the observational result of the change in the brightness of the SL-8 R/B in the low earth orbit.



Light curve of LEO debris (SL-8 R/B)

低軌道デブリのライトカーブ観測
Light curve observations of LEO debris

○黒崎裕久, 柳沢俊史
（宇宙航空研究開発機構）
○Hirohisa Kurosaki and Toshifumi Yanagisawa
(JAXA)

Introduction

Many space objects (space satellite, rocket, and debris, etc.) are orbiting the earth. As for these, the orbit is always observed by the optical observation and the radar observation.
However, the state of attitude of the object is not known so much.
As for the change in brightness, when the object on a spinning satellite and a different reflection side rotates, the periodic change is seen.
In the debris removal in the future, it is necessary to examine the capture method according to the rotating state of the object.

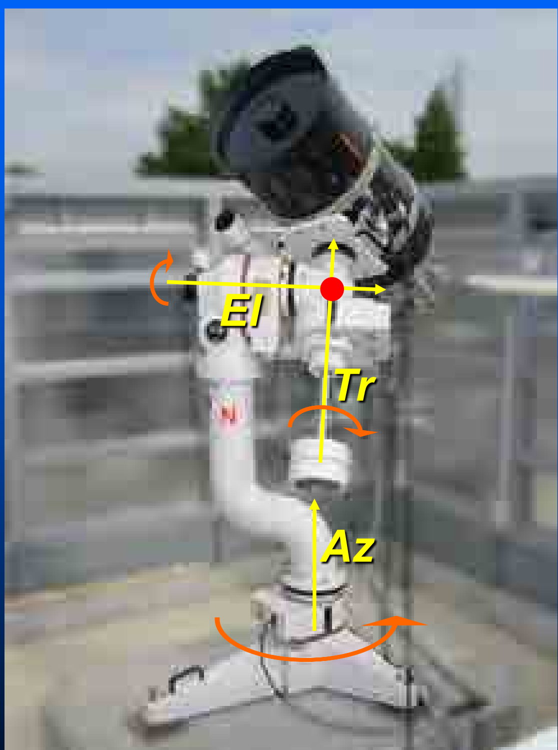
It reports on the observational result of the change in the brightness of the SL-8 R/B in the low earth orbit.

Optical observation system

Observation Site
JAXA, Aerospace Research Center
Chofu, Tokyo
Lat. 35°40′42″
Long. 139°33′24″
Alt. 55m

(35cm low earth orbit satellite tracking system)

Tri-Axial alt-azimuth Mount



3 axes
- Azimuth (Az)
- Elevation (El)
- Tracking (Tr)

are controlled independently.

This alt-azimuth mount
No singular point on the celestial sphere, and can track any space debris even passing through the zenith.

For tracking a target, the Tr axis is used mainly that enables a stable tracking.
The hand controller can adjust the angular speed of El and Tr axes.

Telescope & CCD Camera

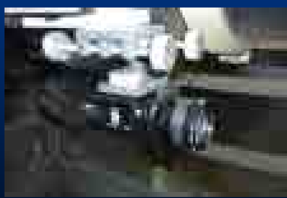
Schmidt Cassegrain SC355L

Diameter	355mm
Focal Length	3910mm F11
	(2400mm (F7) with reducer)

BITRAN

Pixel Number	1.4M (1360x1024)
Pixel size	□6.45μm
CCD size	8.8×6.6mm
A/D	16bit
Trans time	0.7sec
Cooling	Perche

Guide Telescope



Guide Camera

This mount operates by a special system software.

The azimuth and the elevation at visible time are calculated from TLE of the object.
This calculation makes the timetable every ten seconds.

⇩

Next, an azimuth and elevation value is converted into the value of the mount of three axes (azimuth, elevation, and tracking).
Neither the azimuth nor the elevation of the mount are the azimuths and the elevations of the object.
The calculation of this conversion makes the timetable every 0.5 seconds.

⇩ Object (Azimuth, Elevation) → Mount (azimuth-axis, elevation-axis, tracking-axis)

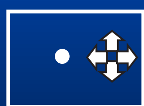
The mount moves to the position of the start time and it stands by.

⇩

The tracking starts at the start time.

The tracking axis smoothly moves to passing the object, and the azimuth axis and the elevation axis move slightly for the correction.

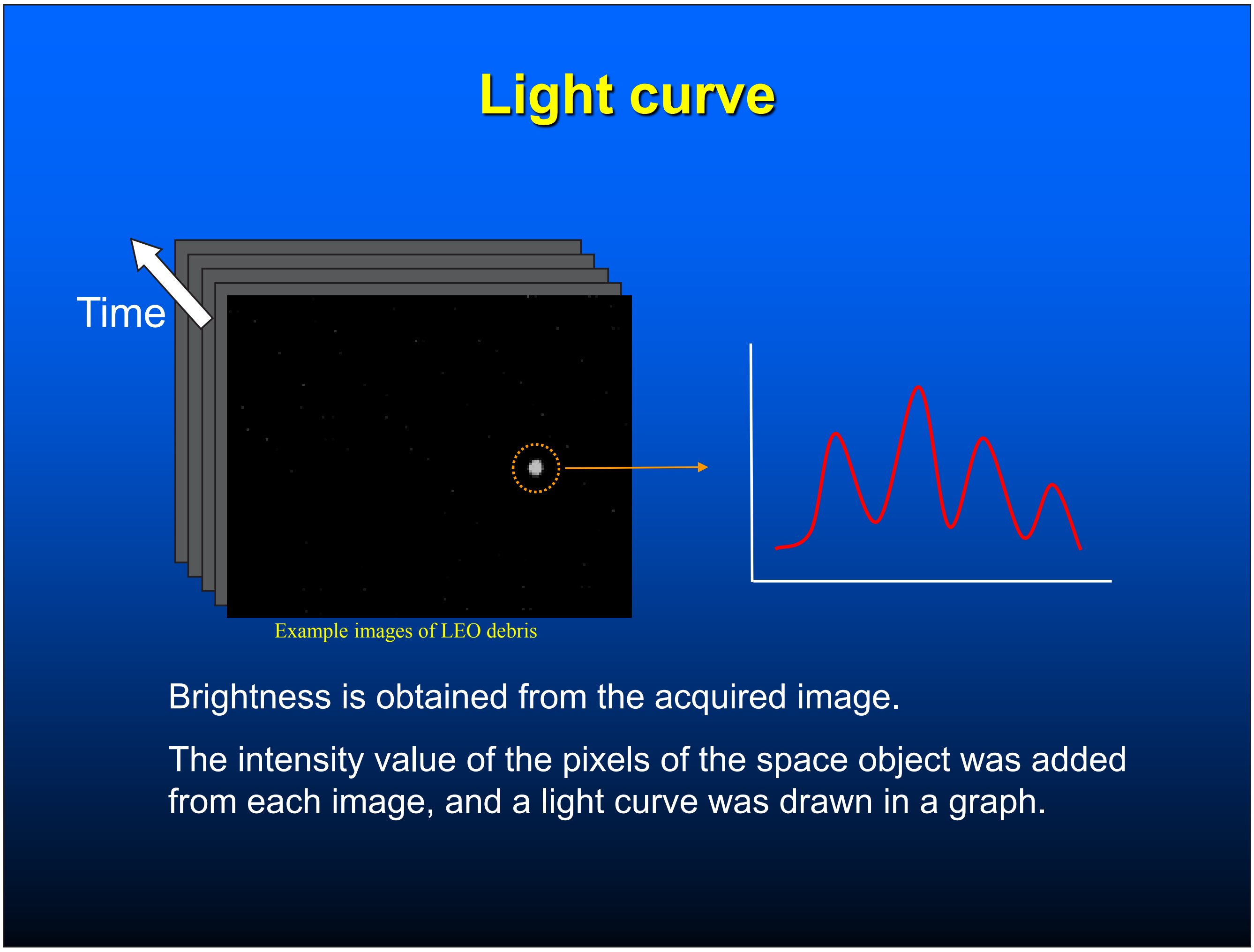
The gap is caused by the accuracy of TLE in the tracking passing.

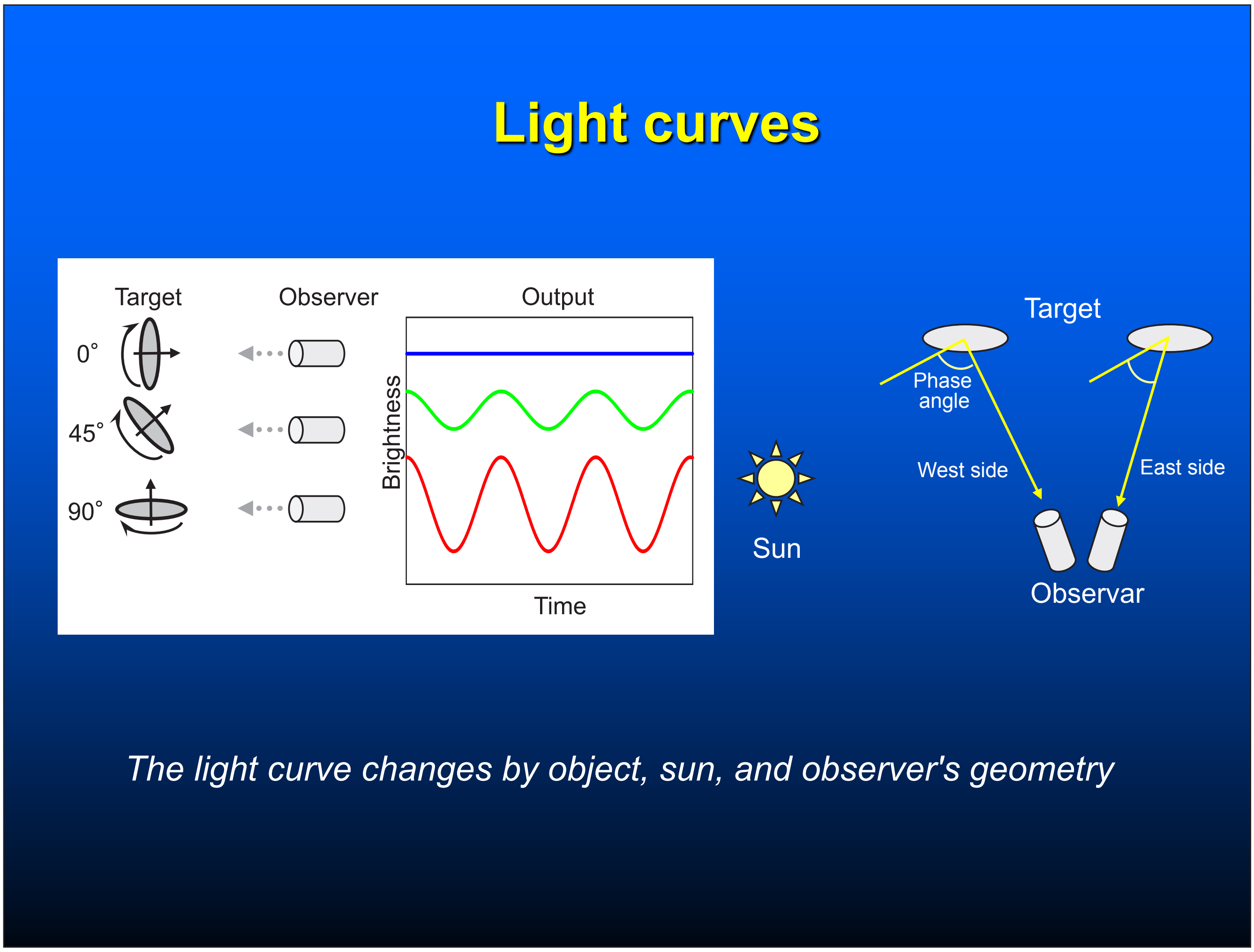


⇩ Hand Operation

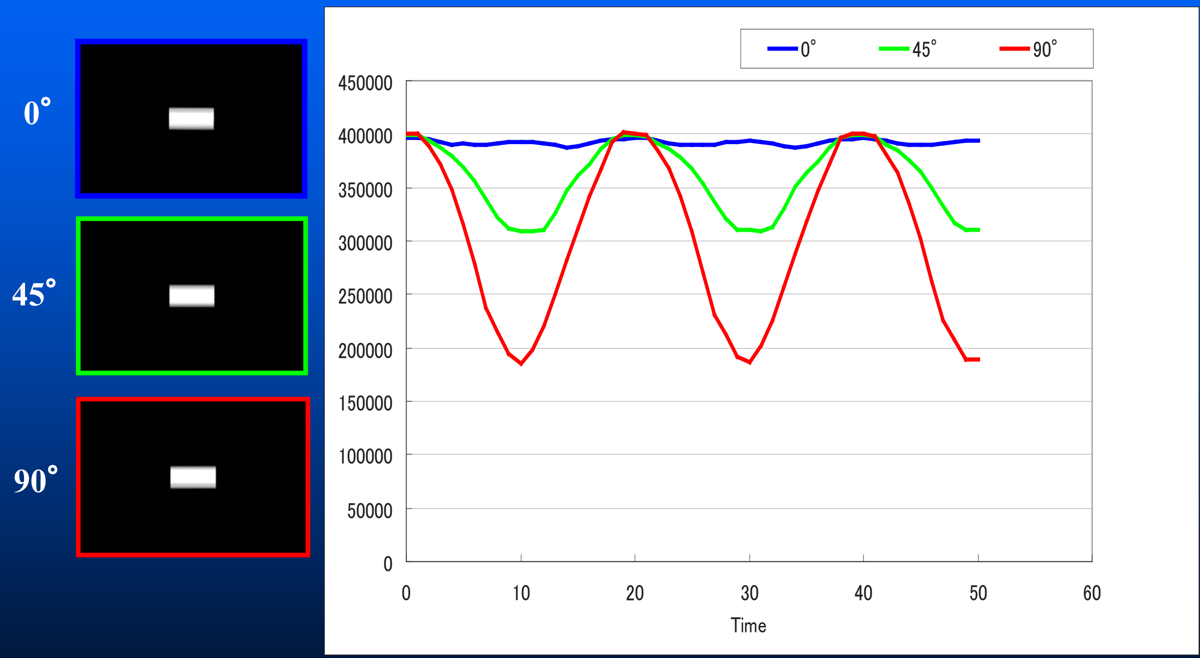
The guide telescope applied to the telescope is monitored, and the object is kept at the center of the monitor by the hand controller.
The hand set can adjust the position in a tracking axis and a elevation axis.
In addition, each acceleration of two axes can be adjusted.
(In this part, there is a studying experience of the auto adjustment by the image recognition, too.)

The drive of the mount stops at the tracking end time.


Light curve
Time
Example images of LEO debris
Brightness is obtained from the acquired image.
The intensity value of the pixels of the space object was added from each image, and a light curve was drawn in a graph.

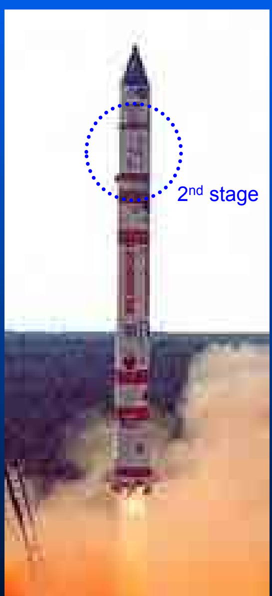

Light curves
Target
Observer
Output
0°
45°
90°
Brightness
Time
Sun
Target
Phase angle
West side
East side
Observar
The light curve changes by object, sun, and observer's geometry

Light curve simulation of circular cylinder



Targets of Observation

✧ SL-8 R/B

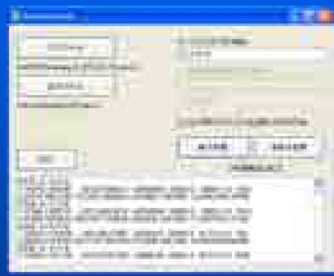


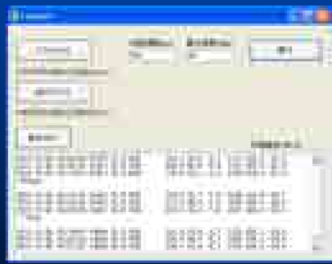
2nd stage of Cosmos-3M rocket of Russia

Shape	Cylindrical	Diameter	2.4 m
		Length	6.4 m
		Dry Weight	8.9 ton

Decision of object of observation

The object is decided with orbit calculation software (Orbitron).





Extraction of object from TLE catalog
Good visible condition is extracted
Original application (made by oneself)

Observed Object (SL-8 R/B)

120822	18986	SL-8 R/B	88023B	1
120827	10121	SL-8 R/B	77059B	1
	16012	SL-8 R/B	85079B	1
	11681	SL-8 R/B	80007B	1
	10521	SL-8 R/B	77119B	1
120828	18986	SL-8 R/B	88023B	2
	16012	SL-8 R/B	85079B	2
	15293	SL-8 R/B	84100B	1
	10521	SL-8 R/B	77119B	2
	20805	SL-8 R/B	90083B	1
120829	10521	SL-8 R/B	77119B	3
	12092	SL-8 R/B	80099B	1
	06708	SL-8 R/B	73042B	1
	21015	SL-8 R/B	90111B	1
	08344	SL-8 R/B	75094B	1
	17160	SL-8 R/B	86093B	1
120905	09638	SL-8 R/B	76128B	1
	08597	SL-8 R/B	76005B	1
	10732	SL-8 R/B	78028B	1
	12443	SL-8 R/B	81041B	1
	09044	SL-8 R/B	76070B	1
120910	18586	SL-8 R/B	87098B	1
	20805	SL-8 R/B	90083B	2
	10677	SL-8 R/B	78019B	1
	27437	SL-8 R/B	02026B	1
	22676	SL-8 R/B	93036B	1
	28910	SL-8 R/B	05048C	1

121001	12836	SL-8 R/B	81091B	1
	14966	SL-8 R/B	84043B	1
	10992	SL-8 R/B	78074B	1
	11870	SL-8 R/B	80056B	1
	18403	SL-8 R/B	87087B	1
	19257	SL-8 R/B	88053B	1
	25592	SL-8 R/B	98076B	1
	21231	SL-8 R/B	91029B	1
121009	24955	SL-8 R/B	97052C	1
	13649	SL-8 R/B	82109B	1
	11427	SL-8 R/B	79060B	1
	15598	SL-8 R/B	85022B	1
	13028	SL-8 R/B	82001B	1
121022	23093	SL-8 R/B	94024B	1
	20046	SL-8 R/B	89042B	1
	13618	SL-8 R/B	82102B	1
	13950	SL-8 R/B	83023B	1
121025	11170	SL-8 R/B	78122B	1
	20509	SL-8 R/B	90017B	1
	12508	SL-8 R/B	81053B	1
121029	20046	SL-8 R/B	89042B	2
	26819	SL-8 R/B	01023B	1
	18945	SL-8 R/B	88016J	1
	06207	SL-8 R/B	72074B	1
	13618	SL-8 R/B	82102B	2
	23432	SL-8 R/B	94083B	1
	07426	SL-8 R/B	74069B	1

121031	06320	SL-8 R/B	72102B	1
121101	13618	SL-8 R/B	82102B	3
	13950	SL-8 R/B	83023B	2
	10918	SL-8 R/B	78053B	1
	19827	SL-8 R/B	89017B	1
121107	25723	SL-8 R/B	99022C	1
	18586	SL-8 R/B	87098B	2
121115	05685	SL-8 R/B	71111B	1
	20104	SL-8 R/B	89050B	1
	10492	SL-8 R/B	77109B	1
121120	17067	SL-8 R/B	86086B	1
	11546	SL-8 R/B	79084J	1
	22308	SL-8 R/B	93001B	1
	11751	SL-8 R/B	80026B	1

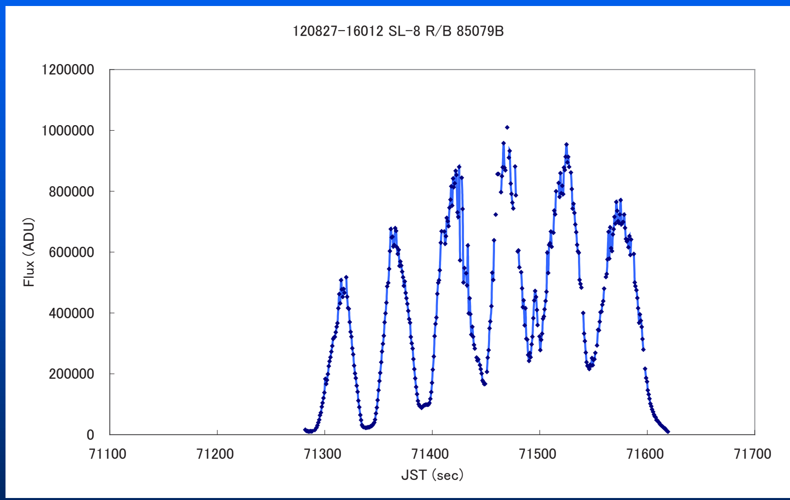
SL-8

～2012.11.20

58／295(TLE Catalog)

SL-8 R/B 85079B

120827-16012

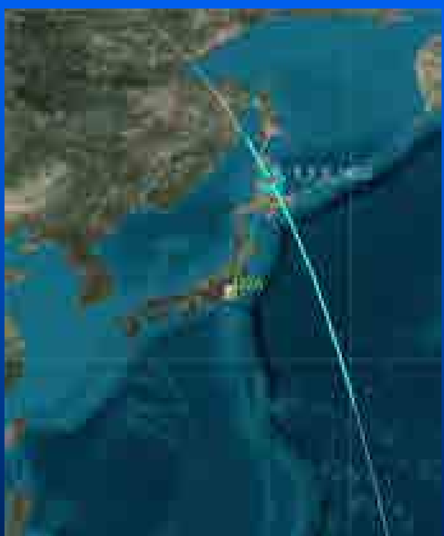


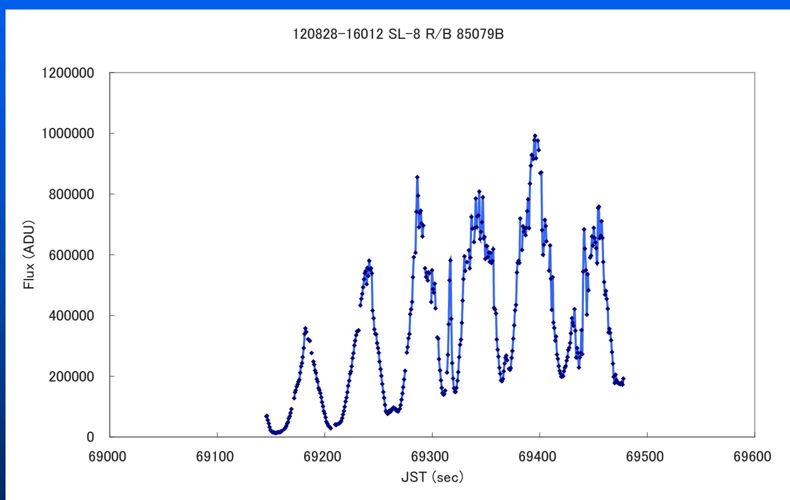
DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-08-27	10:46:12	16012	SL-8 R/B	347.2	20.0	6.5	1718	297.1	-18.0
2012-08-27	10:49:53	16012	SL-8 R/B	72.5	78.7	4.7	784	297.7	-18.7
2012-08-27	10:52:40	16012	SL-8 R/B	155.7	28.4	5.8*	1397	298.2	-19.2

388sec

SL-8 R/B 85079B

120828-16012



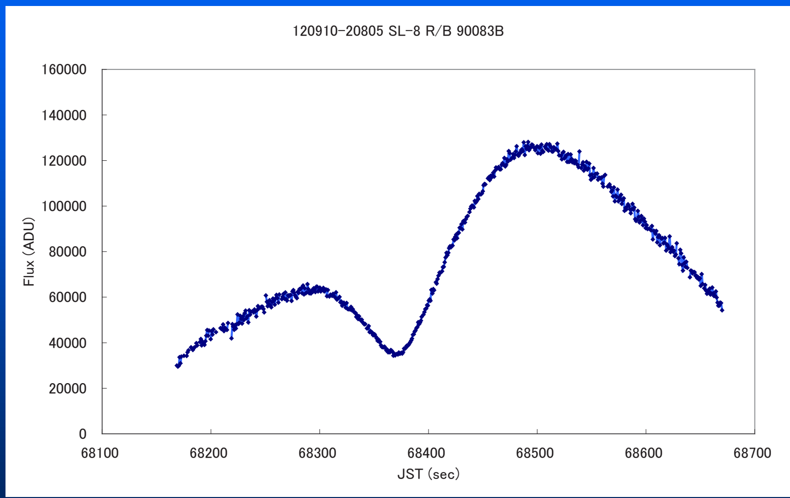


DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-08-28	10:10:56	16012	SL-8 R/B	4.4	20.0	6.5	1717	290.9	-11.8
2012-08-28	10:14:15	16012	SL-8 R/B	68.5	45.1	5.3	1035	291.5	-12.4
2012-08-28	10:17:34	16012	SL-8 R/B	132.7	20.0	6.3	1714	292.0	-13.0

398sec

SL-8 R/B 90083B

120910-20805

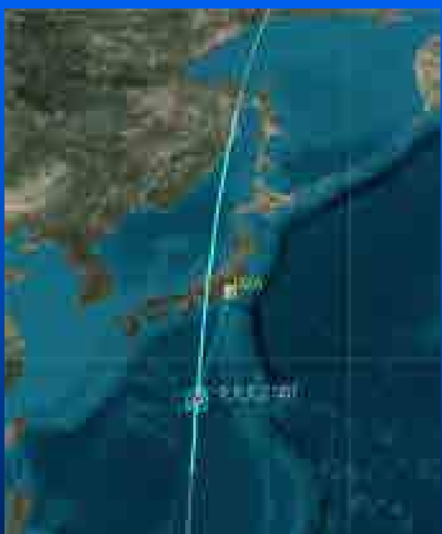


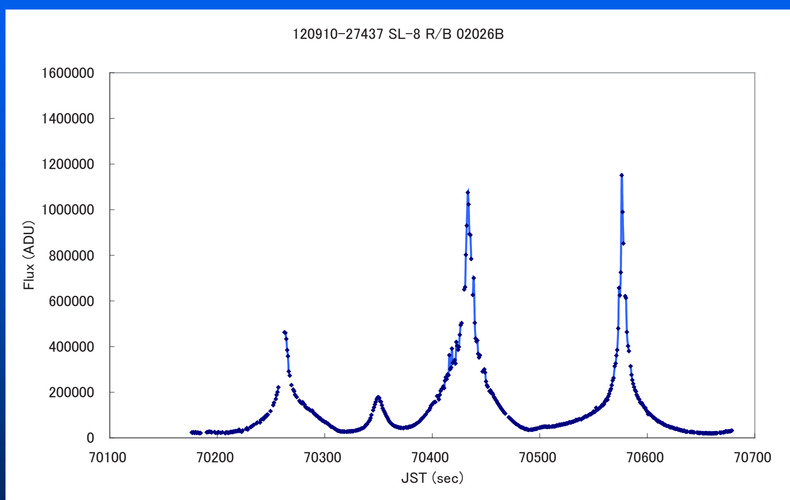
DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-09-10	09:55:38	20805	SL-8 R/B	189.1	20.1	6.9	2124	285.4	-12.7
2012-09-10	10:00:15	20805	SL-8 R/B	276.4	82.5	5.3	1013	286.1	-13.6
2012-09-10	10:04:53	20805	SL-8 R/B	3.1	20.1	7.0	2132	286.8	-14.5

555sec

SL-8 R/B 02026B

120910-27437



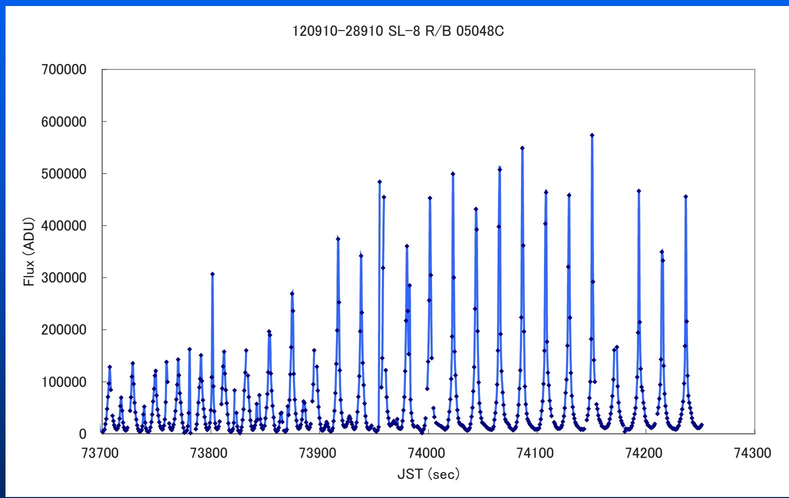


DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-09-10	10:29:11	27437	SL-8 R/B	191.6	20.1	6.8	2138	290.8	-19.1
2012-09-10	10:33:49	27437	SL-8 R/B	275.7	78.3	5.3	1032	291.6	-20.0
2012-09-10	10:38:29	27437	SL-8 R/B	1.5	20.0	6.9	2146	292.5	-20.9

558sec

SL-8 R/B 05048C

120910-28910

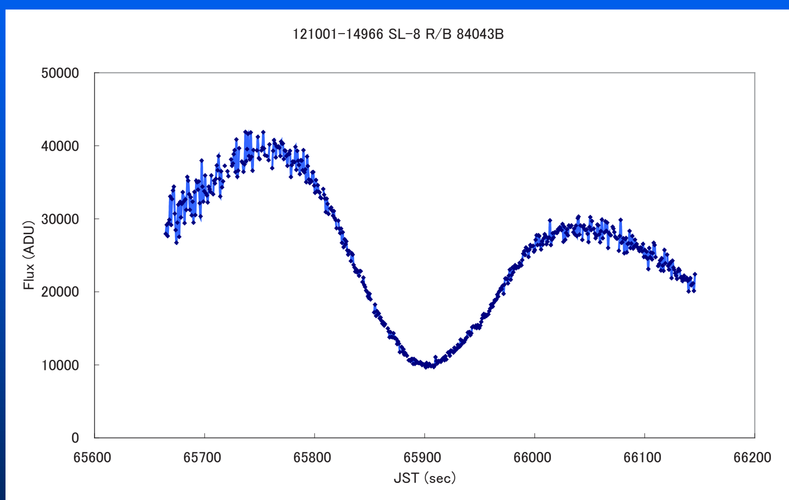


DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-09-10	11:26:41	28910	SL-8 R/B	222.0	20.0	?	2861	301.6	-29.6
2012-09-10	11:32:20	28910	SL-8 R/B	283.5	43.9	?	1921	302.8	-30.6
2012-09-10	11:37:59	28910	SL-8 R/B	344.9	20.0	?	2861	304.0	-31.6

678sec

SL-8 R/B 84043B

121001-14966

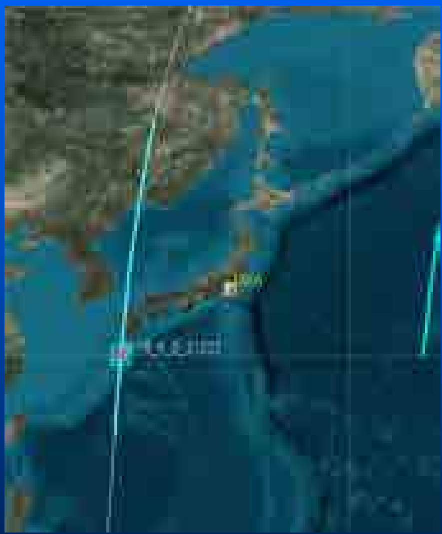


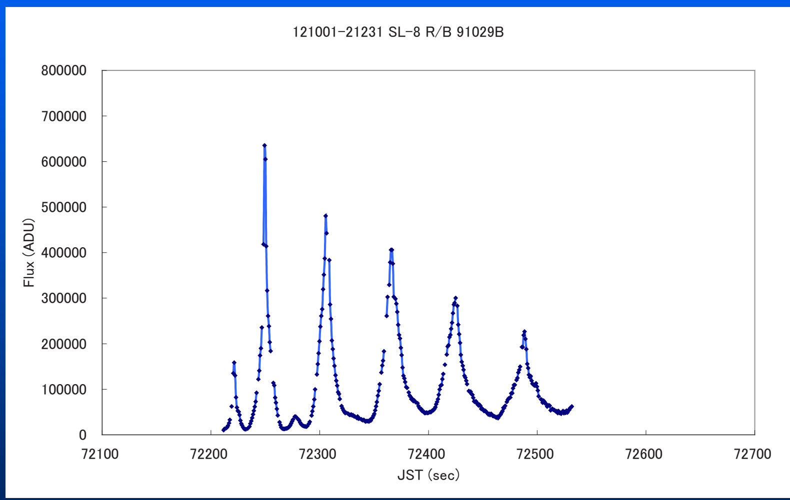
DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-10-01	09:13:41	14966	SL-8 R/B	201.1	20.0	7.0	2116	273.4	-10.6
2012-10-01	09:18:10	14966	SL-8 R/B	278.3	63.7	5.6	1095	274.1	-11.5
2012-10-01	09:22:39	14966	SL-8 R/B	355.2	20.0	7.0	2120	274.8	-12.4

538sec

SL-8 R/B 91029B

121001-21231



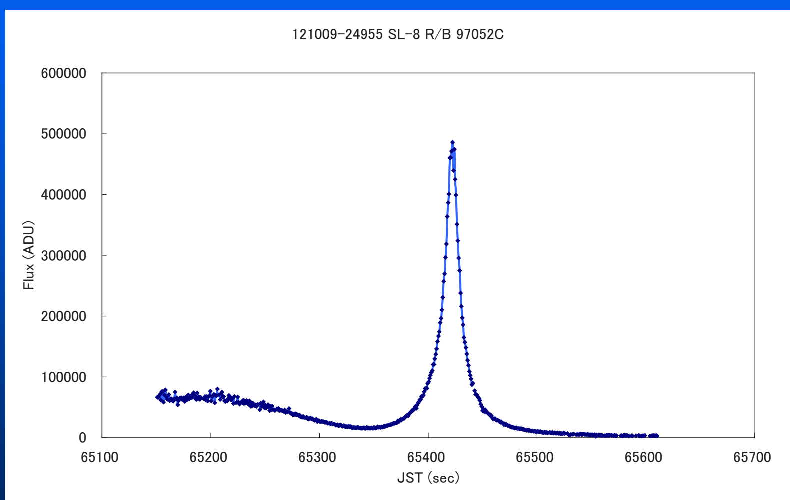


DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-10-01	11:01:02	21231	SL-8 R/B	217.6	20.0	6.7	2052	291.1	-31.9
2012-10-01	11:04:59	21231	SL-8 R/B	280.8	44.7	5.7	1290	291.8	-32.6
2012-10-01	11:08:59	21231	SL-8 R/B	344.1	20.0	6.7	2074	292.6	-33.4

477sec

SL-8 R/B 97052C

121009-24955

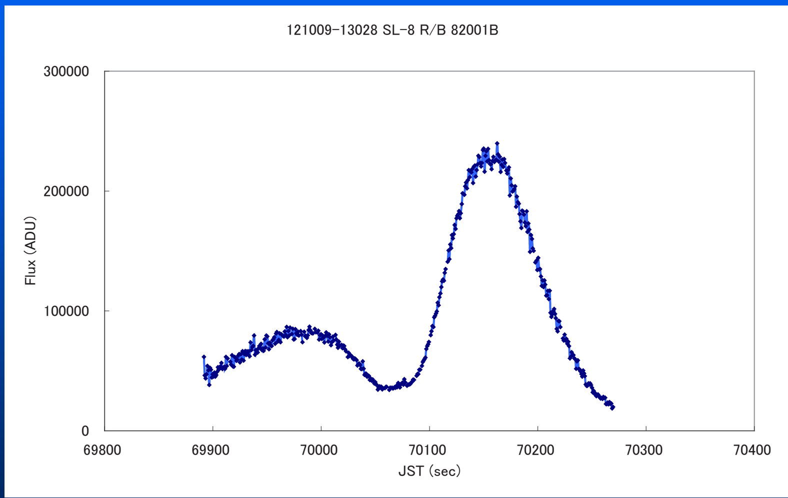


DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-10-09	09:04:30	24955	SL-8 R/B	347.6	20.0	7.0	2097	269.9	-11.0
2012-10-09	09:09:00	24955	SL-8 R/B	266.3	73.8	5.4	1013	270.5	-11.9
2012-10-09	09:13:26	24955	SL-8 R/B	184.9	20.1	6.9	2068	271.2	-12.8

536sec

SL-8 R/B 82001B

121009-13028

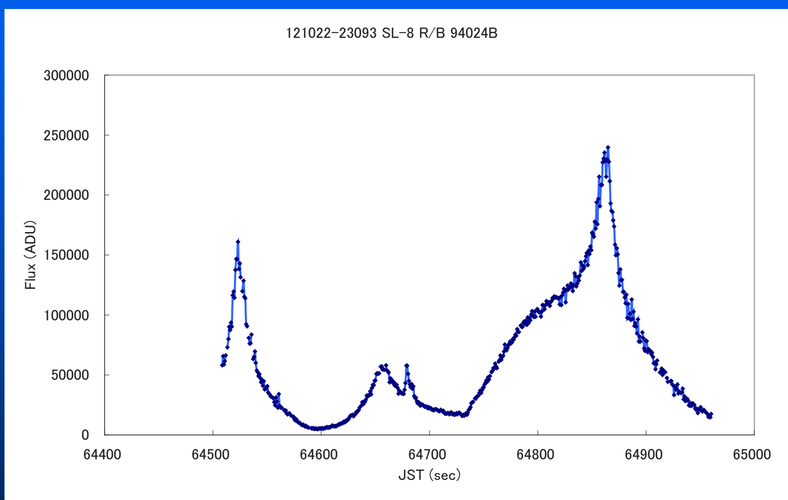


DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-10-09	10:24:00	13028	SL-8 R/B	208.7	20.0	6.3	1698	282.1	-27.0
2012-10-09	10:27:36	13028	SL-8 R/B	289.2	68.1	4.7	813	282.7	-27.7
2012-10-09	10:31:11	13028	SL-8 R/B	8.5	20.1	6.2*	1698	283.3	-28.5

431sec

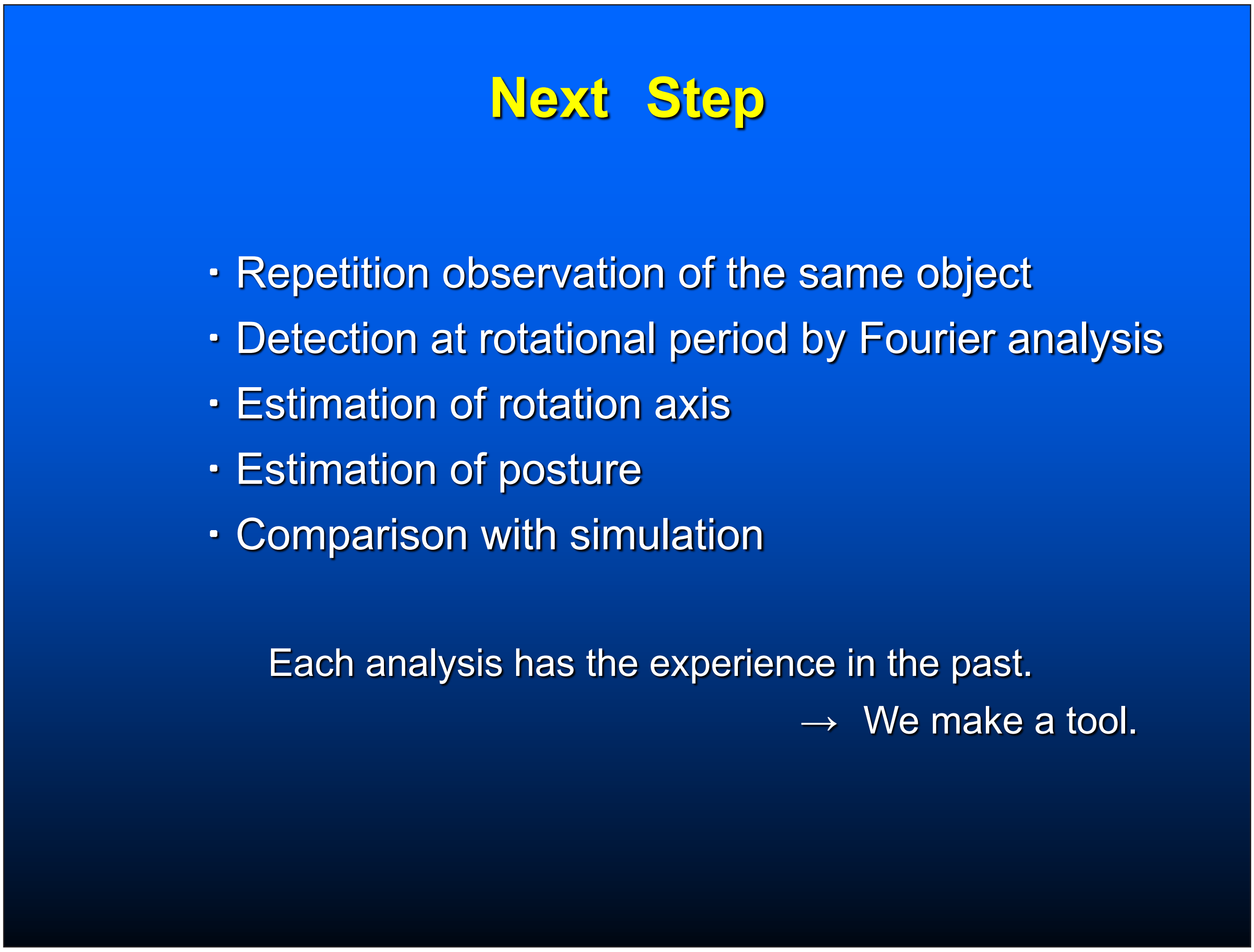
SL-8 R/B 94024B

121022-23093



DATE	TIME	SSC	NAME	Az	El	Mag.	Ran	Az(Sun)	El(Sun)
2012-10-22	08:54:18	23093	SL-8 R/B	193.9	20.1	7.0	2067	264.8	-12.2
2012-10-22	08:58:44	23093	SL-8 R/B	276.4	74.5	5.3	1003	265.4	-13.1
2012-10-22	09:03:12	23093	SL-8 R/B	359.9	20.0	6.8	2075	266.1	-14.0

534sec


Next Step
・Repetition observation of the same object
・Detection at rotational period by Fourier analysis
・Estimation of rotation axis
・Estimation of posture
・Comparison with simulation
Each analysis has the experience in the past.
→ We make a tool.

F8

低軌道デブリ地上光学観測システムの検討

Investigation of ground-based optical observation system for LEO objects

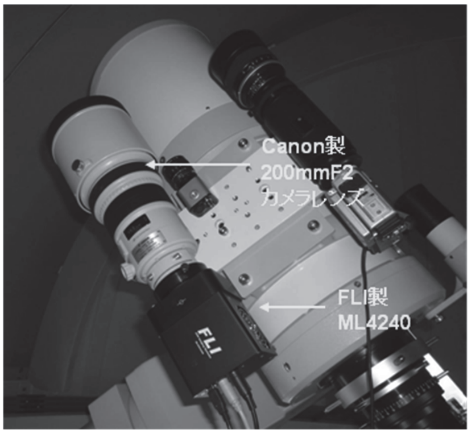
○柳沢俊史，黒崎裕久（宇宙航空研究開発機構）
○Toshifumi Yanagisawa and Hirohisa Kurosaki (JAXA)

低軌道は多くの地球観測衛星等が投入される重要な軌道である。近年、デブリや衛星同士の衝突、破砕事故などで低軌道の環境は悪化の一途をたどっている。人類の宇宙活動を継続するために、このような状況に早急に対処する必要がある。現在、低軌道デブリはレーダーによって主に観測されている。一方、光学観測装置による低軌道デブリの観測可能性が議論され始めている。光学観測装置による低軌道デブリの観測は日照や天候による影響をうけるという弱点をもつが費用が抑えられるという利点がある。市販の安価なCCDカメラやPCを多数利用した光学観測システムを世界中に展開することにより、現在のレーダー観測網を上回る能力を引き出すことができるかもしれない。

今回は低軌道デブリを対象とした40台の光学観測装置を持つ2つの観測サイトでの精密軌道決定の有効性の検討を行った。STK を用いたシュミレーションにより、多くの観測データの中から、経度の離れた2局、4台の観測装置の観測データにおける同一物体の対応付けが可能であることがわかった。このことはこのような観測システムを用いることにより、多数の未カタログデブリの精密な軌道決定ができるということを示している。

The low earth orbit is very important as many earth observation satellites are entered. Recently, this orbit is deteriorated by numerous pieces of space debris which is caused by collisions of satellite, breakups and so on. In order to maintain human activities in space, we have to cope with the space debris problem as soon as possible. Currently radar equipments are primary methods to observe LEO debris. Optical observation has an advantage of low cost, although it is effected by lighting condition of the sun and weather. The optical observation system consisted of large number of cost-effective CCDs and high-speed PCs at various sites in the world may overcome the current radar observation network.

We have examined the possibilities of precise orbit determination using two observation sites containing 40 sets of optical equipments. Simulations using STK have shown that identical objects were recognized from the data of 4 individual equipments installed on 2 separate sites using the lots of circular orbital elements calculated from many observation data. This enables us to determine orbits of many un-cataloged LEO objects precisely.



低軌道デブリ光学観測装置

Optical observation equipment for LEO debris

5th Space Debris Workshop

Investigation of ground-based optical observation system for LEO objects

Japan Aerospace Exploration Agency(JAXA)
Aerospace Research and Development Directorate
Innovative Technology Research Center

T.Yanagisawa and H.Kurosaki

JAXA

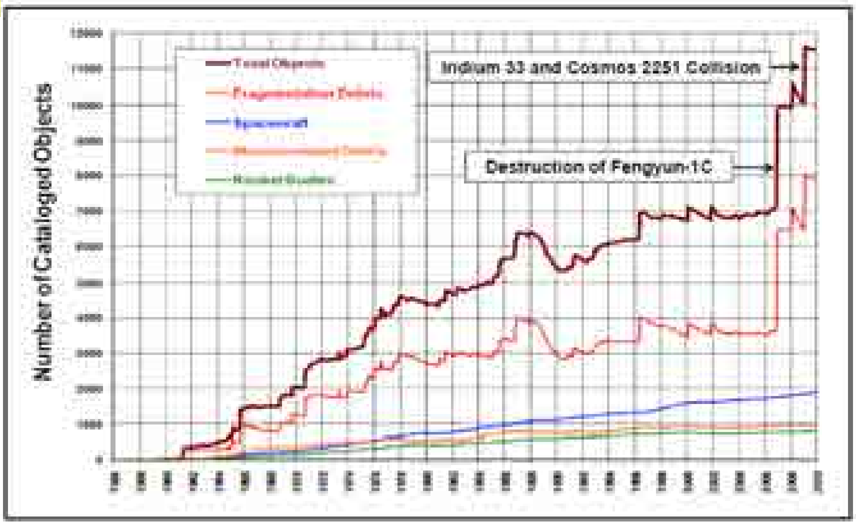
Abstract

The low earth orbit is very important as many earth observation satellites are entered. Recently, this orbit is deteriorated by numerous pieces of space debris which is caused by collisions of satellite, breakups and so on. In order to maintain human activities in space, we have to cope with the space debris problem as soon as possible. Currently radar equipments are primary methods to observe LEO debris. Optical observation has an advantage of low cost, although it is effected by lighting condition of the sun and weather. The optical observation system consisted of large number of cost-effective CCDs and high-speed PCs at various sites in the world may overcome the current radar observation network.

We have examined the possibilities of precise orbit determination using two observation sites containing 40 sets of optical equipments. Simulations using STK have shown that identical objects were recognized from the data of 4 individual equipments installed on 2 separate sites using the lots of circular orbital elements calculated from many observation data. This enables us to determine orbits of many un-cataloged LEO objects precisely.

JAXA

Background



LEO environment (around 800-1000km altitude where lots of Japanese satellites reside) is being deteriorated rapidly by the ASAT, the collision caused by Iridium 33 and Cosmos 2251, and so on.

Error of conjunction assessments become large because of inaccuracy of TLE. Japanese satellites in LEO fully rely on the alert information of JSpOC of U.S. However we don't know how accurate it is.

Japan needs to have own methods to evaluate the environment of LEO.

Background

Phased array of Kamisaibara Spaceguard Center

Russian ISON network using a lot of optical telescopes

Observation methods of LEO debris

①Radar observation

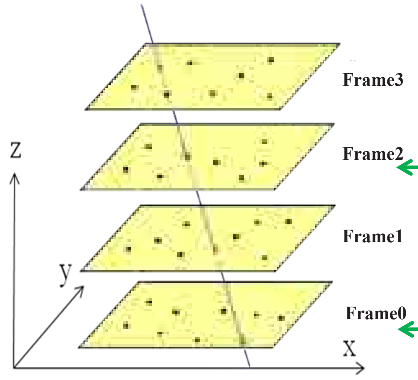
24-hour observation. SSN of U.S. Japan also has a radar observation facility owned by JSF(Japan Space Forum) in Kamisaibara. Its detection ability is 1m at 600km altitude which is not enough for small sized LEO debris. A disadvantage of radar observation system is a huge expenditure for its construction and maintenance.

②Optical observation

A few hours observation because of lighting condition of the Sun. Effected by weather conditions. ISON network of Russia. Basic research is being carried out by Innovative technology research center of JAXA. Very cost effective system.

Investigated the usefulness of the large array of optical sensors for LEO debris observation

Observation equipments and data analysis software



Concept of the line-identifying technique

Many frames

↓

Candidates are searched using a threshold and a shape parameter

↓

Candidates which create straight line are detected as moving object

Observation equipments:

- Canon EF200mmFL IS USM
- FLI 2K2K back-illuminated CCD camera ML4240

FOV : 7.65×7.65°

Exposure interval : 1.5 sec

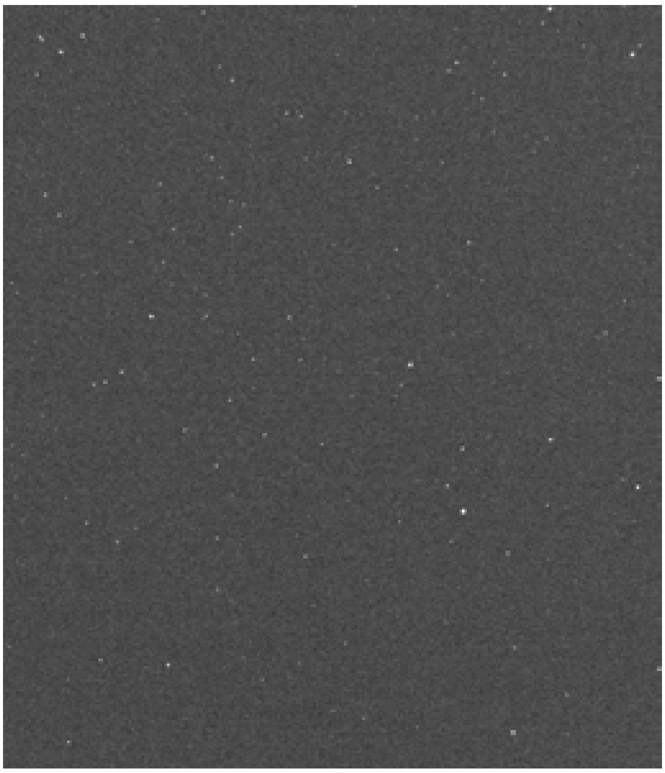
Data analysis software:

The line-identifying technique developed for GEO debris detection.

It can detect moving objects with constant velocity.

The equipments and the software enable us to detect LEO objects of 60cm at 1000km altitude.

Observation

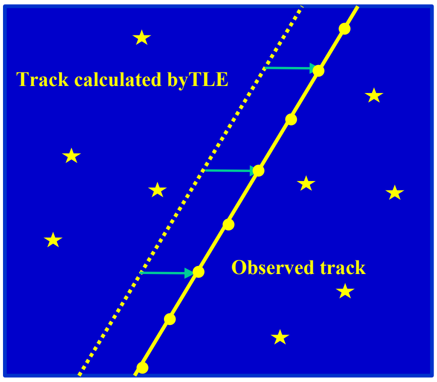


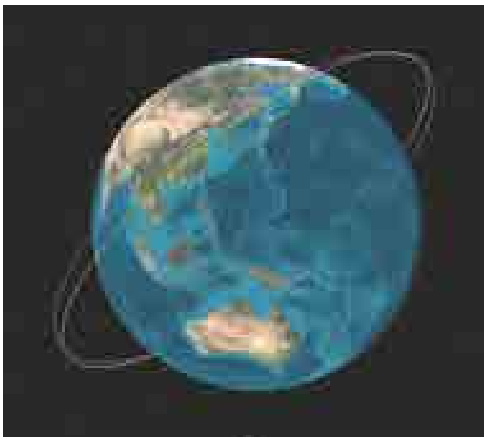
Sequential images of 17525 (MOMO-1)

Exposure time: 50msec

Interval: 1.5 sec

Possibility of orbit improvement

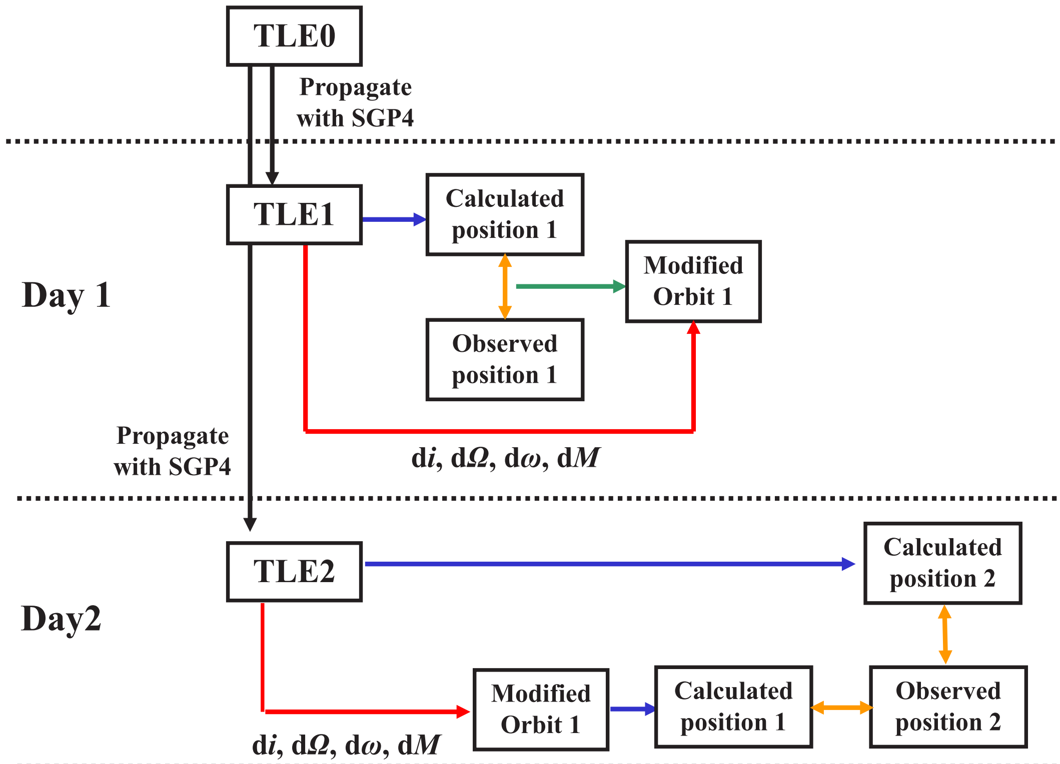




4 elements of TLE are improved to fit the observed track using the least square method.

Positions in the next day are calculated with improved orbit and evaluated the improvements by comparing calculated positions with observed ones.

Orbit improvement and its evaluation



Analysis result 1（O-C(TLE)）

date	time(UT)	Observed RA,Dec		Calculated RA,Dec		O-C in RA,Dec	
2011-09-07	17.86012	86.0493	39.0816	86.0322	39.1818	79.580	-360.882
2011-09-07	17.86056	85.5900	38.6503	85.5795	38.7440	89.275	-337.166
2011-09-07	17.86106	85.0919	38.1484	85.0692	38.2408	104.008	-332.604
2011-09-07	17.86150	84.6509	37.7052	84.6239	37.7932	123.072	-316.736
2011-09-07	17.86194	84.2094	37.2540	84.1820	37.3411	129.840	-313.681
2011-09-07	17.86237	83.7774	36.8000	83.7536	36.8951	107.273	-339.651
2011-09-07	17.86281	83.3423	36.3432	83.3186	36.4345	106.127	-328.854
2011-09-07	17.86325	82.9143	35.8833	82.8871	35.9697	121.109	-311.191
2011-09-07	17.86369	82.4903	35.4121	82.4590	35.5000	138.224	-319.364
2011-09-07	17.86413	82.0631	34.9382	82.0345	35.0278	125.788	-322.724
2011-09-07	17.86457	81.6465	34.4673	81.6134	34.5509	144.646	-301.074
2011-09-07	17.86506	81.1718	33.9217	81.1488	34.0153	100.880	-336.825
2011-09-07	17.86551	80.7581	33.4331	80.7254	33.5193	141.000	-310.236
2011-09-07	17.86598	80.3186	32.9075	80.2874	32.9971	133.978	-322.726
2011-09-07	17.86642	79.9170	32.4170	79.8809	32.5047	154.201	-312.769
2011-09-07	17.86686	78.5160	31.9230	78.4778	32.0088	162.316	-308.803
2011-09-07	17.88650	64.7380	8.2280	64.6998	8.3057	142.617	-279.827
2011-09-07	17.88694	64.4740	7.7076	64.4322	7.7836	151.812	-273.688
2011-09-07	17.88741	64.1865	7.1529	64.1493	7.2283	135.172	-271.273
2011-09-07	17.88785	63.9251	6.6314	63.8860	6.7106	138.859	-285.135
2011-09-07	17.88829	63.6647	6.1138	63.6267	6.1952	137.688	-293.163
2011-09-07	17.88873	63.4078	5.6065	63.3689	5.6822	140.025	-272.598
2011-09-07	17.88917	63.1536	5.0954	63.1134	5.1716	145.442	-274.468
2011-09-07	17.88961	62.9013	4.5926	62.8681	4.6636	140.741	-255.472
2011-09-07	17.89005	62.6508	4.0883	62.6091	4.1581	150.457	-251.188
2011-09-07	17.89048	62.4033	3.5882	62.3603	3.6552	155.009	-269.983
2011-09-07	17.89092	62.1563	3.0843	62.1193	3.1664	133.350	-295.444
2011-09-07	17.89136	61.9124	2.5899	61.8748	2.6683	135.368	-284.404
2011-09-07	17.89185	61.6437	2.0416	61.6051	2.1182	139.048	-275.036
2011-09-07	17.89229	61.4064	1.5550	61.3651	1.6288	148.680	-258.876

stddev in RA = 133.458　**1.645km on orbit**

stddev in Dec = 301.852　**0.727km on orbit**

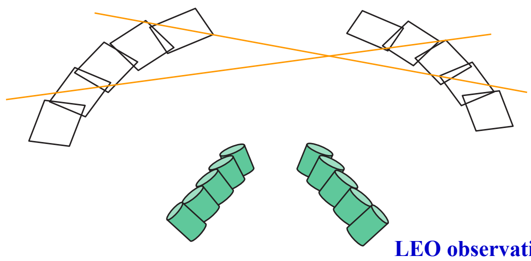
Analysis result 2（O-C(improved)）

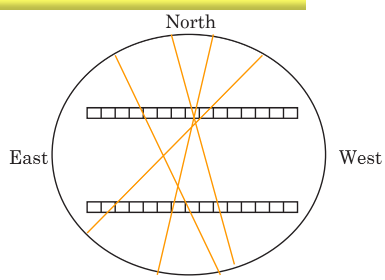
date	time(UT)	Observed RA,Dec		Calculated RA,Dec		O-C in RA,Dec	
2011-09-07	17.86012	86.0493	39.0816	86.0545	39.0900	-29.508	-58.065
2011-09-07	17.86056	85.5900	38.6503	85.6023	38.6597	-15.357	-33.996
2011-09-07	17.86106	85.0919	38.1484	85.0926	38.1562	-3.138	-28.175
2011-09-07	17.86150	84.6509	37.7052	84.6470	37.7083	14.383	-11.230
2011-09-07	17.86194	84.2094	37.2540	84.2064	37.2560	13.626	-7.158
2011-09-07	17.86237	83.7774	36.8000	83.7784	36.8097	-4.478	-32.144
2011-09-07	17.86281	83.3423	36.3432	83.3439	36.3489	-7.056	-20.307
2011-09-07	17.86325	82.9143	35.8833	82.9128	35.8838	6.530	-1.808
2011-09-07	17.86369	82.4903	35.4121	82.4858	35.4146	22.381	-9.094
2011-09-07	17.86413	82.0631	34.9382	82.0611	34.9414	8.604	-11.618
2011-09-07	17.86457	81.6465	34.4673	81.6405	34.4843	26.215	10.888
2011-09-07	17.86506	81.1718	33.9217	81.1761	33.9284	-10.764	-24.172
2011-09-07	17.86551	80.7581	33.4331	80.7534	33.4322	20.115	3.244
2011-09-07	17.86598	80.3186	32.9075	80.3158	32.9099	11.944	-8.536
2011-09-07	17.86642	79.9170	32.4170	79.9097	32.4172	31.199	2.040
2011-09-07	17.86686	78.5160	31.9230	79.5078	31.9212	38.238	6.580
2011-09-07	17.88650	64.7380	8.2280	64.7398	8.2244	-1.807	13.192
2011-09-07	17.88694	64.4740	7.7076	64.4728	7.7026	7.160	17.846
2011-09-07	17.88741	64.1865	7.1529	64.1892	7.1477	-9.718	18.711
2011-09-07	17.88785	63.9251	6.6314	63.9268	6.6305	-6.253	3.379
2011-09-07	17.88829	63.6647	6.1138	63.6668	6.1155	-7.640	-6.155
2011-09-07	17.88873	63.4078	5.6065	63.4091	5.6029	-4.729	12.887
2011-09-07	17.88917	63.1536	5.0954	63.1537	5.0920	-0.332	3.473
2011-09-07	17.88961	62.9013	4.5926	62.9005	4.5951	2.749	28.905
2011-09-07	17.89005	62.6508	4.0883	62.6496	4.0801	4.246	29.656
2011-09-07	17.89048	62.4033	3.5882	62.4009	3.5776	8.580	3.212
2011-09-07	17.89092	62.1563	3.0843	62.1600	3.0893	-13.290	-17.829
2011-09-07	17.89136	61.9124	2.5899	61.9156	2.5922	-11.480	-8.421
2011-09-07	17.89185	61.6437	2.0416	61.6459	2.0421	-8.057	-1.687
2011-09-07	17.89229	61.4064	1.5550	61.4060	1.5511	1.311	14.113

stddev in RA = 14.317　**0.082km on orbit**

stddev in Dec = 19.596　**0.107km on orbit**

Large array of optical sensors for LEO debris observation





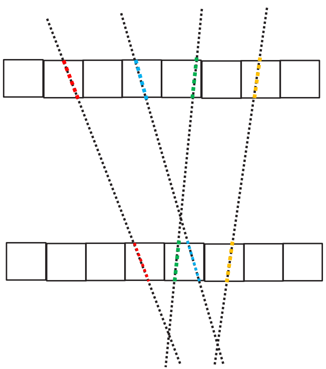
LEO observation system using many optical sensors

Detections of identical object at 2 sites

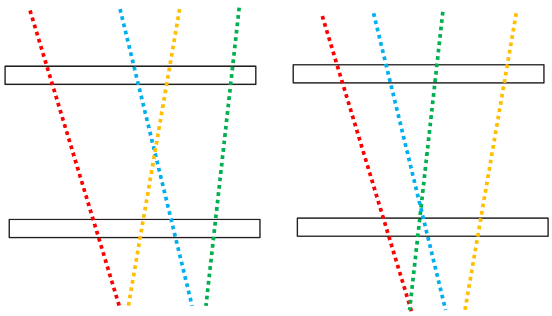
●Many optical observation units are installed to cover large area since each unit has narrow FOV. In order to get long arc for accurate orbit determination, 2 narrow rectangular regions which separate about 80-degree are observed using 40 observation units.

●Observation of 2 consecutive passes enable us to do accurate orbit determination. For this reason, 2 longitudinally separated sites are considered.

Observational simulation



Identification of same objects in 2 sets at each site



Identification of same objects at 2 sites

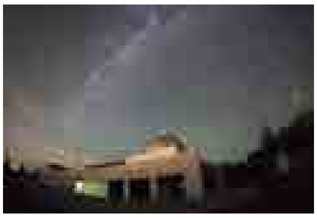
Accurate orbit determination

One object is observed 2 times at each site (4 times in total). Identifications of same objects from many observed positions are needed.

Observational simulation

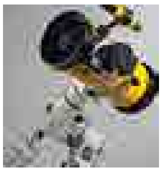
Observation sites:

Ishigakijima Observatory (Okinawa)



Rikubetsu Observatory (Hokkaido)

Observation equipments:

[ + ] ×40

20 units are pointed to Az 0-degree and El 50-degree, other 20 units Az 180-degree and El 50-degree. Each set is located to observe east-west-elongated rectangular region.

Observation date and time: Apr/11/2012　8:40-11:40(UT)　Rikubetsu

Apr/11/2012　10:20-13:29(UT)　Ishigaki

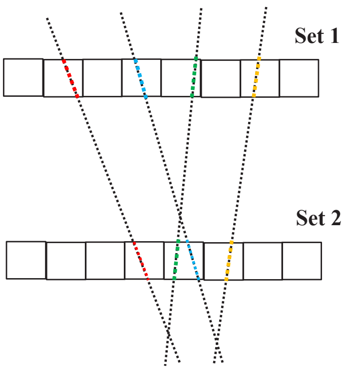
Targets: 14574 TLEs of Apr/11/2012 distributed at Space Track web site.

Observed coordinates(RA and Dec) of each object at each site are calculated every second interval using STK(Satellite Tool Kit) software.

Observational simulation

872 and 636 objects were detected at the set 1 and 2 of Ishigaki, respectively. 473 objects were detected at both sets.

916 and 934 objects were detected at the set 1 and 2 of Rikubetsu, respectively. 458 objects were detected at both sets.



Identification at each site

Identification conditions

①Difference of observation times: Less than 700-sec

②Change rate of circular radiuses: Less than 0.1-degree

③Difference of inclinations: Less than 1.0-degree

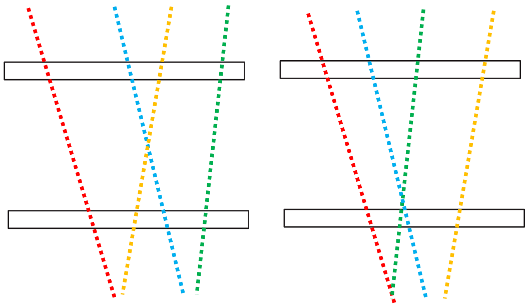
④Difference of RAANs: Less than 1.0-degree

⑤Difference of direction cosines at the middle of observation time of 2 set: Less than 5.0-degree

↓

465 objects out of 473 ones at Ishigaki (98.3%) and 454 objects out of 458 ones at Rikubetsu (99.1%) are identified.

Observational simulation



Ishigaki Rikubetsu

Out of Ishigaki's 463 and Rikubetsu's 454 identified objects, 154 objects were observed at both sites.

Identification condition

① Difference of observation times: 5600－7700-sec

② Change rate of circular radiuses: Less than 0.05

③ Difference of inclinations: Less than 1.5-degree

④ Difference of RAANs: Less than 1.0-degree: Less than 1.0-degree

⑤Difference of direction cosines at the middle of observation time of either of the two sits: Less than 90-degree

↓

143 objects out of 154 ones (92.9%) are identified

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.

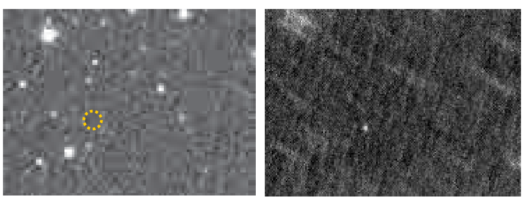
Future Plan

- Improvement of equipments①: Camera lens → Small telescope
- Improvement of equipments②: Development of fast detection devices (CMOS sensor and so on)
- Improvement of analysis method: Line-identifying method → Stacking method

↓

Objective: Detection of 10cm objects at 1000km altitude

- Orbit determination experiment using the data taken at Rikubetsu and Ishigaki
- Cooperation with space based optical observation system for LEO debris



A detected object using the stacking method. Before-analysis (left) and after-analysis (right).

Space based optical observation system

Summary

It is possible to establish a large array system of optical sensors for LEO debris observation which is able to carry out accurate orbit determination of many LEO objects with relatively low cost.

In the future, we would like to improve observation equipments and analysis methods to detect 10cm objects at 1000km altitude. We also will carry out actual orbit determinations using the data taken at 2 separated observation site and evaluate its accuracy.

付録　講演プログラム

第５回スペースデブリワークショップ

2013 年１月 22 日（火），23 日（水）

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

1 月 22 日(火) 09:55 ～ 17:55

09:55　**開会挨拶**　平子敬一(JAXA)

国際セッション(英語)

10:00　**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(UNCOPUOS 議長)

10:30　**宇宙航空研究開発機構のスペースデブリ関連活動について**
　○伊東康之(JAXA)

11:00　**The Long-Term Stability of the LEO Debris Population and the Challenges for Environment Remediation**
　○J.-C. Liou(NASA)

11:30　**Active Debris Removal activities in CNES**
　○Christophe Bonnal(CNES)

12:00～13:20　**昼休み**

13:20　**世界のデブリ管理状況と JAXA の対応**
　○加藤明(JAXA)

13:40　**JAXA におけるデブリ除去の研究状況**
　○河本聡美，大川恭志，片山保宏，上村平八郎，中西洋喜，井村信義，北村正治，木部勢至朗，平子敬一(JAXA)

14:00　**スペースデブリ除去を実施する上での宇宙諸条約上の制約と解決策のための予備的検討**
　○岸人弘幸(JAXA)

14:20　**デブリ除去プロジェクト立上げとビジネスへの展開**
　○峰正弥(SJAC)

14:40　**デブリ推移モデルによる将来予測**
　○有吉雄哉，花田俊也(九大)，河本聡美(JAXA)

15:00　**非協力的ターゲットへの接近ストラテジ**
　○山元透，村上尚美，山中浩二(JAXA)

15:20～15:35　**休憩**

15:35　**デブリ除去における画像計測と運動推定の検討**
　○片山保宏，上村平八郎，西田信一郎，河本聡美(JAXA)

15:55　**推進系取付のストラテジ・機構の検討**
　○中西洋喜，河本聡美(JAXA)

16:15　**軌道上実証を目指した導電性テザー技術の研究開発**
　○大川恭志，河本聡美，松本康司，塩見裕，北村正治(JAXA)

16:35　**デブリ除去実現に向けた HTV による導電性テザー実証実験**
　○辻田大輔，原田正行，河本聡美，大川恭志(JAXA)

16:55　**イオンビーム照射を用いる静止軌道デブリの除去**
　○北村正治，早川幸男，大川恭志，河本聡美(JAXA)

17:15　**帯電衛星によるスペースデブリの軌道変換**
　○中宮賢樹，赤司陽介，山川宏(京大)

17:35　**デブリ除去プロジェクト考察**
　○大塚聡子，桑尾文博(NEC)，河本聡美(JAXA)，池内正之(NT スペース)，廣田賢治，渡辺順一郎(TECS)

18:30～20:20　**懇親会**（JAXA 調布食堂）

1月23日(水) 10:00 ～ 18:20

10:00 Kevlar･Beta Clothの微小デブリ貫通限界重量と厚さ
○東出真澄，小野瀬直美，長谷川直(JAXA)
10:20 発泡アルミに対する衝突実験：軽量デブリバンパの開発に向けて
○小野瀬直美，東出真澄，長谷川直(JAXA)
10:40 スラスタ用窒化ケイ素セラミックスの超高速衝突損傷評価
○川合伸明，長谷川直，佐藤英一(JAXA)
11:00 衛星設計を目的とした微小デブリの2重壁への衝突過程の数値解析による貫通限界曲線の推定
○竹場敦史，片山雅英(伊藤忠テクノソリューションズ，CTC)，仁田工美(JAXA)
11:20 薄板への超高速衝突におけるプラズマ発生の研究
○田中孝治(JAXA)，長岡洋一(総研大)，佐々木進(JAXA)
11:40 超高速飛翔体衝突により生ずるイジェクタのサイズ分布
○西田政弘，林浩一(名工大)，長谷川直(JAXA)

12:00～13:20 昼休み

13:20 スペースデブリ接近評価－衝突リスク低減の経験－
○成田兼章，中村信一，田島徹，染谷一徳，阿部旬也(JAXA)
13:40 デブリに係わる損害保険
○鈴木茂雄(あいおいニッセイ同和)
14:00 軌道上微小デブリ計測技術の研究開発 -JAXA宇宙環境グループでの開発センサを中心に-
○北澤幸人(IHI)，松本晴久，奥平修，木本雄吾(JAXA)，Pauline Faure(九工大)，
服部真希(東大)，花田俊也(九大)，唐木敦(IHI)，桜井晃，船越国広，八坂哲夫(QPS研究所)
14:20 デブリ衝突損傷リスク解析ツール(TURANDOT)の機能拡張
金正浩，○八田真児 (MUSCATスペース･エンジニアリング)，東出真澄，河本聡美(JAXA)
14:40 きぼう搭載微小粒子捕獲実験装置(MPAC)の観測結果について
木本雄吾(JAXA)，○和気美幸(AES)
15:00 静止軌道周辺の破砕事象の観測とモデル化
○上津原正彦，花田俊也(九大)，柳沢俊史(JAXA)，北澤幸人(IHI)

15:20～15:35 休憩

15:35 TDIモードを応用したデブリの短周期ライトカーブ観測
○奥村真一郎，浦川聖太郎，西山広太，坂本強，高橋典嗣(日本スペースガード協会)，
吉川真(JAXA，日本スペースガード協会)
15:55 軌道上光学デブリ観測ミッションの検討
○松本晴久(JAXA)，奥平修(JAXA)，柳沢俊史(JAXA)，北澤幸人(IHI)，田川真(九大)，
黒崎裕久(JAXA)
16:15 軌道上光学センサによるLEOデブリ観測
○田川真，花田俊也(九大)，柳沢俊史，松本晴久(JAXA)，北澤幸人(IHI)
16:35 再突入物体のレーダ観測及び予測解析
○染谷一徳，阿部旬也，田島徹(JAXA)，足立学，亀山雅也(富士通)
16:55 鹿島35cm望遠鏡を用いた人工衛星の観測
○布施哲治(NICT)
17:15 軌道シミュレーションを用いた静止軌道上物体の複数地点観測の有効性評価
○樋川治，泉山卓，大塚健功(IHI)
17:35 低軌道デブリのライトカーブ観測
○黒崎裕久，柳沢俊史(JAXA)
17:55 低軌道デブリ地上光学観測システムの検討
○柳沢俊史，黒崎裕久(JAXA)

18:15 閉会挨拶 中橋和博(JAXA)

5th Space Debris Workshop

January 22-23, 2013

Administration Bldg. No1 2F Lecture-hall, JAXA Chofu Aerospace Center

Tuesday 22 January 09:55 ～ 17:55

09:55 Opening remarks *Keiichi Hirako(JAXA)*

International Session(English)

10:00 Long Term Sustainability of Outer Space and Role of UNCOPUOS
○*Yasushi Horikawa(Chair of UNCOPUOS)*

10:30 Overview of JAXA's Space Debris related Activities
○*Yasuyuki ITO(JAXA)*

11:00 The Long-Term Stability of the LEO Debris Population and the Challenges for Environment Remediation
○*J.-C. Liou(NASA)*

11:30 Active Debris Removal activities in CNES
○*Christophe Bonnal(CNES)*

12:00～13:20 Luncheon

13:20 Global Debris Mitigation Control and Corresponding Activities in JAXA
○*Akira Kato(JAXA)*

13:40 Current status of studies on active debris removal at JAXA
○*S. Kawamoto, Y. Ohkawa, Y. Katayama, H. Kamimura, H. Nakanishi, N. Imura, S. Kitamura, S. Kibe, K. Hirako (JAXA)*

14:00 Some constraints of international space law on the conduct of active debris removal and preliminary studies to searching for a solution
○*Hiroyuki Kishindo(JAXA)*

14:20 Promoting the Active Debris Removal Project on Business
○*Masaya Mine(SJAC)*

14:40 Prediction of Orbital Debris Population with an Orbital Debris Evolutionary Model
○*Yuya Ariyoshi, Toshiya Hanada(Kyushu University), Satomi Kawamoto(JAXA)*

15:00 Approach Strategy to a Non-Cooperative Target
○*Toru Yamamoto, Naomi Murakami, Koji Yamanaka(JAXA)*

15:20～15:35 Break

15:35 Vision-based Measurement and Motion Estimation for Space Debris Removal
○*Yasuhiro Katayama, Heihachiro Kamimura, Shinichiro Nishida, Satomi Kawamoto(JAXA)*

15:55 The Strategy and Technology for Non-cooperative Target Capture
○*H. Nakanishi and S. Kawamoto(JAXA)*

16:15 R&D of Electrodynamic Tether for On-orbit Demonstration
○*Yasushi Ohkawa, Satomi Kawamoto, Koji Matsumoto, Hiroshi Shiomi, and Shoji Kitamura(JAXA)*

16:35 The Plan of Electrodynamic Tether Experiments on HTV for Debris Removal
○*Daisuke Tsujita, Masayuki Harada, Satomi Kawamoto, Yasushi Okawa(JAXA)*

16:55 GEO Debris Removal using Ion Beam Irradiation
○*Shoji Kitamura, Yukio Hayakawa, Yasushi Ohkawa, Satomi Kawamoto(JAXA)*

17:15 Orbital change of space debris using the charged satellite
○*Masaki Nakamiya, Yosuke Akashi, Hiroshi Yamakawa(Kyoto Univ.)*

17:35 Study of Active Debris Removal Project
○*Akiko Otsuka, Fumihiro Kuwao(NEC), Satomi Kawamoto(JAXA), Masayuki Ikeuchi(NTS), Kenji Hirota, Jun-ichiro Watanabe(TECS)*

18:30～20:20 Reception（JAXA Chofu Cafeteria）

Wednesday 23 January　10:00 ～ 18:20

10:00　Ballistic Limit Weight and Thickness of Kevlar and Beta Cloth for Sub-millimeter Debris Impact
○Masumi Higashide, Naomi Onose, Sunao Hasegawa(JAXA)

10:20　Impact experiments on aluminum foam targets: as a favored candidate material for a light-weight space debris bumper shield
○Naomi Onose, Masumi Higashide, Sunao Hasegawa(JAXA)

10:40　Damage evaluation of silicon nitride ceramics subjected to hypervelocity impact
○N. Kawai, S. Hawegawa, E. Sato(JAXA)

11:00　An Estimation of the Ballistic Limit Curves by Performing Numerical Analyses of the Small-Size Space Debris Impacts on the Components of Satellites for the Purpose of their Designs
○Atsushi Takeba, Masahide Katayama(ITOCHU-Techno Solutions, CTC), Kumi Nitta(JAXA)

11:20　Plasma Generation caused by Hypervelocity Impact against Thin Sheet Materials
○Koji Tanaka(JAXA), Yoichi Nagaoka(Sokendai), Susumu Sasaki(JAXA)

11:40　Size distribution of ejecta resulting from hypervelocity impacts of projectiles
○Masahiro Nishida, Koichi Hayashi(NITech), Sunao Hasegawa(JAXA)

12:00～13:20　Luncheon

13:20　Space Debris Conjunction Assessment -- Collision Risk Mitigation Experience --
○Kaneaki Narita, Shinichi Nakamura, Toru Tajima, Kazunori Someya, Junya Abe(JAXA)

13:40　Non-life insurance related to Space debris
○Shigeo Suzuki(Aioi Nissay Dowa Insurance)

14:00　R&D on in-situ measurement MMOD sensors at JAXA
○Y. Kitazawa(IHI), H. Matsumoto(JAXA), O. Okudaira,(JAXA), P. Faure(Kyutech),
Y. Akahoshi (Kyutech), M. Hattori(The University of Tokyo), T. Hanada(Kyushu University),
A. Karaki(IHI), A. Sakurai, K. Funakoshi, T. Yasaka(iQPS)

14:20　Expansion of Tactical Utilities for Rapid ANalysis of Debris on Orbit Terrestrial
Jeongho Kim, ○Shinji Hatta(MUSCAT Space Engineering), Masumi Higashide, Satomi Kawamoto(JAXA)

14:40　KIBO/MPAC Experiment Summary
Yugo Kimoto(JAXA), ○Miyuki Waki(AES)

15:00　Measurement and modeling of breakup events in the geostationary region
○Masahiko Uetsuhara, Toshiya Hanada(Kyushu Univ.), Toshifumi Yanagisawa(JAXA), Yukihito Kitazawa(IHI)

15:20～15:35　Break

15:35　Short-period light-curve observations of space debris using TDI technique
○Shin-ichiro Okumura, Seitaro Urakawa, Kota Nishiyama, Tsuyoshi Sakamoto,
Noritsugu Takahashi(Japan Spacegaurd Association), Makoto Yoshikawa(JAXA, JSGA)

15:55　Feasibility study for Space-Based optical observation mission of space Debris
○Haruhisa Matsumoto, Osamu Okudaira, Toshifumi Yanagisawa(JAXA), Yukihito Kitazawa(IHI),
Makoto Tagawa(Kyushu Univ.), Hirohisa Kurosaki(JAXA)

16:15　Low Earth orbit debris observation using space-based optical sensors
○Makoto Tagawa, Toshiya Hanada(Kyushu Univ.), Toshifumi Yanagisawa, Haruhisa Matsumoto(JAXA),
Yukihito Kitazawa(IHI)

16:35　Observation and Prediction for Re-entry Objects
○Kazunori Someya, Junya Abe, Toru Tajima(JAXA), Gaku Adachi and Masaya Kameyama(FUJITSU)

16:55　Observations of Artificial Satellites with Kashima 35cm Optical Telescopes
○Tetsuharu Fuse(NICT)

17:15　Evaluation of multi-site observation of GEO objects by simulation
○Osamu Hikawa, Taku Izumiyama, Takenori Otsuka(IHI)

17:35　Light curve observations of LEO debris
○Hirohisa Kurosaki and Toshifumi Yanagisawa(JAXA)

17:55　Investigation of ground-based optical observation system for LEO objects
○Toshifumi Yanagisawa and Hirohisa Kurosaki(JAXA)

18:15　Closing address　*Kazuhiro Nakahashi(JAXA)*

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