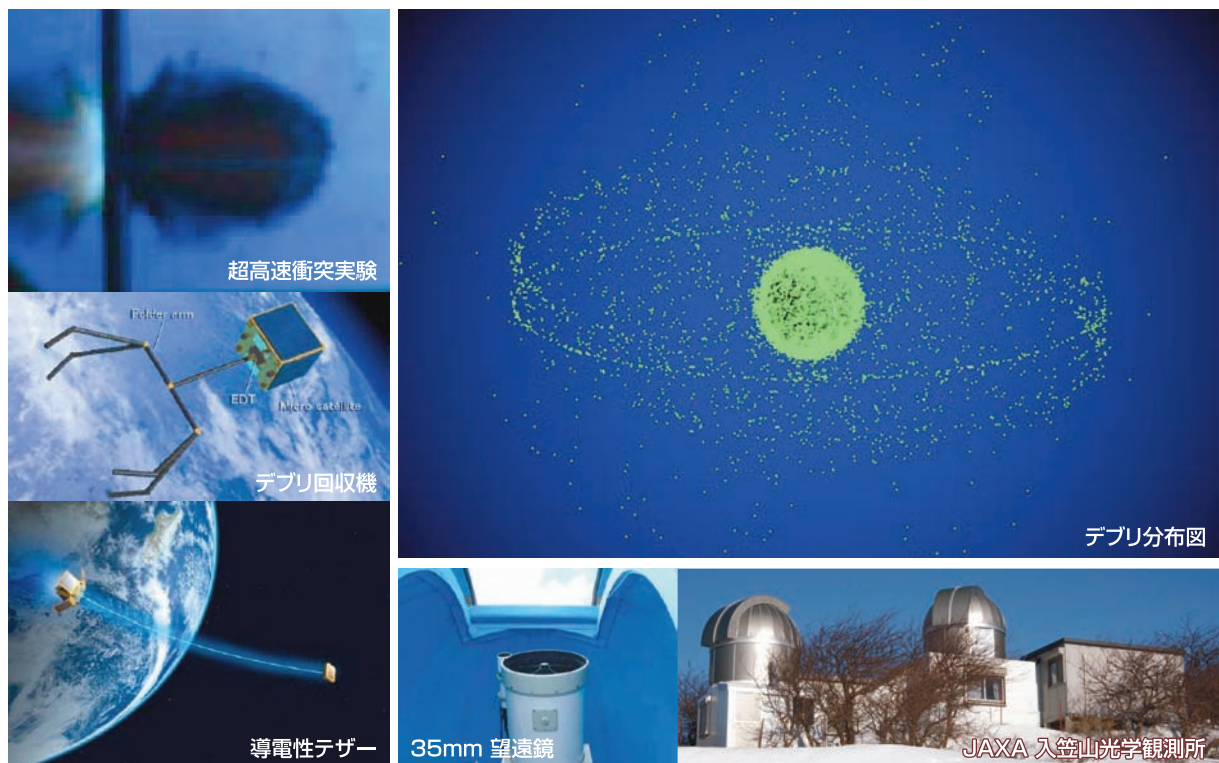


第3回「スペースデブリワークショップ」 講演論文集

Proceedings of the 3rd Space Debris Workshop



2008年1月21日、22日
日本科学未来館

宇宙航空研究開発機構
総合技術研究本部 宇宙先進技術研究グループ

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

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総合技術研究本部
宇宙先進技術研究グループ
Advanced Space Technology Research Group
Institute of Aerospace Technology

2008年2月

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

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北村正治（宇宙航空研究開発機構 総合技術研究本部 宇宙先進技術研究グループ長）

Preface

Shoji Kitamura (Advanced Space Technology Research Group/Institute of Aerospace Technology/JAXA)

2008年1月21日と22日の両日、日本科学未来館において第3回スペースデブリワークショップが開催された。本資料は、同ワークショップで発表された報告をまとめたものである。

スペースデブリに対する関心は、専門家の間では古くからあったと思われるが、よく知られるようになったのは、国際宇宙ステーション(ISS)において、スペースデブリに対する防御壁や回避運用の必要性が言われてからではないかと思われる。また、スペースシャトルの窓ガラスにデブリの衝突跡が付くなどが広く紹介され、スペースデブリに対する関心が深まったと思われる。これら有人宇宙機に対する問題に加え、近年では無人の人工衛星においてもデブリの衝突例が報告され、回避運用が検討される状況になりつつある。更に、個々のデブリ衝突の問題に止まらず、極めて深刻な問題が提起されている。すなわち、デブリで混み合った軌道上では既にデブリ同士の衝突が発生し始めており、今後打ち上げられる衛星を軌道上に放置することを無くしたとしても、デブリの自己増殖が起これ、宇宙の持続的利用が困難になると警告する専門家もいる。

このように、デブリ問題に関する重要性はますます高まりつつあるが、「スペースデブリ」と冠したワークショップや講演会の類は、私の知る限り、我が国ではこの「ワークショップ」だけでないか、と思われる。平成14年2月に第1回を開催し(旧航空宇宙技術研究所が主催)、今回で第3回を迎えた。

今回のワークショップでは、基調講演1件、招待講演としてNASAからの招待者による講演1件、観測・モデル化に関し5件、防御に関し3件、デブリ低減対策に関し5件、国際セッションとして4件の貴重な講演があった。参加者は2日間で延べ約120人に達し、外国からの参加者を含め会場から活発な質疑が出されるなど、非常に盛会であった。デブリ問題の専門家、宇宙開発関係者、あるいは更に広範な分野の方々に一堂に会して頂き、ご専門のデブリ問題に関してご報告頂くとともに、デブリ問題の解決に向けて、色々な面からご議論頂く場として役立てたものと考えている。

最後に、このワークショップを実りあるものにして頂いた講演者、参加者および関係者の方々に謝意を表します。



会場(科学未来館)正面



会場内(招待講演)

I. 国際セッションー1 基調講演、招待講演

I1-1 スペースデブリ対策 R&D 戦略

○加藤 明（宇宙航空研究開発機構／総合技術研究本部／事業推進部）

R & D Strategy for Space Debris Related Issues

Akira Kato (Program Management and Integration Department, Institute of Aerospace Technology (IAT) / JAXA)

Key Words: Debris, Strategy, Mission Assurance

概要

本報告は JAXA で承認された戦略ではない。「スペースデブリ対策推進会議」の事務局の立場からの提案であり、今後本書の内容は同会議で審議され、更に各 R&D 計画は個別に上位の会議で審議されて実行可能となる。

デブリ問題の背景として、増加を続けるデブリと 2007 年に発生した 2 回の破砕事象が重要である。デブリ環境は各国でモデル化されており、モデル間の相違も議論になっているところではあるが、当該破砕事象によりこれらのモデルに一層の見直しをかける必要は生じている。これとは別に NASA の解析によれば、今後の打上げが全く無いとしてもデブリの相互衝突により自己増殖を始める恐れがあるとのことである。世界的には国連の「デブリ低減ガイドライン」が採択され、デブリの低減に関する国際的合意が得られ、デブリの増加は当面問題の無い程度に緩和される見論見であったが、事態は楽観できるものではなくなった。

現実の JAXA ミッションに対するデブリのリスクはもはや無視できるものではない。リスク評価の結果から、最近の衛星の外部配線には衝突被害防止のためのシートを貼って対応している。軌道上の重要な衛星にはデブリの衝突を未然に防ぐための監視作業が日常的に行われている。

JAXA の今後 5 年間のデブリ対策戦略としては、デブリ発生防止に対する条件がほぼ揃ったことともあり、その比重を①ミッション保証（より正確なデブリ分布状況の把握と被災予測による衝突リスク評価の高精度化、衝突被害防止設計標準の整備、回避対策の充実などからなる）、②環境保全と再突入地上安全（デブリ発生防止要求への一層の遵守と、落下するデブリからの地上の安全確保等）、③環境改善（連鎖衝突反応を未然に防ぐために、国際協力により混雑する軌道から 100 個程度の不要衛星を除去する）へ移すことを提案する。

I1-1

The R&D Strategy for Space Debris Related Issues (スペースデブリ関連研究開発戦略)

The 3dr Space Debris Workshop
21, January, 2008 @ Tokyo, Japan
Program Management and Integration Department
Institute of Aerospace Technology
JAXA
(JAXA総合技術研究本部／事業推進部 加藤明)

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Remark

- This Strategy has not been approved in JAXA yet.
- This is a draft proposal from a portion of the secretary of the “JAXA Space Debris Committee” (スペースデブリ対策推進会議 to be more exact) to make it a baseline to coordinate debris related works within JAXA.
- Total JAXA R&D plan will be discussed by the upper committee. Then, effective and attractive proposals will be authorized to start. This strategy will support such process and be subjected to it.

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Contents

1. Orbital Environment
 - 1.1 Number of Orbital Objects
 - 1.2 Causes of Generation of Debris
 - 1.3 Mitigation Measures and their effects
 - 1.4 Two Major Events Contaminating Environment in 2007
 - 1.5 Break-up Events in History
 - 1.6 Influence of Chinese ASAT on JAXA Spacecraft
 - 1.7 Expected population growth of debris
2. Risk by Debris
3. Activities in the World
4. Strategy for Debris Issue
 - 4.1 Major Considerations for Debris Issues
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 - 4.3 Technology Map for mission assurance in debris environment.
 - 4.4 Major Elements of Strategy
 - 4.5 Roadmap for Debris Mitigation
 - 4.6 Major R&D items
 - 4.7 Portfolio for Debris Related R&D
5. Conclusion

3

1 Orbital Environment

1.1 Number of Orbital Objects

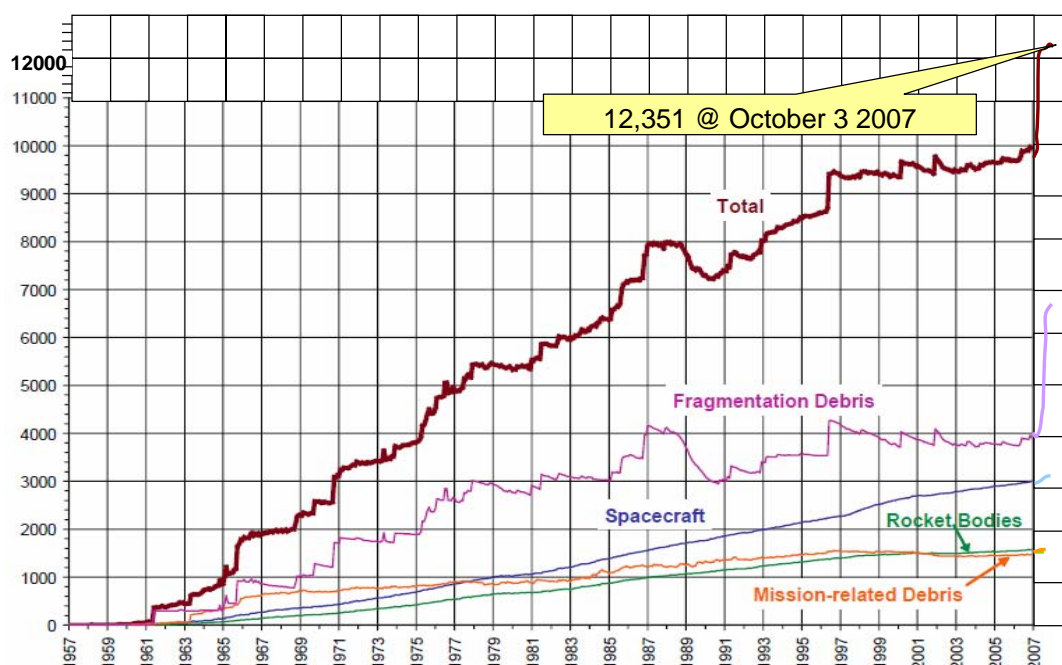


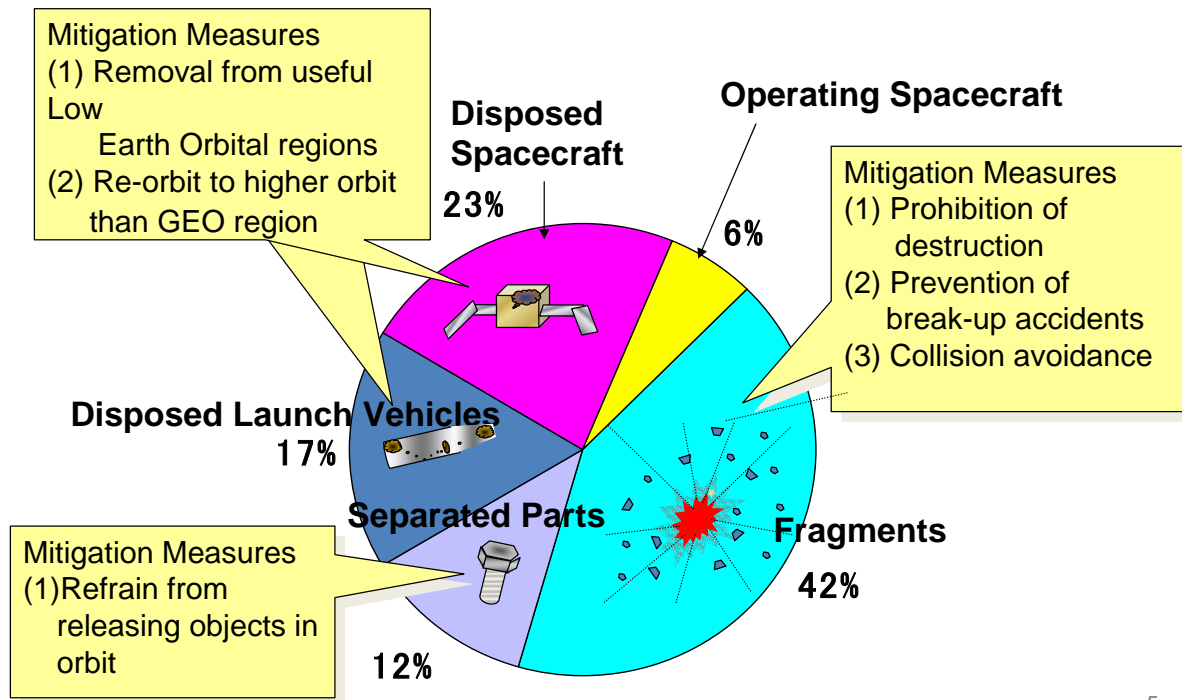
Fig.-1 Number of Objects Observed by the Ground Facility
(This chart is based on the data provided by NASA *Orbital Debris Quarterly News*)

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1 Orbital Environment

1.2 Causes of Generation of Debris

(@2006)

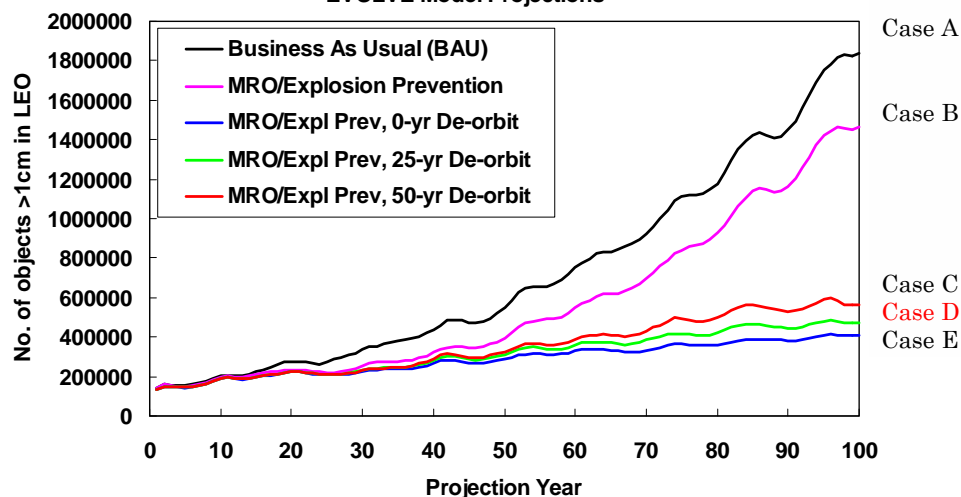


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1 Orbital Environment

1.3 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.]

>1cm Population Evolution
EVOLVE Model Projections

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.

1 Orbital Environment

1.4 Two Major Events Contaminating Environment in 2007



Chinese Intentional Destruction
Feng Yun 1C: Chinese weather satellite, launched 1999 (958 kg), was destroyed by a missile on January 11th 2007 by “kinetic kill”.



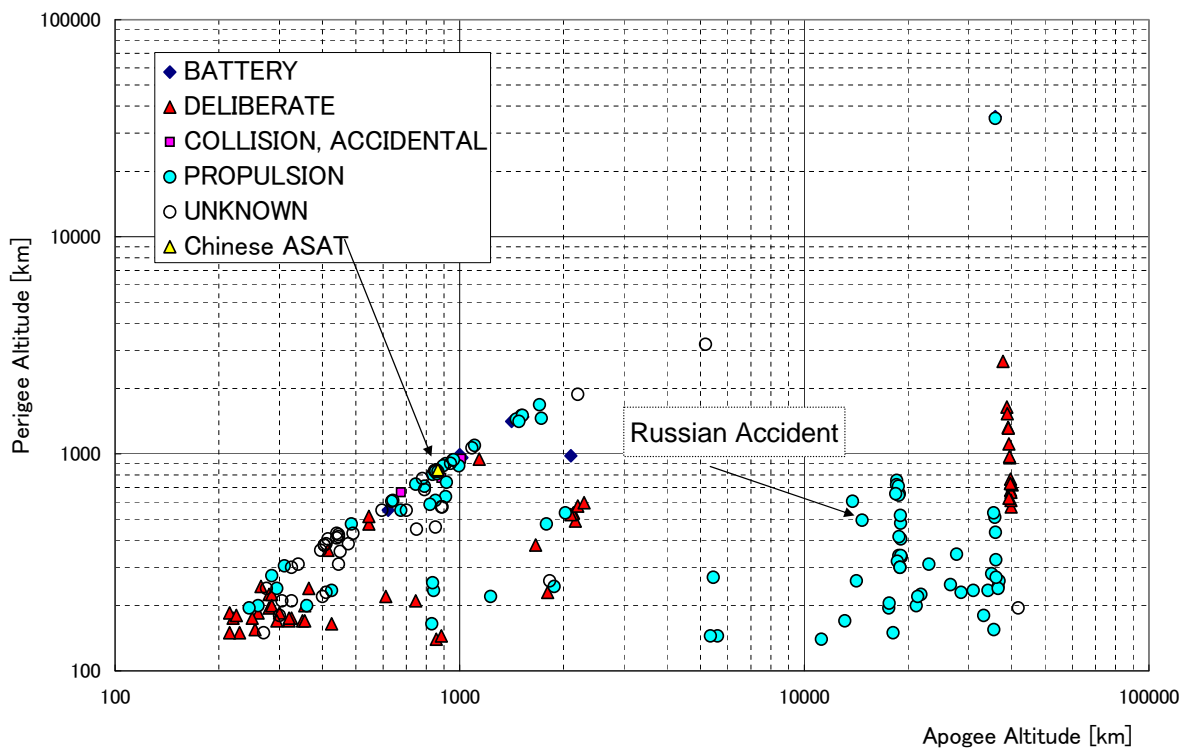
Accidental Explosion
Breeze-M-4th stage for Proton-M was drifting after failure to inject payload with at least half of the hypergolic propellant, and suddenly exploded on February 19th 2007.

Two large break-up events were occurred by
 Chinese Intentional Destruction
 and Russian Accidental Explosion

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1 Orbital Environment

1.5 Break-up Events in History @Feb. 2007



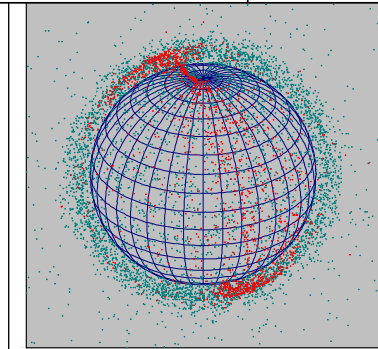
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1.6 Influence of Chinese ASAT on JAXA Spacecraft

Satellite	Altitude (km)	Number of objects		Rate of Increase (%)
		Other debris	Fragments from Fang Yun 1C	
ASTRO-EII	550	1437	336	23.4
ASTRO-F	750	2360	958	40.6
INDEX	610	1945	551	28.3
OICETS	610	1565	406	25.9
ALOS	691	2048	742	36.2
SOLAR-B	600	2123	743	35.0

Above table shows the number of objects which approach to JAXA spacecraft within $\pm 20\text{km}$ and its increasing rate by Chinese ASAT

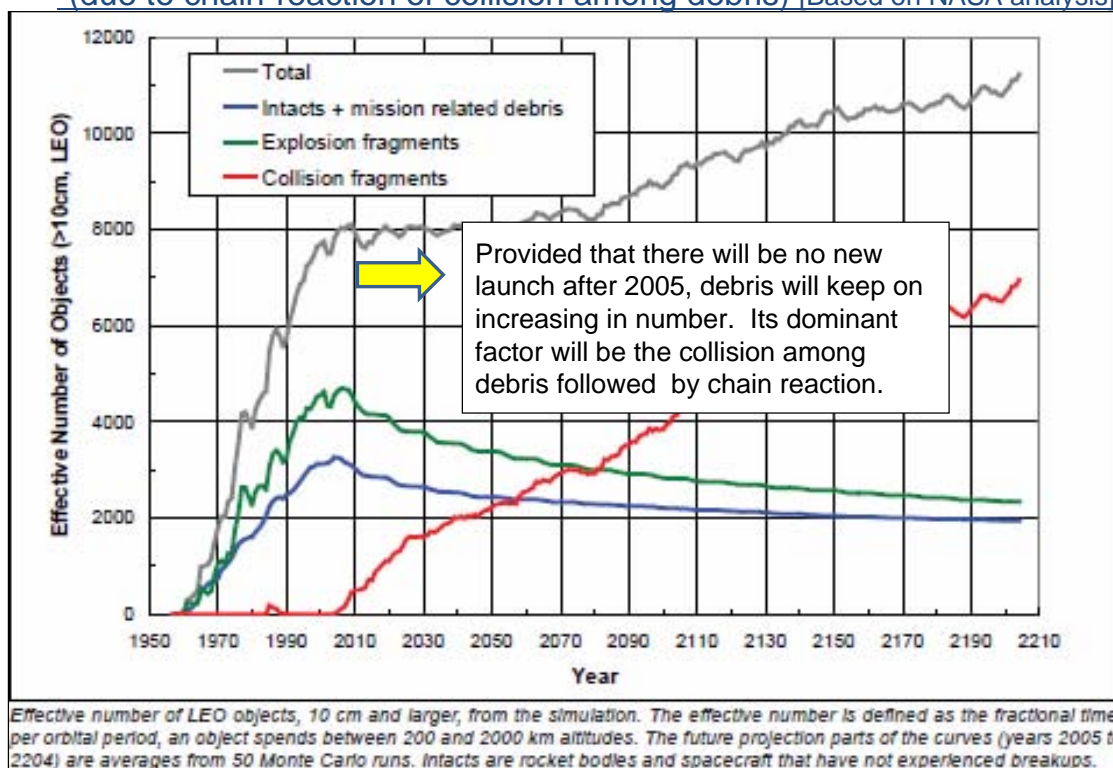
By Dr. Horii, JAXA Tracking Control Center



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1.7 Expected population growth of debris

(due to chain-reaction of collision among debris) [Based on NASA analysis]



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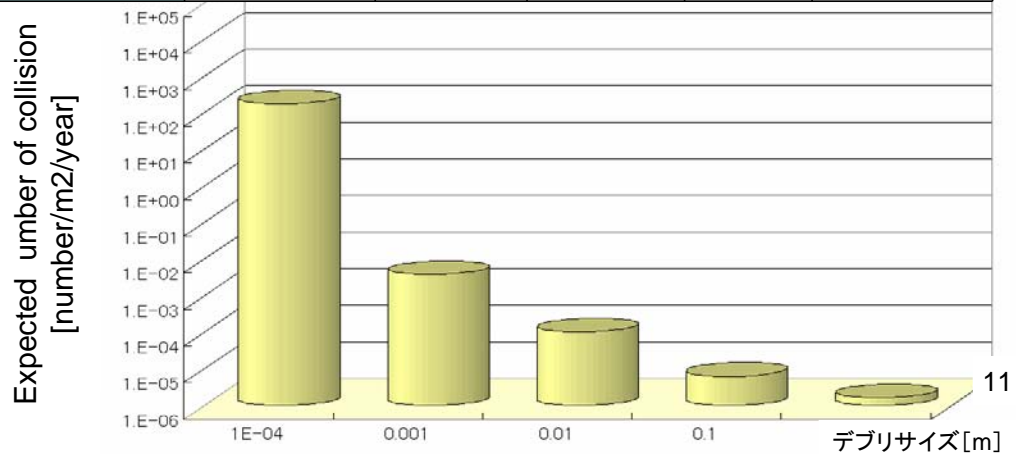
2.1 Risk in Low Earth Orbit

2 Risk by Debris

Collision probability & damage of impact

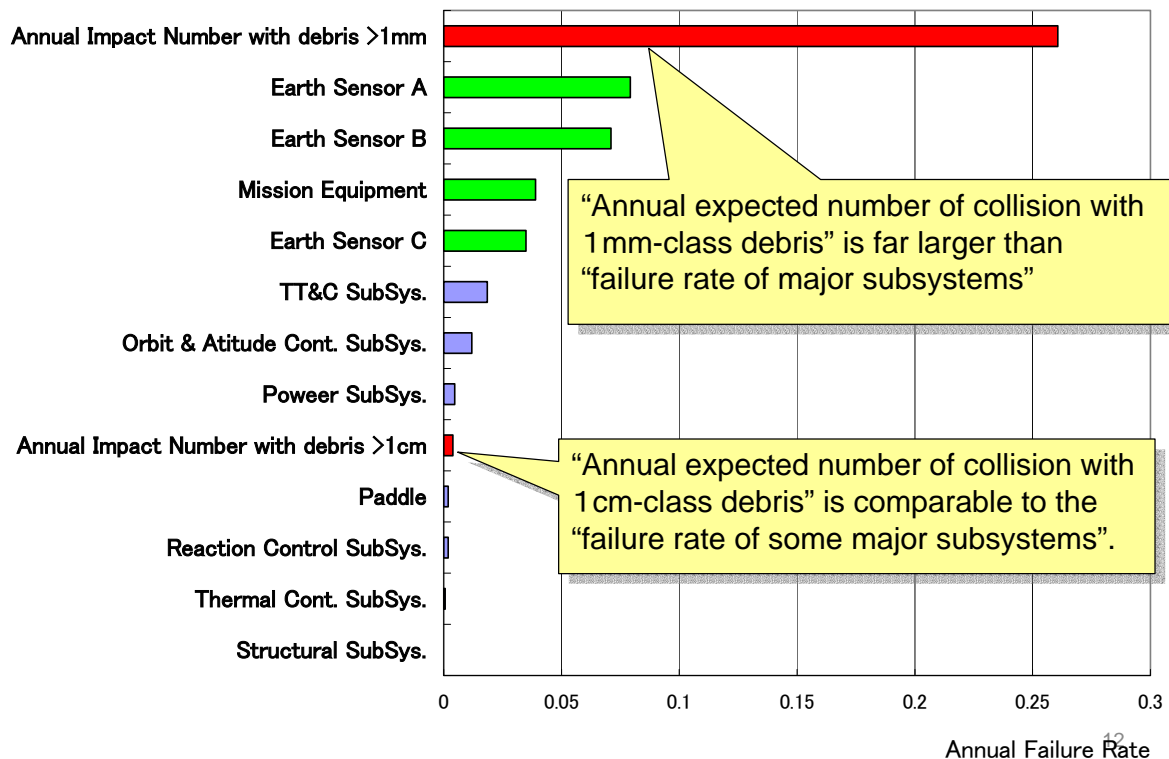
[Cross Sectional Area: 20m², Operation-life: 5 years, Altitude: 700km]

Size of Debris	0.1 mm	1 mm	1 cm	10cm	> 1 m
Damage	Degradation	partial loss of function	Loss of function	Break-up	
Expected number of Collision during 5 years	9000	0.4	0.01	0.0006	0.0001



2 Risk by Debris

2.2 Failure Rate of LEO Satellite and Number of Debris Impact

[Altitude: 600-700km, Cross Sectional Area: 20m², Based on Expected Reliability of each sub-system]

2 Risk by Debris

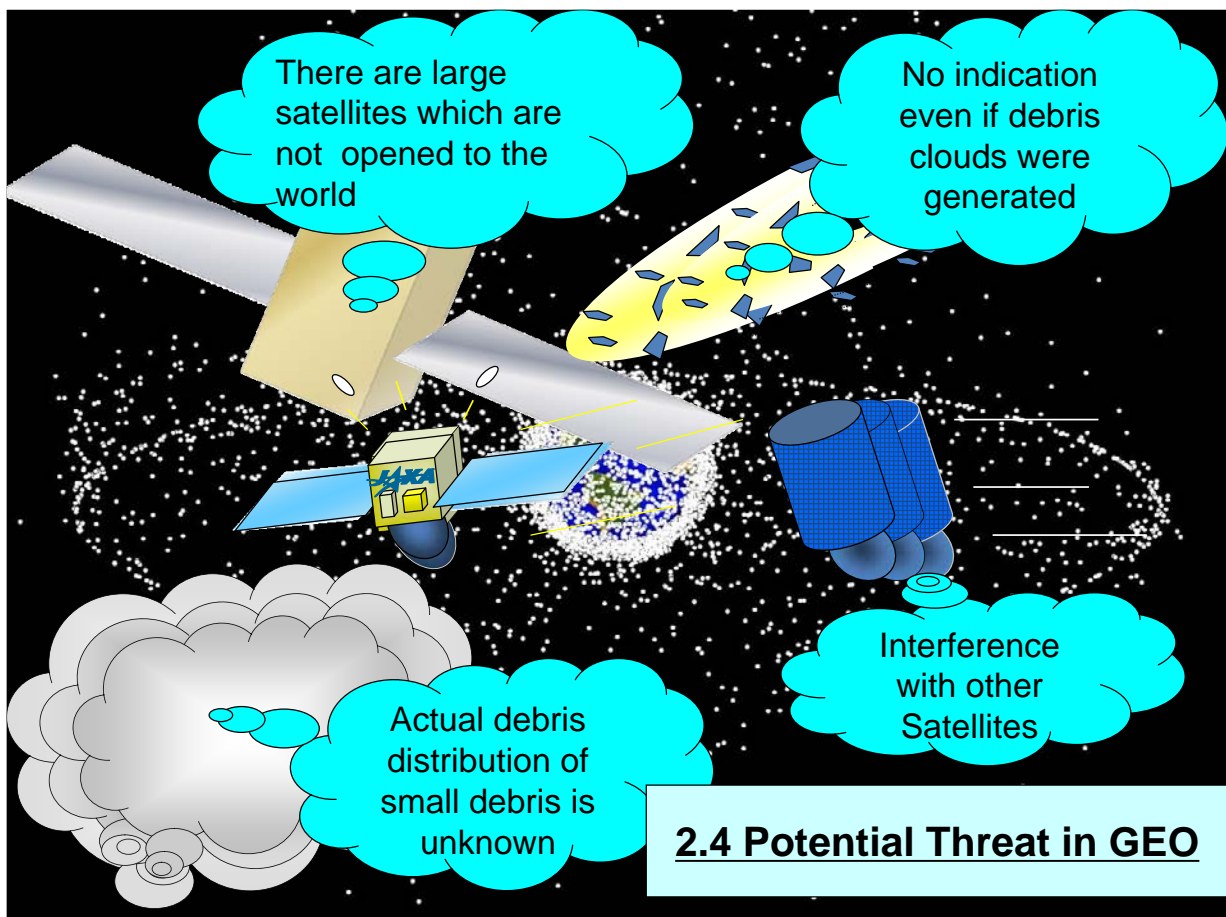
2.3 Risk Assessment Matrix for LEO satellite

requires action, required determination, requires monitor

	Minor: Degradation	Significant : Partial loss of function	Critical: Total loss of function	Catastrophic: Break-up
Probability (collisions / five years)	>1 Collision with 0.1mm class debris ⇒ protection design			Action
		Collision with 1mm class debris ⇒ protection design		
			Collision with 1cm class debris ⇒ no effective measures	
				Collision with 10cm class debris ⇒ collision avoid.

Assumptions: Cross sectional area: 20m², Risk requirement: significant failure rate shall be less than 10⁻³

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3.1 World Situation

3 Activities in the World

2.1.1 Rules and Practices

- a) In Advanced nations, international organizations, ISO, United Nations, **guidelines and standards** have been (or are being) developed.
- b) In USA and UK, space activities can 't **get license** without debris mitigation plan.
- c) In major space fairing nations, debris mitigation measure are being applied.

2.1.2 Mission Assurance

2.1.2.1 Measurement and Modeling

- a) **USA has world-wide-observation network**, and provides the data to the world.
- b) US and European agencies are accumulating data by detectors and retrieved spacecraft. Several **debris models** have been developed reflecting the data.

2.1.2.2 Prevention of Collision Damage

- a) Impact test facilities and analysis tool have been developed. Protection manuals are published. JAXA are protecting harness outside structural body in recent satellites.
- b) NASA, ESA and CNES are monitoring the conjunction of major satellite and debris and conduct **collision avoidance maneuver** if necessary.

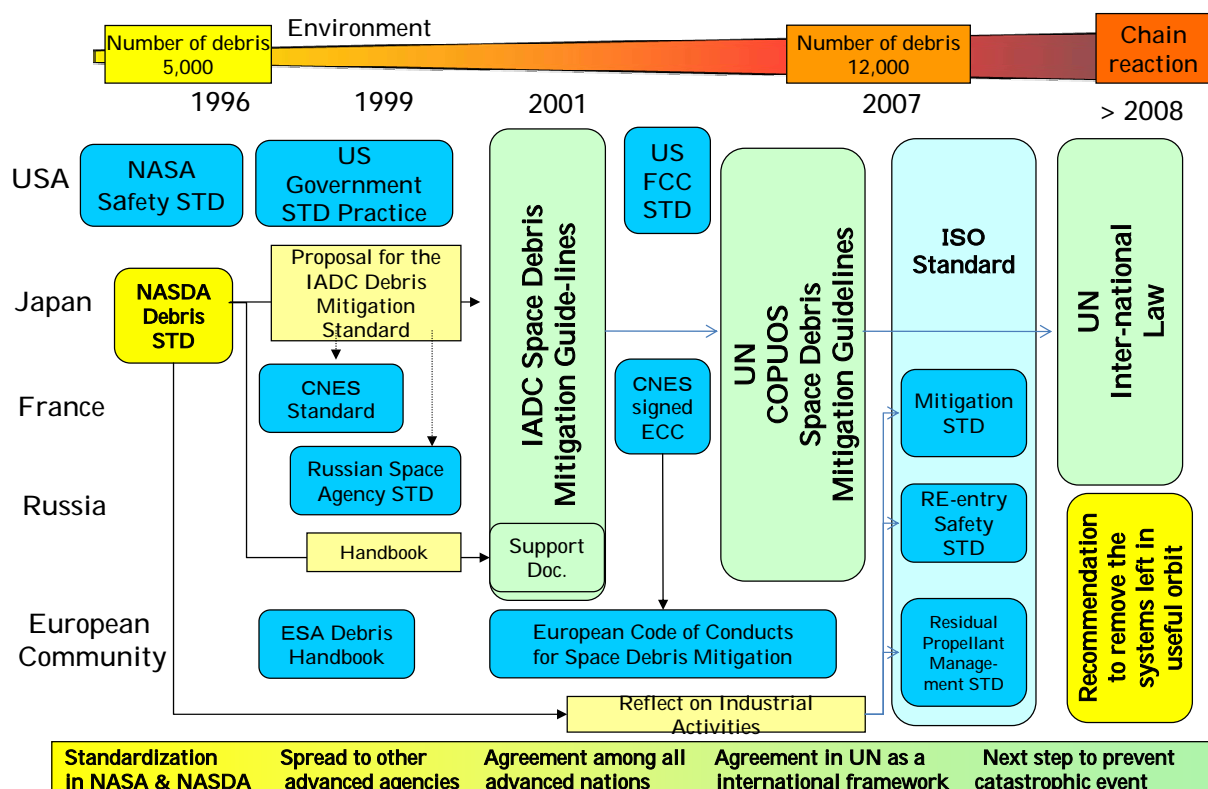
2.1.3 Ground safety

- a) Large satellites are targeted to the public ocean by **controlled re-entry**.
- b) NASA, ESA, CNES developed re-entry survivability analysis tool.

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3 Activities in the World

3.2 International Framework for Debris Control



4.1 Major Considerations for Debris Issues

(1) Mission Assurance: Mission shall be ensured by the protection measures according to the importance of the mission. Because the failure is major cause of debris generation, mission success is the best mitigation measure.

(2) Preservation of environment: To ensure sustainable space development, generation of debris shall be refrained with considering the balance with cost and reliability.

Also, ground safety from re-entering objects (as a result of deorbit) shall be ensured.

(3) International Coordination: Debris issues can not be solved by the limited nations. Then try to coordinate and corporate among international community, and contribute on the solution. Also establish the international competitive environment for industrial community with accepting fair penalty.

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4.2 Strategy for Debris Related Issues

- **Category-A: Mission Assurance**

Mission assurance to provide benefit from space activities shall have the best priority.

[Tactics: Observation and modeling, Risk assessment and management, Protection design, Monitoring of debris and Collision avoidance, etc.]

- **Category-B: Preservation of Environment and Safety Assurance on ground**

Ensure sustainable development of space activities, and ground safety from fallen objects from orbit.

[Tactics: Debris mitigation management, Estimation of future debris population, Safety control for re-entry objects, Monitoring re-entry objects, etc.]

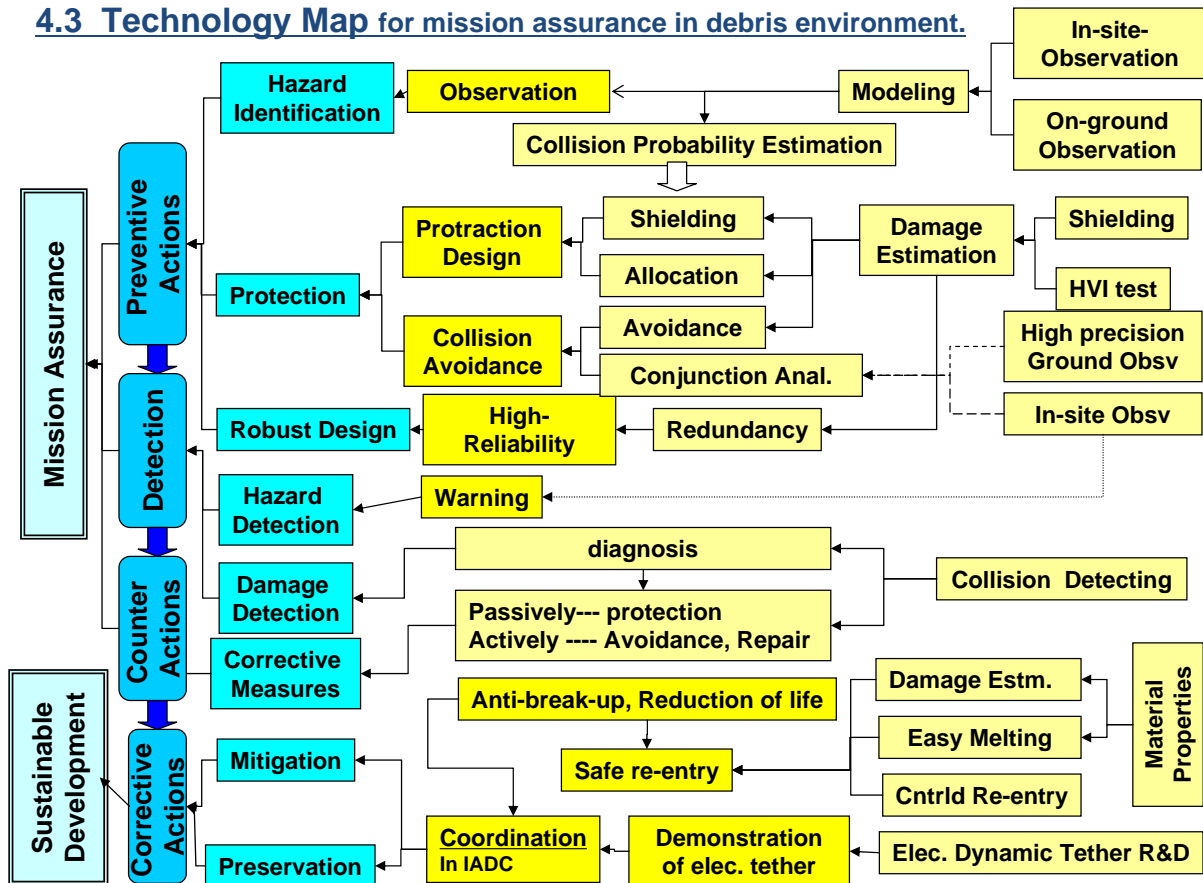
- **Category-C: Improvement of Orbital Environment**

To prevent chain reaction of debris generation by collision among orbital objects, remove disposed objects from densely populated orbital regions.

[Tactics: Removal of existing large objects by international corporation]

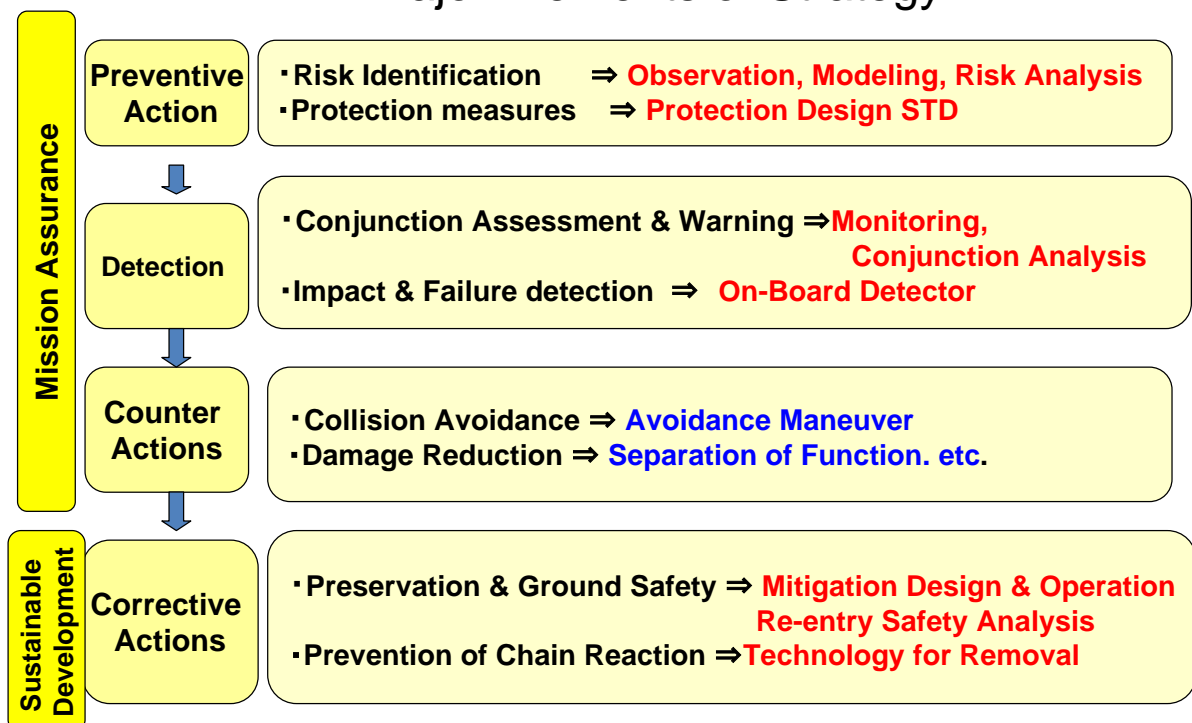
18

4.3 Technology Map for mission assurance in debris environment.



4 Strategy for Debris Issue

4.4 Major Elements of Strategy



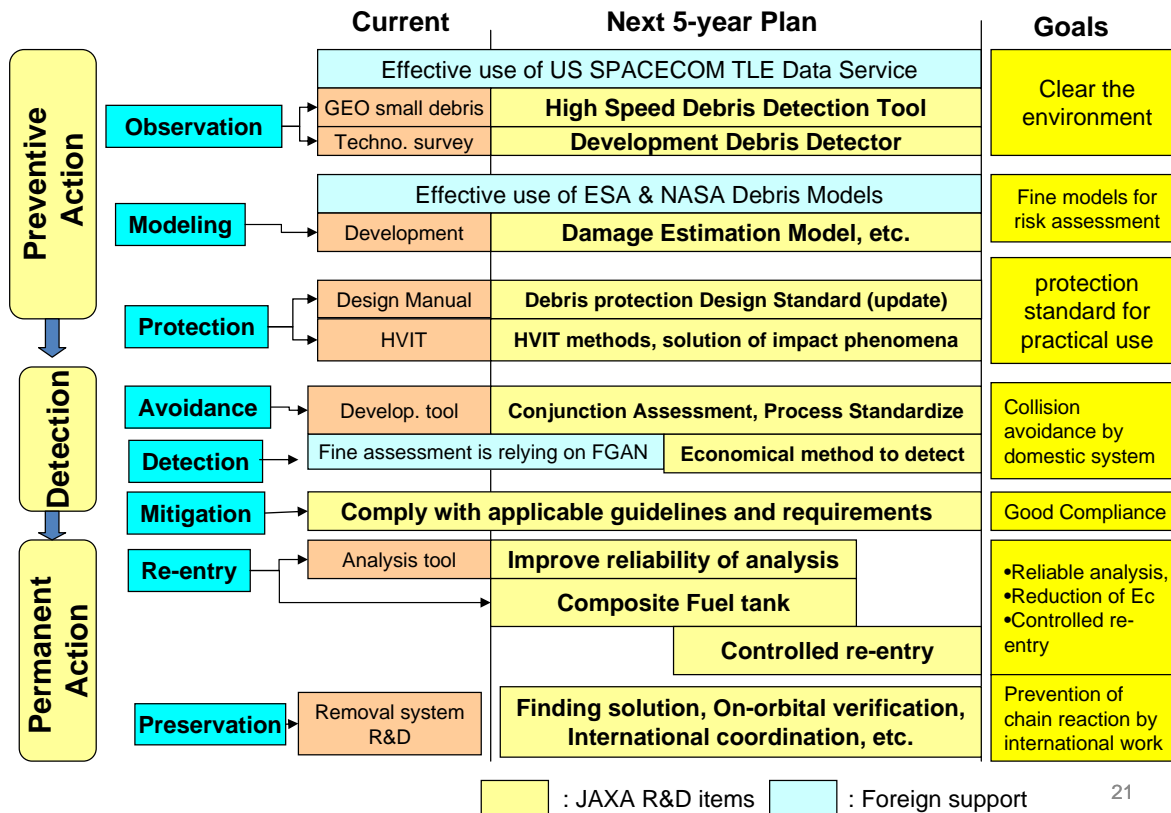
Red Parts: Primary R&D items,

Blue Parts: Vehicles and spacecraft projects team will promote.

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4.5 Roadmap for Debris Mitigation

4 Strategy for Debris Issue



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4.6.1 Mission Assurance: On-Ground Observation

4 Strategy for Debris Issue

Future Goals in 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.

Current Status

- a) The *automatic debris detection tool* for optical telescope data has been developed and wait for improving processing speed.
- b) Feasibility study to apply the optical telescope for collision avoidance is being conducted.

Corporation with the world space agencies

- a) Orbital element data of catalogued objects are expected to be provided by USA, and continued for future.

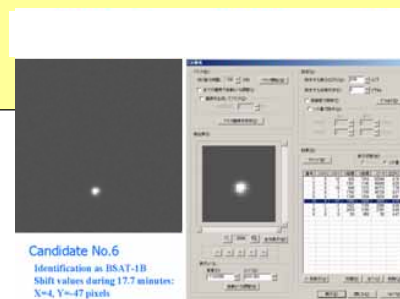


Image of the automatic debris detection tool

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4.6.2 Mission Assurance: Modeling

4 Strategy for Debris Issue

Future Goals in Modeling

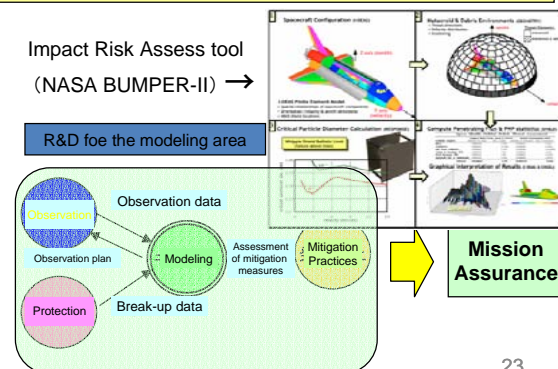
- a) Future debris population can be prospected, and adequate policy will be implemented in advance.
- b) Collision risk management will be conducted by analyzing the impact probability, damage estimation, and protection design.

Current Status

- a) *Debris Mitigation Action Assessment Tool* (DEMIST) was developed and served to JAXA projects to support debris mitigation design.
- b) A debris evolutionary model for LEO (LEODEEM) was developed.
- c) *Impact Probability Analysis Tool* will be developed and served from next April.

Relation with the world agencies

- a) Basic data for debris population is provided by foreign agencies.
- b) MASTER 2005 (and advanced version in future) and ORDEM are used to estimate collision probability.
- c) MASTER and ORDEM are not agreed in small size of objects. Yet large break-ups occurred in 2007 might have changed environment significantly.



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4.6.3 Mission Assurance: Protection Design

4 Strategy for Debris Issue

Future Goals in Protection Design

Goals in next 5-year-plan

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

Current Status

- a) Impact testing techniques was studied (correlation between shaped charge devices and gas-gun, and that among different impact velocity, etc.)
- b) Impact testing on CFRP was conducted and data was accumulated in DB.
- c) Protection Design Analysis Method is being studied for CFRP structure.
- d) Protection Design Manual is being drafted for JAXA spacecraft projects.

Relation with the world agencies

- a) The IADC Protection Manual is one of important technical bases.
- b) Impact test are conducted also in foreign facilities.

“Debris Protection” is being applied in recent JAXA satellites particularly to protect wireharness exposed to orbital environment.

(Ex. ETS-8, WINDS, ALOS)

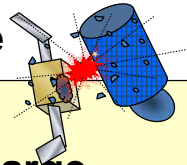


To keep technique and facilities in Japan which assure to conduct various types of impact test is also a important matter for this projects.

4.6.4 Mission Assurance: Collision Avoidance

Future Goals in Collision Avoidance

Prevent collision between major satellites and large debris by avoidance maneuver

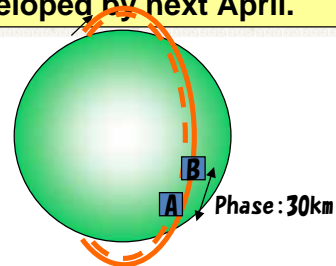


Current Status

- a) For major JAXA satellites the conjunction assessment are being conducted every day. Particularly for ALOS the conjunction probability is notified by e-mail. If the probability would exceed 0.001 the German FGAN radar will be used to confirm the necessity for avoidance maneuver.
- b) The JAXA Conjunction Analysis tool will be developed by next April.

Relation with the world agencies

- a) The conjunction assessment is provided by US, which will be replaced to a JAXA tool in next April.
- b) Fine conjunction assessment is done with using FGAN RADAR.
- c) Orbital characteristics of orbital objects are provided by US-SSN.



To separate the phase distance (@ prediction epoch of collision) by about 30km

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4.6.5 Mission Assurance: Debris Detector

4 Strategy for Debris Issue

Future Goals in Debris Detector

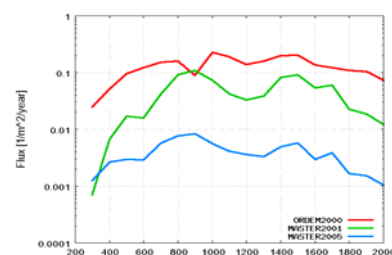
- a) The debris detector will be launched to confirm debris distribution. The debris larger than $100 \mu\text{m}$ will be detected with its size, and the data will be sent to the ground. The data will contribute on the world debris models.

Current Status

- a) Population of debris, whose size is $100 \mu\text{m} \sim 1\text{mm}$, is not agreed in the world agencies. Especially after Chinese Destructive Experiment, world debris models are forced to be revised for practical use. The catalogued debris population has increased up to 40% in a certain orbital region.
- b) At the conceptual design of the Debris Detector, one method has been selected. (If debris would damage the part on fine mesh of harness, the damage area will indicate the size of impact debris.)

Relation with the world agencies

- a) JAXA are enjoying great benefit from the foreign Debris Engineering Models such as MASTER 2005 and ORDEM2000, but has not contributed on them enough.



Disagreement in MASTER and ORDEM

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4.6.6 Ground Safety

Future Goals in Ground Safety after deorbit

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

Current Status

- a) A re-entry analysis tool has been improved in analysis functions, human-interface, utility programs, and support documents.
- b) Re-entry risk objects (heavier than 1000 kg) are monitored and re-entry time prediction are being conducted to estimate the risk to Japan.
- c) Related database (material property, human distribution) are improving.
- d) A composite fuel tank is planned to be developed which demises easily.

Relation with the world agencies

- a) NASA provided a re-entry survivability analysis tool (ORSAT), and has provided technical assistance to JAXA to improve it.
- b) JAXA is proposing a "IADC Standard Process for Re-Entry Risk Assessment" to ensure better accountability to the rest of world.



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

4.6.7 Preservation and improvement of the environment

Future Goals in Electrodynamic Tether system

- First step: The tether will apply to large satellites as an economical deorbit devices.
- Final Step: Mission terminated constellation satellites will be removed by an international project.

Current Status

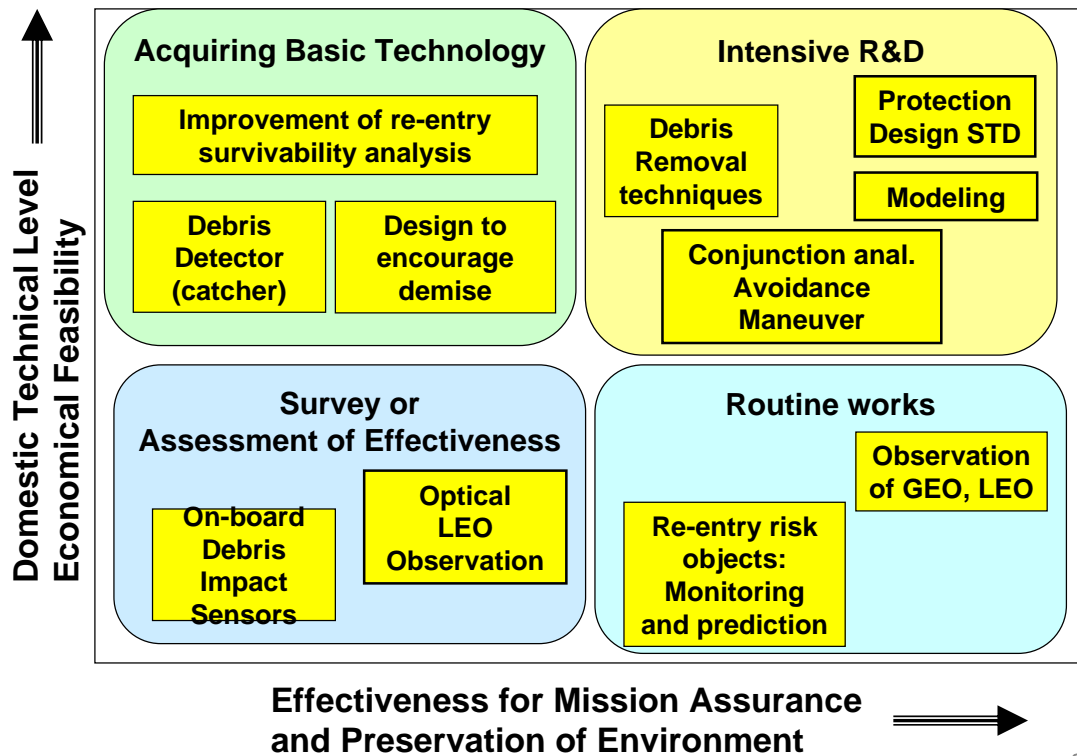
- a) The electrodynamic tether system has been studied, and the technology seems to be matured only to wait a chance to demonstrate in orbit.
- b) As explained in p7, chain reaction of orbital collision shall be prevented in near future.

Relation with the world agencies

- a) IADC studied the benefit and risk of tether system and reported that "the system has strong potential to become effective mitigation measures, but various problems are still to be solved".



4.7 Portfolio for Debris Related R&D items



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5. Conclusion

- International consensus to mitigate debris seemed to be established. But ambitious of a few nations to create new power balance sometimes sacrifice the environment.
- Even if the international guidelines would reduce the growth of debris, the chain reaction of collision among debris would deteriorate the environment in future. ⇒ It might be essential to remove existing debris by the international corporation.
- There is a disagreement among the world debris models in small size. Also recent explosions might cause greater disagreement with models and actual figure. ⇒ Debris detector will help to know the actual environment. JAXA will provide the data to the world, and contribute on improvement of the world models.
- R&D Strategy would identify important three areas as (1) Mission Assurance, (2) preservation of environment and ground safety, (3) Improvement of environment.

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I1-2 Orbital Debris Research in the United States

Gene Stansbery

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Abstract

The United States has one of the most active programs of research of the orbital debris environment in the world. Much of the research is conducted by NASA's Orbital Debris Program Office at the Johnson Space Center. Past work by NASA has led to the development of national space policy which seeks to limit the growth of the debris population and limit the risk to spacecraft and humans in space and on the Earth from debris. NASA has also been instrumental in developing consistent international policies and standards. Much of NASA's efforts have been to measure and characterize the orbital debris population. The U.S. Department of Defense tracks and catalogs spacecraft and large debris with its Space Surveillance Network while NASA concentrates on research on smaller debris. In low Earth orbit, NASA has utilized short wavelength radars such as Haystack, HAX, and Goldstone to statistically characterize the population in number, size, altitude, and inclination. For higher orbits, optical telescopes have been used. Much effort has gone into the understanding and removal of observational biases from both types of measurements. NASA is also striving to understand the material composition and shape characteristics of debris to assess these effects on the risk to operational spacecraft. All of these measurements along with data from ground tests provide the basis for near- and long-term modeling of the environment. NASA also develops tools used by spacecraft builders and operators to evaluate spacecraft and mission designs to assess compliance with debris standards and policies which limit the growth of the debris environment.

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Orbital Debris Research in the United States

**Gene Stansbery
Program Manager**

**NASA Orbital Debris Program Office
Lyndon B. Johnson Space Center**

January 2008

National Aeronautics and Space Administration

Presentation Outline



- 1. Policies and Standards**
- 2. Tracking and Catalog Maintenance**
- 3. Characterization (Measurements) of Small Debris**
- 4. Near and Long Term Environment Modeling**
- 5. Satellite Reentry Risk Assessment**
- 6. Debris Assessment Software (DAS) 2.0**
- 7. Threat Assessment**



United States Space Policy

- President Ronald Reagan's update of the U.S. National Space Policy, signed January 5, 1988, was the first White House declaration to address specifically the topic of orbital debris and to recognize the need for its mitigation to preserve near-Earth space for future generations.
- Each succeeding president has updated and expanded upon this directive in subsequent national space policies.
- The most recent, signed by President George W. Bush on August 31, 2006 states:

Orbital debris poses a risk to continued reliable use of space-based services and operations and to the safety of persons and property in space and on Earth. The United States shall seek to minimize the creation of orbital debris by government and non-government operations in space in order to preserve the space environment for future generations. Toward that end:

- *Departments and agencies shall continue to follow the United States Government Orbital Debris Mitigation Standard Practices, consistent with mission requirements and cost effectiveness, in the procurement and operation of spacecraft, launch services, and the operation of tests and experiments in space;*
- *The Secretaries of Commerce and Transportation, in coordination with the Chairman of the Federal Communications Commission, shall continue to address orbital debris issues through their respective licensing procedures; and*
- *The United States shall take a leadership role in international fora to encourage foreign nations and international organizations to adopt policies and practices aimed at debris minimization and shall cooperate in the exchange of information on debris research and identification of improved debris mitigation practices.*



USA Government Orbital Debris Mitigation Standard Practices

- Approved in 2002 and applicable to all US Government Agencies

Objectives*

- Objective 1 – Control of Debris Released During Normal Operations
- Objective 2 – Minimizing Debris Generated by Accidental Explosions
- Objective 3 – Selection of Safe Flight Profile and Operation Configuration
- Objective 4 – Postmission Disposal of Space Structures

* Full text provided in backup charts

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New NASA Orbital Debris Mitigation Requirements and Standards



- **Effective 17 August 2007 a new NASA Procedural Requirements for Limiting Orbital Debris (NPR 8715.6) superseded NASA Policy Directive 8710.3B as the principal, top level agency guidance on orbital debris mitigation.**
- **NPR 8715.6 includes several new requirements:**
 - Formal End-of-Mission plans are required prior to launch and are to be up-dated during the mission as events warrant, e.g., in the case of spacecraft system degradations.
 - Prompt notifications are required in the event of intended or unintended generation of orbital debris.
 - Vehicles flying to the Moon, Mars, and Earth-Sun Lagrangian points are now addressed.
 - Routine conjunction assessments required for all maneuverable spacecraft in LEO and GEO.

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New NASA Orbital Debris Mitigation Requirements and Standards (cont.)



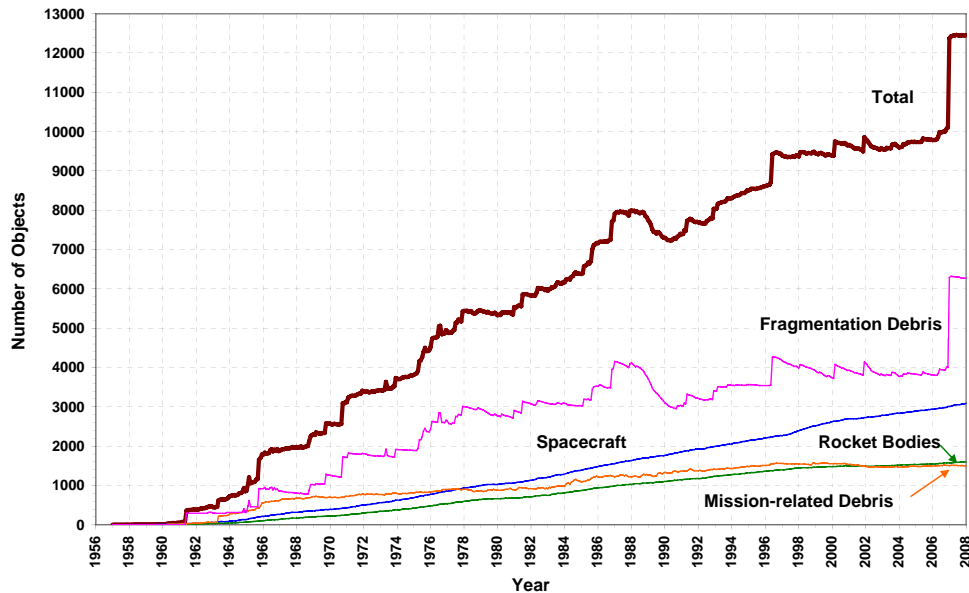
- **Also in August 2007, NASA Technical Standard 8719.14 replaced NASA Safety Standard 1740.14 as the source of detailed orbital debris mitigation requirements for each NASA space program or project.**
- **No major new requirements added, but noteworthy changes include**
 - Disposal orbits of GEO spacecraft must not come within GEO + 200 km for at least 100 years.
 - Spacecraft are limited to 25 years in LEO after mission termination but no more than a total of 30 years after launch.
 - Potentially injurious reentering debris defined as having kinetic energy of 15 Joules or greater.
 - Human casualty risk from reentering debris now evaluated by explicit probability of injury rather than debris casualty area. Desired limit of risk remains 1 in 10,000 per reentry event.

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Tracking and Catalog Maintenance

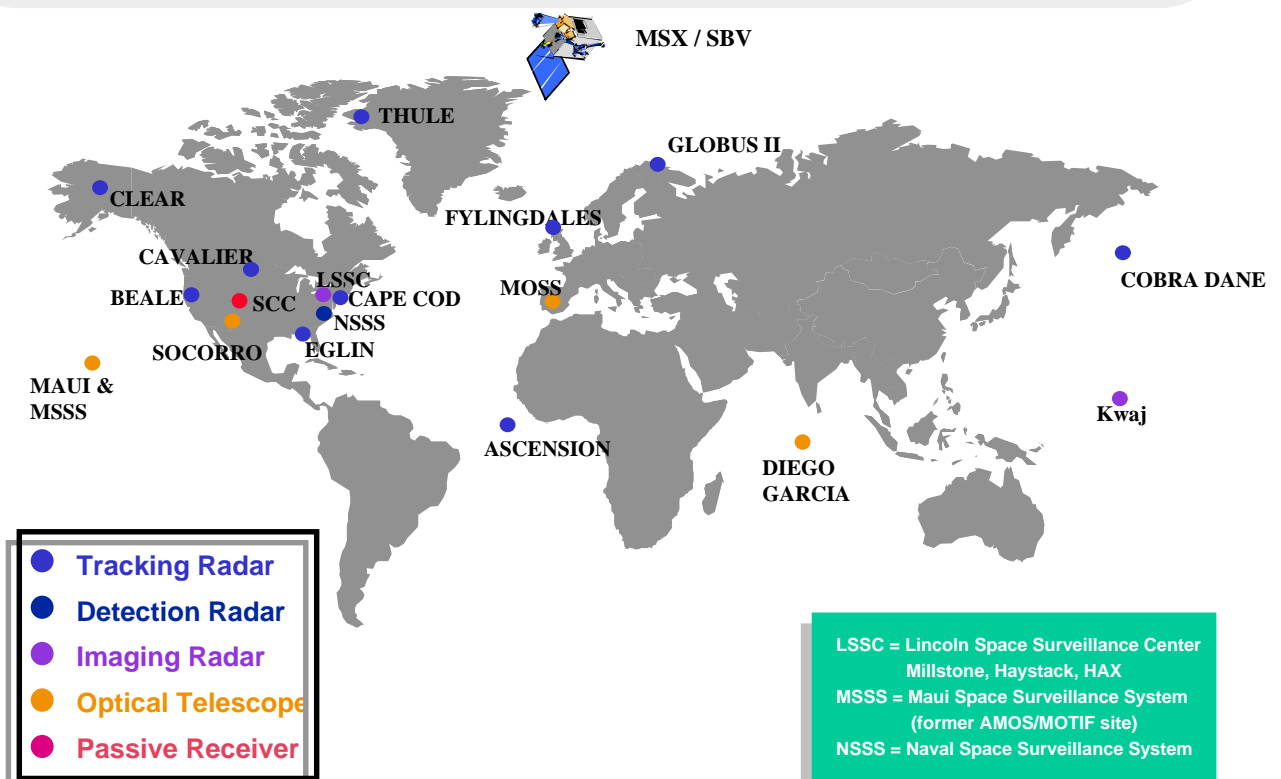
- The US Department of Defense maintains a worldwide network of sensors which catalogs and tracks man-made orbital debris
 - Although some cataloged debris is as small as 5 cm diameter, the nominal size of debris in the catalog is 10 cm in low earth orbit and 1 m at geosynchronous altitudes
 - Catalog currently has more than 12,000 objects in orbit



7



US Space Surveillance Network



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Haystack and HAX Radars

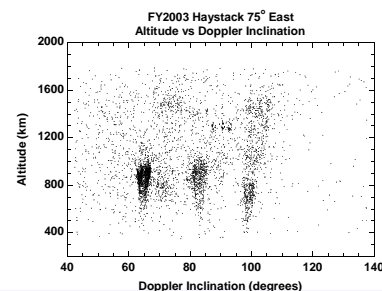
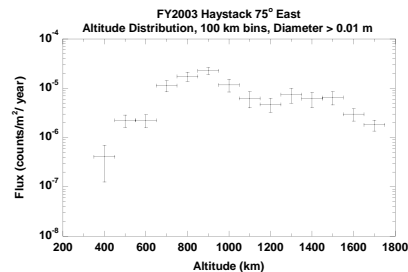
Orbital Debris Radar Observations – Objective

- Haystack and HAX are the prime sources of data for orbital debris smaller than 10cm. Haystack and HAX collect debris data in the critical size region between 1cm and 10cm.
- Both radars annually collect between 500 hours to 700 hours of debris observation data which provides enough statistics for developing orbital debris models.



Radar Description

- Collocated in Tyngsboro, Massachusetts at a latitude of 42.6°.
- The main reflector of the Haystack and HAX radars are 36.6m and 12.2m diameter, respectively.
- A pulsed continuous wave (CW) single frequency waveform is used for debris detection. Haystack transmits X-band and HAX transmits K-band.
- Both radars observe a range window of ~ 300 to 1900 km.
- Haystack can observe debris down to 5 mm and HAX can observe down to 2cm for LEO observations.



Data Collection and Processing

- NASA conducted the Orbital DEbris RADar Calibration Spheres (ODERACS) experiments on two space shuttle missions in 1994 and 1995 to validate data processing at NASA JSC.
- The experiments showed that the Haystack radar is calibrated within nominal limits, with measured RCS values accurate to ± 1.5 dB.



Goldstone Radar

Goldstone Radar Overview

- The NASA Jet Propulsion Laboratory Goldstone radar is used on a limited basis to supplement orbital debris observations made by Haystack and HAX.
- Collects nearly 100 hours of data annually
- Goldstone provides a measurement of the debris environment between 2 mm and 1 cm.

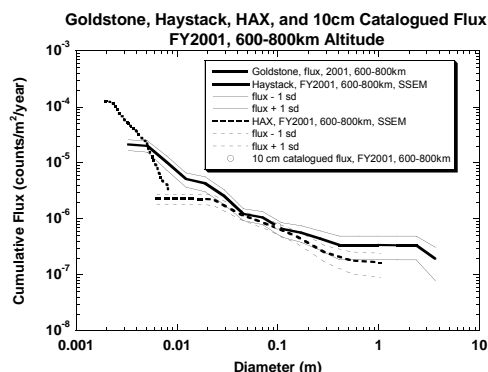
Radar Description

- Collocated in southern California's Mojave desert at a latitude of 35.2°.
- Pairs of up chirp and down chirp X-band pulses are used for debris detection.
- Observable range window of ~ 350 to 3300km.
- Observable range rates of ± 0.85 km/s.
 - This dictates a staring observation mode near the zenith which makes Doppler inclination measurements unreliable.
 - Upgrades to the data acquisition system are currently being tested to increase the observable range rates. This would allow pointing away from the zenith and hence a reliable Doppler inclination measurement.
- The radar cross section measurements have greater uncertainties than that of Haystack or HAX since the Goldstone radar:
 - does not calibrate using a calibration satellite
 - does not have a monopulse system to determine the position of the debris within the radar beam.



Data Collection and Processing

- The data collected at the radar is processed at JSC using software supplied by JPL.
- The processed data is thoroughly inspected at JSC for quality control before subsequent extensive analysis.

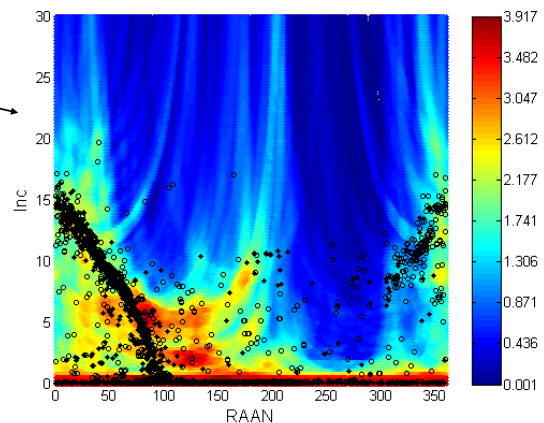
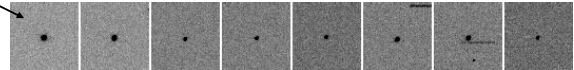


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Michigan Orbital Debris Survey Telescope (MODEST)



- **GEO debris survey telescope (0.6/0.9 Schmidt Telescope)**
- **Located near La Serena, Chile at the Cerro Tololo Inter-American Observatory (CTIO)**
- **Collecting data since 2002**
- **Data used in modeling of the future environment (sample data shown middle right)**
- **Limiting Magnitude $\sim 19 M_v$ in R (corresponding to a size of 30 cm if you assume 0.13 albedo)**
- **Figure (bottom right) shows a probability map of where we have looked and the detections seen**
 - Red shows the orbit planes that were the most visible, while blue shows the orbit planes that were the least visible
 - Solid diamonds are correlated targets and the open circles are uncorrelated targets
- **Status of Survey Project**
 - Collecting survey data every observing run
 - Collecting light curve data in specific photometric bands on uncorrelated targets
 - Use of two telescopes to refine orbits and the orbit determination process
- **Special Projects – High Area-to-Mass (A/m)**
 - Joint project through IADC for objects of high A/m
 - Following IADC high A/m objects at sites around the world for a more complete orbit
 - Efforts being made to determine source and material of these objects



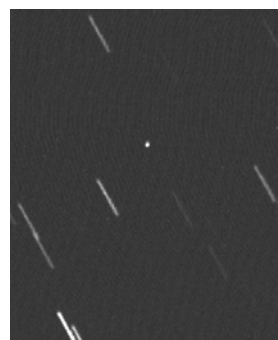
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GEO/LEO Observations from Kwajalein Atoll



- **GEO**
 - Comprehensive assessment of debris environment
 - High A/m debris
 - Determination of orbital parameters as inputs to NASA's environment model
 - Current capability
 - Broadband color photometry of targets to 16th magnitude (~ 50 cm diameter) via an autonomous 0.35 m telescope (an element of the AFRL High Accuracy Network Determination System – HANDS).
 - Planned capability
 - Designing a 1 m, 0.88 deg FOV autonomous survey telescope (Meter Class Autonomous Telescope - MCAT to be installed 3Q 2010) for detection and multi-spectral (Optical/NIR) photometry of targets to 20th magnitude (10 cm diameter)
- **LEO**
 - MCAT will detect new LEO debris and enable a statistical assessment of the low-inclination (0-20 deg) debris environment in the 1-10 cm diameter size regime

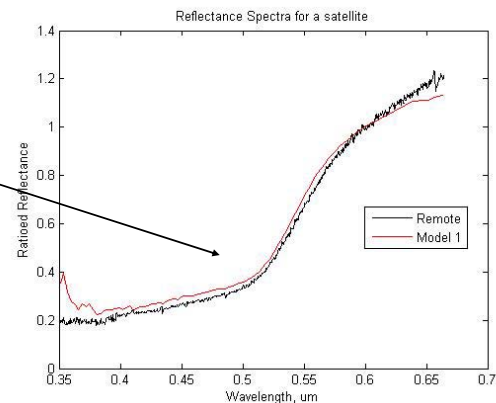
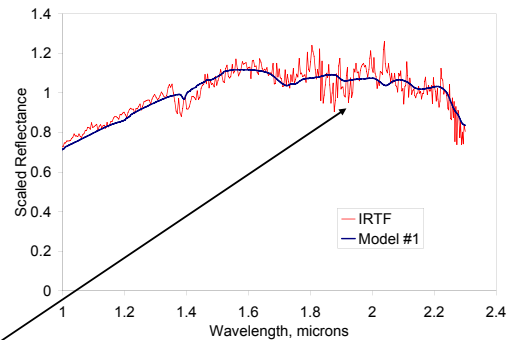


12



Spectral Studies

- **Use reflectance spectroscopy in the visible and near-infrared to determine the surface material of space objects**
 - Knowledge of material yields better size estimation data
- **Each material has specific absorption features that make it unique**
 - Using those features, as well as slope, creates a model for materials that best fits the spectrum taken of the object in space
- **Results**
 - Placed objects into categories based on spectral response
 - See example on top right, where the object was thought to be either an asteroid or a human-made object
 - Determined to be human-made due to spectral signature of white paint
 - Measured pristine spacecraft prior to launch and looked at space weathering of materials
 - See example at the bottom right, where the model is based on pre-flight measurements showing great agreement in slope and absorption features
 - Received first data on debris objects (all large pieces)
- **Status of the project – Work in Progress**
 - Continued material modeling
 - Determine cause of the unexpected increase in slope for remote measurements as compared to laboratory measurements
 - Taking ground truth data on spacecraft prior to launch to get better idea of changes in material spectra
 - Obtain more remote measurements of cataloged objects and debris

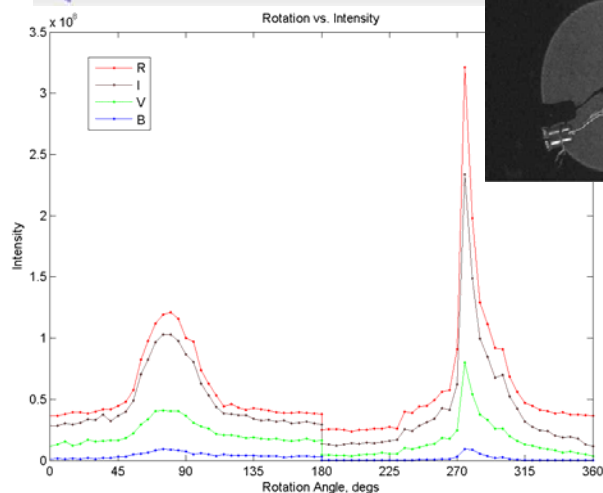
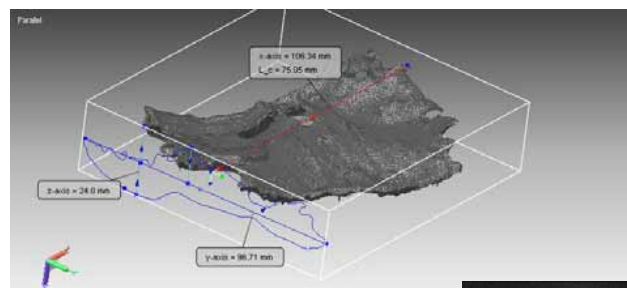


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Optical Measurement Center (OMC) and 3D Scanner



- **Goal**
 - OMC
 - To develop an optical size estimation model comparable to the existing radar size estimation model and a photometric database of samples similar to orbital debris
 - 3D Scanner
 - To clearly define the measuring techniques of samples and establish a digital database for future and current users
- **Current work**
 - 3-D Handyscan establishes a characteristic length and digital image of each sample, where X, Y, Z are the three orthogonal projections of a object as seen in top figure.
 - $L_c = 1/3(X+Y+Z)$
 - Sample is placed in robotic arm, illuminated with a pseudo-solar spectrum lamp, and rotated through various phase angles as seen in middle figure.
 - Photometric light curve data is collected with Johnson/Bessell filters (BVRI) on a CCD as shown in bottom-right figure.
 - Photometric light curves are analyzed along with results from spectroscopic data to determine material type and shape
- **Future work**
 - Determining the size of the object from these light curves



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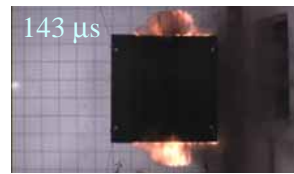
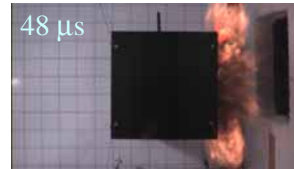
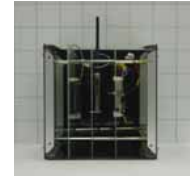
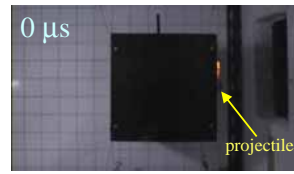
Joint NASA-Japan Satellite HVI Tests

Objectives

- To better characterize fragment size, shape, and material density distributions

Status

- Five tests conducted on similar micro satellites (V_{low} and V_{hyper}) since 2005
- About 1500 fragments were collected per test
- Each fragment was measured and photographed; selected fragments will be scanned and measured for additional shape, photometric, and spectral data
- Plan to test a larger satellite (50×50×50 cm) covered with MLI is under review



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NASA Orbital Debris Engineering Model: ORDEM2007

The ORDEM series of models is in the process of an upgrade to ORDEM2007

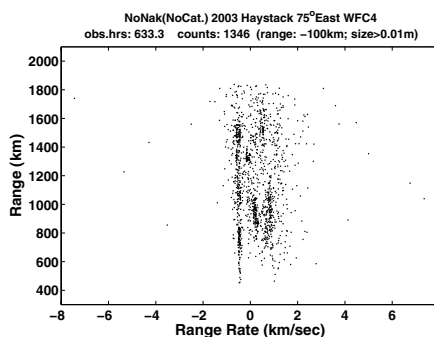
- Time range – 1995 to 2035
- Altitude range – 200 km to 38000 km
- Size range – 10 μm to 1 m

Main Datasets and complementary Models

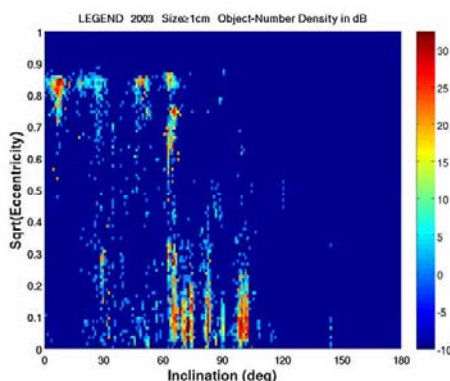
- SSN, Haystack, STS window impacts, MODEST
- LEGEND, NaKModule, SRMSlag, Degradation/Ejecta

Statistical estimation of ORDEM2007 OD populations

- The Bayesian algorithm developed in the statistical size estimation model (SSEM) is used throughout
 - Particularly suitable for data in the form of counts
- Based on reference populations such as LEGEND, NaK Module, SRM slag model ...
- Populations estimated for each year from 1995 to 2035



Haystack
Detections:
Fragments
size ≥ 1 cm
FY2003



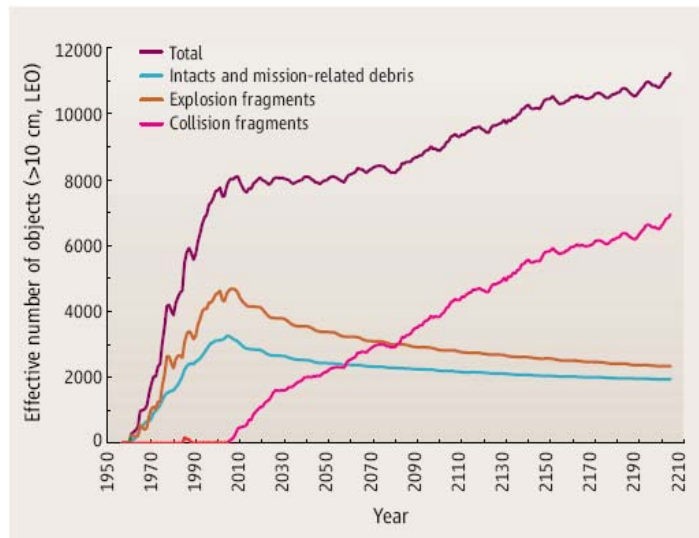
Estimated
Population:
(orbital
distribution)
Fragments
size ≥ 1 cm
FY2003

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LEGEND (A LEO-to-GEO Environment Debris Model)

- **A state-of-the-art orbital debris evolutionary model**
 - Can mimic the historical environment, and project it into the future (based on user-selected scenarios)
 - Has a fast pair-wise comparison algorithm to estimate P_{col} among orbiting objects
 - Includes two reliable orbit propagators for GEO and LEO/GTO objects
 - Uses the NASA Standard Breakup Model to create simulated breakup fragments
 - Is the tool for the study published in *Science*, and the latest active debris removal analysis



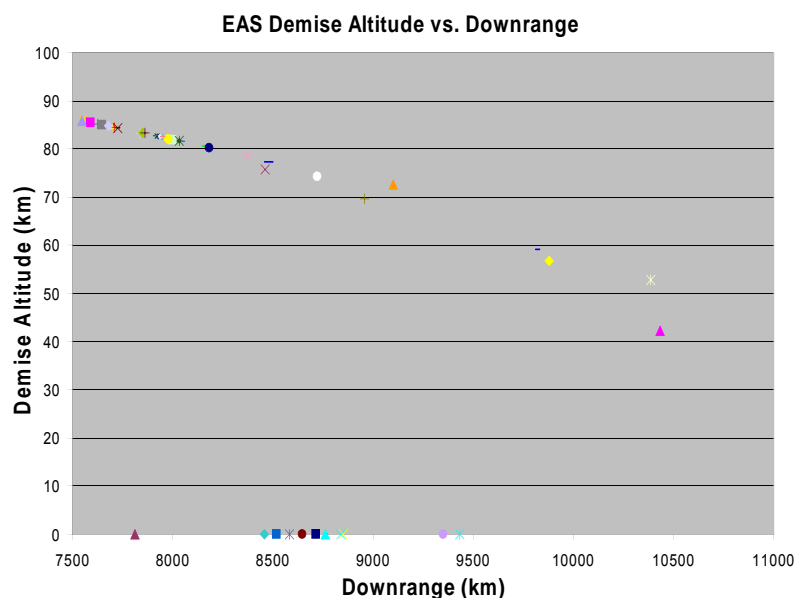
Growth of future debris populations. Effective number of LEO objects, 10 cm and larger, from the LEGEND simulation. The effective number is defined as the fractional time, per orbital period, an object spends between 200- and 2000-km altitudes. Intacts are rocket bodies and spacecraft that have not experienced breakups.



Satellite Reentry Risk Assessment

Object Reentry Survivability Analysis Tool (ORSAT)

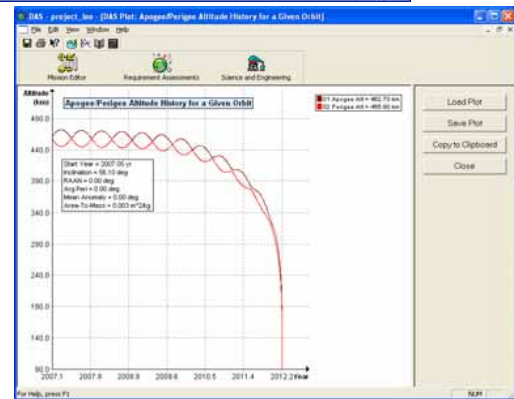
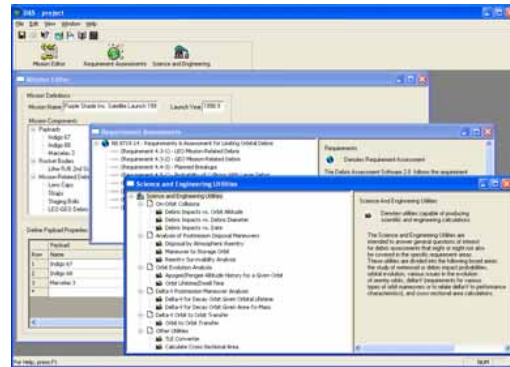
- This code is used to generate trajectory, atmosphere, aerodynamics, aeroheating, thermal, and ablation response of objects during a simulated Earth reentry
 - Predict demise altitude of objects which burn-up during reentry
 - Computes footprint and debris casualty area of items which do not burn up
- **ORSAT Debris Assessments of note**
 - Hubble Space Telescope
 - Atlas V and Delta IV Rocket Bodies
 - Tropical Rainfall Measuring Mission (TRMM)
 - National Polar-orbiting Operational Environment Satellite System (NPOESS)
 - Compton Gamma Ray Observatory (CGRO)
 - Early Ammonia Servicer (EAS) (ISS Jettison)





Debris Assessment Software (DAS) 2.0

- **NASA's DAS 2.0 is designed to assist NASA programs in performing orbital debris assessments.**
 - Assessment requirements are described in NASA-STD 8719.14 "Process for Limiting Orbital Debris"
 - DAS 2.0 addresses most requirements point-by-point
- **Recent upgrades to DAS for the 2.0 version include:**
 - Improvements to the orbit propagators and debris environment model
 - Improvements to the reentry survivability model and casualty estimation method
 - Improvements to the user interface and documentation
 - Recommendations from users of the current DAS (1.5.3)
 - Changes in the debris mitigation guidelines

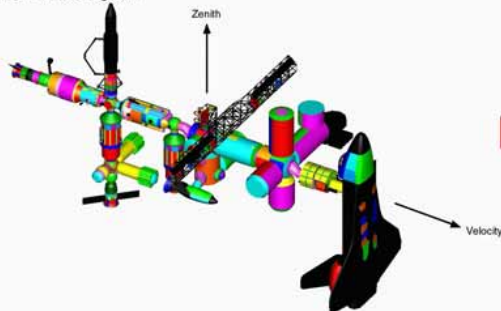


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NASA/JSC BUMPER-II Meteoroid/Debris Threat Assessment Code

Spacecraft Configuration (I-DEAS Finite Element Model)

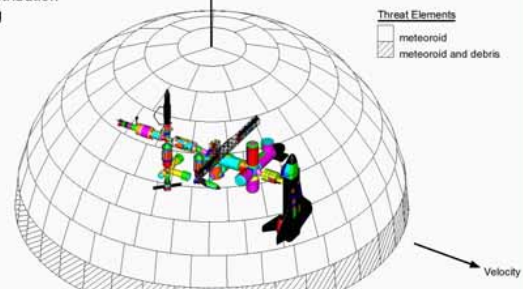
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines M/OD shield regions



• Approximately 120,000 elements in ISS assembly complete mated configuration FEM

Meteoroid & Debris Environments (GEOMETRY)

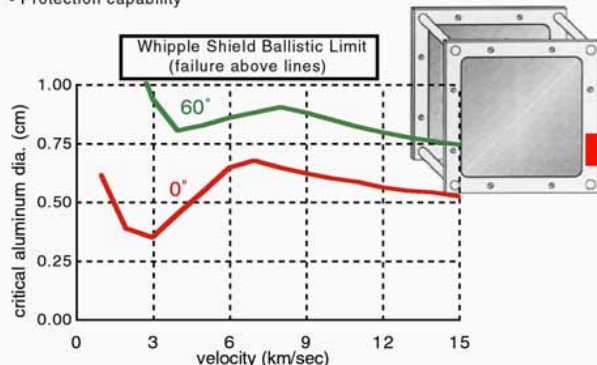
- Threat directions
- Velocity distribution
- Shadowing



• 90 debris threat cases and 149 meteoroid threat cases assessed for each element in the FEM

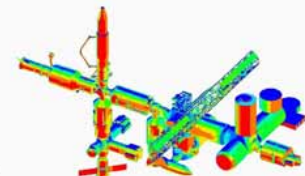
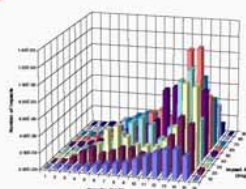
Critical Particle Diameter Calculation (RESPONSE)

- Protection capability



Computation of Penetrating Flux and PNP (SHIELD) Graphical Interpretation of Results (EXCEL & I-DEAS)

Space Station Orbital Debris Threat Assessment				
Station Region	Impact Risk From 1mm Ø Debris		Debris Penetration Risk	
	Probability No Impact	Odds of Impact	Probability No Penetration	Odds of Penetration
FGB	0.995338	1/214	0.995341	1/224
Service Module	0.999335	1/1505	0.999796	1/4912
Node 2	0.999485	1/105	0.999968	1/625000
Hab Module	0.995074	1/29	0.998523	1/928
Lab Module	0.985522	1/69	0.996022	1/1023
CRV	0.997443	1/391	0.999839	1/8223
TOTALS	0.934622	1/15	0.993132	1/146



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Backup Slides

National Aeronautics and Space Administration

DEBRIS MITIGATION STANDARD PRACTICES: NORMAL OPERATIONS



OBJECTIVE

1. CONTROL OF DEBRIS RELEASED DURING NORMAL OPERATIONS

Programs and projects will assess and limit the amount of debris released in a planned manner during normal operations.

MITIGATION STANDARD PRACTICES

- 1-1. *In all operational orbit regimes:* Spacecraft and upper stages should be designed to eliminate or minimize debris released during normal operations. Each instance of planned release of debris larger than 5 mm in any dimension that remains on orbit for more than 25 years should be evaluated and justified on the basis of cost effectiveness and mission requirements.

DEBRIS MITIGATION STANDARD PRACTICES: ACCIDENTAL EXPLOSIONS



OBJECTIVE

2. MINIMIZING DEBRIS GENERATED BY ACCIDENTAL EXPLOSIONS

Programs and projects will assess and limit the probability of accidental explosion during and after completion of mission operations.

MITIGATION STANDARD PRACTICES

- 2-1. *Limiting the risk to other space systems from accidental explosions during mission operations:* In developing the design of a spacecraft or upper stage, each program, via failure mode and effects analyses or equivalent analyses, should demonstrate either that there is no credible failure mode for accidental explosion, or, if such credible failure modes exist, design or operational procedures will limit the probability of the occurrence of such failure modes.
- 2-2. *Limiting the risk to other space systems from accidental explosions after completion of mission operations:* All on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when they are no longer required for mission operations or postmission disposal. Depletion should occur as soon as such an operation does not pose an unacceptable risk to the payload. Propellant depletion burns and compressed gas releases should be designed to minimize the probability of subsequent accidental collision and to minimize the impact of a subsequent accidental explosion.

DEBRIS MITIGATION STANDARD PRACTICES: COLLISIONS



OBJECTIVE

3. SELECTION OF SAFE FLIGHT PROFILE AND OPERATIONAL CONFIGURATION

Programs and projects will assess and limit the probability of operating space systems becoming a source of debris by collisions with man-made objects or meteoroids.

MITIGATION STANDARD PRACTICES

- 3-1. *Collision with large objects during orbital lifetime:* In developing the design and mission profile for a spacecraft or upper stage, a program will estimate and limit the probability of collision with known objects during orbital lifetime.
- 3-2. *Collision with small debris during mission operations:* Spacecraft design will consider and, consistent with cost effectiveness, limit the probability that collisions with debris smaller than 1 cm diameter will cause loss of control to prevent post-mission disposal.
- 3-3. *Tether systems* will be uniquely analyzed for both intact and severed conditions.

DEBRIS MITIGATION STANDARD PRACTICES: DISPOSAL



OBJECTIVE

4. POSTMISSION DISPOSAL OF SPACE STRUCTURES

Programs and projects will plan for, consistent with mission requirements, cost effective disposal procedures for launch vehicle components, upper stages, spacecraft, and other payloads at the end of mission life to minimize impact on future space operations.

MITIGATION STANDARD PRACTICES

- 4-1. *Disposal for final mission orbits:* A spacecraft or upper stage may be disposed of by one of three methods:
- a. Atmospheric reentry option: Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission. If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit. If a space structure is to be disposed of by reentry into the Earth's atmosphere, the risk of human casualty will be less than 1 in 10,000.
 - b. Maneuvering to a storage orbit: At end of life the structure may be relocated to one of the following storage regimes:
 - I. Between LEO and MEO: Maneuver to an orbit with perigee altitude above 2000 km and apogee altitude below 19,700 km (500 km below semi-synchronous altitude)
 - II. Between MEO and GEO: Maneuver to an orbit with perigee altitude above 20,700 km and apogee altitude below 35,300 km (approximately 500 km above semi-synchronous altitude and 500 km below synchronous altitude.)
 - III. Above GEO: Maneuver to an orbit with perigee altitude above 36,100 km (approximately 300 km above synchronous altitude)
 - IV. Heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit, into a heliocentric orbit.

Because of fuel gauging uncertainties near the end of mission, a program should use a maneuver strategy that reduces the risk of leaving the structure near an operational orbit regime.
 - c. Direct retrieval: Retrieve the structure and remove it from orbit as soon as practical after completion of mission.
- 4-2. *Tether systems* will be uniquely analyzed for both intact and severed conditions when performing trade-offs between alternative disposal strategies.

Ⅱ．セッション—1 観測・モデル化

1-1 JAXA 総研本部におけるデブリ光学観測技術の研究

○中島厚、黒崎裕久、柳沢俊史（宇宙航空研究開発機構／総合技術研究本部）

R&D on Space Debris Optical Observation in IAT/JAXA

Atsushi Nakajima, Hirohisa Kurosaki and Toshifumi Yanagisawa (IAT / JAXA)

Key Words: Optical Observation Facility, GEO debris, CCD Camera

概要

軌道上を周回する人工物体はその軌道が確定しているものだけでも 12,000 個以上に達し、1996 年以降高水準で推移している。大部分は運用を停止した衛星や打上げロケット及びこれらの爆発により発生した破片からなるデブリで、運用されている衛星は全体の 6%程度である。今後、観測能力の向上により、より小さなデブリまで軌道決定されると共に、より多くの微小破片の群の存在も観測されるようになり、正確な宇宙環境の把握が進められる。低軌道デブリ（以下、LEO デブリ）は、国際的なレーダー網の整備により追跡され、日々軌道更新が行なわれている。また、高高度デブリに対しても、世界中に光学観測施設が展開されており、より小さなデブリに対しても観測・軌道決定が行われている。口径 1 m クラスの望遠鏡では 10cm～20cm サイズのデブリまで検出可能といわれている。我が国におけるデブリ観測施設は、LEO デブリに対しては、(財)日本宇宙フォーラム(JSF)が所有する上斎原スペースガードセンター(KSGC)のフェーズドアレイレーダーと追跡観測が可能な光学系として JAXA の口径 35cm 望遠鏡、JSF が所有する美星スペースガードセンター(BSGC)50cm 望遠鏡及び 2 つの公共天文台（陸別及び富山の 1 m 望遠鏡）が対応可能である。静止軌道デブリ（以下、GEO デブリ）に対しては、BSGC の 1 m 望遠鏡が実験的運用観測を行っており（JAXA の委託業務）、更に研究開発用として JAXA 入笠山光学観測所に口径 35cm 望遠鏡を設置している。

JAXA 総合技術研究本部では、小型の光学観測施設を整備し、画像取得・解析を行いつつ、デブリ検出技術等の開発を進めている。

LEO デブリ観測用の低軌道衛星追尾装置は、旧 NAL であった 1999 年に口径 35cm シュミットカセグレン(SC)望遠鏡を搭載した 3 軸 X-Y 追尾架台を製作し、2000 年 5 月の ISS/シャトルドocking、2003 年 3 月のミール宇宙ステーションの落下前の画像等を取得している。またロケットボディー等のデブリに対しては、追尾しながら光度観測を行い、軌道上における姿勢運動の推定技術の開発を進めている。GEO デブリに対しては、20cm サイズの微小デブリ検出技術の確立が主要課題であり、そのためには観測条件の良いサイトでのデータ（高画質データ）取得が必要となる。欧米においては、2,000m 以上の高地に望遠鏡を設置して観測しており、これに匹敵する我が国の観測サイトとして、長野県入笠山（標高 1,955m）付近を選定した。2006 年 11 月には、標高 1,870m の入笠高原に 3m ドーム 2 基と口径 35cm 及び口径 25cm の望遠鏡が整備された。光学望遠鏡による GEO デブリ観測の手法は、望遠鏡を固定して静止軌道付近を比較的短時間露光（5 秒～10 秒）してデータを取得する。恒星は線像となり、運用中の静止衛星は点像となる。GEO デブリは若干の軌道傾斜角を持っているため恒星とは別の線像（点像に近い）として区別される。しかしながらこの方法では、検出能力は望遠鏡の口径に依存し、検出限界をあげるためにより大型の望遠鏡が必要となる。筆者らは検出限界を上げる手法として、多数の画像を重ね合わせ、S/N を上げると共にデブリを自動検出するソフトを開発している。本ソフトは、あらゆるデブリの移動方向及び移動量を推定して計算するため、検出するために時間がかかることが懸念される。その時間短縮の方法として、複数の計算機を使用した分散処理システムを試作し、更にビニング処理手法を取り入れることにより、大幅な短縮が可能となった。

本講演においては、観測施設の概要とデブリ検出ソフトの機能について発表する。

3rd Space Debris Workshop, Tokyo(Jan. 21-22, 2008)



R&D on Space Debris Optical Observation in IAT/JAXA

JAXA総研本部におけるデブリ光学観測技術の研究

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***National Museum of Emerging Science and Innovation,
Tokyo, Japan
Jan. 21 - 22, 2008***



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Space Debris Observation Facilities in Japan

- ★ **FY1997/98 Preliminary Designs of Japanese Space Debris Observation Facilities**
- ★ **FY1999/01 Optical Observation Telescopes(1.0m, 0.5m) at BSGC**
- ★ **FY1999 - 0.35m X-Y Mount Telescope located at Chofu for LEO Debris Tracking**
- ★ **FY2001/03 Radar System for LEO Debris Observation at KSGC**
- ★ **FY2001- 0.35m Telescope located at Nyukasa-highlands for GEO Debris/Asteroid Detection Software Development**
- ★ **FY2006 - New JAXA Nyukasayama Observatory(0.35m and 0.25m Telescopes) for Technology Developments and Space Debris Survey/Tracking Observation**



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NEO/Space Debris Observation Facilities

Constructed by JSF and
Operated by JAXA/JSGA

Okayama Pref.



KSGC



BSGC

- FY1999~FY2003
- Phased Array Radar
- 0.5m, 1.0m Telescopes

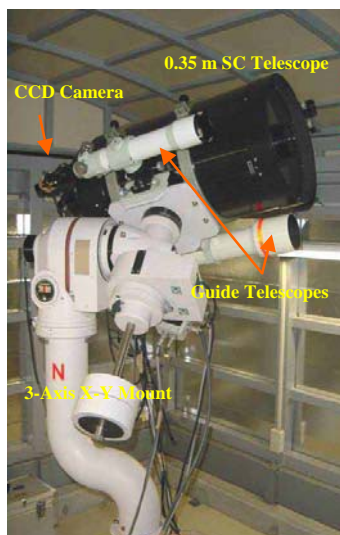
Joint Observation/Technology
Exchange with IAT/JAXA



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LEO Debris Tracking Facility

Location:HQ of JAXA at Chofu/Tokyo (Lat:+35°40'30", Long:139°33'40"E, Alt:60m)
Schmidt Cassegrain Telescope(Dia.:350 mm, Focal Length:3910 mm(F/11))
3 axes(Az, Tr, El) controlled X-Y mount
CCD Camera:Sony ICX085AL, 1280×1024, Pixel:6.7 μ m×6.7 μ m, 12bit/18MHz



LEO Debris Tracking Telescope and Example Images

MIR 6hrs before re-entry



ISS under construction



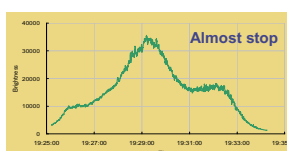
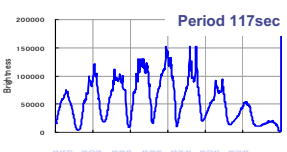
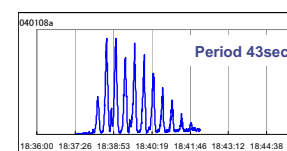
2004.1.7
18:37:26-18:42:15 (UT)



2004.8.19
10:15:52-10:26:44 (UT)



2005.5.31
19:25:12-19:34:16 (UT)



Spin Rate Variations of COSMOS 2082 R/B

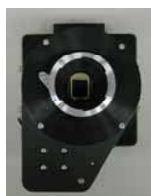


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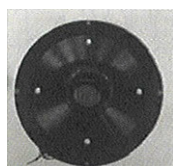
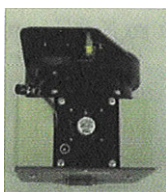


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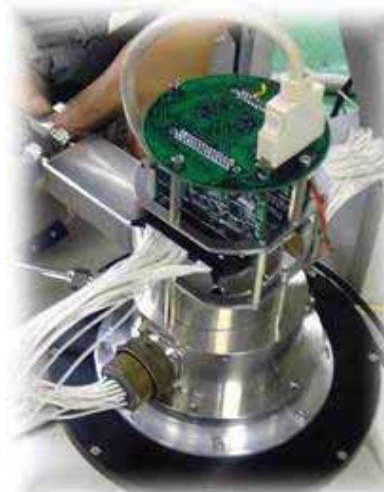
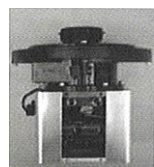
① 高速読み出し大型CCDカメラの開発
 冷凍機冷却大型CCDカメラ(4K×4K)の試作と機能評価



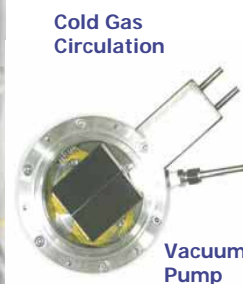
1k × 1k CCD Camera
 Pixel size : $13\mu\text{m} \times 13\mu\text{m}$
 Clock : 16bit/500kHz
 Read/Write : 4sec



2k × 2k CCD Camera
 Pixel size : $13.5\mu\text{m} \times 13.5\mu\text{m}$
 Clock : 16bit/1MHz, 2ch
 Read/Write : 4sec
 FOV for ε -350 : $1.27^\circ \times 1.27^\circ$



4k × 4k (=2K × 4K × 2) Mosaic CCD Camera
 Pixel size : $15\mu\text{m} \times 15\mu\text{m}$
 Dimension : $61.4\text{mm} \times 61.4\text{mm}$
 Read+Write : within 10sec





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Main Characteristics of Nyukasayama Observatory

Coordinates

Longitude : 138°10'18", Latitude : 35°54'05", Altitude : 1,870m.

Telescopes

Takahashi ε -350, ϕ 355mm, f=1,248mm, F/3.6, Image Circle ϕ 70mm

Takahashi BRC-250M, ϕ 250mm, f=1,268mm, F/5.1, Image Circle ϕ 100mm

Mount types

Showa Kikai Equatorial Folk-Mount for 35cm Telescope

Showa Kikai Elbo-Mount for dual 25cm Telescopes

Domes

Nisshin dome, ϕ 3m, 2 sets

Cameras

NIL 1Kx1K back illuminated CCD, $13 \mu\text{m} \times 13 \mu\text{m}$, Mechanical/Electric Shutters

NIL 2Kx2K back illum. CCD, $13.5 \mu\text{m} \times 13.5 \mu\text{m}$, Mechanical Shutter,

FOV: $1.3^\circ \times 1.3^\circ$ for ε -350

NIL 2Kx4Kx2 back illuminated Mosaic CCD, $15 \mu\text{m} \times 15 \mu\text{m}$, Mech.Shutter,

FOV: $2.4^\circ \times 2.4^\circ$ for BRC-250M

Debris Detection Accuracy

Time resolution : 10 msec (mechanical shutter on/off time are measured by GPS)

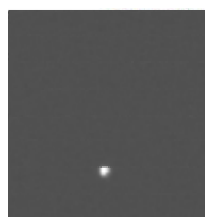
Position : 0.2 arc sec (for bright debris), 1 arc sec (for faint debris by the calculation of mean motion)



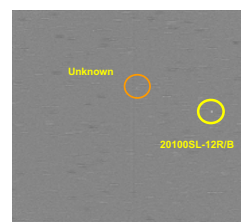
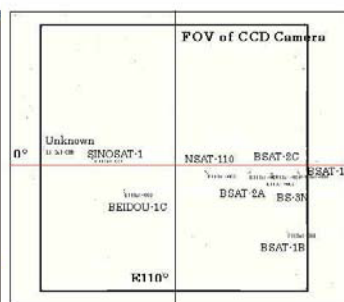
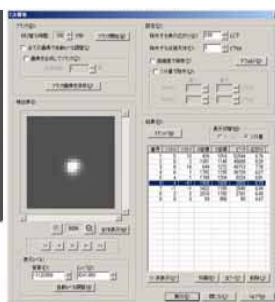
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R&D on Space Debris Observation Technologies by using Nyukasayama Observatory

- Nyukasayama Observatory has been operational since Nov.2006.
- Debris Detection Software was developed for GEO objects survey and tracking observations.
- Limiting magnitude for 35cm telescope is 17.5 and will be improved to 19 by using this software.
- Participation in the international campaign observation is available from this autumn.
- 25cm telescope will be used mainly for survey observation and 35cm telescope will be used for faint objects tracking.



Candidate No.6
Identification as BSAT-1B
Shift values during 17.7 minutes:
X=4, Y=-47 pixels



2006.10.18 12:25:48(UT)



2006.10.19 18:59:18(UT)

GEO Objects detected by Debris Detection Software

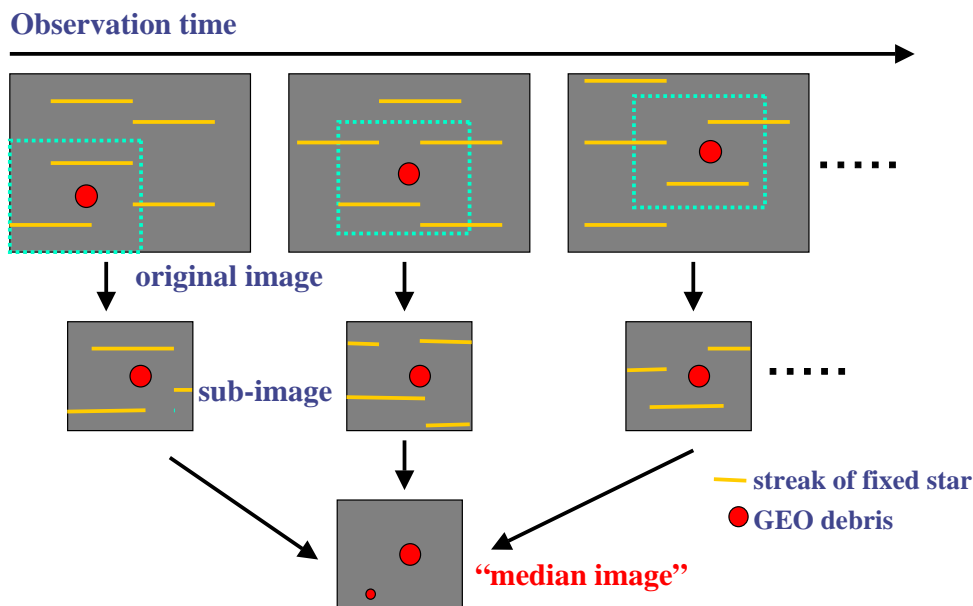
IADC Campaign Observation



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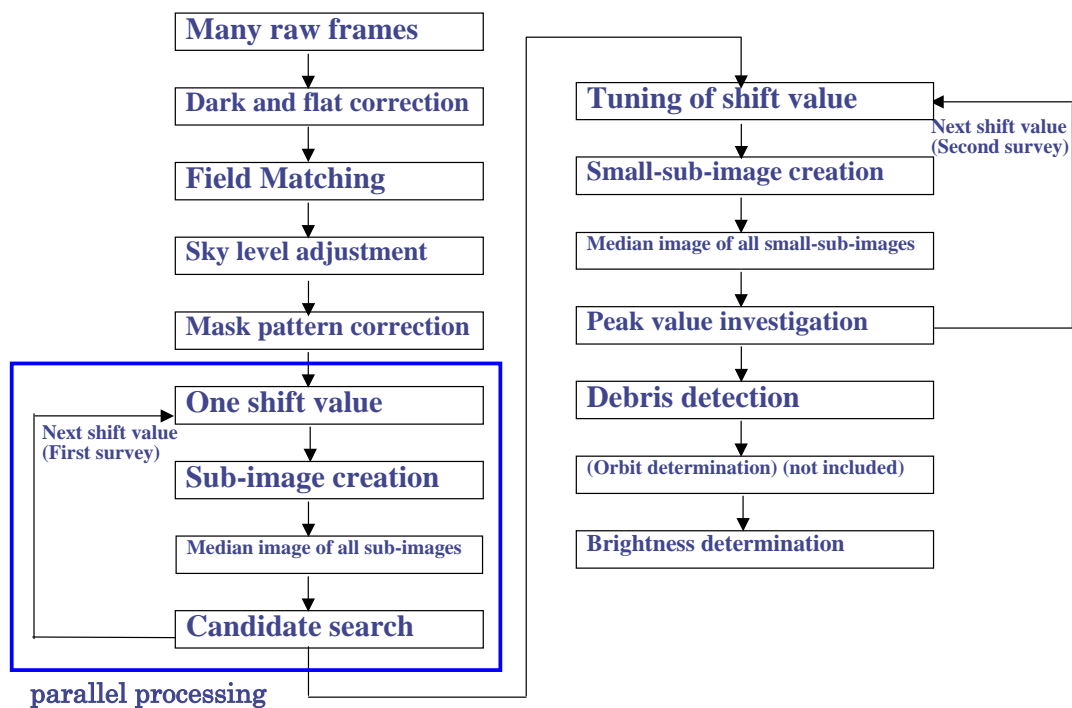
Small GEO Debris Detection Technology

- Automatic Debris Detection Software by Stacking Method -



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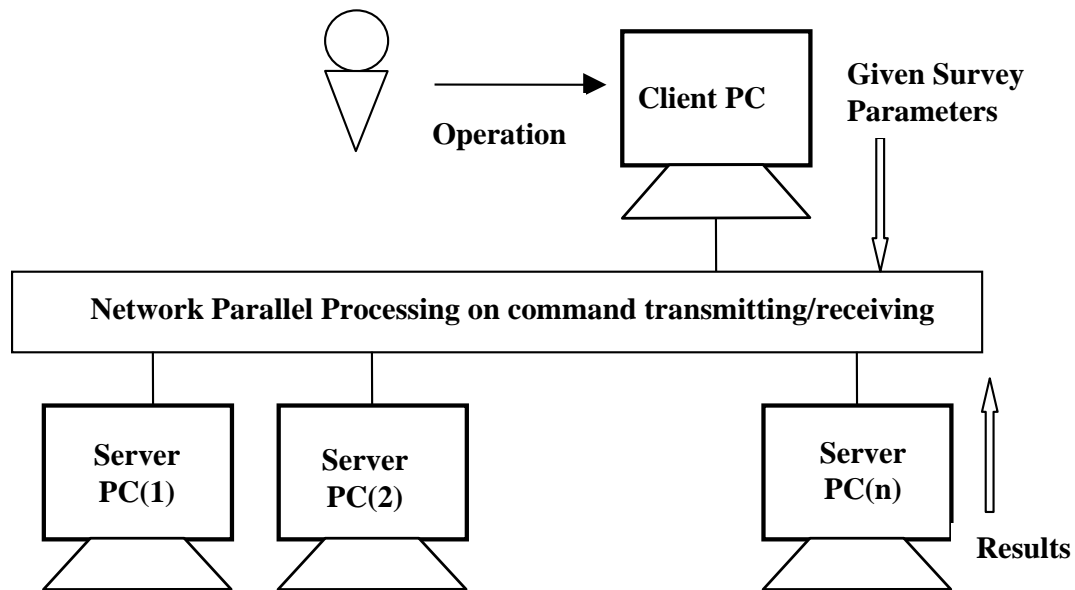
Automatic Debris Detection Software Flow Chart





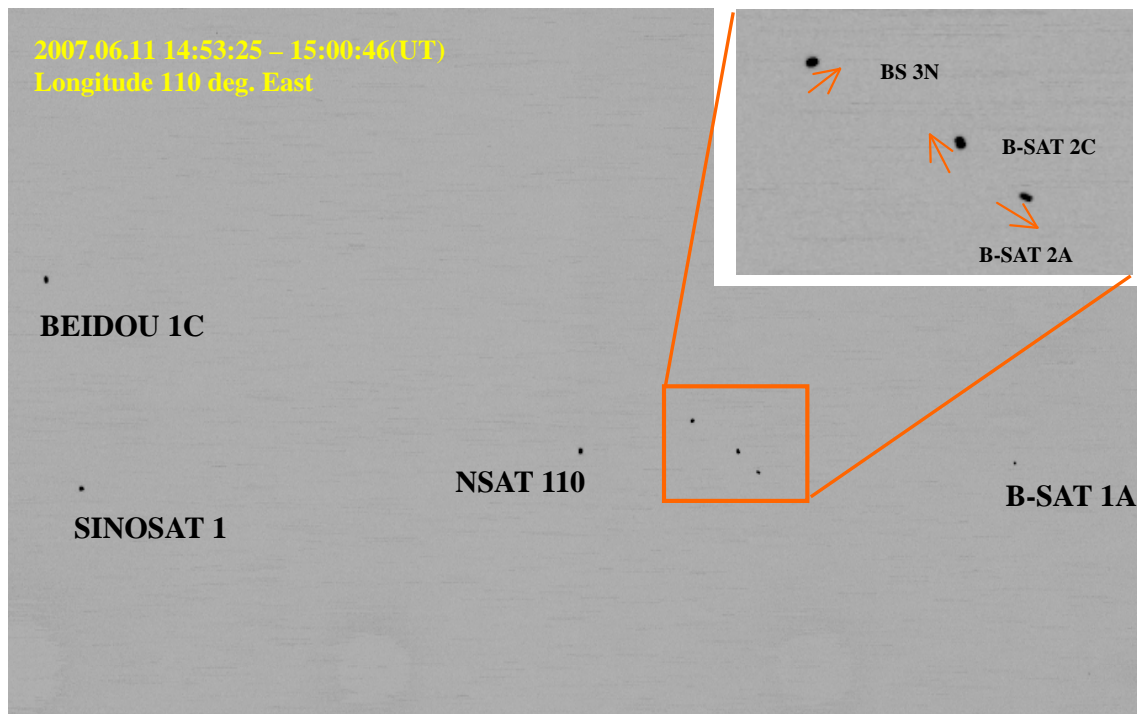
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Parallel Processing Subsystem at First Survey Mode (for calculation time reduction)



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GEO Satellites(Example 1) Moving Directions of BS 3N, B-SAT 2C and B-SAT 2A





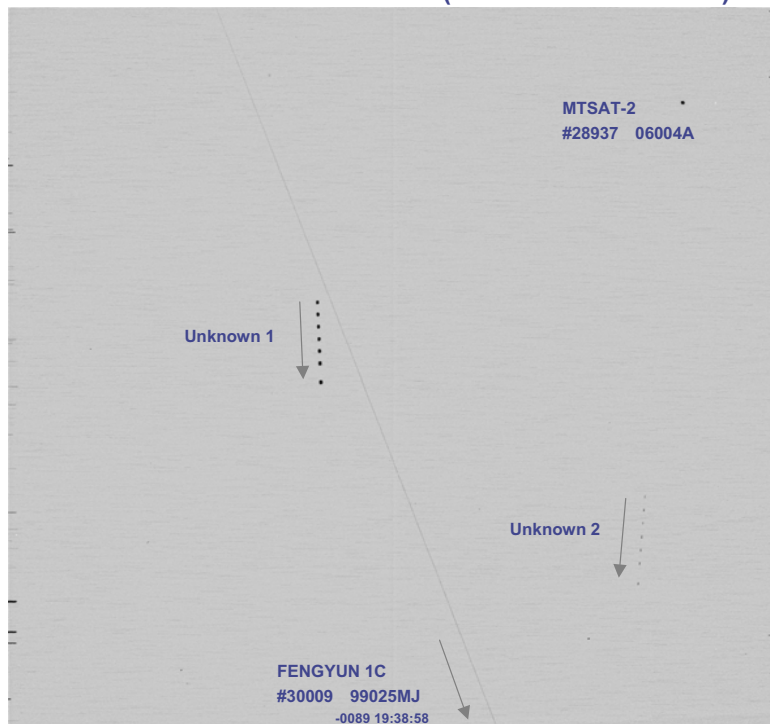
GEO Debris(Example 2)

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2007.3.21 19:38:05-19:43:19 (UT)

Az: 167°55'43.4" El: 47°12'49.2"

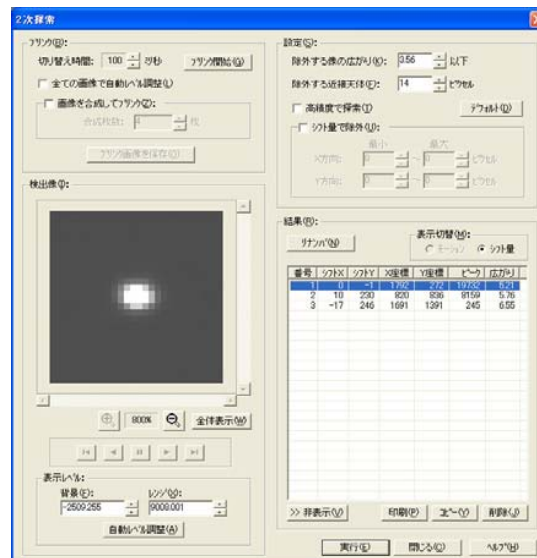
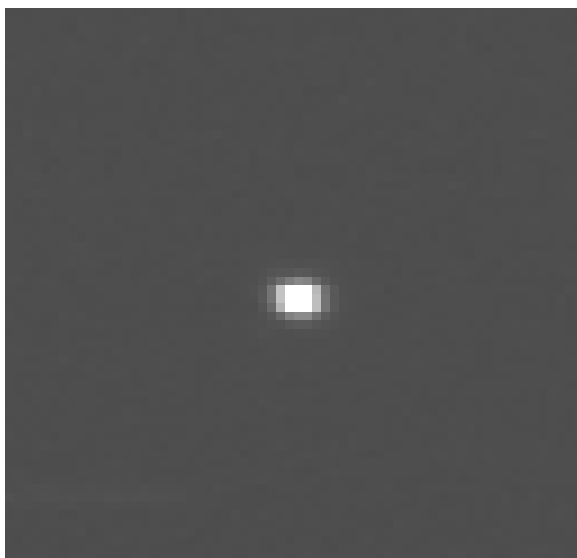
(File No: 0087 ~ 0100)



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MTSAT- 2 shift X: 0 Y:-1

	RA	Dec	Az	El	Mag
2007 03 20 19 40 13.205	17 15 17.023	-05 42 16.17	168 30 36.02	+47 45 27.39	+10.2
2007 03 20 19 41 13.205	17 16 17.186	-05 42 16.34	168 30 35.91	+47 45 27.82	+10.2

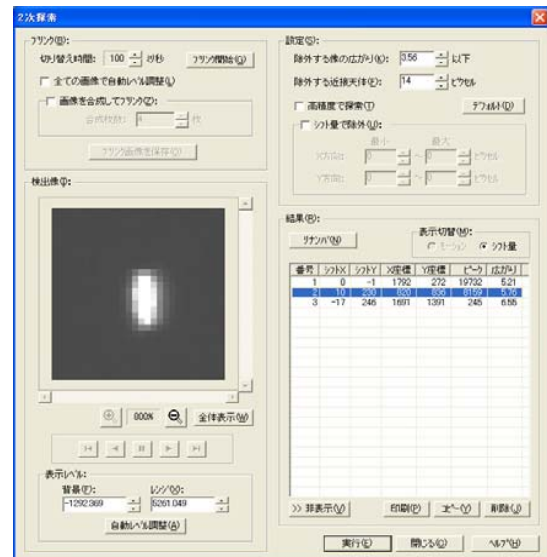
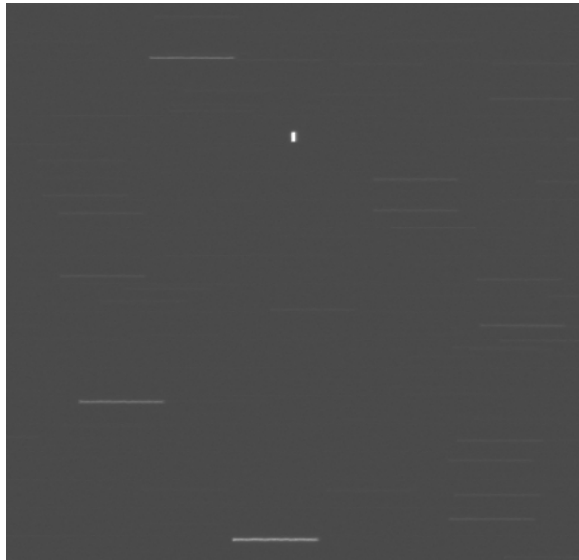




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Unknown 1 shift X:10 Y:230

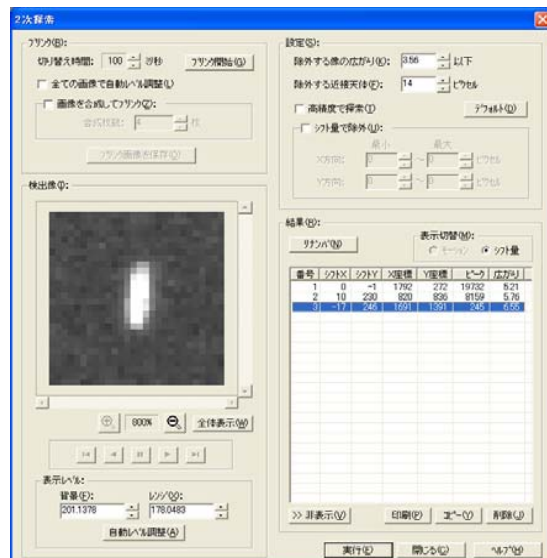
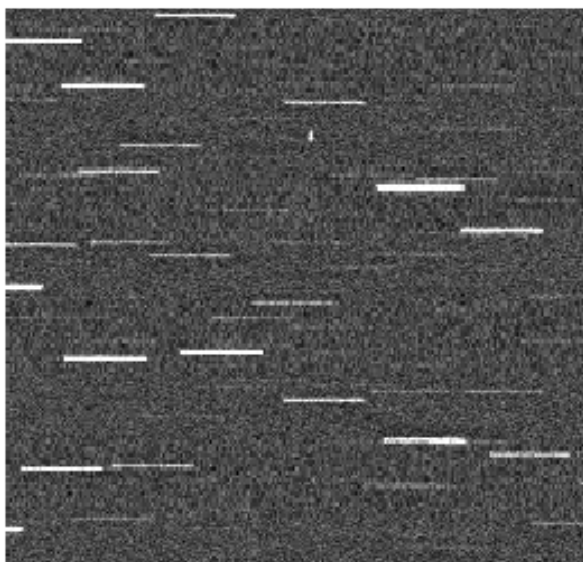
	RA	Dec	Az	El	Mag
2007 03 20 19 40	13.205 17 17	42.337 -06 07 00.99	167 43 58.52	+47 15 01.42	+10.4
2007 03 20 19 41	13.205 17 18	42.176 -06 08 43.74	167 44 31.46	+47 13 21.66	+10.4



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Unknown 2 shift X:-17 Y:246

	RA	Dec	Az	El	Mag
2007 03 20 19 40	13.205 17 15	32.360 -06 27 53.81	168 35 53.39	+46 59 48.63	+14.1
2007 03 20 19 41	13.205 17 16	32.994 -06 29 43.71	168 36 08.94	+46 57 59.63	+14.1





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Calculation Time Improvement by Parallel Processing

Calculation Time for the Example 1

Shift Value:-30X to +30X, 0Y to +300Y

Survey Counts:1,216

First Survey Calculation Time for 20 images

Single Processing: 10 hours 38.25 min.

Parallel Processing: 1 hour 29.3 min.

Calculation Time for the Example 2

(1) Shift Value:-50X to +50X, -400Y to +400Y

Survey Counts:5,226

First Survey Calculation Time for 14 images

Single Processing: more than 30 hours

Parallel Processing: 3 hour 46.7 min.

(2) Shift Value:-20X to +20X, -20Y to +250Y

Survey Counts:748

First Survey Calculation Time for 14 images

Single Processing: more than 3 hours

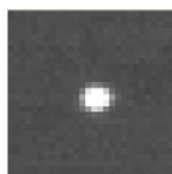
16.3 minutes(4x4 binning)

Parallel Processing: 2.3 minutes(4x4 binning)

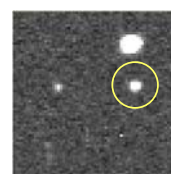
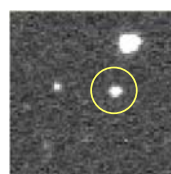
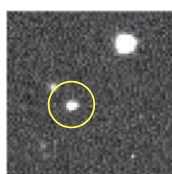
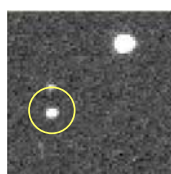


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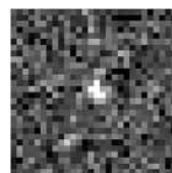
Evaluation of the Stacking Method Asteroid Detection Capability Improvement



(a-0) Stacking Image



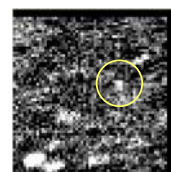
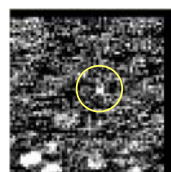
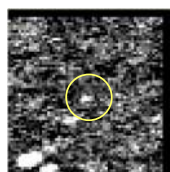
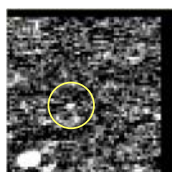
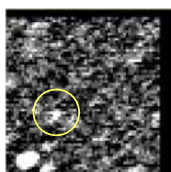
(a-1) Blinking Image of Bright Asteroid (17.0 mag.)



(b-0) Stacking Image



(b-1) Blinking Image of Faint Asteroid (21.3 mag.) (Undetectable)



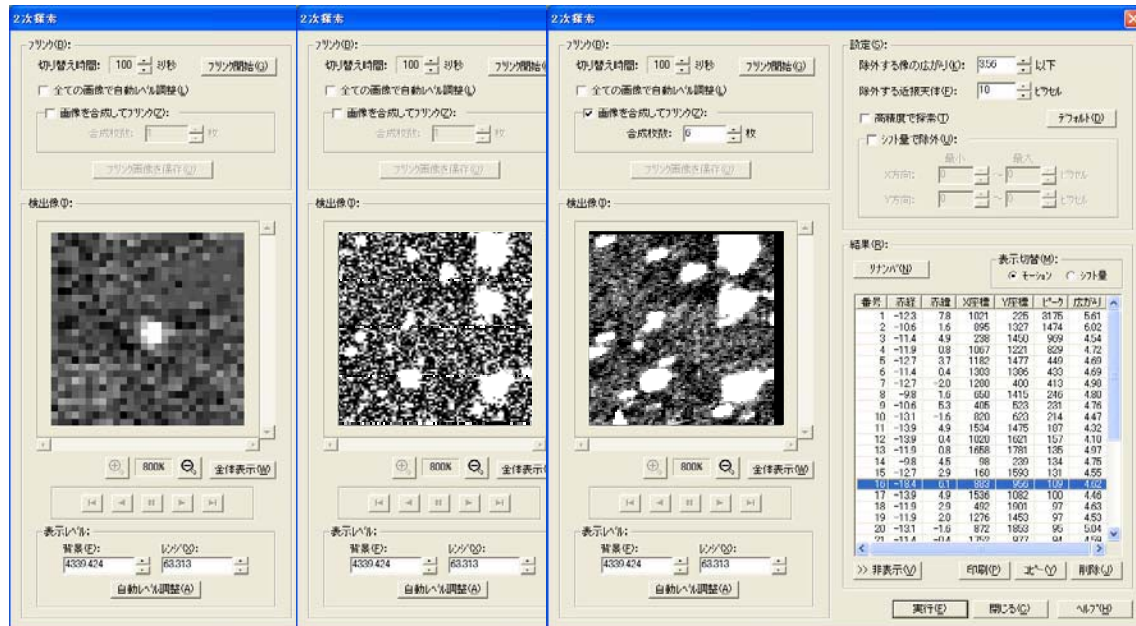
(b-2) Stacked Blinking Image of Faint Asteroid (21.3 mag.)



3rd Space Debris Workshop, Tokyo(Jan. 21-22, 2008)

25143 Itokawa

Observation Data: 18 Dec. 2006,15:35:49 ~17:50:55 (UT)

Stacking Image
(40 images)Single
Blinking

Stacked Blinking (6 images)



3rd Space Debris Workshop, Tokyo(Jan. 21-22, 2008)

Conclusions

★ Optical Observation Facilities in IAT/JAXA

- Nyukasayama Observatory with 0.35m and 0.25 m Telescopes for GEO/GTO Space Debris and Asteroids Observation
- LEO Debris Tracking Facility with 0.35m Telescope onboard the X-Y Mount System at Chofu/Tokyo

★ R&D on Optical Observation Technologies

- Debris Detection Software with Stacking Method
 - * Evaluation of the Method(for Ex. Asteroid Detection)
 - * Parallel Processing for Calculation Time Reduction
 - * Small Size GEO Debris(20cm size) Detection Capability
- High Speed Read-out CCD Cameras(1Kx1K, 2Kx2K, 4Kx4K)

1-2 光学望遠鏡を用いた未知静止デブリの軌道決定法の提案

○ 柳沢俊史、黒崎裕久、中島厚（宇宙航空研究開発機構／総合技術研究本部）、
梅原広明（情報通信研究機構）

Orbital determination of unknown GEO debris using an optical telescope

Toshifumi Yanagisawa, Hirohisa Kurosaki, Atsushi Nakajima (IAT / JAXA) and Hiroaki Umehara (NICT)

Key Words: GEO debris, optical observation

概要

静止軌道付近の離心率をもったデブリの検出及び軌道決定は、静止軌道で運用中の人工衛星の安全及び今後の人類の宇宙活動を確保する上で重要である。静止軌道付近のデブリの観測は主に光学望遠鏡によって行われているが、光学望遠鏡は観測視野が狭いという欠点があり、このため一度検出した静止デブリを軌道決定用に再検出することが困難である。本講演では、この欠点をおぎなう効率的な観測手法を紹介する。

摂動項を無視した場合、地球を周回している静止デブリは必ず慣性空間中の同じ地点を通る。つまり、慣性空間中のある領域を観測しつづければ、同一静止デブリを複数回検出することが可能であり、軌道決定に有効な情報を提供してくれる。また、限られた領域のみを観測していればよいので狭視野の光学望遠鏡には好都合である。本手法では、2日間の観測で2回検出された静止デブリに対し、簡易的な軌道決定を行い、3日目の観測により正確な軌道決定を行う。これにより複数の静止デブリを効率的に観測、軌道決定をすることが可能である。

本手法を用いた試験観測を入笠山光学観測所にて実施した。約3時間の観測を2晩実施し、12物体を両日で観測することができた。その12物体について2晩のデータから求めた簡易軌道を用いて3晩目の位置を予測して観測した結果12物体すべてを検出することができ、3晩のデータを用いて精度よい軌道を決定することができた。12物体のうち2物体が未知の静止デブリであった。

3rd Space Debris Workshop

Orbital determination of unknown GEO debris using an optical telescope

T.Yanagisawa, H.Kurosaki, A.Nakajima(JAXA)
and
H.Umehara(NICT)

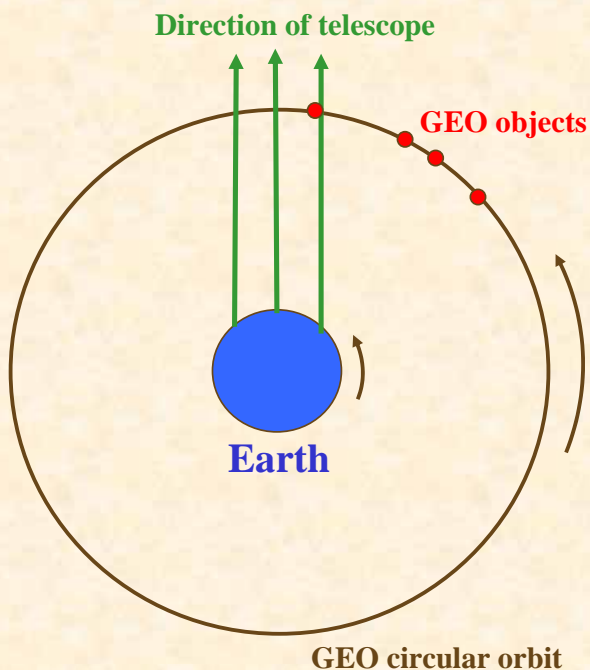
Abstract

Detections of eccentric GEO objects and determinations of their orbits are very important issues.

Narrow field of view of an optical telescope hinders us from doing this.

I propose a new observation strategy to detect many eccentric GEO objects systematically with one telescope and determine their orbits precisely.

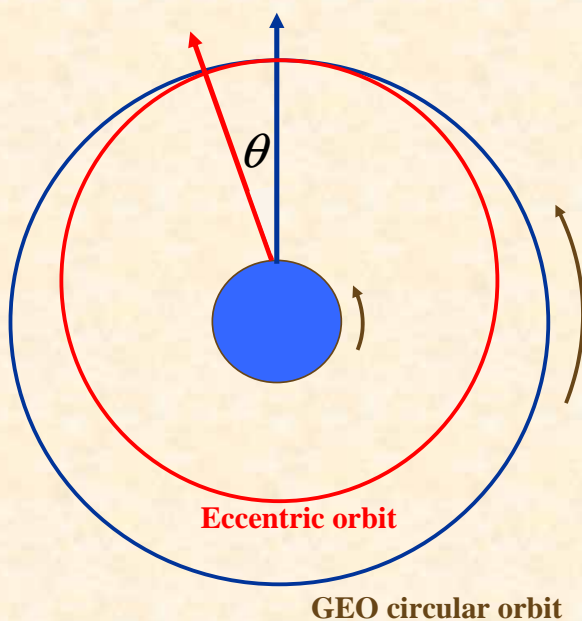
Typical observation strategy



Observe one RA and Dec region for a few hours or one night.

Observing one RA and Dec region is good for statistical study of GEO objects because many objects are detectable.

Weak point of this strategy



Circular orbit is assumed to detect GEO object a few hours later or on the second night. But it is impossible to detect eccentric GEO objects because of a quite narrow field of view.

Long continuous observation is needed for one object to get a long arc which is enough for determination of eccentric orbit.

e	4h $\theta (^{\circ})$	24h $\theta (^{\circ})$
0.1	6.9	55.5
0.05	3.4	27.4
0.01	0.7	5.4

Typical field of view is only a **1.0 × 1.0**-degree.

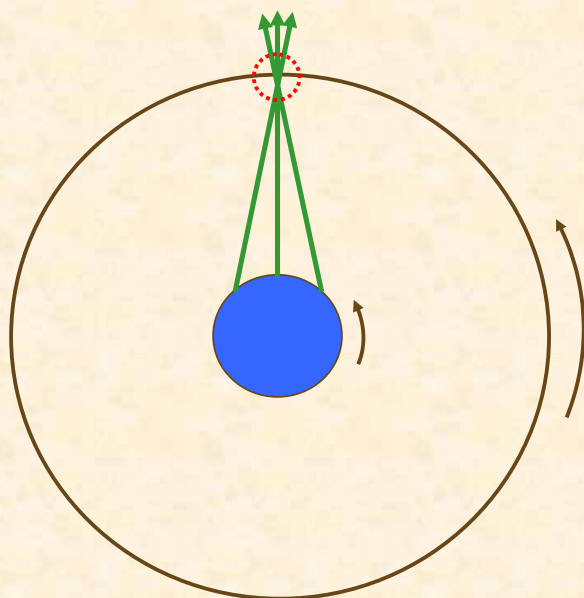
New observation strategy

Two nights' observations of one inertia position around GEO altitude.

Follow up observation assuming minimum eccentric orbit on the third night.

New observation strategy

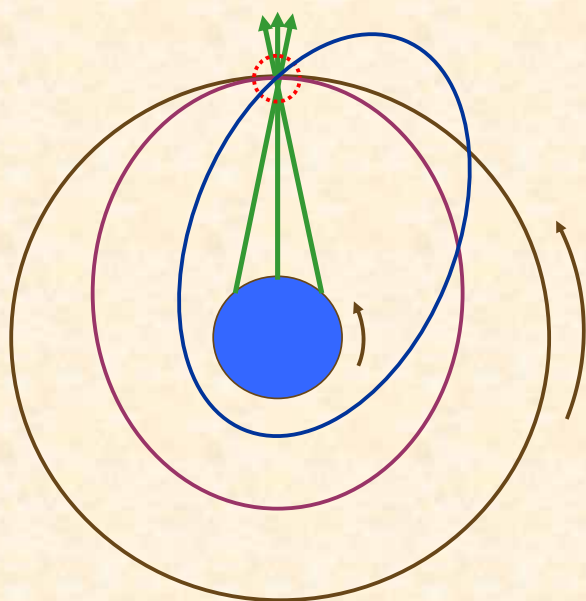
First and second night



Observing one inertia position around GEO altitude is different from observing one celestial region. Telescope must change its direction many times during the observation.

New observation strategy

First and second night



If we detect some objects in the first night, those objects must pass same position in the second night.

We don't know when those objects come back in the second night. It depends on their semi-major axes.

How to identify same object

Assume circular orbit from one night data. And compare its semi-major axis (a' , not true one), inclination (i) and RAAN (Ω) to search pairs.

First night objects

	1.	2.	3.	4.	5.	6.
a' (km)	42150	43052	41937	42236	42278	41875
i (°)	10.5	7.6	2.3	15.1	4.9	12.3
Ω (°)	90.3	16.7	45.0	120.2	62.1	58.6

Second night objects

	1.	2.	3.	4.	5.	6.
a' (km)	41954	42136	43007	42245	41903	42312
i (°)	2.4	10.4	7.4	15.0	12.3	4.8
Ω (°)	44.8	89.7	17.1	122.0	59.2	63.3

Minimum eccentric orbit

Once a pair is identified, we can calculate the true semi-major axis (a) from its orbital period. We can also estimate the minimum eccentricity (e').

Observational time of the first and second night



Orbital period

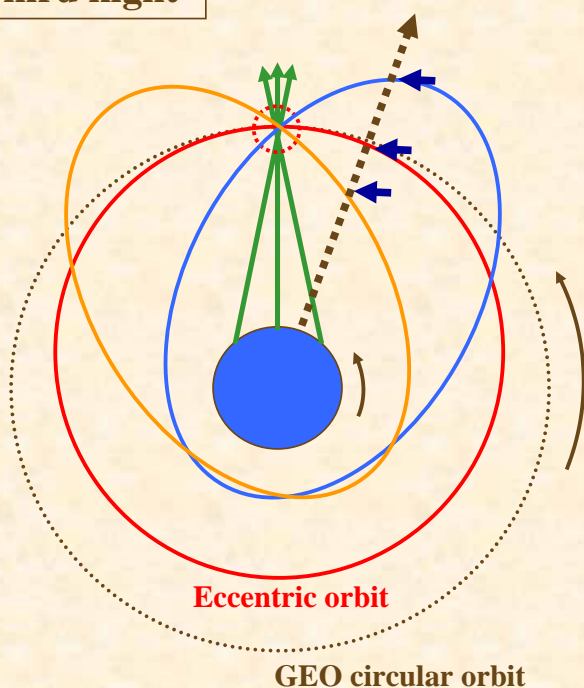


True semi-major axis (a)

$$a = 42164.170 \times \left(\frac{P}{23.93447} \right)^{\frac{2}{3}}$$

Third night observation

Third night



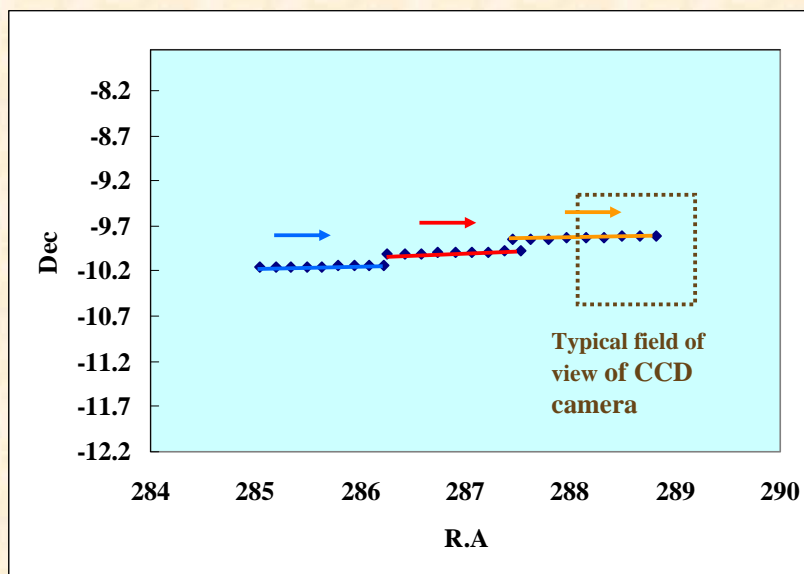
$$e' = \frac{|a' - a|}{a}$$

$$e \geq e'$$

To determine true eccentricity and argument of perigee, separated region from first two nights is observed on the third night.

Third night observation

30 degrees from the first two nights' region.



Third night is used to follow up. 20 min for each object is enough.
By using 3 nights' data, we can determine their orbits precisely.

Observational simulation for Titan fragments

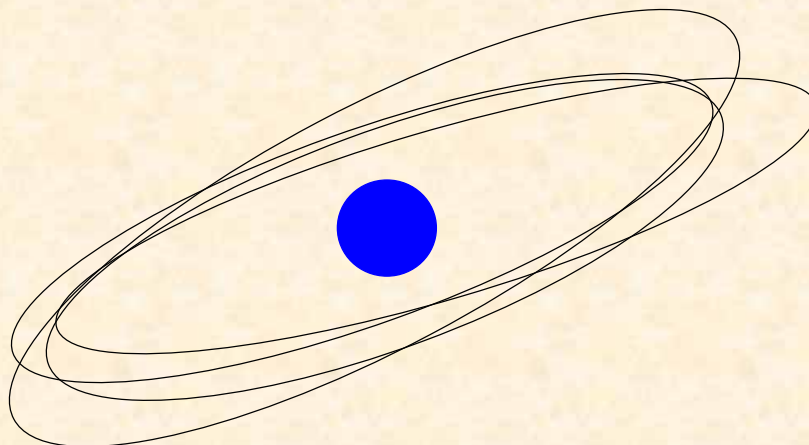
Titan fragments are the result of the explosion of U.S. Titan 3C Transtage that occurred near GEO in 1992.

NASA Standard Break up model and LEGEND (orbital propagator) are used to simulate current orbital elements of 237 Titan fragments larger than 10cm.

The observation of these fragments is simulated. The orbital elements are determined from simulated observational data (errors are included) and compared with the elements of LEGEND.

Simulated observation site is the Cerro Tololo Inter-American Observatory in Chile and observation date are the 25, 26 and 27 of April 2007.

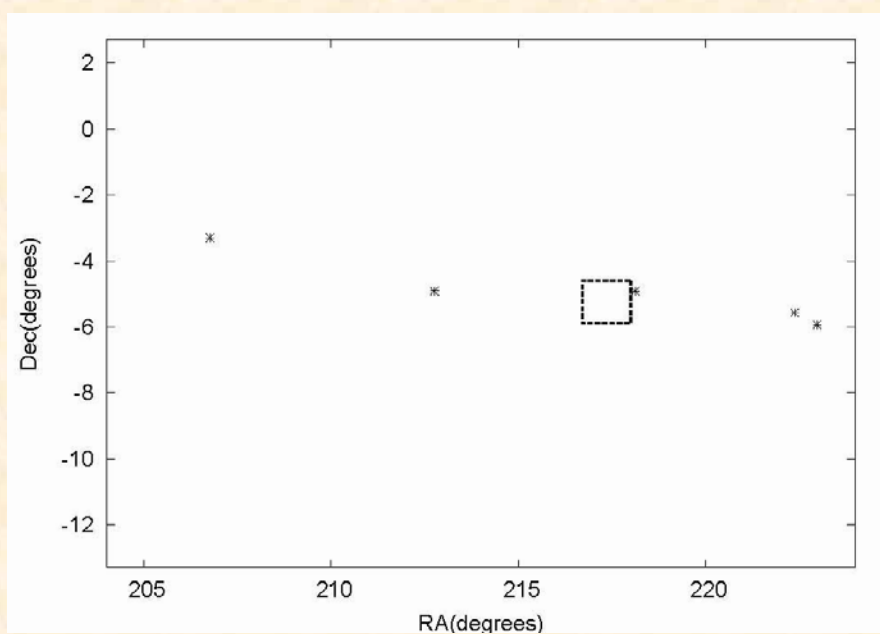
Observational simulation for Titan fragments



Observed point for the first and second night:
RA=214° , Dec=-9° , R=41394km

The telescope observes the point for 8 hours in the first and second night. CCD camera with a FOV of $1.3 \times 1.3^\circ$ takes an image every 36 seconds.

Observational simulation for Titan fragments



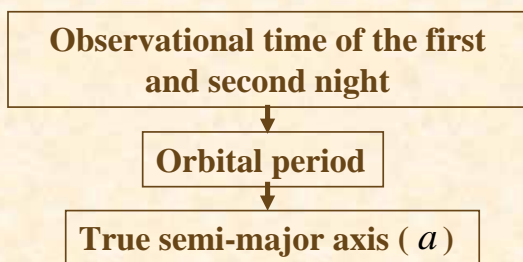
A sample of the simulated observation for the first night.

Observational simulation for Titan fragments

Out of 237 fragments, 68 and 67 are detected in the first and second night, respectively.

Pair from the first and second nights are searched by comparing a' , i , and Ω .

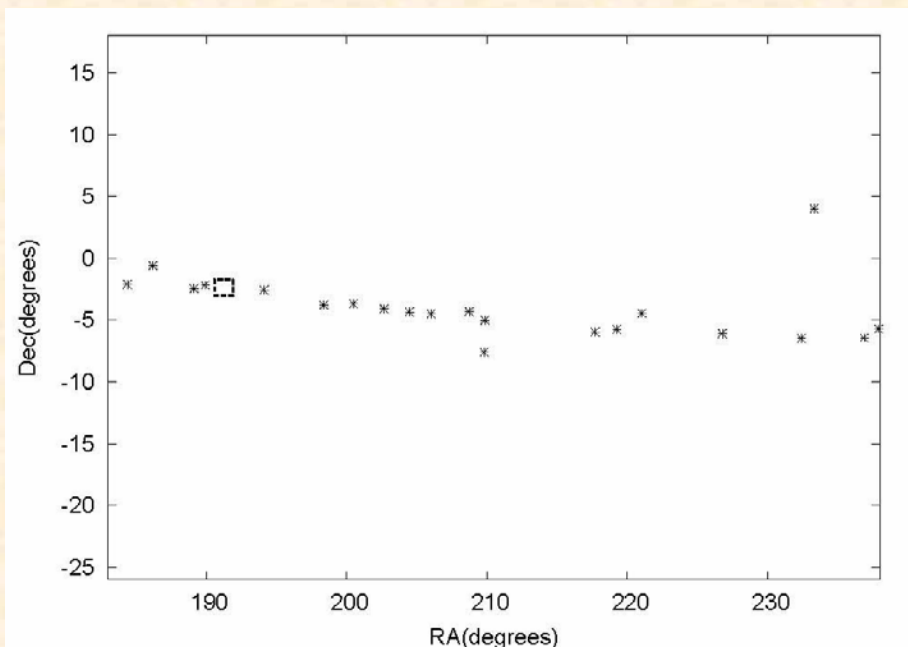
38 pairs are found as one-to-one relation. Minimum eccentric orbits are determined for these pairs to predict third night position.



$$a = 42164.170 \times \left(\frac{P}{23.93447} \right)^{\frac{2}{3}}$$

$$e' = \frac{|a' - a|}{a}$$

Observational simulation for Titan fragments



A sample of the simulated observation for the third night.

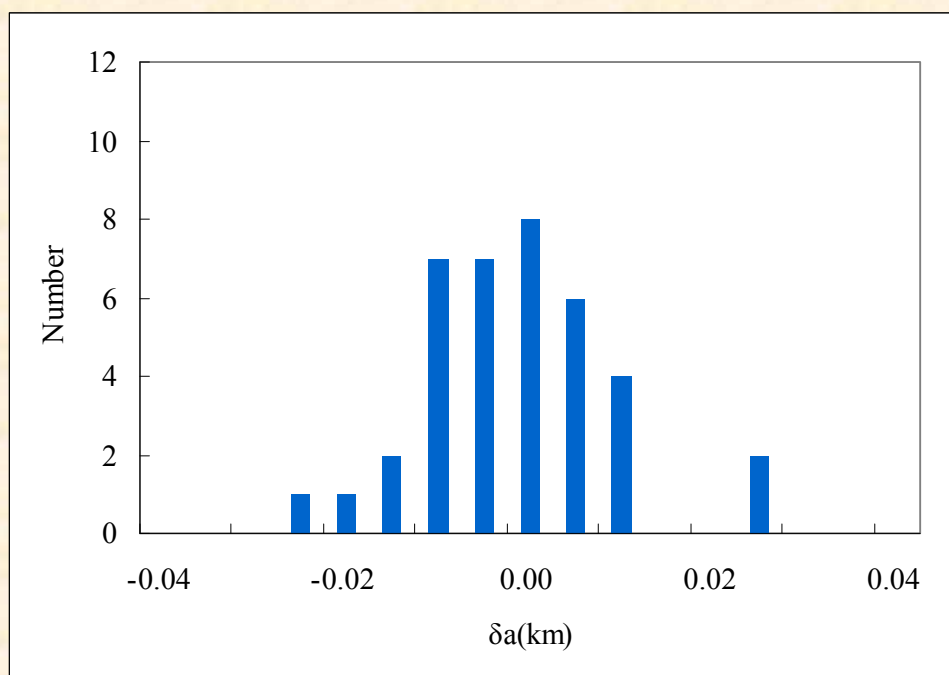
Observational simulation for Titan fragments

All 38 objects are detected in the third night.

Although another object comes into the FOV in some cases, O-C values can easily identify which object is the correct one.

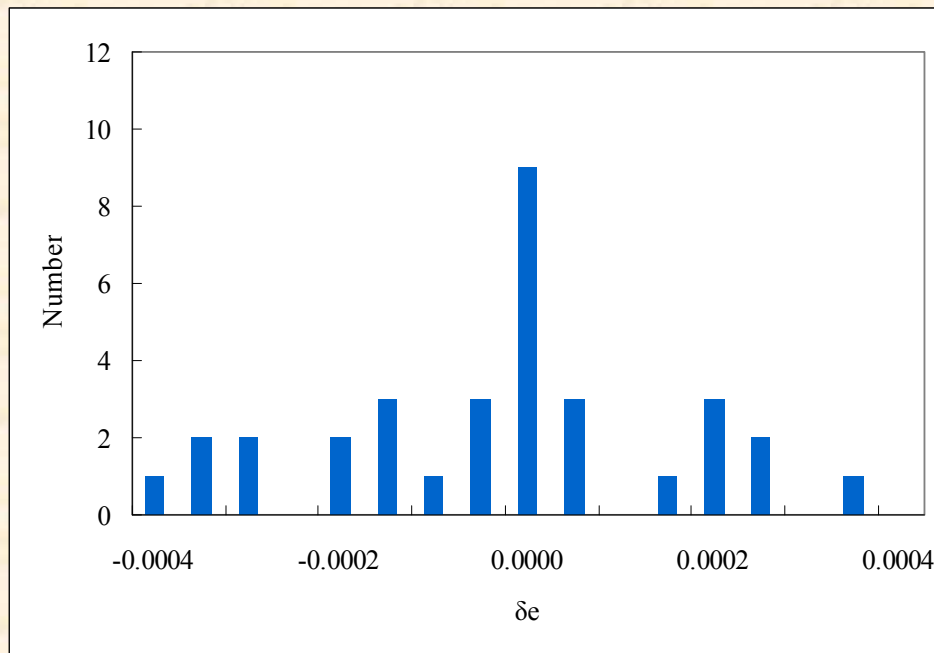
Calculated orbital elements from 3 nights' data are very close to the elements of LEGEND .

Observational simulation for Titan fragments



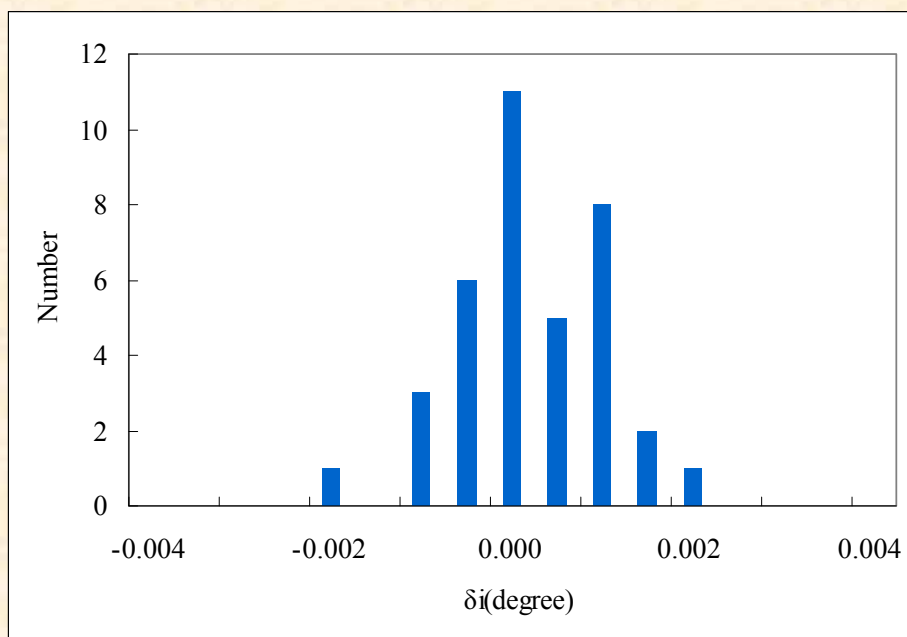
The error distribution of the semi-major axis (the calculated value minus the initial value).

Observational simulation for Titan fragments



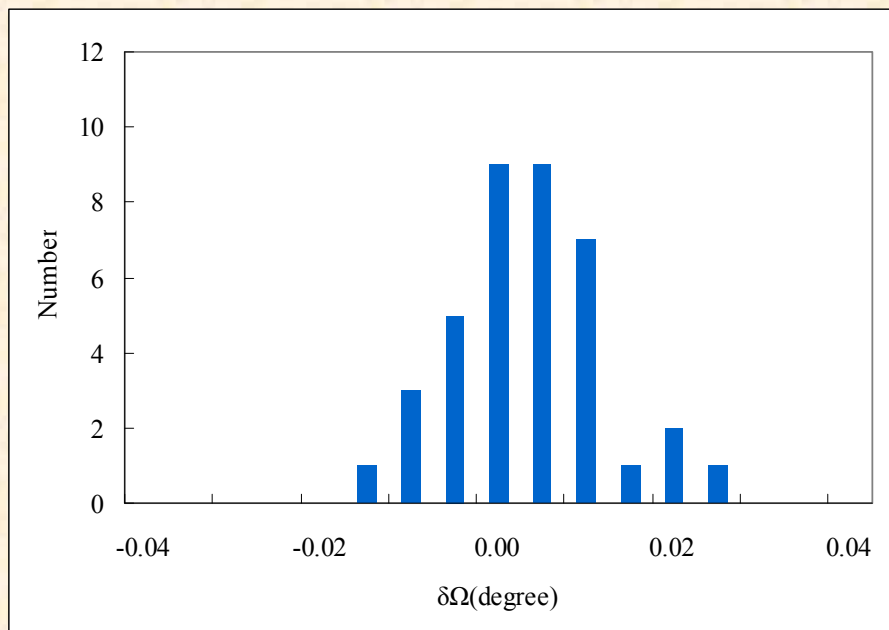
The error distribution of the eccentricity (the calculated value minus the initial value).

Observational simulation for Titan fragments



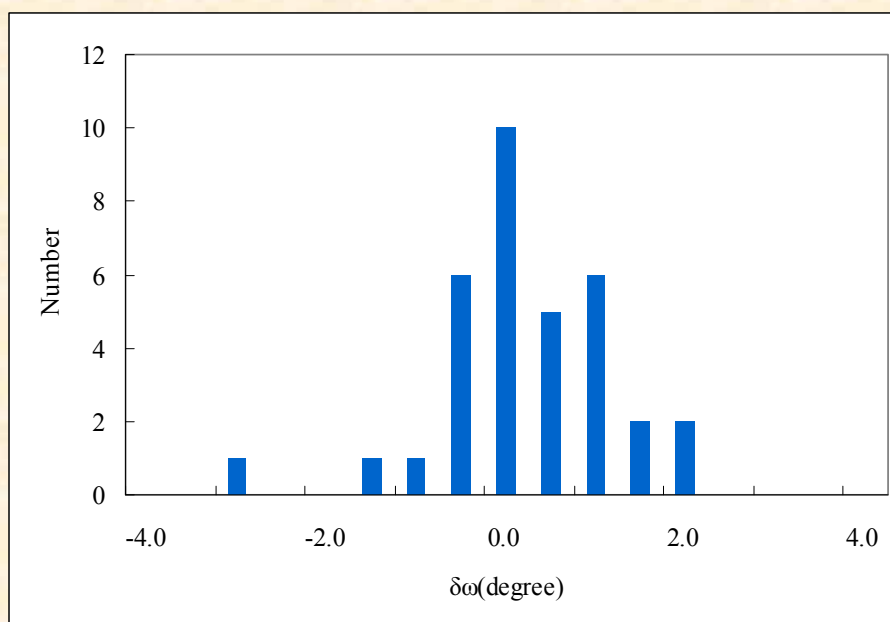
The error distribution of the inclination (the calculated value minus the initial value).

Observational simulation for Titan fragments



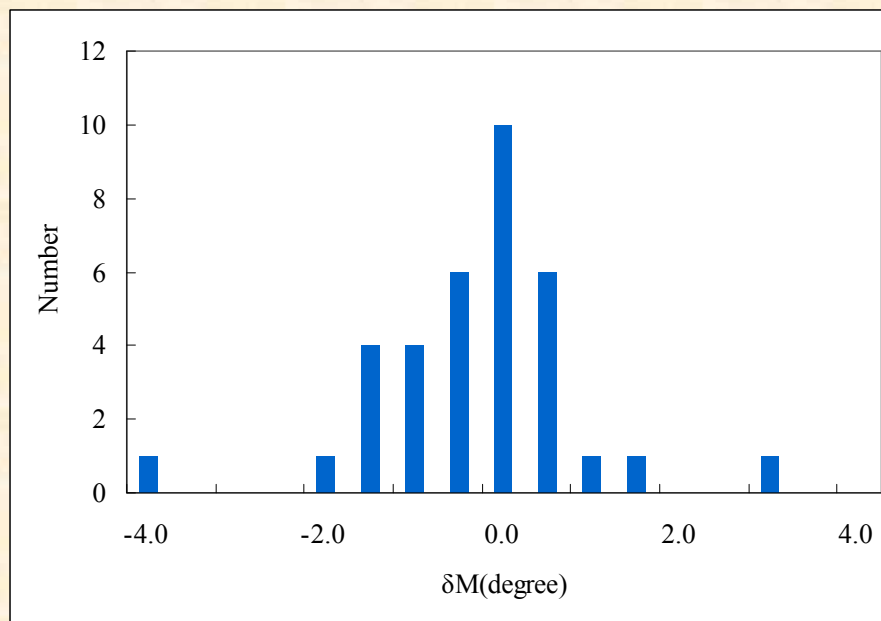
The error distribution of RAAN (the calculated value minus the initial value).

Observational simulation for Titan fragments



The error distribution of the argument of perigee (the calculated value minus the initial value).

Observational simulation for Titan fragments



The error distribution of the mean anomaly (the calculated value minus the initial value).

Test observation

Site: Mt.Nyukasa Astronomical Observatory, Nagano

Equipments: 35cm-telescope and 2K2K-CCD camera

Field of view: 1.27×1.27 -degree

Date: Dec 14,16,17 2007

Observed point for the first and second night:

RA=55° , Dec=-1° , R=42164km

Observation time: 3 hours

Exposure time: 3 sec

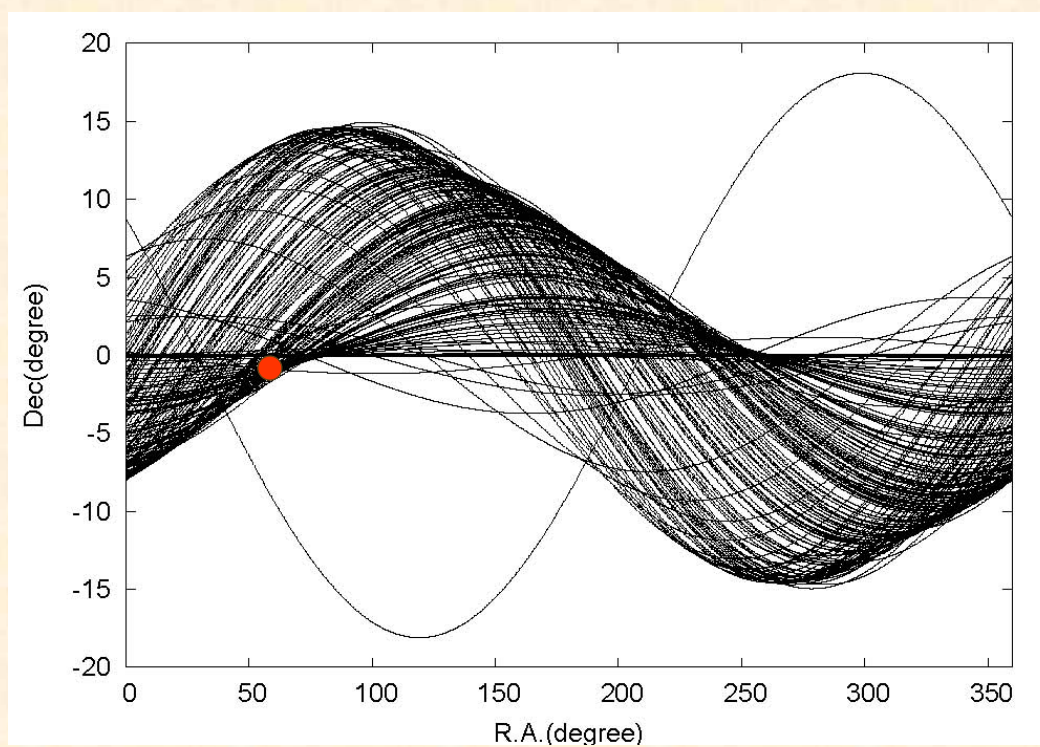


Observational equipments



Telescope: Takahashi ε -350
 D=350mm f=1248mm F/3.5
Equatorial mount: SHOWA Fork-type 25EF
CCD camera: N.I.L. FCC-104B
 Chip: Marconi CCD42-40

Observed region



Test observation results

First night(12/14): 20 objects

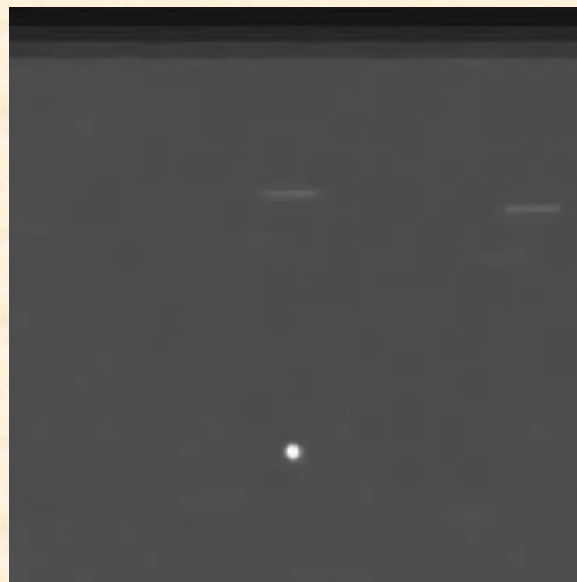
Second night(12/16): 18 objects

12 pairs (2 of them are UCT) are found as one-to-one relation.

All the 12 objects were detected by using minimum eccentric orbits on the third night(12/17).

Precise orbital determinations were carried out for the 12 objects using the 3 nights' data.

Detected object (UCT)



O-C values after the orbital determination

#	Name	Stddev of $\Delta RA(^{\circ})$	Stddev of $\Delta Dec(^{\circ})$
1	TDRS6	0.728	2.312
2	UCT	0.516	3.685
3	UCT	0.710	4.104
4	Intelsat605	0.461	4.649
5	Superbird6	0.470	4.591
6	OputsB1	0.695	7.699
7	SuperbirdA1	0.809	4.546
8	Eutelsat2-F1	0.867	2.187
9	Thaicom3	0.485	7.245
10	SL-12R/B	0.433	0.760
11	Fengyun2B	0.368	4.398
12	Cosmos2397	0.530	4.966

Conclusion

The observation strategy which enables the detection of many GEO objects and precisely determines their orbits was introduced. The simulation using Titan fragments and the test observation showed that the strategy worked well. Further testing will be conducted by using actual observation datasets in the near future.

1-3 JAXA におけるデブリ衝突回避運用の検討

堀井 道明（宇宙航空研究開発機構／宇宙基幹システム本部／統合追跡ネットワーク技術部）
森 茂博（同上）、工藤 伸夫（同上）、廣瀬 史子（同上）

Study of Space Debris Collision Avoidance Maneuvers in JAXA

Michiaki Horii (Consolidated Space Tracking and Data Acquisition Department,
Office of Space Flight and Operations (OSFO / JAXA))
Shigehiro Mori (ditto), Nobuo Kudoh (ditto), Chikako Hirose (ditto)

Key Words: Space debris, Collision avoidance maneuver, Mission assurance, Radar observation

概要

昨今の宇宙デブリ増加に伴い、海外の人工衛星においても、宇宙デブリとの衝突と思われる機能喪失事故が報告されており、衛星運用において宇宙デブリとの衝突の可能性を無視できない状況になってきている。

宇宙航空研究開発機構の統合追跡ネットワーク技術部（JAXA 追跡）では、2006 年 1 月に打上げられた世界最大級の地球観測衛星である「だいち」（ALOS）に対して、宇宙デブリの衝突回避運用の検討を進めてきた。

「だいち」は、軌道高度約 700km の太陽同期準回帰軌道（極軌道）にて周回する衛星であり、この軌道を横切る（「だいち」と衝突する可能性のある）宇宙デブリの数は、米国宇宙監視網（SSN）が把握しているだけでも約 2050 個（2008 年 1 月現在）に上る。

JAXA 追跡では、SSN が把握している宇宙デブリの軌道情報を基に、「だいち」との接近状況を常時監視している。この監視にて衝突の確率が無視できないほど大きい宇宙デブリがあった場合、その宇宙デブリの軌道をより高精度に把握するために、レーダによる観測を行う。この観測に用いるレーダ局として、(財)日本宇宙フォーラムが所有しているデブリ観測専用レーダ（上齋原レーダ）、JAXA が所有しているロケット追尾用レーダ（内之浦レーダ）、およびドイツ応用自然科学研究協会（FGAN）が所有するレーダ（FGAN レーダ）を想定している。

これらのレーダ局による観測の結果、それでも衝突確率が高く無視できない場合は、緊急運用として「だいち」に対して衝突回避制御（CAM）を実施することになる。

本講演では、JAXA 追跡がこれまで検討を進めてきた衝突回避運用の概要、及び宇宙デブリの分布や「だいち」へのこれまでの接近状況について述べる。

3rd Space Debris Workshop

1-3 JAXAにおけるデブリ衝突回避運用の検討

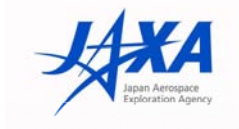
堀井道明、森茂博、工藤伸夫、廣瀬史子

宇宙航空研究開発機構
宇宙基幹システム本部 統合追跡ネットワーク技術部 軌道力学チーム

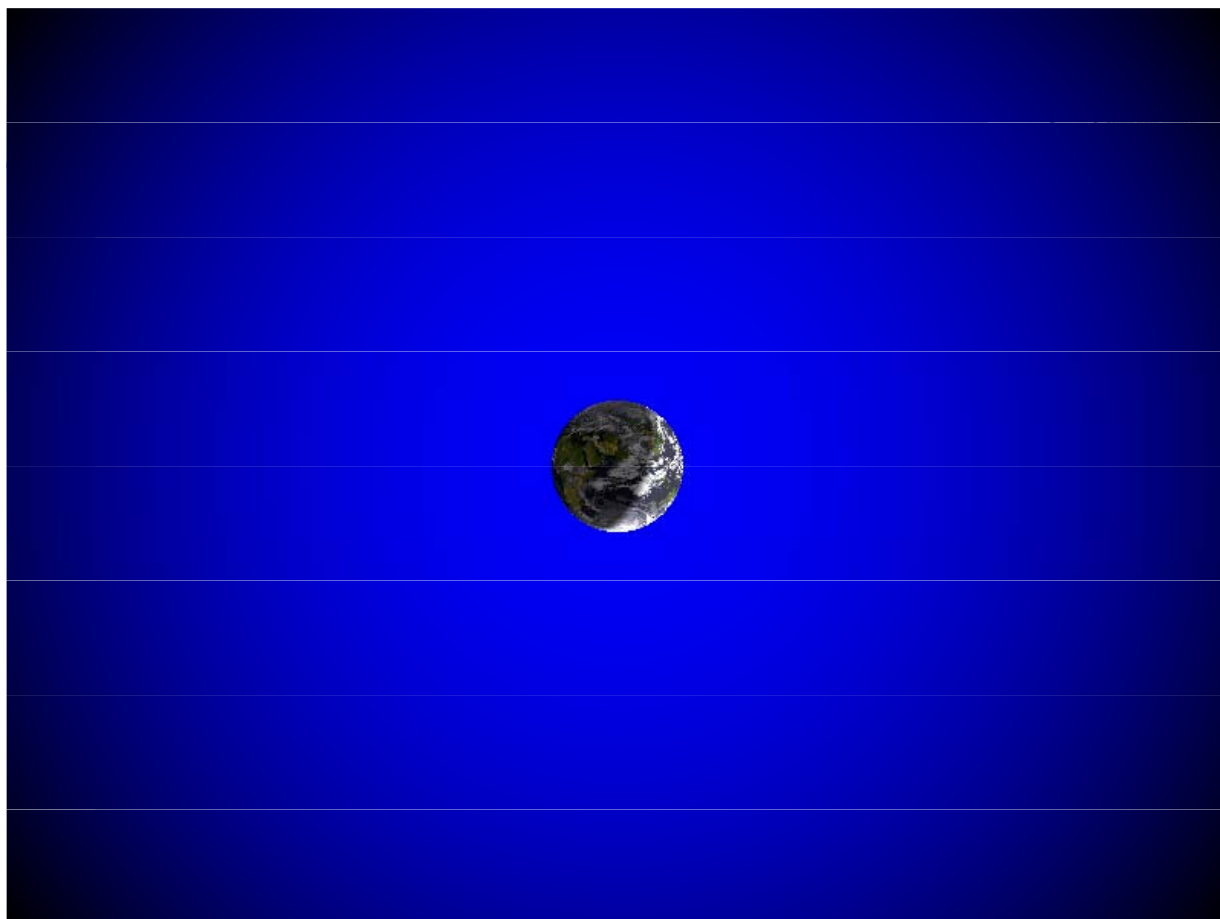
Study of Space Debris Collision Avoidance Maneuvers in JAXA

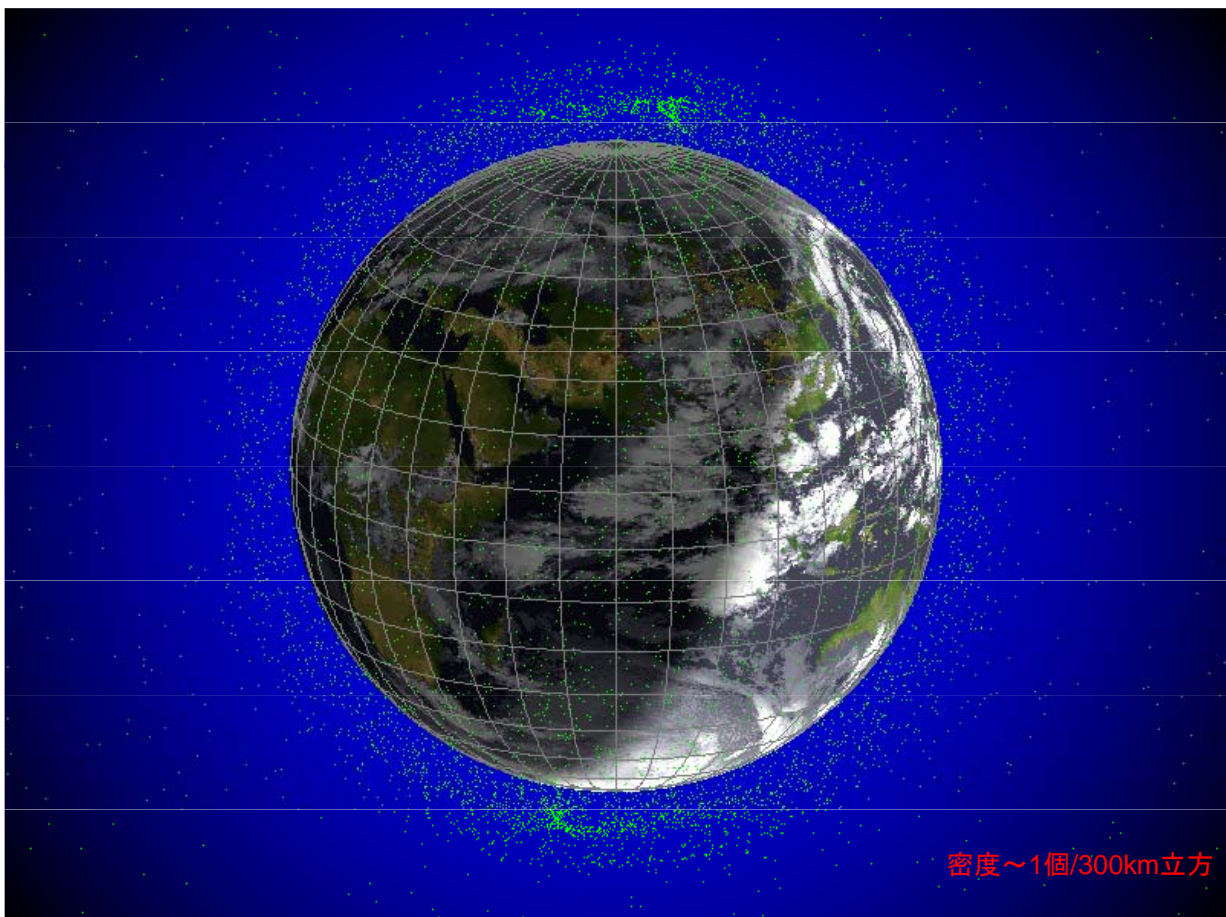
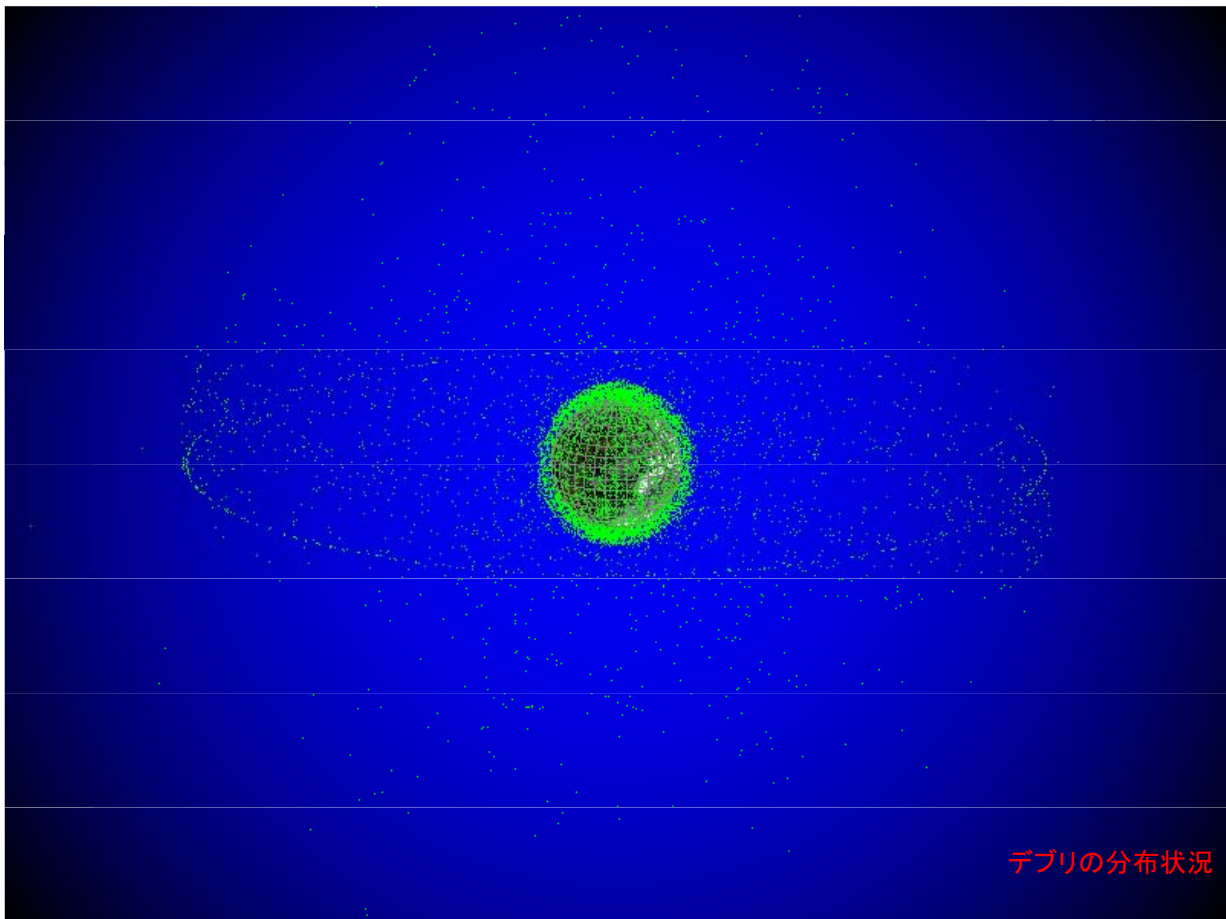
Michiaki Horii, Shigehiro Mori, Nobuo Kudoh, Chikako Hirose

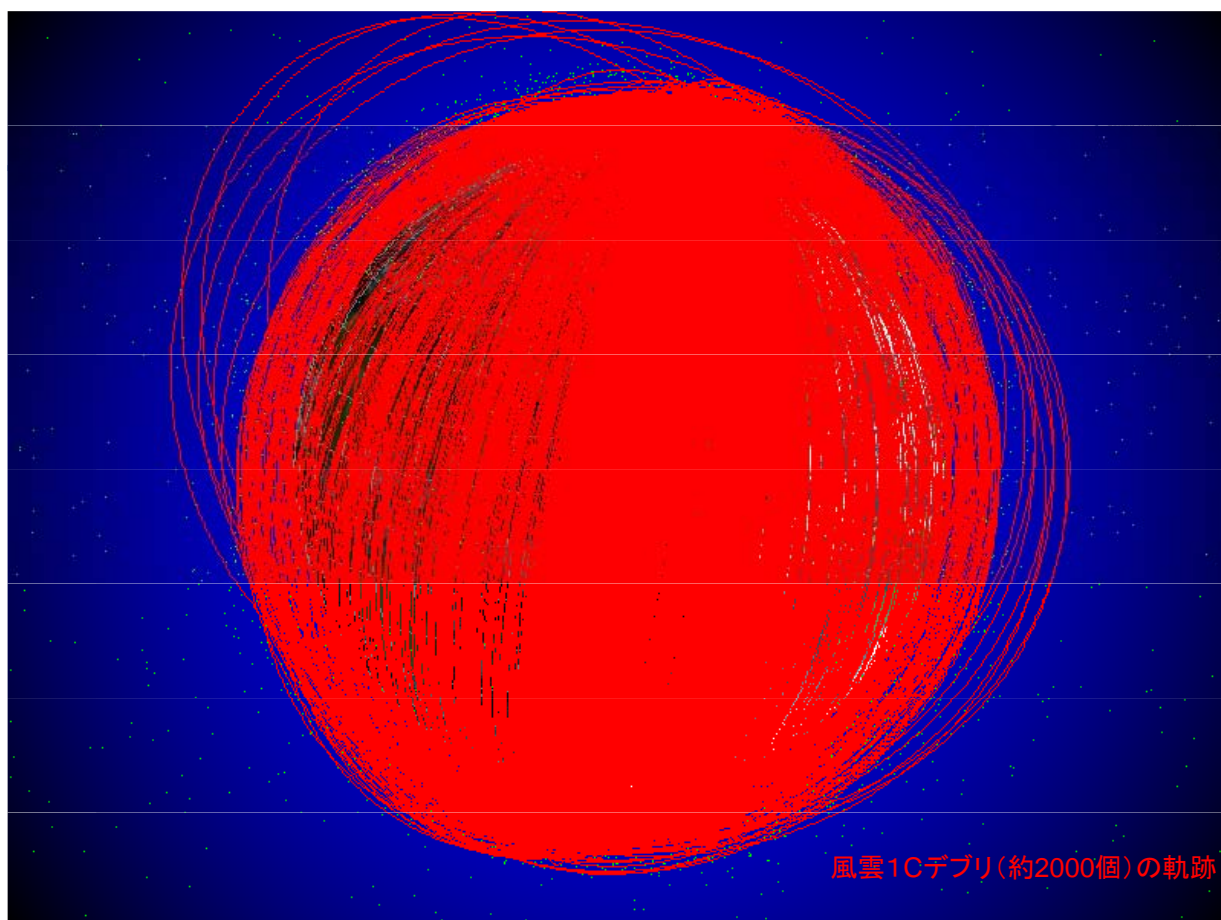
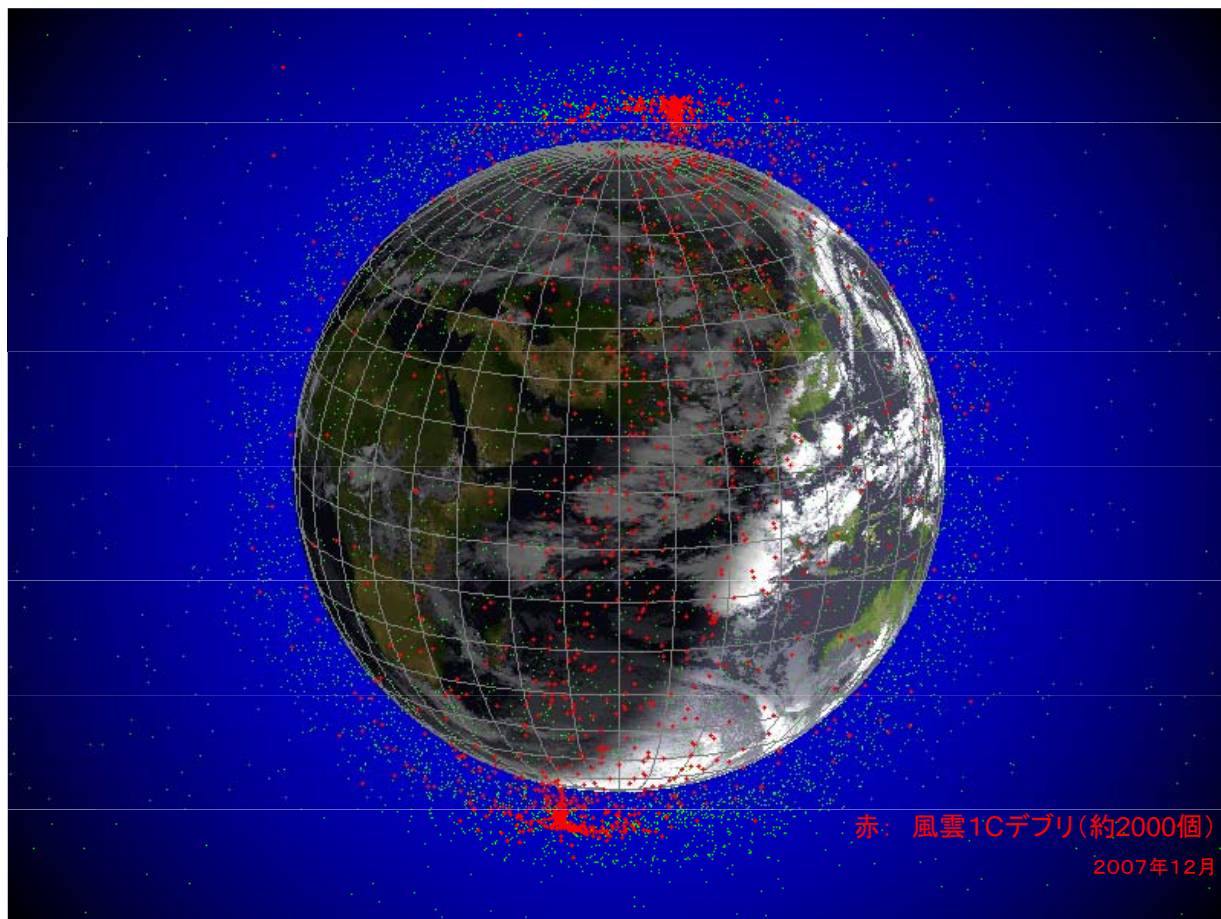
Flight Dynamics Division
Consolidated Space Tracking and Data Acquisition Department
Office of Space Flight and Operations, Japan Aerospace Exploration Agency

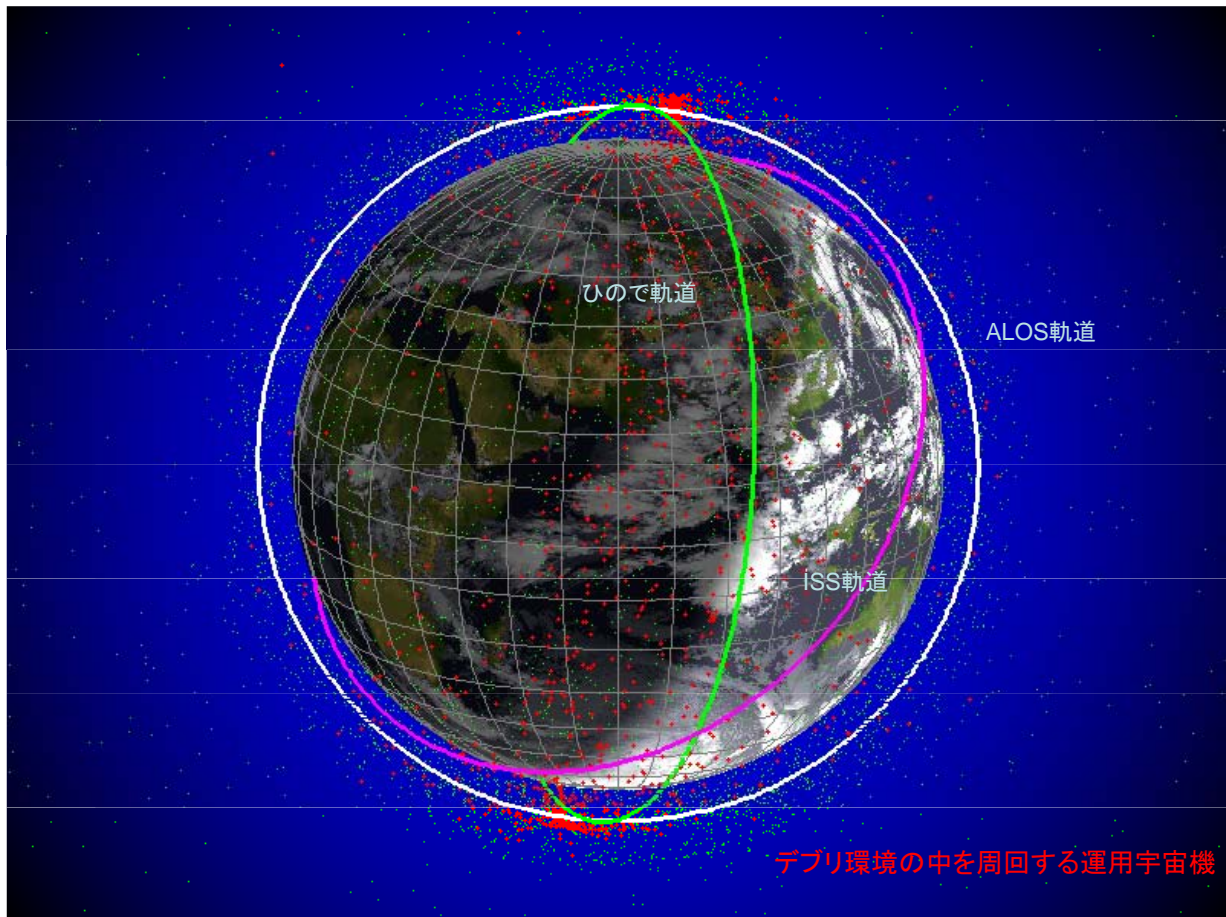


Miraikan, 21-22 Jan 2008









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3. CAM strategy - *when do we perform CAM?*
4. Maneuver methods - *how do we perform CAM?*
5. CAM system
 - 5.1. Radar systems
 - 5.2. CAM software
6. Monitoring conjunction events
7. Future plans
8. Reference

1. Introduction

- Risk of space debris



JAXA started to study a collision avoidance maneuver (CAM) for the purpose of mission assurance and the space environment protection.

The probability that 1mm ϕ space debris clashes to a satellite per year is comparable with the failure rate of some major subsystems.

Table 1. Number of objects which crash to one satellite (alt.700km, area 20m²) in 5 years

Debris size	0.1mm	1mm	1cm	10cm	> 1m
Satellite's damage	Functional deterioration E.g. Solar array	Partial functional loss	Complete loss	Complete destruction	Complete destruction
Expected number of collision in 5 years	9000	0.4	0.01	0.0006	0.0001
Observable?	No	No	Yes and no	Yes	Yes
Defensibility?	Yes	Yes	No	Yes by CAM	Yes by CAM

Chart by Dr. Kato, JAXA 9

1. Introduction (contd.)

- Collision avoidance maneuver at NASA and ESA



➤ Collision avoidance maneuver (CAM) at NASA and ESA

✓ NASA^[1]

Oct 2005: Earth observation satellite "TERRA" performed CAM against a piece of debris from SCOUT G-1 upper stage

Jun 2007: "TERRA" against "Fengyun 1C debris" (Chinese debris by ASAT)

Jul 2007: "Cloudsat" against "Shinoh 1" (Russian satellite launched in October 2005)

✓ ESA^[2]

ESA routinely monitoring conjunction events of ERS-2, SPOT-2 and ENVISAT and performs CAM when the collision probability and minimum distance violate the threshold. The following table shows the number of CAM alarms and CAM performance of ERS-2 and ENVISAT between March 19 and December 27, 2004.

	CAM alarms	CAM performance
ERS-2	Twice	Once
ENVISAT	5 times	Twice

1. Introduction (contd.) - ALOS specifications



We have studied a collision avoidance maneuver (CAM) for ALOS with ALOS project group since 2006. ALOS is a Japanese large land observation satellite at altitude of about 700km. It was launched in January 2006.

Table 2. ALOS orbit

Orbit Type	Solarsynchronous, sub-recurrent, frozen
Height	691.65 km
Period	98.7 mins
Eccentricity	0.001
Inclination	98.16 degs
Recurrent days	46 days
Local time of descending node	10h30m ± 15m AM
Weight	4 tons

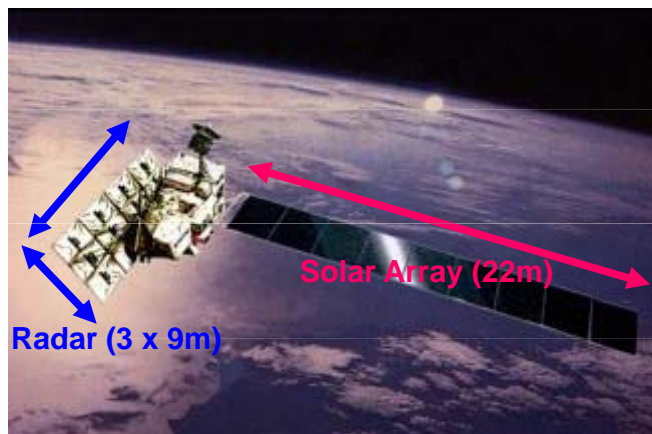


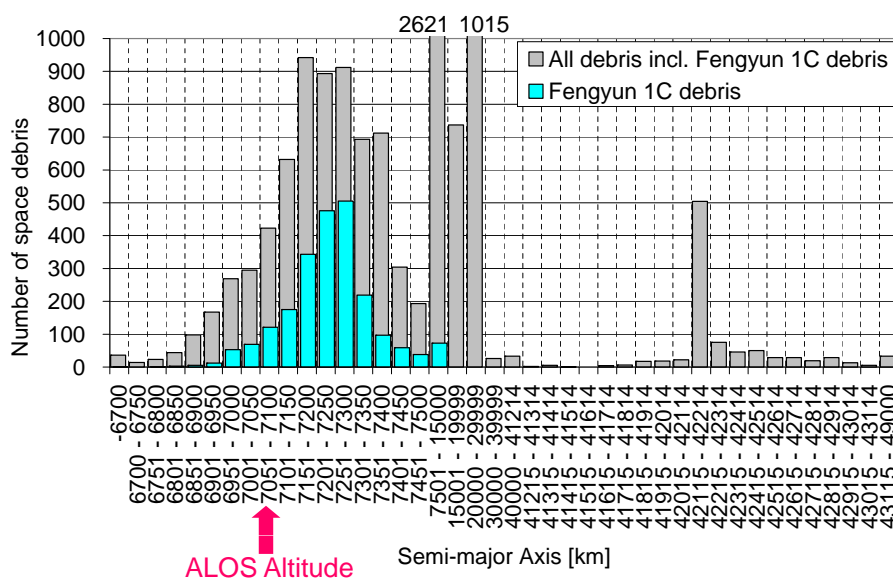
Fig. 1. ALOS

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1. Introduction (contd.) - ALOS's surroundings



Approximately 2,050 space debris exist around ALOS orbit based on the space debris observation by U.S. Space Surveillance Network (SSN)^[3].



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2. Process of studying CAM

Date	Events
'06 Jan	• ALOS launch
Jul	• Start of studying CAM for ALOS
Nov	• Test observation by FGAN radar (in Germany)
Nov	• Start of collision avoidance monitoring
'07 Mar	• Study of ALOS maneuver strategy and CAM operation timeline
May	• 1 st test observation by JAXA radar (in Uchinoura, Japan)
Jul	• Start of developing analysis software for CAM
Dec	• 2 nd test observation by JAXA radar (in Uchinoura, Japan)
'08 Jan	• ALOS CAM operation, step by step

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3. CAM strategy

The current CAM strategy is shown in figure 2.

The 1st screening for monitoring risk objects is analyzed by the US SSN data. However, those data released to the public still contain some prediction errors especially in in-track direction. Thus the following precise debris observation, usually by radar, is expected for precise conjunction analysis. Once the collisional object is detected by the precise analysis, CAM decision will be made.

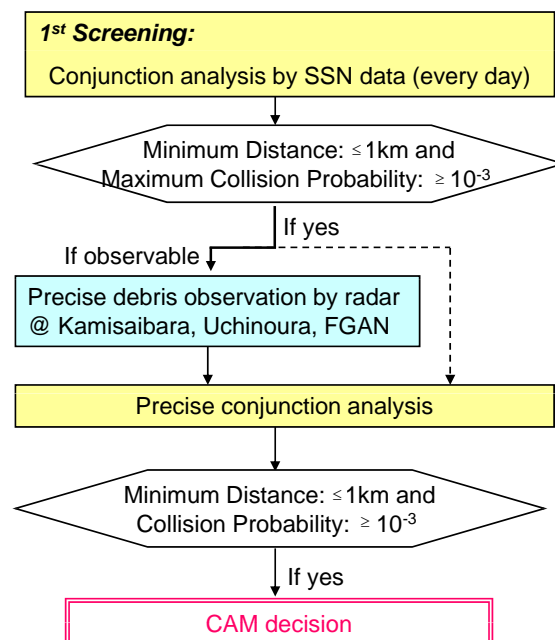


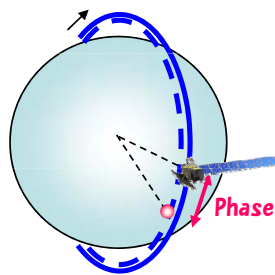
Fig. 2. The current CAM strategy

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4. Maneuver methods

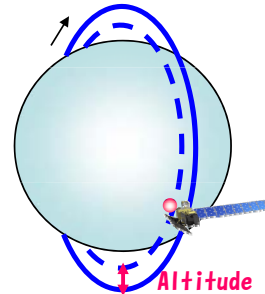
Two methods can be applied for collision avoidance maneuvers in general. One is a phase control and another is an altitude control.



➤ **Separate the phase** distance (case of ALOS; 30km) at predicted collision epoch

Returning to the nominal orbit: about **10days**, conducting 5 maneuvers

➡ **Suitable for ALOS**



➤ **Rise the altitude**

Returning to the normal orbit: about **a few months** (because of the constraint of maneuver timing caused by its sensor)

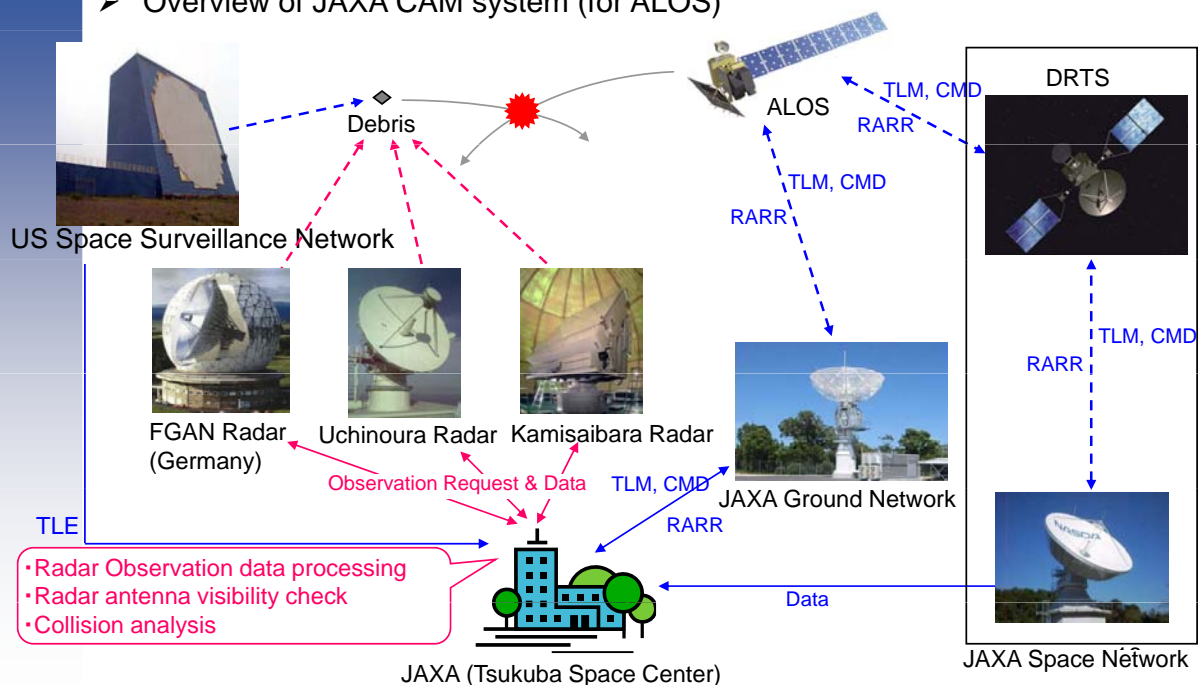
➡ **Unsuitable for ALOS**

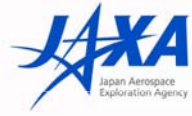
15

5. CAM system



➤ Overview of JAXA CAM system (for ALOS)





5.1. Radar systems

When the minimum distance and the maximum collision probability are over the threshold by the 1st screening, JAXA requests observations to radar stations for more precise orbit information of the risk object.

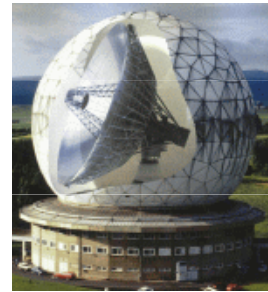
Candidates of radar stations



Kamisaibara (KSGC) Radar
/ Japan Space Forum
Detectability: 1m ϕ at 577km



Uchinoura Radar
/ JAXA
1m² at 1960km



TIRA Radar
/ FGAN, Germany
2cm ϕ at 1000km [2]

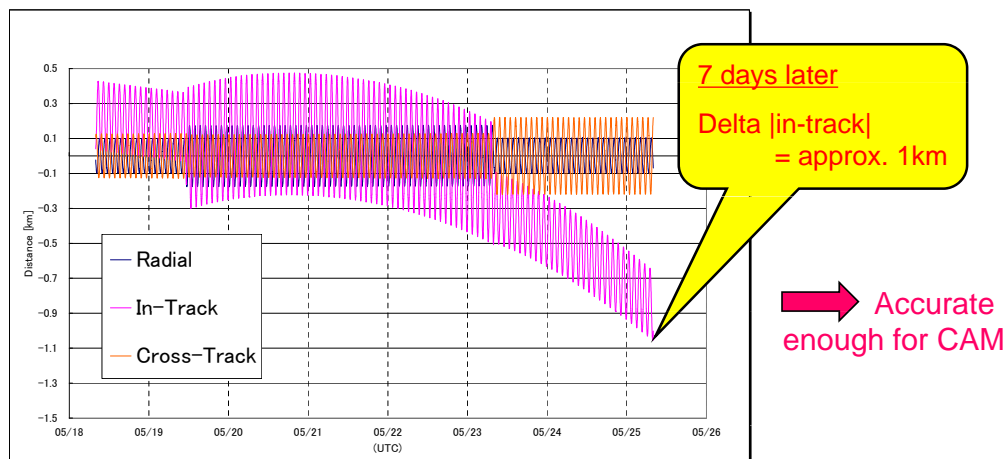
17

5.1. Radar systems (contd.) - JAXA Uchinoura radar



➤ JAXA Uchinoura radar

We compared an operational satellite (**ASTRO-E2**) orbital element derived from the radar data (**2 passes for 2 days**) with the one derived from RARR data (position error: about 10m).



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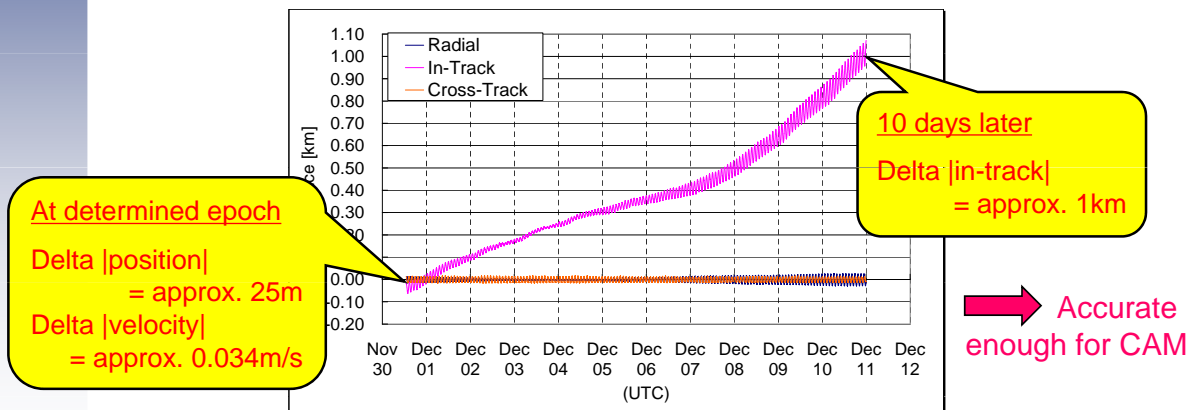


5.1. Radar systems (contd.)

- FGAN TIRA radar

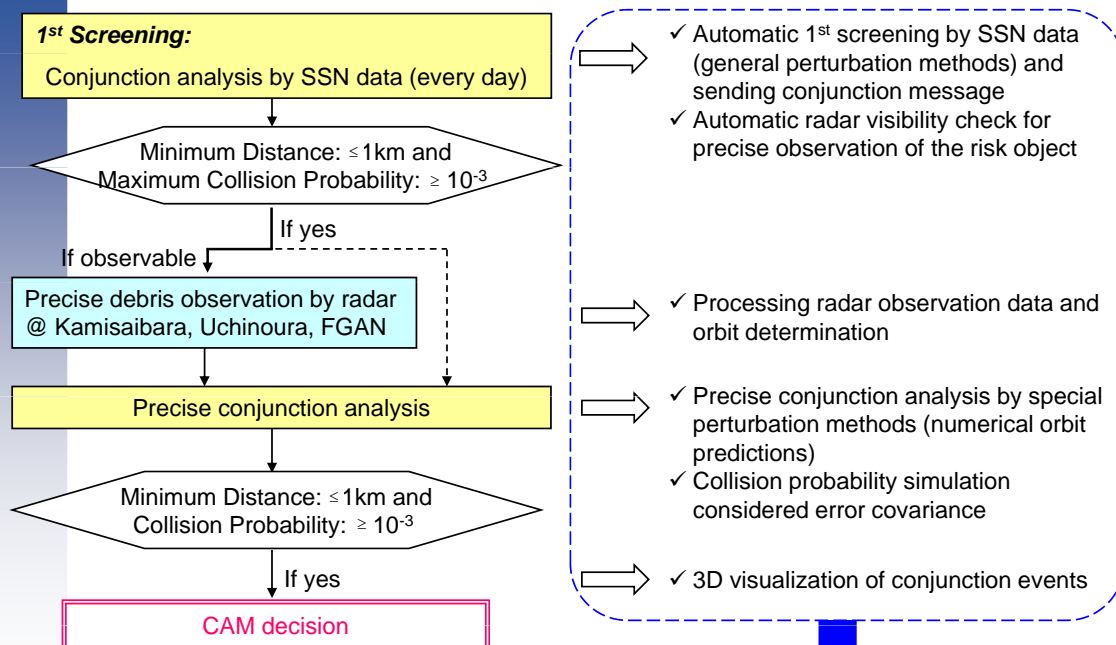
➤FGAN (TIRA) radar

The main candidate of precise observation is FGAN radar. We compared an operational satellite (**ALOS**) orbital element derived from the radar data (**4 passes for 2 days**) with the one derived from precise orbit determination data (position error: 30cm).



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5.2 CAM software



Software development completes by this spring 20



6. Monitoring conjunction events

The figure 3 shows the objects which have approached to ALOS within 5km since JAXA started monitoring conjunction events of our operational satellites in November 2006. Although 394 objects have approached to ALOS in 5km since then, any objects which violated the threshold have not been detected for ALOS yet.

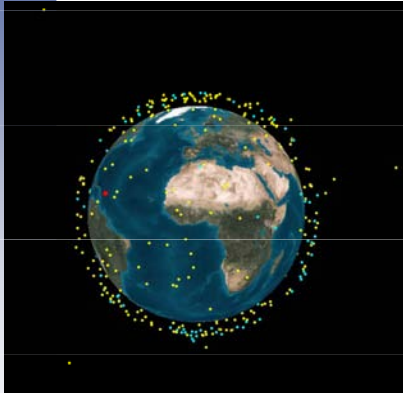


Fig. 3. Objects approached to ALOS in 5km since Nov. 2006

(Red: ALOS, blue: Fengyun 1C debris, yellow: the other approached debris)

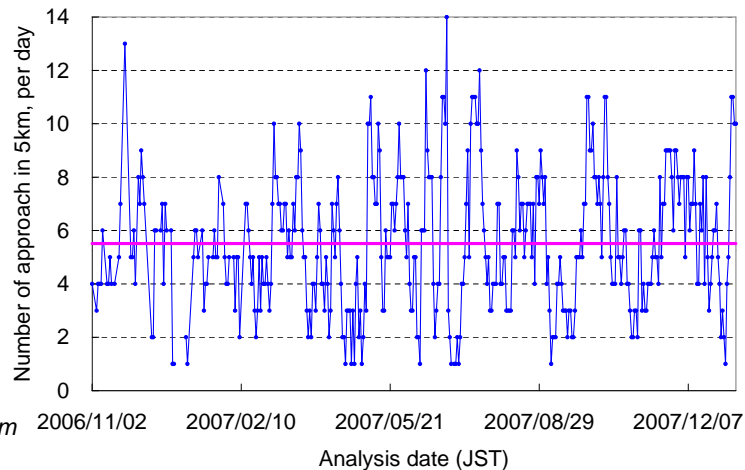


Fig. 4. Number of approach to ALOS in 5km, per day (Pink line: average number of approach during this period)



7. Future plans

➤ Remaining works

•Operation rehearsal

Rehears the CAM operation including satellite projects (preparation of satellite operation procedure) and radar stations to confirm the timeline and the strategy

•Evaluation of CAM software

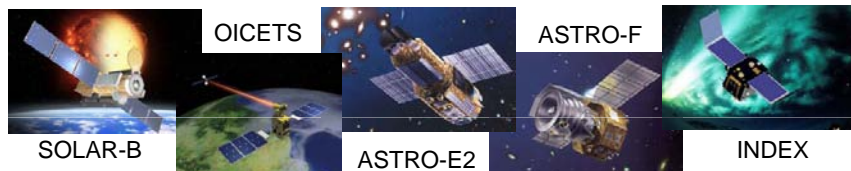
Evaluates the software and improves it as necessary

➤ Enhancement and maintenance of observation system (radars / telescopes) is necessary for CAM against small debris

➤ Needs to reduce the maneuver amount by precise orbit prediction

➤ CAM application to other satellites, if required

After ALOS execution, we will apply CAM operation to other operational satellites (below) using similar strategy if required.





8. Reference

- [1] NASA Orbital Debris Quarterly News, *Volume 10, issue 1*, January 2006
NASA Orbital Debris Quarterly News, *Volume 11, issue 4*, October 2007
- [2] H. Klinkrad. Space Debris, Models and Risk Analysis, *Springer*, 2006
- [3] Space Track. <http://www.space-track.org/>

1-4 JAXA におけるデブリ解析ツールの開発

○河本 聡美（宇宙航空研究開発機構／総合技術研究本部／宇宙先進技術研究グループ）

DEVELOPMENT OF DEBRIS ANALYSIS TOOLS IN JAXA

Satomi Kawamoto (Advanced Space Technology Research Group, Institute of Aerospace Technology, JAXA)

Key Words: Debris, Collision risk analysis, Debris mitigation standard

概要

現在 JAXA 総合技術研究本部 宇宙先進技術研究グループでは、デブリ対策研究の一つである「デブリモデル化の研究」として、デブリに関連するモデル、解析ツールの開発を行っている。

デブリの発生を抑制するため、JAXA は JMR-003 デブリ発生防止標準としてロケットおよび宇宙機の計画段階、設計段階、および運用段階において考慮すべき事項について制定している。そこで、宇宙機の設計段階で、設計者がデブリのリスクを簡易的に評価し、JMR-003 の要求を満足しているかの確認を支援するための「デブリ評価支援ツール」を開発し、現在 JAXA 内で試験配布している。

また、現在軌道上、特にデブリ密度の高い低軌道ではデブリの超高速衝突による損傷のリスクは無視できないレベルに達しており、クリティカルなコンポーネントをデブリ衝突頻度の低い場所に配置する、構造部材などで防御する、あるいは運用中にデブリ衝突リスクの低い姿勢に変更するなどの防御策をとることが有効である。外国ではこれらの対策をすでに実施しており、JAXA でも開始するためには、宇宙機の形状や姿勢、部材による隠蔽も考慮して、宇宙機の各部に衝突するデブリを解析するための「デブリ衝突リスク解析ツール」が必要となっている。

本講演では、上記の解析ツールの機能や解析手法、開発状況について紹介する。なお、デブリの将来分布を予測するデブリ推移モデルは九州大学との共同研究により開発中であり、次の講演にて報告する。

3rd Debris Workshop (2008.1.21)

JAXAにおけるデブリ解析ツールの開発

DEVELOPMENT OF DEBRIS ANALYSIS TOOLS IN JAXA

河本 聡美(宇宙航空研究開発機構 総合技術研究本部
宇宙先進技術研究グループ)
Satomi Kawamoto (Advanced Space Technology Research Group
Institute of Aerospace Technology/JAXA)

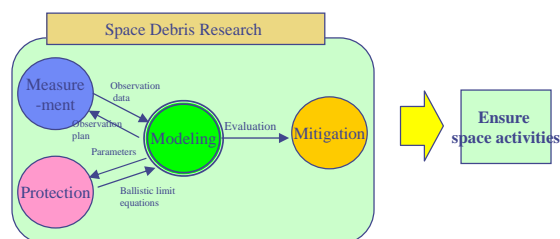
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Introduction

◆ Space debris research

- Measurement
- Modeling
- Protection
- Mitigation



◆ JAXA has started development of

- Debris assessment tools
(Debris mitigation standard support tools)
- Debris collision risk analysis tool
- LEO evolutionary model
 - ◆ collaboration with Kyushu University

	Debris Assessment	Engineering model	Evolutionary model	Reentry analysis	collision risk
NASA	DAS	ORDEM, NASA90	LEGEND, EVOLVE, CHAIN	ORSAT	BUMPER-II
ESA	DRAMA	MASTER, DISCOS	DELTA, SDM, CHAINEE	SCARAB	ESABASE/DEBRIS
	CNES			IMPACT	
	TUBS	MASTER	LUCA, (CHAIN)		
	DLR			ASTOS/EDA	
	ASI	CODRM	SDM/STAT		
	DLR	SDETES			MDPANTO
			DELTA, IDES, DA		SHIELD, SCALP
			MAGE, FADE	REPORT	BUFFER, COLLO, PS C
Russia		SDPA	SDPA, Nazarenko	NAME ?	ARMOR, MODAOST
China	SDEM	NAME ?	SDEAP	NAME ?	
ISRO		SIMPLE, SIMPGE		NAME ?	
Japan	DEMIST		LEODEEM		NAME ?



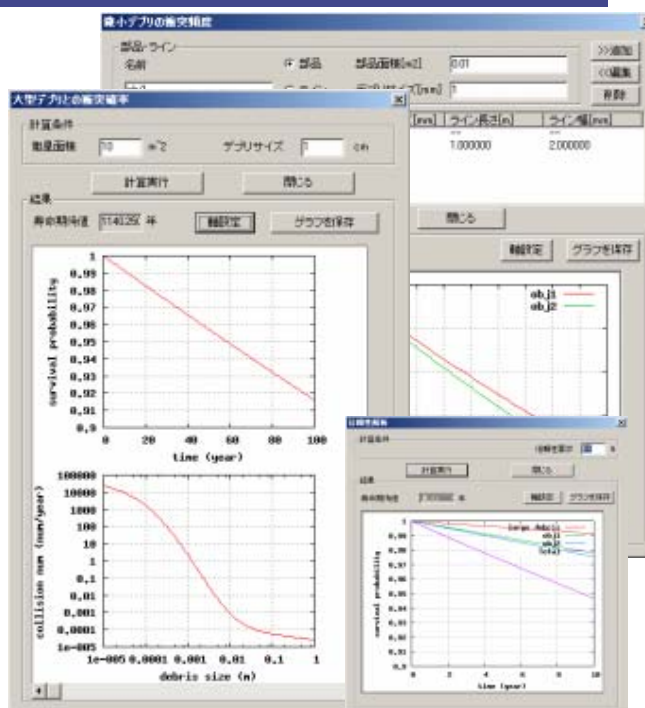
Debris Assessment Tools (Debris Mitigation Standard Support Tools)

- ◆ Objectives
 - Assess debris risk
 - Assist space system planners in complying with JMR-003 debris mitigation standard
 - ◆ Japan established space debris mitigation standard in 1996
- ◆ DEMIST (Debris Mitigation Standard Support Tools)
 - Simple tools to assess debris collision probability, lifetime, ...
 - ORDEM2000 debris flux model is used
 - Have a Graphical User Interface
 - Run on Microsoft Windows 2000/XP
 - Developed last year and currently under evaluation



Functions of DEMIST (1)

1. Impact probability with large debris
 - probability of impacts (e.g. > 1cm) that will result in total loss of the mission
 2. Impact probability with small debris
 - probability of failure of critical components due to impacts with small debris
 3. Whole system reliability
 - total survival probability of the space system considering both large debris and small debris
- ◆ orientation of the space system and shielding effects are not considered

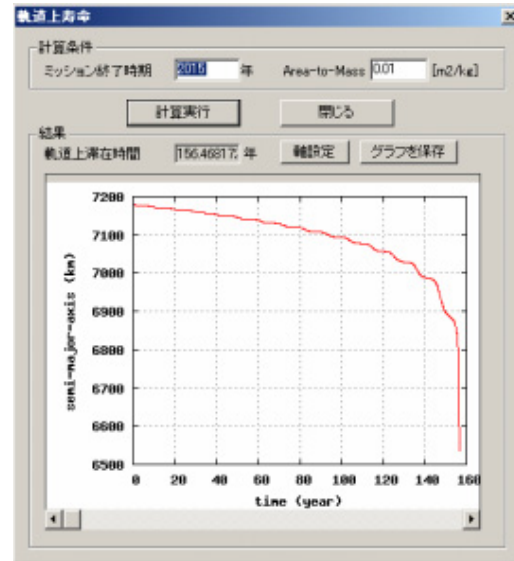




Functions of DEMIST (2)

4. Orbit lifetime

- Atmospheric drag with a time-dependent model, luni-solar gravity, solar pressure and J2 effect are considered
- If orbit lifetime exceeds 25 years, transfer to a disposal orbit must be investigated



Functions of DEMIST (3)

5. De-orbit maneuver

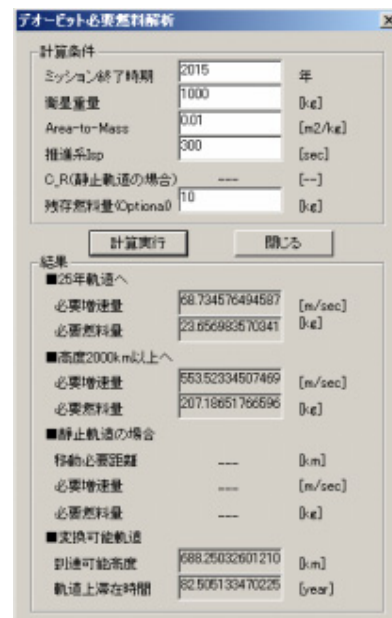
- calculates the delta-V and propellant mass required for de-orbit or re-orbit at the end of mission.
- LEO: for lowering perigee to decrease the orbit lifetime to less than 25 years, and to increase altitude to more than 2000 km
- GEO: for transferring to a higher orbit by

(Required transference distance)
= $235 + 1000 \times CR \times A/M$ [km]

Where:

CR : Solar radiation coefficient

A/M : Area to Mass [m²/kg]





Functions of DEMIST (4)

6. Collision avoidance maneuver

- Calculates the expected number of collision avoidance maneuvers using the flux of catalog sized debris
- Calculates the required delta-V and fuel
- It is just a demonstration and to be updated since JAXA is now investigating collision avoidance strategies

7. Reentry maneuver

- computes the delta-V and fuel to lower perigee of 60 km altitude



Functions of DEMIST (5)

8. Reentry analysis

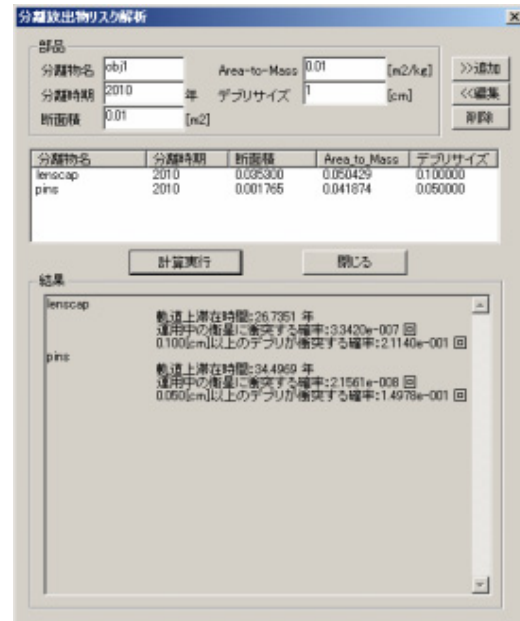
- ORSAT-J (updated version of NASA ORSAT, Object Reentry Survival Analysis Tool) is used
- Criteria for risk evaluation are
 - ◆ the casualty area
 - ◆ the predicted number of injuries
- If the predicted number of injuries is more than 1×10^{-4} for one reentry, the feasibility of a controlled reentry should be studied



Functions of DEMIST (6)

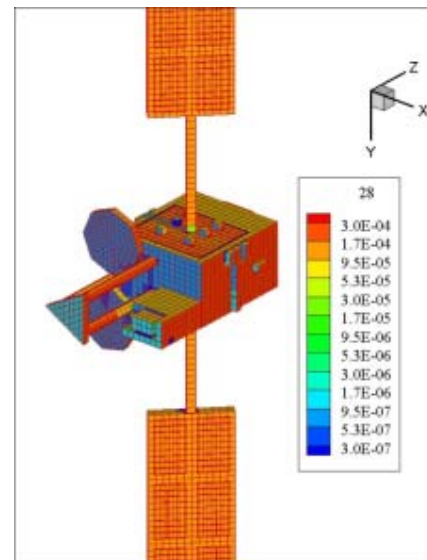
9. Impact risk of released objects

- Calculates orbit lifetimes and
- Collision probability with
 - ◆ operational objects
 - ◆ debris of a defined size that will result in the creation of further small debris



Debris Collision Risk Analysis Tool

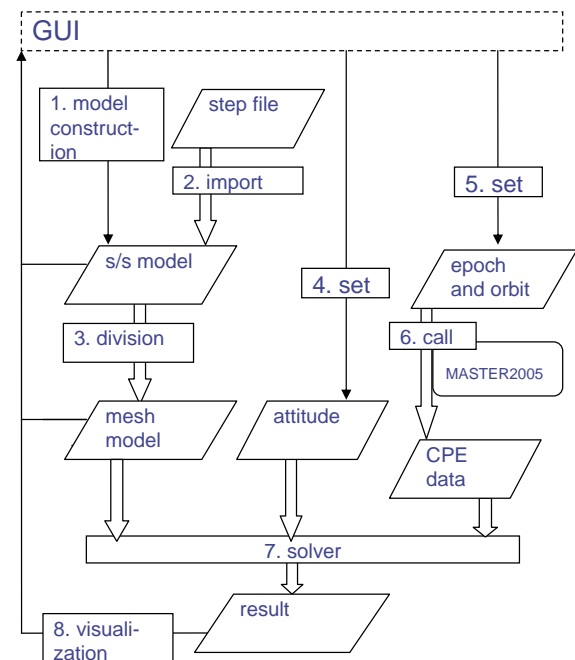
- ◆ Objectives
 - Calculate collision probability to each part of a space system considering its shape and attitude
 - ◆ critical components may be placed where the probability of debris impact is lower, or shield them using other structures or special protective shields
 - ◆ attitude of a space system may be altered to minimize impact risks
 - Evaluate damage risk (probability of penetration) by implementing the ballistic limit equations in the future
- ◆ MASTER 2005 Cell Passage Events (CPEs) dump function is used
 - impact velocity, angle, size and type of the impactor can be calculated





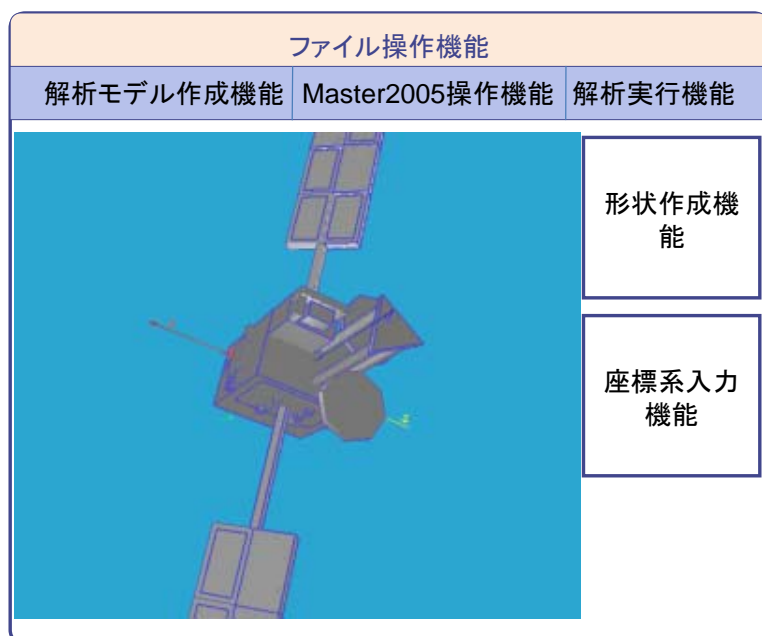
Process flow

1. Construction of space system model
 - 3D user interface is available
2. Import of STEP format file
 - The tool can also read STEP format files exported by CAD software
3. Division
 - The surface of the space system is divided into a small mesh
4. Attitude settings
5. Epoch and orbit settings
6. MASTER2005 execute
 - MASTER 2005 program is executed to calculate debris flux
7. Solver
 - Calculate the directions of impacts to each mesh considering shielding effects
8. Visualization



Construction of space system model

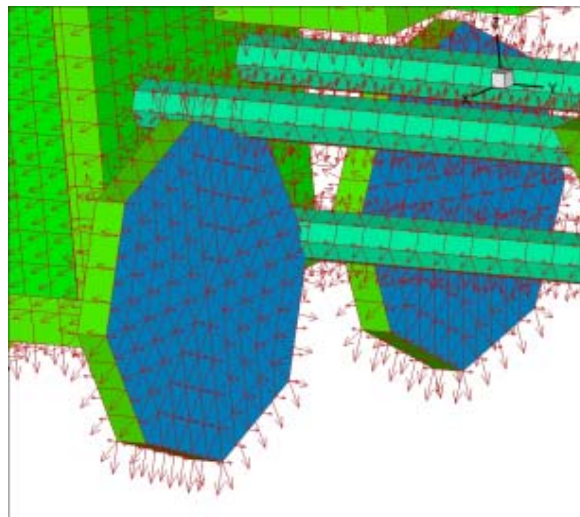
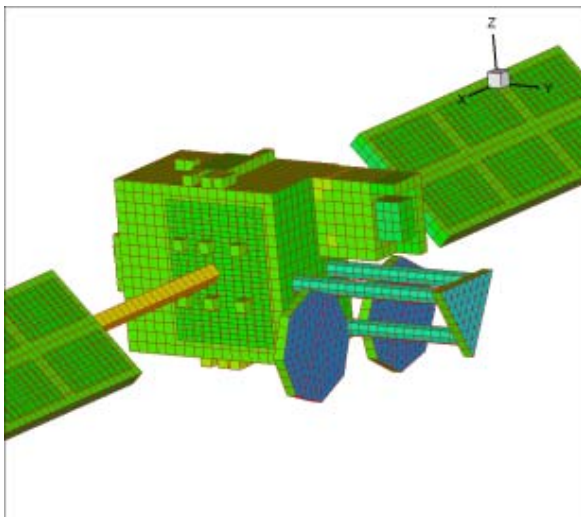
1. A simple model can be constructed using GUI or
2. STEP format can be imported from CAD software





Division

3. The surface of the space system is divided into a small mesh



Parameter settings and debris flux calculation

4. Attitude settings
 - Attitude in local horizontal coordinate and its subsequent orientation, such as Earth-oriented, Sun-oriented and inertially fixed, can be selected
5. Epoch and orbit settings
 - Epoch and the orbit of the space system are defined
6. MASTER2005 execute
 - MASTER 2005 (ESA's debris flux model) is executed using its command line interface with the time and orbit parameters defined in the above steps. This generates CPE (Cell Passage Events) dump files for use by the solver





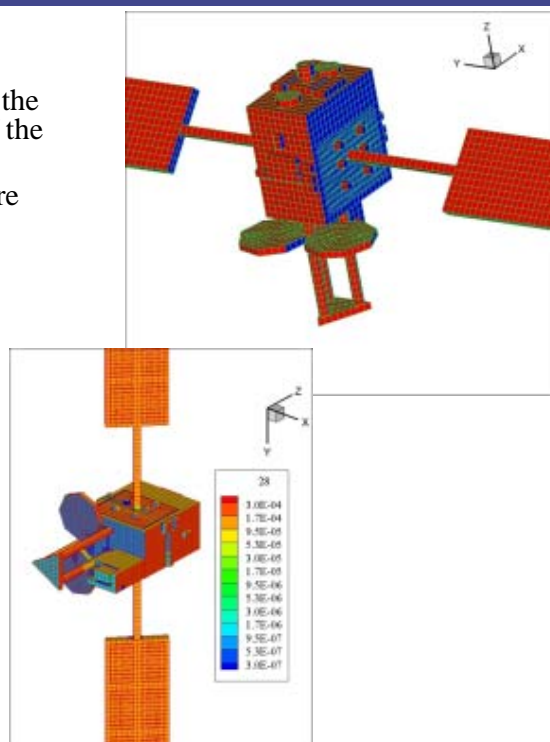
Solver and visualization

6. Solver

- The CPEs are analyzed to calculate the directions of impacts to each cell of the surface mesh
- Shielding effects by other meshes are considered

7. Visualization

- Results are depicted in a 3D view



Summary and future works

◆ Summary

- Current status of the following analysis tools are introduced
 - ◆ Debris assessment tools (Debris mitigation standard support tools)
 - to be used during the planning phase of space system development for performing debris risk assessment and determining compliance with debris mitigation guidelines
 - ◆ Debris collision risk analysis tool
 - for calculating the collision probability for each part of a space system considering its shape, attitude, and shielding effects

◆ Future works

- Further investigation and update of debris related tools and models
- Assist JAXA's projects to use these tools for mission success

1-5 地球低軌道におけるスペースデブリ環境の推移モデル

鳴海智博, ○花田俊也 (九州大学), 河本聡美 (宇宙航空研究開発機構)

An Evolutionary Model of Low-Earth Orbital Debris Environment
Tomohiro Narumi, Toshiya Hanada (Kyushu University), and Satomi Kawamoto (JAXA/IAT)

Keywords: Orbital Debris.

低軌道の環境推移モデルは NASA の LEGEND, ESA の MASTER, イタリア学術会議の SDM, イギリス国防研究所の IDES などがあり, 我が国でも九州大学において静止軌道における環境予測のモデルが既に作られているが, スペースデブリの数が特に集中する低軌道においてはまだ独自のモデルが存在せず, 研究開発が急がれていた.

新しい低軌道環境推移モデル LEODEEM(Low Earth Orbital Debris Environment Evolutionary Model)は近地点高度 2000km 以下, サイズが 1cm 以上の物体の軌道環境の推移を予測する. LEODEEM において, スペースデブリのベースラインとなるデータは IADC (Inter-Agency Debris Coordination Committee)が配布しているものを使用しているが, 軌道計算や衝突確率計算などにおいては多機関のモデルとは異なる方法を用いている.

環境推移モデルのような長期間の軌道要素の変化をみる場合, 物体の短周期運動は重要ではなく, 長周期の変化及び永年変化のみが必要になる. そこで LEODEEM では, 軌道要素の変化の時間平均をとる手法を用いている. この解析的な手法による計算結果は数値解や実際の履歴と比較しても誤差は小さく, 長期の環境変化を見るための手法としては十分に適用可能なものであることが分かっている.

LEODEEM では Business as Usual シナリオとして, 2002 年 1 月 1 日のスペースデブリ環境の初期条件とし, IADC が記載している 1994~2001 年の軌道投入の履歴を 100 年間程度繰り返し使用し, 環境の推移を計算する. 軌道上物体の爆発率についても, IADC による爆発履歴を用いている.

爆発・衝突によって新たに発生した破片については, NASA の標準破碎モデルを用いて, その個数, 質量, サイズ, 面積質量比, 質量ならびに放出速度を計算している.

2 物体間の衝突率を計算する方法としては, 軌道が最も接近する位置での距離を算出し, 衝突する可能性の有無を判定した後, 気体分子運動論を応用した手法で衝突率の算出を行い, 乱数と比較することで衝突判定を行う.

シミュレーション結果の例を以下に示す. 計算回数は 30 回とし, その平均を結果とする. 下に示した図は, Business as Usual, ロケット上段機体の爆発の抑制であるが, 他のスペースデブリ低減条件などを考慮した場合の計算も可能である.

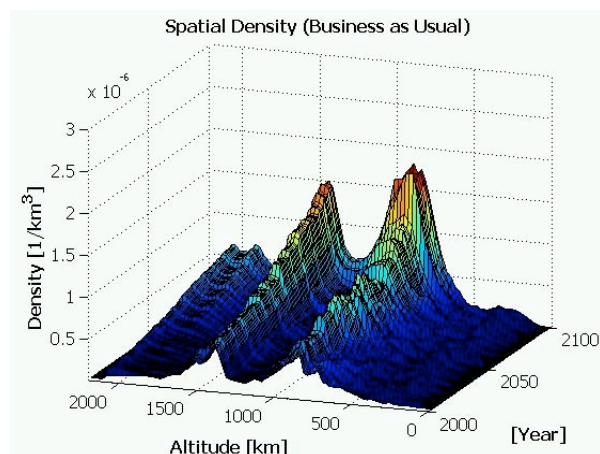


Fig.1 空間密度分布(BAU)

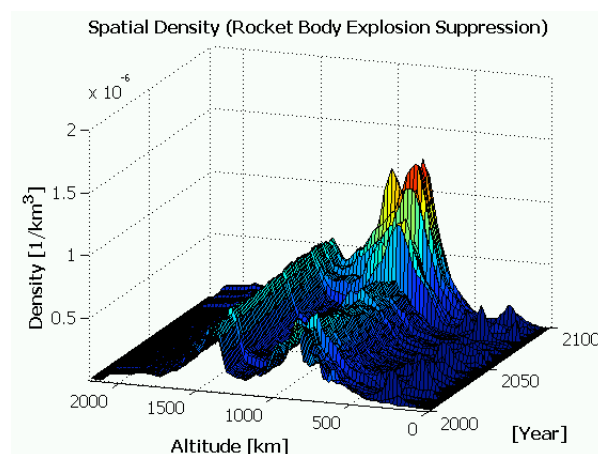


Fig.2 空間密度分布(RB 爆発抑制)

An Evolutionary Model of Low-Earth Orbital Debris Environment

T. Narumi¹, T. Hanada¹, and S. Kawamoto²

¹ Kyushu University, Fukuoka, Japan

² IAT/JAXA, Tokyo, Japan

Background and Motivations

- Each space agency has own orbital debris evolutionary models. For examples,
 - NASA's LEGEND (LEO-to-GEO Environment Debris Model),
 - BNSC's IDES (Integrated Debris Evolution Suite), and
 - ASI's SDM (Semi-Deterministic Model for Space Debris Long-term Evolution).
- Does JAXA have own model? — **No.**
- Kyushu University have developed an orbital debris evolutionary model, **but for geosynchronous Earth orbit.**
- This study aims to build an orbital evolutionary model for low Earth orbit through collaboration between Kyushu University and JAXA.

LEODEEM Modeling Concept

- Intact objects are tracked individually.
- Mission related objects and breakup fragments are binned by dimensions of **perigee and apogee radii, inclination, and ballistic coefficient**.
 - Resolution of inclination determines spatial resolution
 - $V_{bin} = \Delta r \times \Delta r \times r \Delta i$
 - Easy to specify colliding bins.
 - Two objects will never approach one another if $(r_p)_{max} - (r_a)_{min} > d$

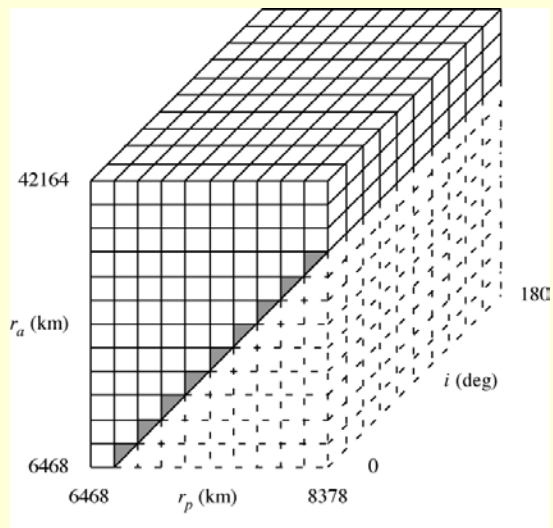


Image of bins.

2008.1.21-22

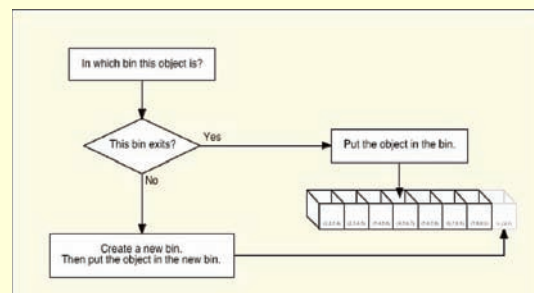
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2

Coding Concept

- Assuming that N objects are binned by dimensions of **perigee and apogee radii** (I - and J -segmented), **inclination** (K -segmented), and **ballistic coefficient** (L -segmented).
- Do we need $I \times J \times K \times L$ bins for N objects?
 - **No**. We need N bins or less.

- How to save CPU memory
 - Allocate memory dynamically for a bin, or
 - Open a file for a bin.



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Projection Flow

1. Initialize orbital debris population
2. Propagate all orbits one year
 - Remove object(s) with $h_p < 90$ km
3. Add new launches
4. Specify object(s) exploded
 - Generate fragments if any
5. Specify objects collided
 - Generate fragments if any
6. Iterate from 2 to 5 during projection period

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LEO Propagator

- Disturbing forces taken into account
 - The Earth's gravity field
 - $J_2 - J_4$ perturbations
 - Atmospheric drag
 - Exponential atmospheric density model
 - Drag coefficient assumed to be 2.2
 - Third body perturbations
 - Sun's position calculated by VSOP87 planetary theory
 - Moon's position calculated by ELP2000/82B lunar theory
 - Solar radiation pressure
 - Reflectivity assumed to be 1.2
- Propagate all 5 elements (a, e, i, Ω, ω) at 5-day intervals

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5

Initial Population

- Based on the [Inter-Agency Space Debris Coordinate Committee's updated modeling baseline](#) of 2002.
- A population snapshot on [January 1, 2002](#) of the LEO/MEO/GTO populations of the 1 cm and larger objects produced by the [NASA's EVOLVE 4.1 projection code](#) and launch database.
- The population represent historical launches, related operational debris, and anomalous debris for which TLE sets are available.
- Verified breakups are also included with breakup fragments deposited via the [NASA Standard Breakup Model 2001 revision](#).
- The population excludes the International Space Station modules and delivery vehicles, and non-fragmentation debris (i.e., NaK droplets, SRM slag).

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Insertion and Breakup Histories

- Based on the [Inter-Agency Space Debris Coordinate Committee's updated modeling baseline](#) of 2002.
- Orbital insertion history for [the years 1994 through 2001](#) for LEO/MEO/GTO objects.
- Several objects purposefully excluded from the traffic cycle.
 - International Space Station (ISS) modules, service vehicles, and debris
 - Mir debris
 - Anomalous debris (i.e. COBE debris)
 - ORBCOMM, IRIDIUM, and GLOBALSTAR constellation spacecraft, rocket bodies, and debris
- Breakup history for [the years 1994 through 2001](#) for LEO/MEO/GTO objects.

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Projection Scenarios

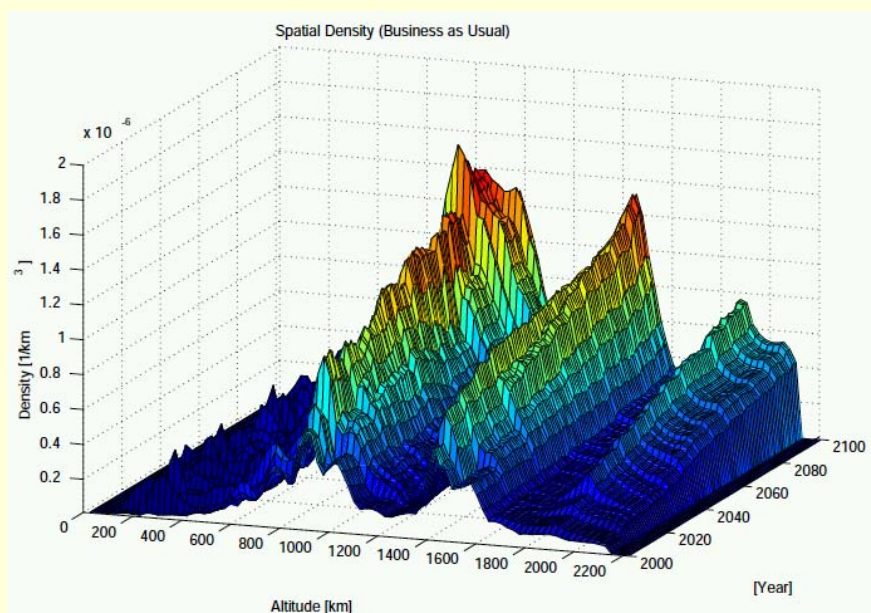
- Baseline Scenario
 - 100-year projection in 1-year increments
 - Insertion history cycled throughout projection period
 - Breakup history cycled throughout projection period
 - Mean of 30 Monte Carlo runs to represent the resulting environment
 - Standard deviation of 30 Monte Carlo runs to represent the error of the model result
- R/B Explosion Suppression Scenario
 - Without breakup history for R/Bs
- Full mitigation scenario
 - Without breakup history for R/Bs
 - All S/C removed within 25 years after completion of their mission.
- No new launch scenario
 - Without insertion history and breakup history for R/Bs

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Spatial Density Growth — Baseline Scenario —

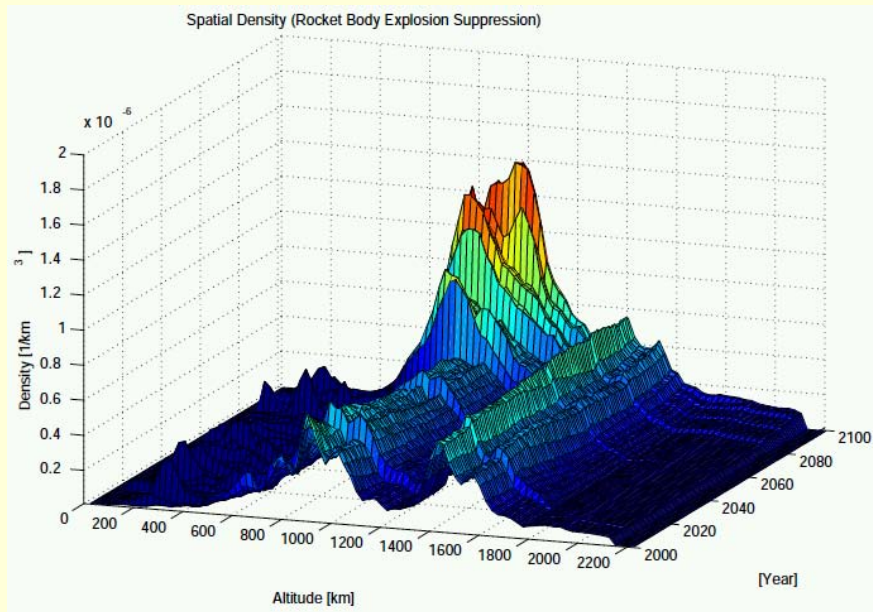


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Spatial Density Growth — R/B Explosion Suppression Scenario —

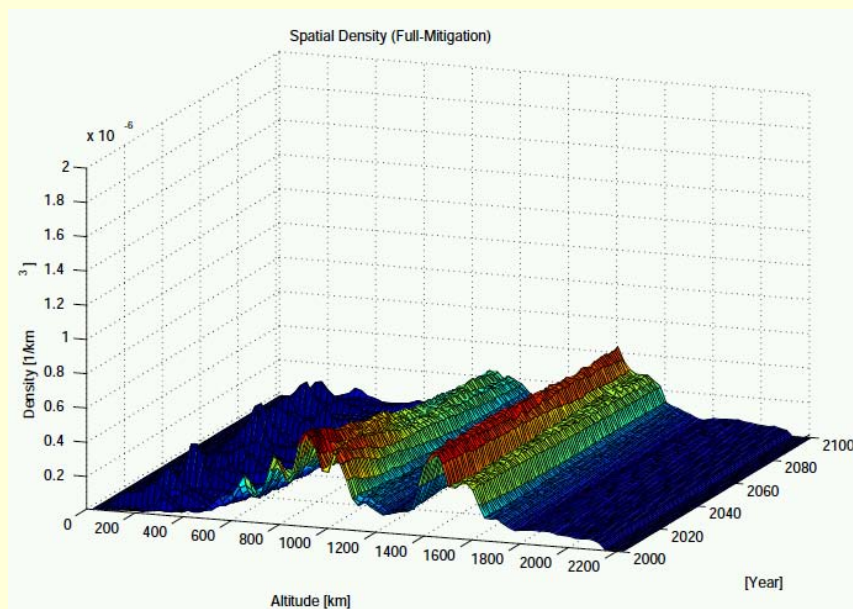


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Spatial Density Growth — Full Mitigation Scenario —

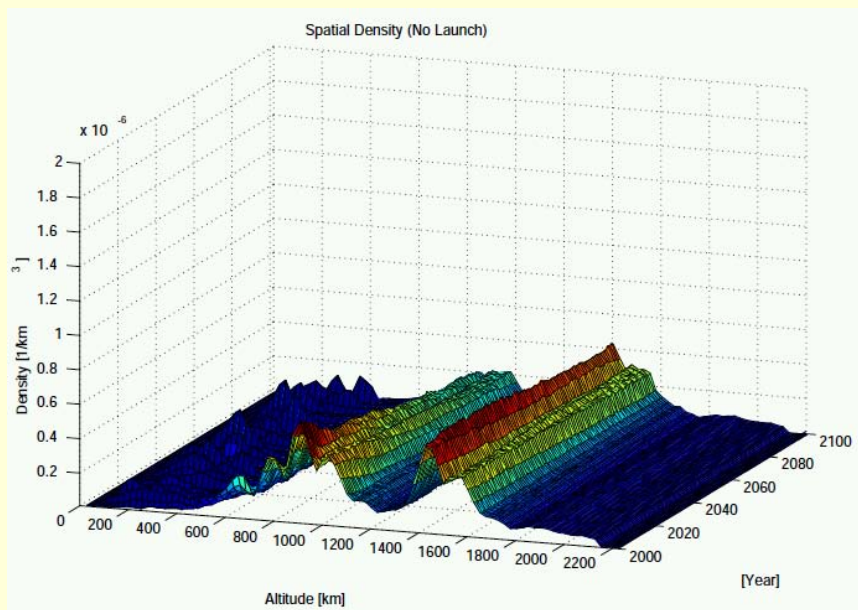


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Spatial Density Growth — No New Launch Scenario —

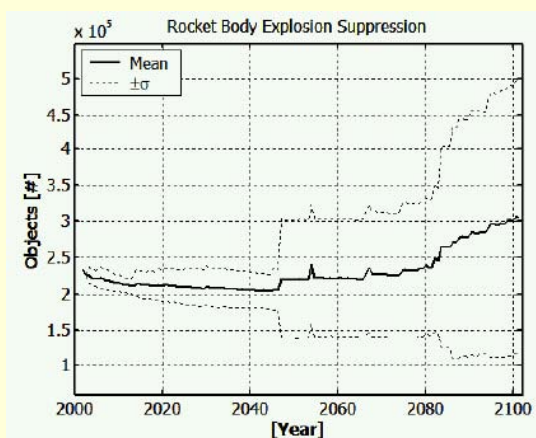
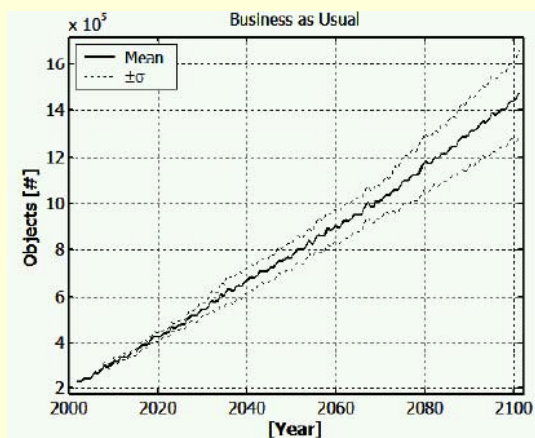


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Comparison of Population Growths



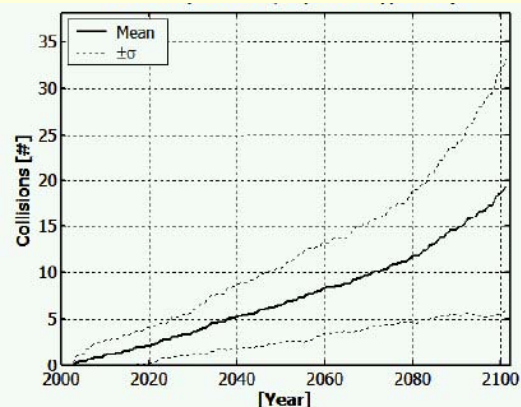
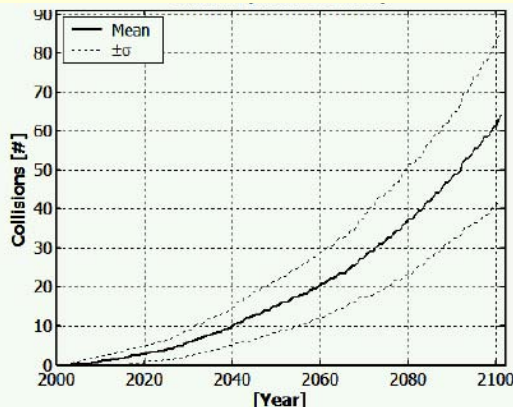
- Rapid growth at the year 2045 in R/B explosion suppression scenario caused by a collision between large intact objects

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Comparison of Collision Activities



- Collision activities reduced by R/Bs explosion suppression, but started to increase exponentially around 2080.

Conclusions

- This paper has introduced an orbital debris evolutionary model for low Earth orbit named LEODEEM, developed through collaboration between Kyushu University and JAXA.
- Future projections using LEODEEM have indicated
 - explosions will continue to contribute population growth in low Earth orbit, and
 - collisions rather than explosions would generate more orbital debris in the future.

Ⅲ. セッション—2 防御

Figure 3. 2019-2020

2-1 JAXA におけるデブリ防御の研究概要

○永尾陽典 (宇宙航空研究開発機構／総合技術研究本部)

The outline of investigation for debris protection in JAXA

Yosuke Nagao (Institute of Aerospace Technology (IAT) / JAXA)

Key Words: Debris Protection, Data base, hypervelocity impact facility

概 要

スペースデブリによる宇宙機への影響は無視できる段階を過ぎ、何らかの対策が求められる時期となりつつある。新規に製造する人工衛星なども、デブリ対策やデブリ衝突による影響を考慮した設計が求められている。人工衛星構造や太陽電池パドルなどの機能品では重量制限が厳しく、積極的なデブリ対策を採ることは難しいがなんらかの損傷低減対策は求められる。一方、有人宇宙基地ではデブリバンパーの採用によって、デブリ衝突による与圧部の損傷防止を積極的に行なっている。いずれの要求であっても、構造や機能品の設計を行なうにはデブリによる超高速衝突事象の把握を行ない、その知見やデータから具体的な対策を立てる事が必要となる。

そのためには、地上での超高速試験設備を充実させデータ取得が必要となる。しかし、デブリ衝突を完全に模擬できる質量と速度を再現できる装置はない。従って、試験とシミュレーションによる内挿や外挿によってデブリ衝突による損傷状況を把握し、この結果に従って設計を行なうとともに地上設備によって耐デブリ特性を確認、実証することが必要になる。

これらを背景に、JAXA で研究を行っている超高速射出装置の開発とその結果を報告する。また宇宙機の構造材料として既に大幅に採用されている、炭素繊維複合材 CFRP に対する超高速衝突試験結果と得られた知見についての概要を報告する。試験を補う手段として既にシミュレーションが多くの分野で活用されているが、CFRP に対する超高速衝突シミュレーション手法の研究も行なっており、その概要についても示す。

(Tokyo, Januarys 21-22, 2008)

第3回スペースデブリワークショップ

The outline of investigation for debris protection in JAXA

Yosuke NAGAO

Japan Aerospace Exploration Agency
Institute of Aerospace Technology

JAXAにおける デブリ防御の研究概要

永尾 陽典

宇宙航空研究開発機構
総合技術研究研本部



Contents



Back ground

Objectives for investigation

Technical Subjects

- Development of Hypervelocity device
- Data base
- Simulation

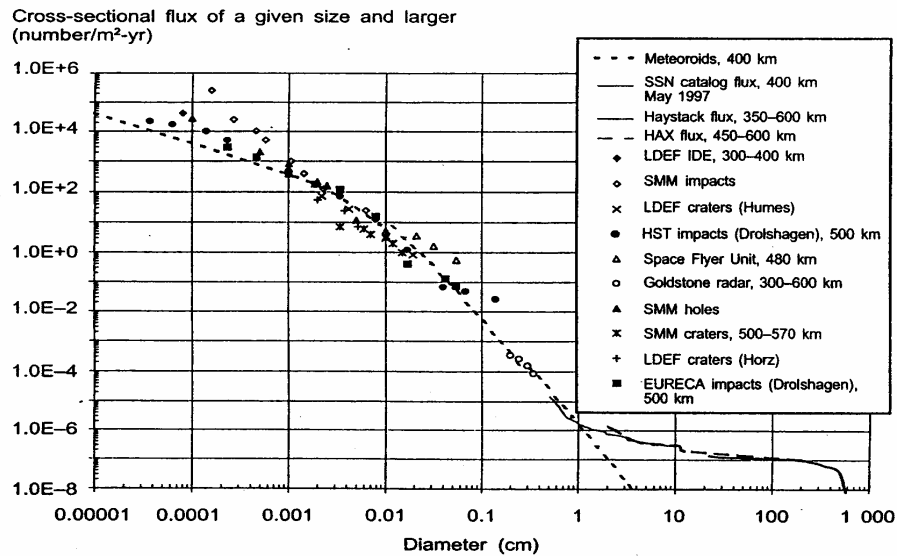
Summary



Background

- Number of debris; 9000 (>10 cm), 4 Million (<.1cm)
- Velocity; 9 km/s in LEO, 200 m/s in GEO

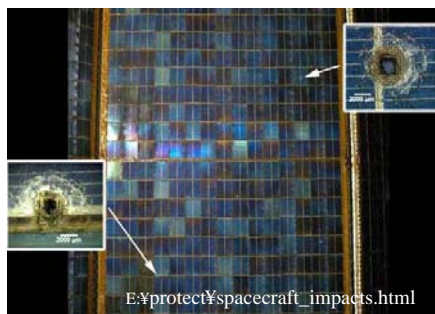
Figure 1. Approximate measured debris flux in low Earth orbit, by object size



2

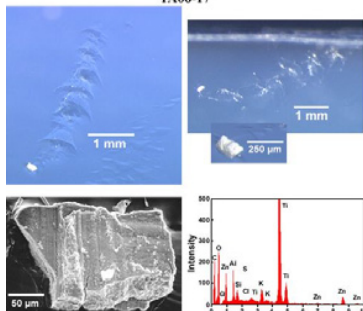


Background



Solar panel: Retrieved from Russian space station Mir

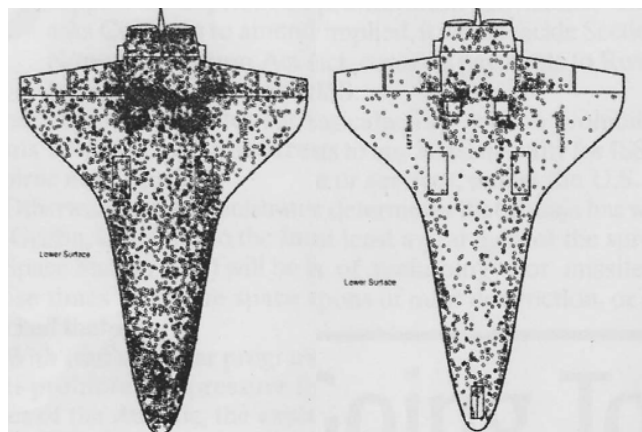
Paint Flake
IA06-17



Impacts Recorded On Orbiter Surface (15,000 times hit)

Lower Surface Impact
STS-6 to STS-110

Lower Surface Impact ≥ 1 inch
STS-6 to STS-110

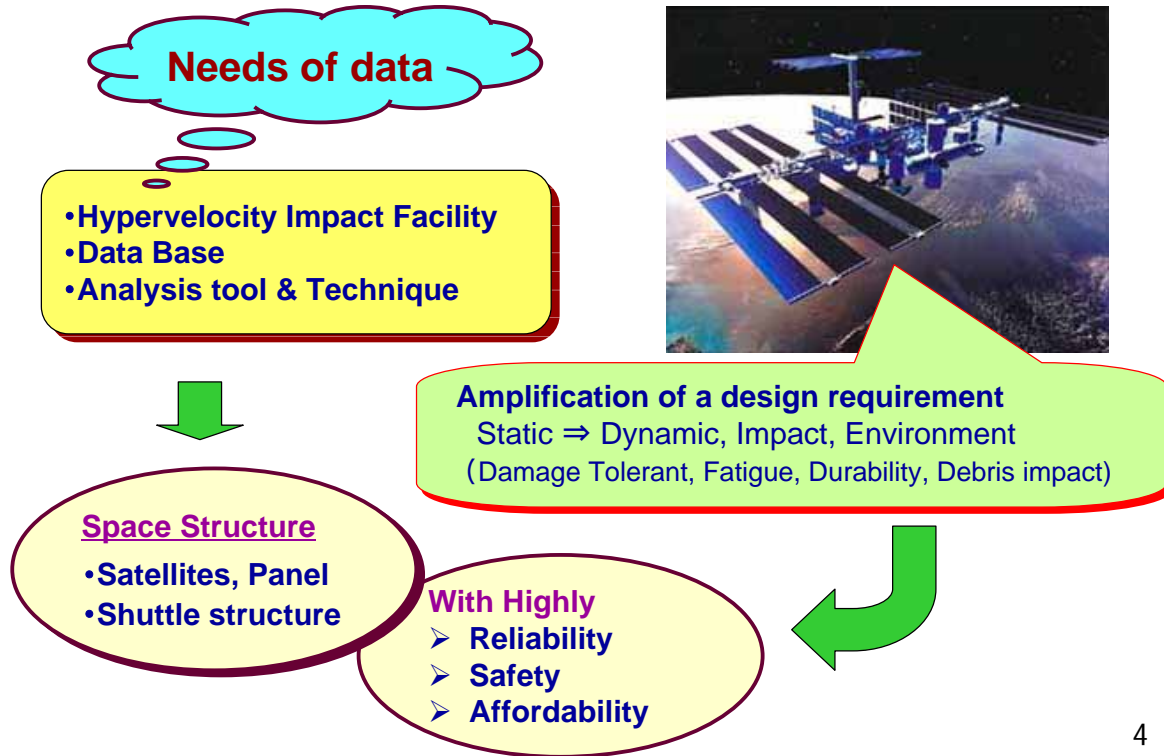


Aviation week & space technology July 4, 2005

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Objectives for Investigation



4



Technical Subjects

1. Development on Hypervelocity Impact Facility

Object 1: The CSC device which can jet a 1g mass out at the 7km/sec (**complete**)

Object 2: Correlation of damage between CSC and 2nd-staged gas (**complete**)

Object 3: Data acquisition and cumulating at hypervelocity impact

2. Investigation and Acquisition on collision data bases with CFRP

Object 1: hypervelocity collision data acquisition for CFRP plate.

Object 2: Correlation of impact energy with damaged area and residual strength

3. Investigation on analytical technology

Object 1: Establish the analytic method of the hypervelocity impact to CFRP by the special analyses software

Object 2: Modify and develop the software by evaluation with test results

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Development on Hypervelocity Impact Facility

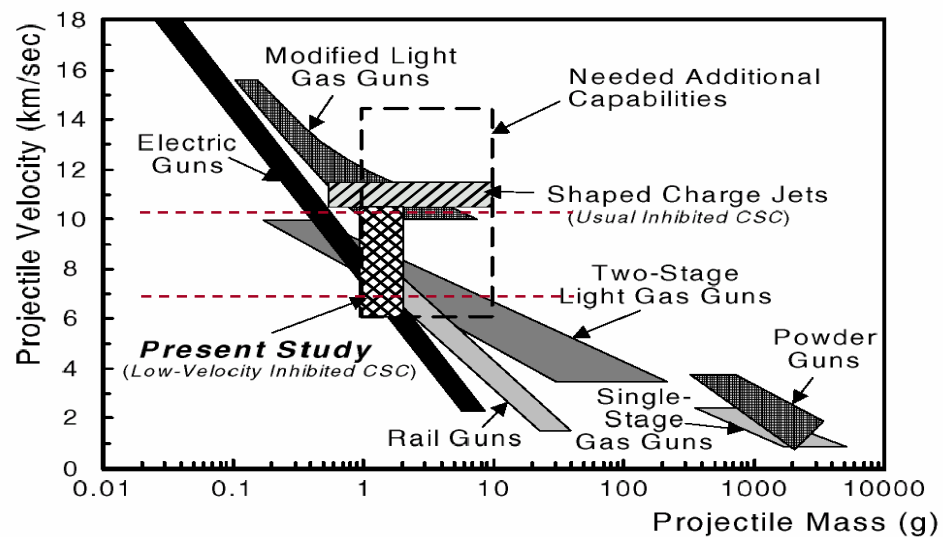
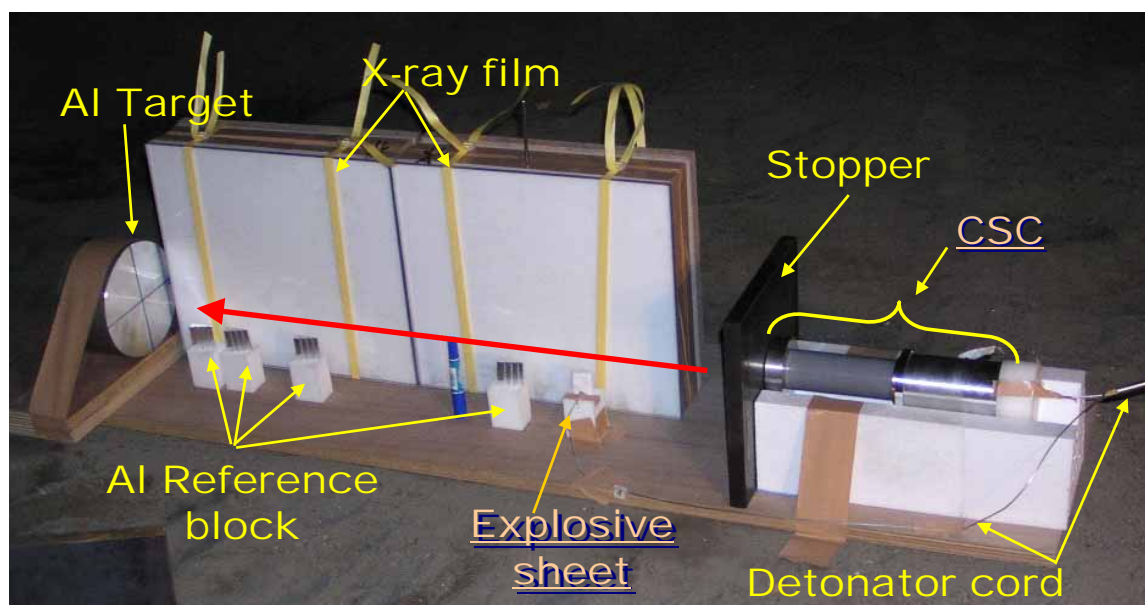


Fig. 1 Capabilities of hypervelocity launch facilities.
(From "ORBITAL DEBRIS" by National Research Council, National Academy Press, 1995)

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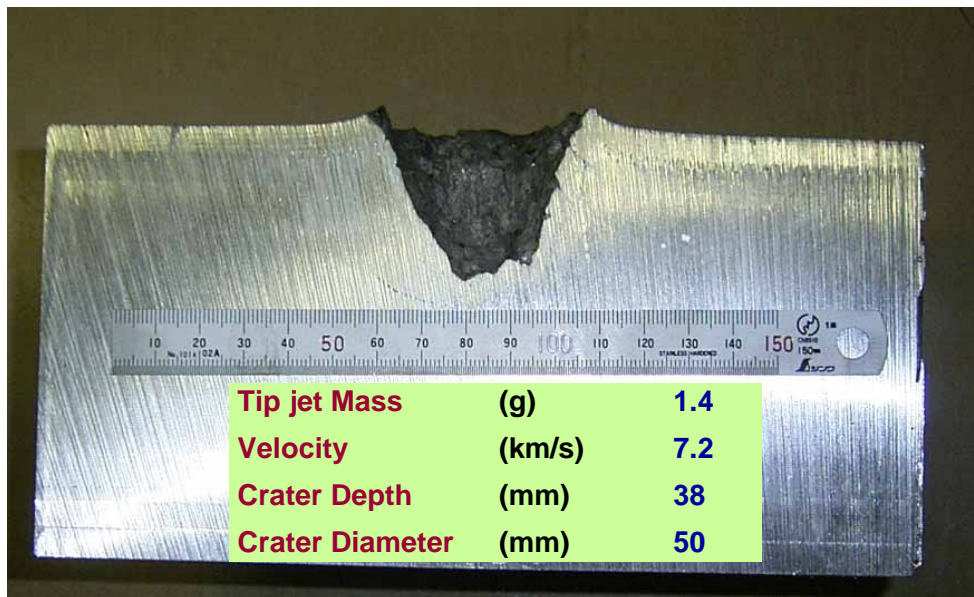
Development of CSC



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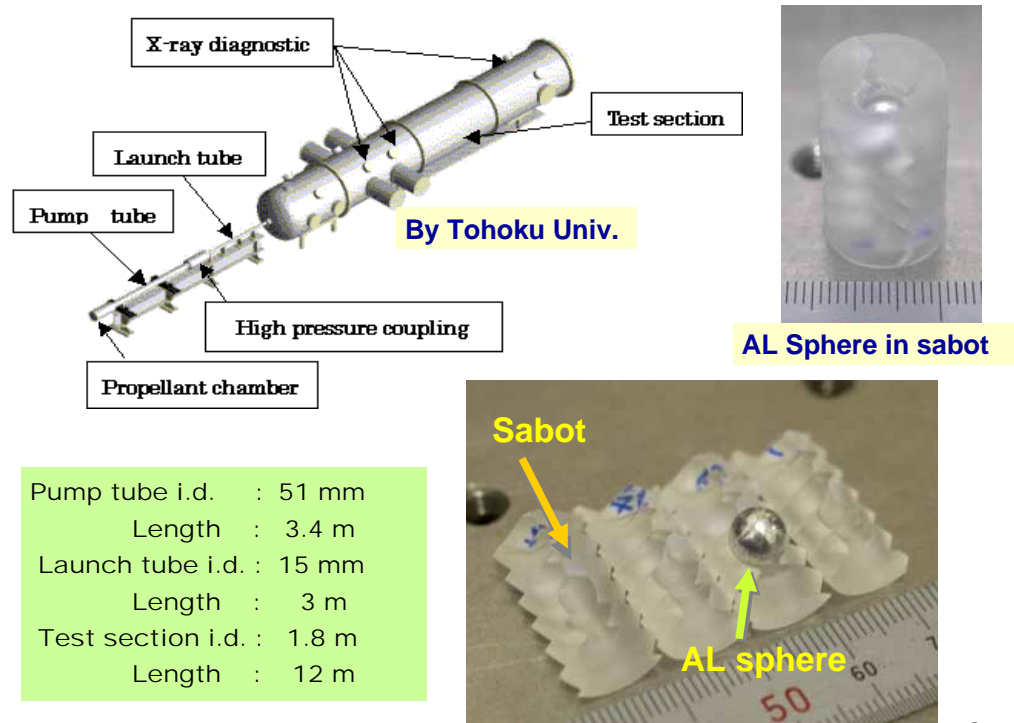
Development of CSC



Section of aluminum target

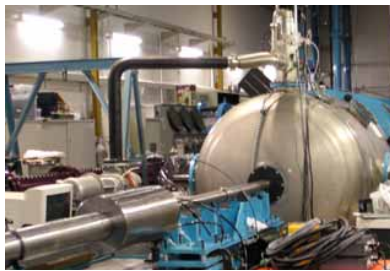
8

Experimental results by Gas Gun



9

Experimental results by Gas Gun

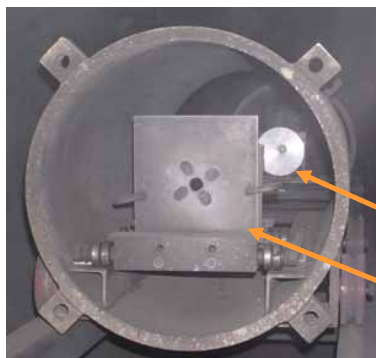


2nd - staged Gas Gun



Sabot collision scar

Sabot stopper



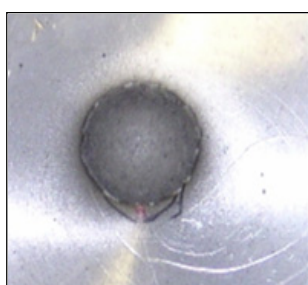
Target plate

Sabot stopper

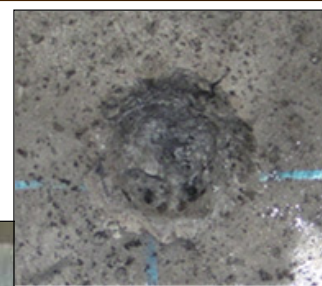
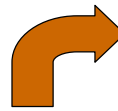
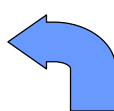
Inside the chamber

10

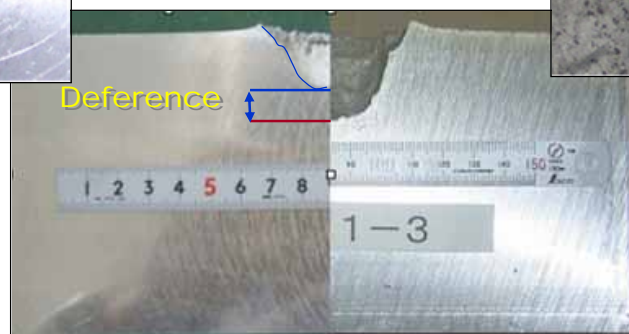
Comparison between Gas gun & CSC



Impact scar by
Gas Gun



Impact scar by
CSC



	Mass (g)	Velocity (km/s)
Gas gun	1.3	6.3
CSC	1.1	7.1

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Collision Data base with CFRP

Object 1: hypervelocity collision data acquisition to a CFRP plate.

Object 2: Correlation of impact energy with damaged area and residual

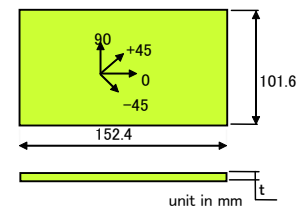
strength

1. Target

- Material ; CFRP IM600/133 (High strength/tough resin)
- Thickness ; $t=2.2\text{mm}$, $t=3.3\text{mm}$, $t=4.3\text{mm}$

2. Projectile

- Material ; Aluminum alloy AI 2017
- Diameter (mm) ; 0.8, 1.5, 1.9, 2.3, 2.9
- Velocity (km/s) ; 2, 4, 5



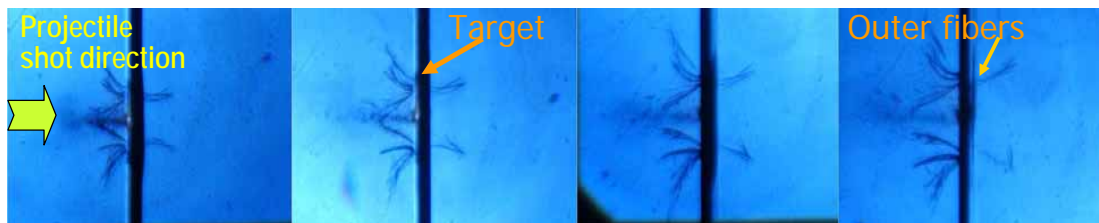
3Thickness x 5dia. x 3velocity = 45 shots

12

Collision Data base with CFRP



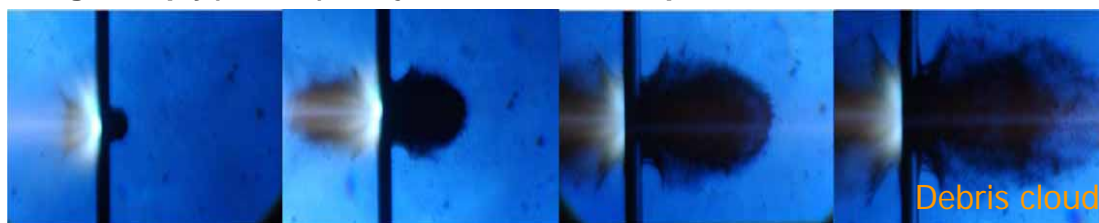
Target: 24ply(3.3mm), Projectile: $\phi 1.5\text{mm}$, Speed: 1985m/s



Picture shot interval : $25 \mu\text{sec}$.

Average pass time : $1.6 \mu\text{sec}$.

Target: 32ply(4.3mm), Projectile: $\phi 2.3\text{mm}$, Speed: 5018m/s

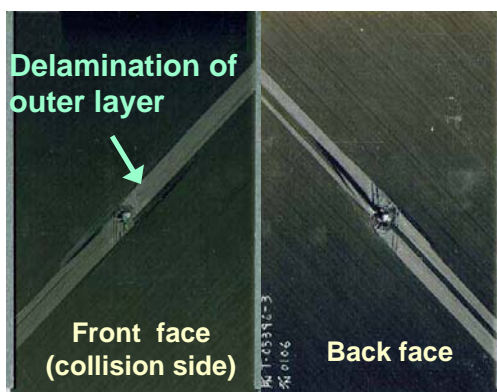


Picture shot interval : $18 \mu\text{sec}$.

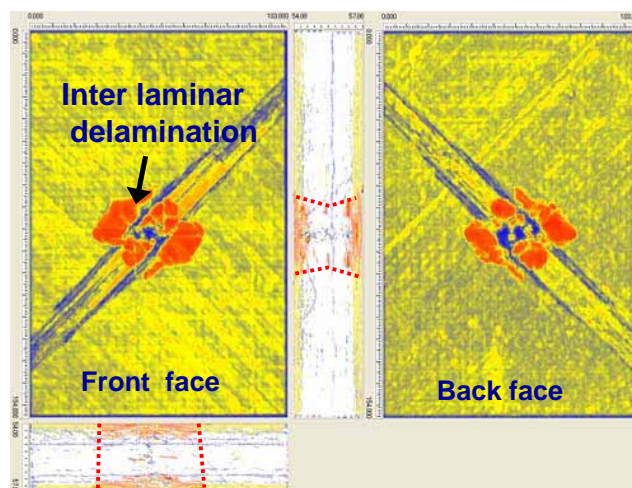
Average pass time : $0.9 \mu\text{sec}$.

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Collision Data base with CFRP



[Picture image](#)



[Ultrasonic inspection image](#)

Target : CFRP 32ply, t=4.3mm

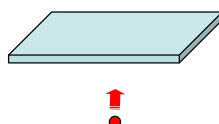
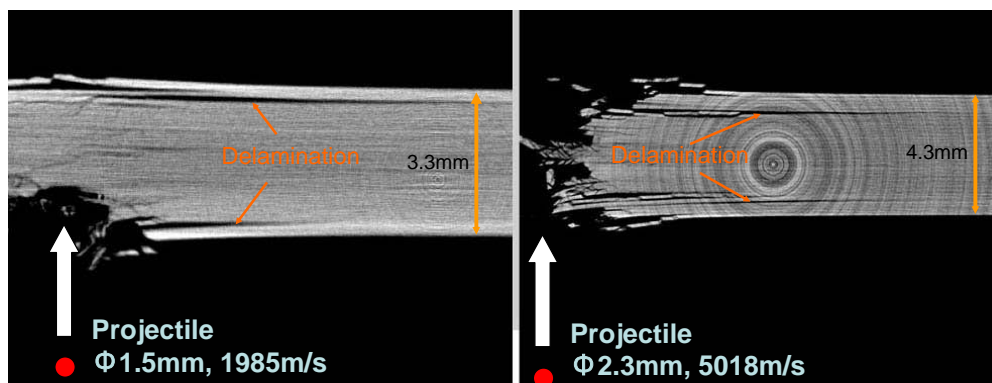
Projectile : ϕ 2.3mm, 5018m/s

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Collision Data base with CFRP



X-ray CT scan

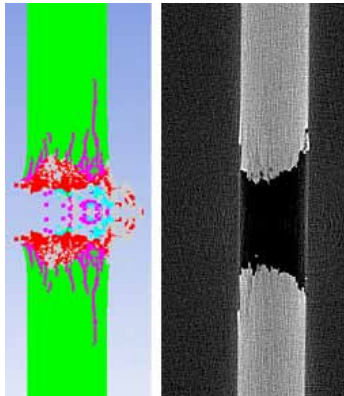


15

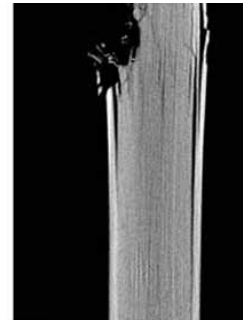


Simulation

Composite material impact simulation (2D)



X-ray CT scan image
32ply, ϕ 1.9 mm, $V=3210$ m/s
(MAT'L; T300/3631)



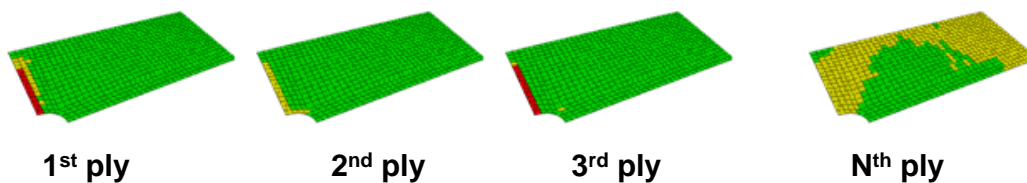
X-ray CT scan
24ply, ϕ 1.5 mm, $V=1985$ m/s
(MAT'L; IM600/133)

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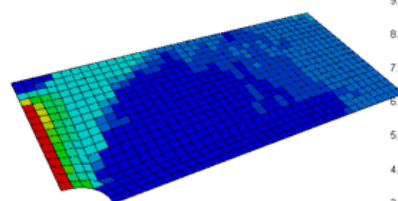
Simulation



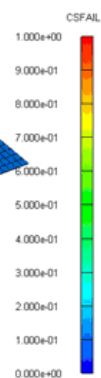
Modify a composite material impact simulation model (3D)



AUTODYN-3D v6.1 from Century Dynamics



exam2
Cycle 4500
Time 4.291E-001 ms
Units mm, g, ms



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Summary



1. Development on Hypervelocity Impact Facility

Clarify the correlation of damage between CSC and
2nd-staged gas gun

2. Investigation and Acquisition on Data Base with CFRP

Clarify Correlation of impact energy with damaged area and
residual strength

3. Investigation on analytical technology

Evaluate and develop the software by comparing with
impact test results

2-2 デブリ防護研究における Hypervelocity Impact Symposium/Society の位置付けについて

○片山 雅英（伊藤忠テクノソリューションズ㈱／科学システム事業部）

The Status of Hypervelocity Impact Symposium/Society in the Community of Space Debris Protection Study

Masahide KATAYAMA (Science & Engineering Systems Division, ITOCHU Techno-Solutions Corporation)

Key Words: Hypervelocity Impact, HVIS, Hydrocode, Launcher, Protection, Space Debris

概要

宇宙機をスペースデブリ衝突から防護するのに必要な最も重要な技術の一つは、15 km/s 程度の速度まで物体を加速する技術である。しかしながら、グラムオーダーの固体物質を 10 km/s 以上の速度まで加速するのは極めて困難なのが現状である。これを補完する技術として、超高速域(Hyper-velocity)の衝突現象を模擬するための数値解析ツールである Hydrocode があり、それをサポートする高圧に関する理論的研究と非線形性の極めて強い材料挙動に関する研究がある。このような超高速領域が問題となる分野としては、宇宙と防衛関連が代表的な分野であるが、このような問題を研究するための意見交換の場として、1980 年代後半に、米国を中心とした世界的な会議として開始されたのが、一連の Hypervelocity Impact Symposia である。さらに、このシンポジウムを運営するために設立されたのが Hypervelocity Impact Society である。その時期は、丁度、宇宙活動が本格化して以来 30 年近くが経過し、人工の宇宙ゴミの脅威が認識されつつあると共に、宇宙ステーションや往還機を中心とする多くの有人ミッションが計画された頃である。この一連のシンポジウムは、現在まで 2～3 年間隔で合計 10 回開催され、各回の参加人員は 200～300 人程度である。一方、発表論文数は 60～90 程度で、シンポジウムで発表された論文は、口頭・ポスターの別を問わず、全て International Journal of Impact Engineering に、上限 12 ページの論文として掲載される。この論文上梓の過程では、各回のシンポジウム技術委員会のメンバーが、ボランティアで 2 日～3 日の缶詰査読会議を実施するため、論文数が多いにもかかわらず、一定の水準をクリアしているものと考えられる。発表論文のうち 6～7 割程度が宇宙分野に関するテーマであり、スペースデブリの防護研究にとって重要な情報源になっている。

一方、同じ“Hypervelocity”という語を冠するシンポジウムが、米国内において 1950 年代後半からアポロ計画が終了する直前の 1969 年頃までに亘って 10 回程度開催されていた。その詳細については、現時点では知り難い部分が多いが、1970 年に R. Kinslow が編纂した、“HIGH-VELOCITY IMPACT PHENOMENA” (Academic Press, 1970) という、固体衝撃分野の研究者にとって、いわば、バイブルと言ってもよい書籍として結実し、現在の技術でも再現し難い内容が多く含まれていることは注目に値する。

本発表では、これら二種類のシンポジウムについて概観すると共に、より多くの資料が存在する新しいシリーズのシンポジウムの詳細と、不可分な関係にある Hypervelocity Impact Society との関係について言及する。

デブリ防護研究におけるHypervelocity Impact Symposium / Societyの位置付けについて

The Status of Hypervelocity Impact Symposium / Society in the Community of Space Debris Protection Study

伊藤忠テクノソリューションズ株式会社

科学システム事業部 エネルギー・産業技術部
衝撃・材料課



Challenging Tomorrow's Changes

ITOCHU Techno-Solutions Corporation

Impact Dynamics & Material Science Team
Energy & Industrial Systems Department
Science & Engineering Systems Division

片山 雅英

Masahide KATAYAMA

The 3rd Space Debris Workshop / JAXA

21 – 22 January, 2008

National Museum of Emerging Science and Innovation (Miraikan)

Old / AIAA Hypervelocity Impact Symposia



Year	Symp. Name	Place
1957	Hypervelocity Impact Effects Symp.	Washington, D.C.
1958	Hypervelocity Impact Symp.	Illinois Inst. of Technology
1960	Hypervelocity Impact Symp.	Eglin AFB, Florida
1961	Hypervelocity Impact Symp.	Colorado School of Mines
1962	Hypervelocity Techniques	Denver
1963	Hypervelocity Impact Symp.	Cleveland, Ohio
1964	Hypervelocity Impact Symp.	Tampa, Florida
1964	Symp. Hypervelocity Techniques	Denver, Colorado
1965	Symp. Hypervelocity Techniques	Tullahoma, Tennessee
1969	Hypervelocity Impact Conference	Cincinnati, Ohio
1986	Hypervelocity Impact Symp.	San Antonio, Texas

(A Historic Overview)

cf. DTX/Ballistics & HVIS (Dynamec Research AB, Sweden),

R. Kinslow (Ed.), HIGH-VELOCITY IMPACT PHENOMENA, Academic Press (1970).

Hypervelocity Impact Society



The Hypervelocity Impact Society is devoted to the advancement of the science and technology of hypervelocity impact and related technical areas, such as:

- experimental techniques,
- theoretical and analytical studies,
- numerical advancements, and
- material response,

required to facilitate an understanding of hypervelocity impact phenomena. Hypervelocity impact is defined as the impact regime in which shock effects are important.

The objectives of the Hypervelocity Impact Society are to foster the development and exchange of technical information in the discipline of hypervelocity impact phenomena by promoting technical excellence, encouraging peer review publications, and holding technical meetings on a periodic basis.

Hypervelocity Impact Society & Symposia



Founding Board of Directors

Charles E. Anderson, Southwest Research Institute

Jr. James R. Asay, Sandia National Laboratories (Washington State Univ.)

Harry D. Fair, The University of Texas at Austin - IAT

William M. Isbell, General Research Corporation (ATA Associates)

Gordon R. Johnson, Honeywell, Inc. (Southwest Research Institute)

Dennis L. Orphal, California Research & Technology (Int. Research Associates)

The Hypervelocity Impact Symposia (HVIS) are held every two to three years for the interchange of technical information and ideas in order to foster an understanding of hypervelocity impact phenomena.

The organizing committee for the Hypervelocity Impact Symposia (HVIS) consists of the Board of Directors and a Symposium Committee appointed by the President, in concurrence with the Board. The Symposium Committee usually consists of a Chair (or Co-Chairs), Technical Program Chair, Symposium Coordinators, a Treasurer and Commercial Exhibits Chair (or Co-Chairs).

Hypervelocity Impact Society & Symposia



- The dues for periods between Symposia are collected as part of the registration fee for the Symposia.
- The proceedings of the Symposia are published as special volumes of ***International Journal of Impact Engineering***, under the guest Editor-in-Chief of IJIE.
(up to 12 pages)
- The reduced subscription price of IJIE is applied to the member of the Society.

Hypervelocity Impact Symposia - Topics



- Hypervelocity Phenomenology Studies
- High Velocity Launchers and Diagnostics
- Spacecraft Meteoroid/Debris Shielding and Failure Analyses
- Spacecraft Shielding
- Spacecraft Studies Space Debris Environment
- Material Response (including EOS)
- Fracture and Fragmentation
- High Velocity Penetration Mechanics and Target Response
- Armor/Anti Armor
- Impact and Penetration
- Analytical and Numerical Techniques
- Asteroid Impact and Planetary Defense Technology
- Penetration Mechanics of Shaped Charges and Explosively-Formed Penetrators

New Hypervelocity Impact Symposia – Place & Chairs



<i>Year</i>	<i>Place</i>	<i>Chair or Co-Chairs</i>
1986	San Antonio (TX)	Charles Anderson, Jr.
1989	San Antonio (TX)	Charles Anderson, Jr.
1992	Austin (TX)	Harry Fair / Tom Kiehne
1994	Santa Fe (NM)	Lalit Chhabildas / Bill Hogan
1996	Freiburg (Germ.)	Alois Stilp
1998	Huntsville (AL)	William Schönberg
2000	Galveston (TX)	Harry Fair / Eric Christiansen
2003	Noordwijk (Neth.)	Michel Lambert / Eberhard Schneider
2005	Lake Tahoe (CA)	Lalit Chhabildas / Dennis Orphal
2007	Williamsburg (VA)	David Dickinson / Leonard Wilson
2010	Freiburg (Germ.)	Frank Schäfer / Stefan Hiermaier

New Hypervelocity Impact Symposia - Award



<i>Year</i>	<i>Place</i>	<i>Distinguished Scientist Award</i>
1986	San Antonio (TX)	N/A
1989	San Antonio (TX)	Alex Charters
1992	Austin (TX)	Alois Stilp & Volker Hohler
1994	Santa Fe (NM)	James Asay
1996	Freiburg (Germ.)	Burton Cour-Palais
1998	Huntsville (AL)	Hallock Swift
2000	Galveston (TX)	Charles Anderson
2003	Noordwijk (Neth.)	Denis Orphal
2005	Lake Tahoe (CA)	Lalit Chhabildas
2007	Williamsburg (VA)	Gordon Johnson

*Alex Charters Student Scholars Program

New Hypervelocity Impact Symposia—Numerical Simulation

- 1989 San Antonio (TX) MESA, CTH, PINON, HULL,
EFHYD (Alwes), PISCES (NASDA)
- 1992 Austin (TX) CTH dramatic increase, NABOR method led van of SPH.
CTH/ZeuS/CALE (JSC), EFHYD (ESTEC),
- 1994 Santa Fe (NM) CTH showed whelming share. CTH (JSC), AUTODYN (NAL),
SPH and AUTODYN showed gradual increase.
- 1996 Freiburg (Germ.) SPH showed dramatic increase. CTH, AUTODYN are even.
CTH/DYNA3D (JSC), EFHYD (ESTEC), KERNEL (Rus.), AUTODYN (NASDA),
- 1998 Huntsville (AL) CTH, AUTODYN are even. EXOS (UoT/JSC),
AUTODYN (ESTEC, NAL), AUTODYN/PAM-SHOCK (Alenia), SOVA (Rus.)
- 2000 Galveston (TX) CTH, AUTODYN are even. AUTODYN/PAM (ESTEC, etc.),
AUTODYN (NAL), Hybrid Particle-Element (Fahrenthold/JSC)
- 2003 Noordwijk (Neth.) 1st AUTODYN, 2nd CTH, AUTODYN (ESTEC, etc.),
Hybrid Particle-Element (Fahrenthold/JSC)
- 2005 Lake Tahoe (CA) 1st AUTODYN, 2nd CTH, AUTODYN (ESTEC, etc.),
Hybrid Particle-Element (Fahrenthold/JSC)
- 2007 Williamsburg (VA)

HVIS 1989, San Antonio, TX (1/2)



Int. J. Impact Engng Vol. 10, pp. 525-534, 1990
Printed in Great Britain

0734-743X/90 \$3.00 + 0.00
Pergamon Press plc

*Probably, the first
publication in Japan on
the space debris impact
study.*

MICROMETEOROID AND DEBRIS IMPACT TEST ON SPACE STATION BUMPER

Yasuki Adachi

National Space Development Agency of Japan
2-4-1 Hamamatsu-cho, Minatoku, Tokyo Japan

Hideshige Ohtaki, Fumio Suehiro, and Yujiro Shirai

Mitsubishi Heavy Industries, Ltd.
10 Oye-cho, Minatoku, Nagoya Japan

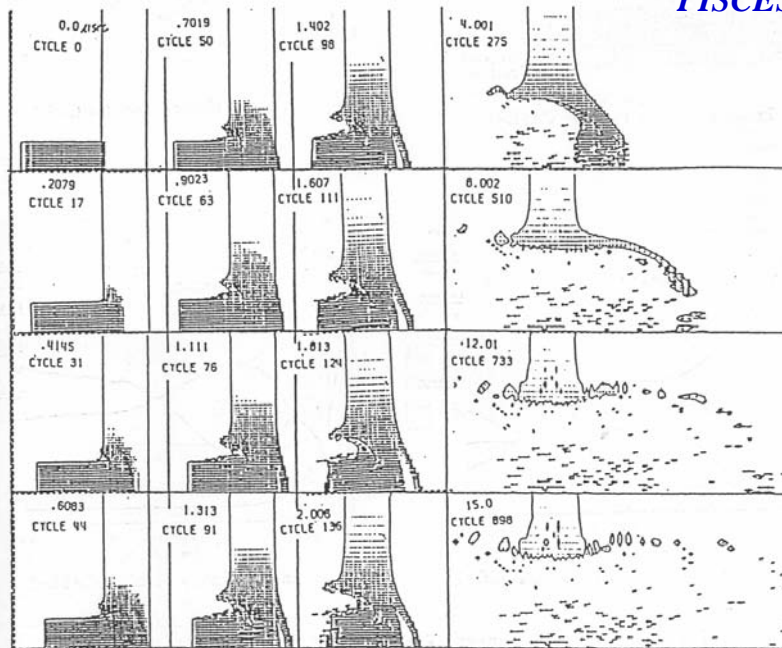
*NB: In September 1989,
the Space Debris Study
Group was established
in the JSASS.*

Abstract

To design the micrometeoroid and debris protection bumper of the outboard structure space station module, we made a two-stage helium light gas gun and carried out hypervelocity impact tests which simulated micrometeoroid and debris impacts on space station. Fundamental characteristics of hypervelocity impact phenomena was investigated, for a projectile mass 0.45gr to 1.5gr, impact velocity about 4km/sec and aluminum-alloy bumpers. When the bumper is of double-sheet type, there exists an optimal front sheet thickness that causes melting of the front sheet. However, for thin front sheets, penetration occurs, and for thick front sheets, spall fracture occurs. In addition to the impact tests, the computational simulation of the typical test result was carried out using the PISCES code with the Tillotson constitutive equation of aluminum-alloy. The computational simulation result had a good agreement with the test result.

HVIS 1989, San Antonio, TX (2/2)

PISCES-2DELK, 1986



Velocity Vector Distributions

HVIS 1992, Austin, TX (1/2)

Int. J. Impact Engng Vol.14, pp.229-240, 1993
Printed in Great Britain

0734-743X/93 \$6.00+0.00
© 1993 Pergamon Press Ltd

A LAGRANGIAN MODEL FOR DEBRIS CLOUD DYNAMICS SIMULATION

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Department of Mechanical Engineering, University of Texas
Austin, TX 78712

ABSTRACT

A new modeling approach has been developed for computer simulation of hypervelocity impacts on multi-plate orbital debris shields. This approach links an Eulerian finite difference code for shield perforation calculations to a Lagrangian finite element code for debris cloud evolution simulations. Mixture theory is used to account for the presence of void space in the debris cloud.

*Coupling between CTH (SNL)
and DYNA2D (LLNL)*

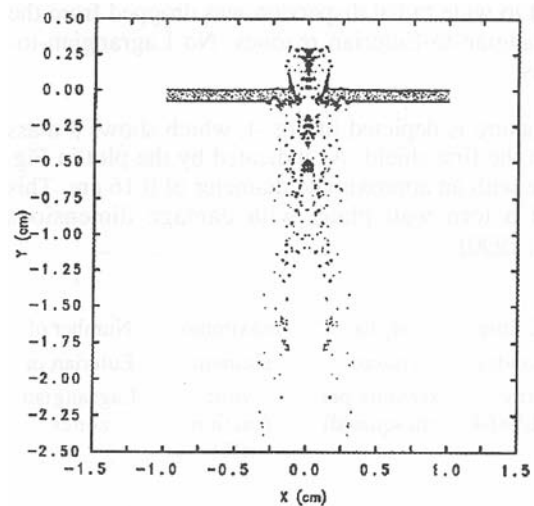


Fig. 4. Wall impact for the multi-plate shield impact simulation

HVIS 1992, Austin, TX (2/2)

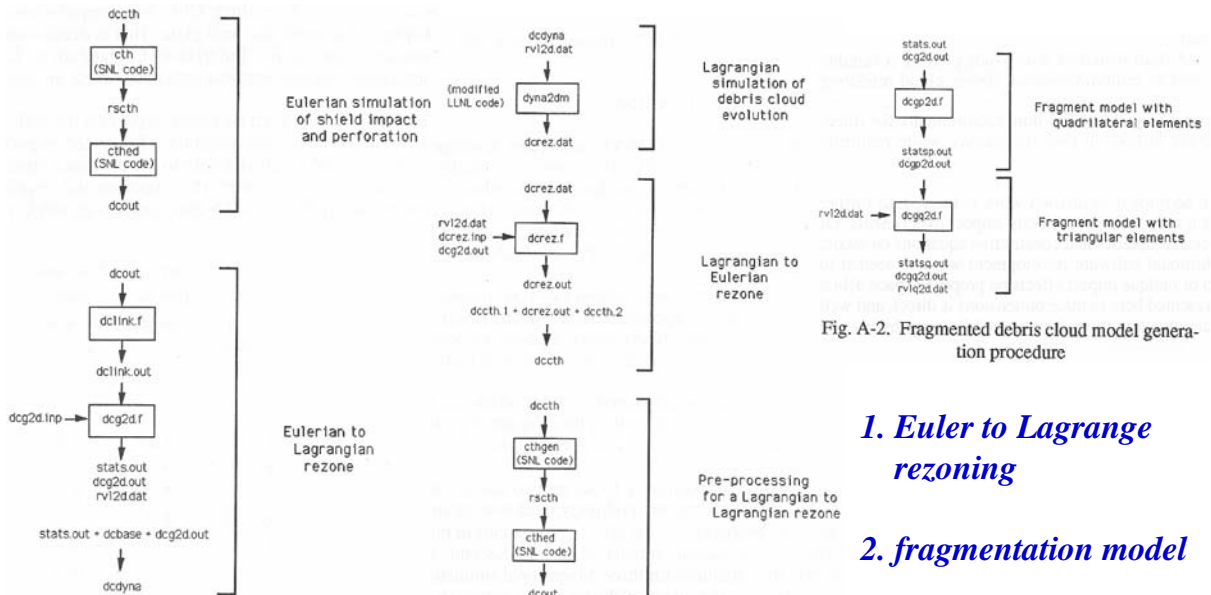


Fig. A-1. Eulerian simulation and rezone procedure

Fig. A-3. Lagrangian simulation and rezone procedure

Fig. A-2. Fragmented debris cloud model generation procedure

HVIS 1994, Santa Fe, NM (2/2)



*Eric L. Christiansen et al.,
NASA/JSC
CTH*

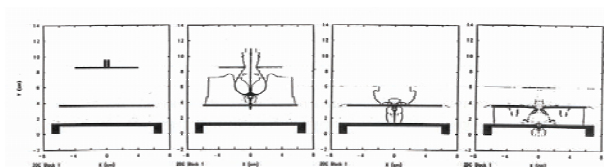


Figure 9. CTH simulation of 500°K, 0.84g, L/D=1.44 hollow cylinder impact at 11.03 km/sec on all-aluminum shield (time = 0, 4, 5.5, 7.81 μs).

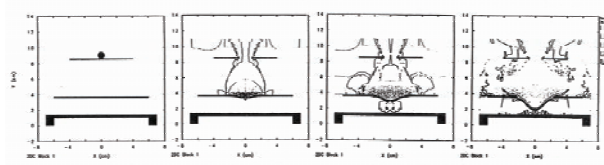


Figure 10. CTH simulation of 298°K, 0.84g, 0.84cm diameter aluminum sphere impact at 11.03 km/sec on all-aluminum shield (time = 0, 6, 7.65, 10.37 μs).

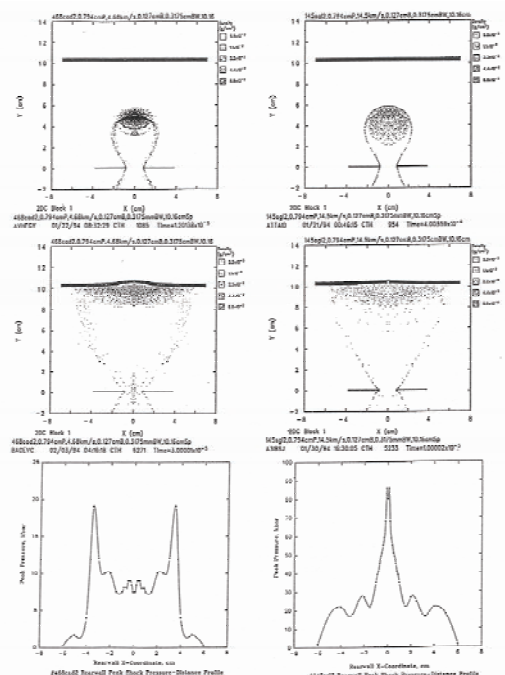


Figure 8. CTH hydrocode simulation showing debris cloud propagation, final rearwall damage, and peak shock pressure for 0.794cm projectile impacting Whipple shield: 0.127cm bumper, 10.18cm spacing, 0.3175cm AlD219-T07 rearwall. (Cd projectile and Cd bumper on left, Al projectile and Al bumper on right)

HVIS 1996, Freiburg, Germany



*V. V. Bashurov et al.,
Russia, KERNEL*

*K. Shiraki et al., NASDA/JEM,
AUTODYN*

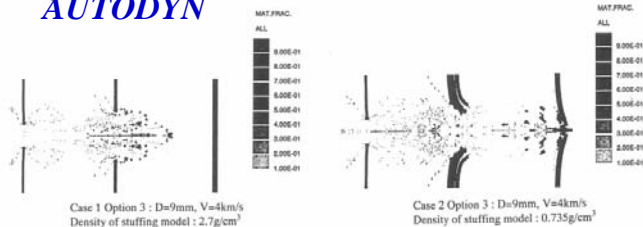


Fig. 15-1. Projectile penetration through bumper, stuffing and module wall for Case 1.

Fig. 15-2. Projectile penetration through bumper, stuffing and module wall for Case 2.

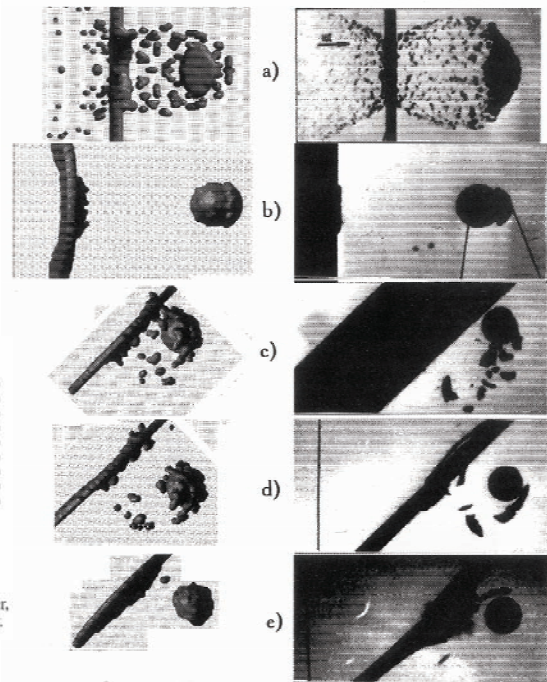
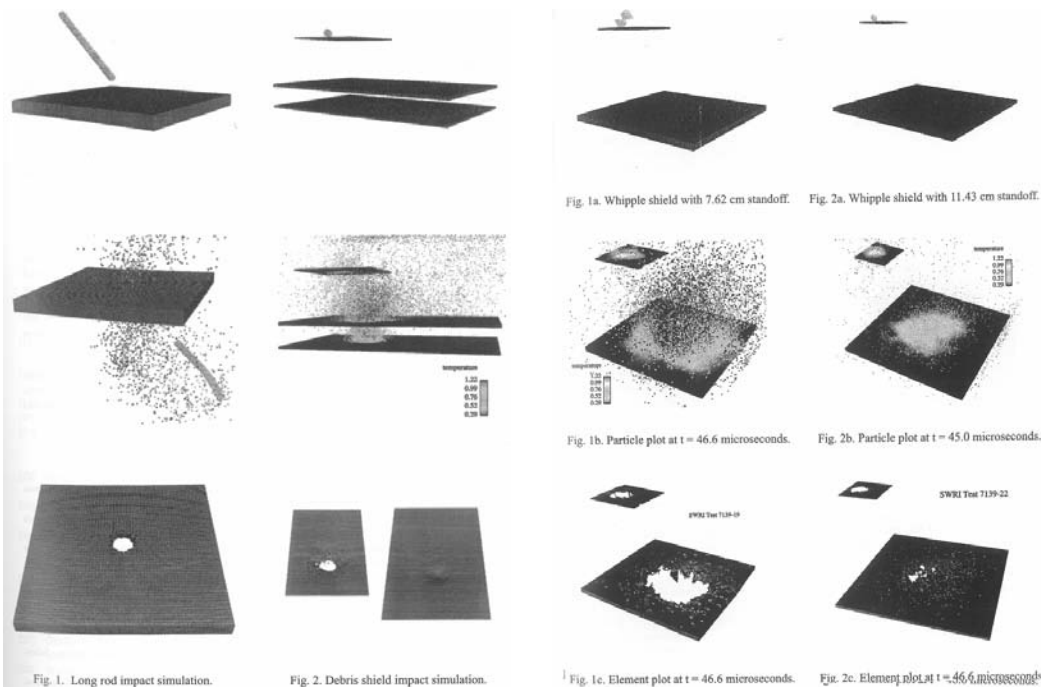


Fig. 1. Results of the first set of experiments (right) and numerical simulation (left).

HVIS 1998, Huntsville, AL



Eric P. Fahrenthold (Univ. of Texas), Hybrid Particle Element



HVIS 2000, Galveston, TX



David Palmieri et al. (Italy) & EMI & ESTEC, AUTODYN

David Palmieri et al. (Italy),
AUTODYN & PAM

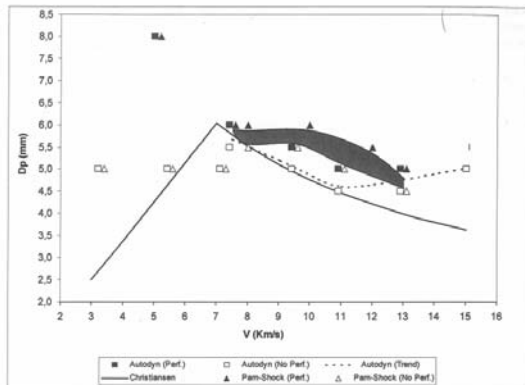


Fig. 6. Comparison of NASA (Christiansen), PAM-SHOCK and AUTODYN ballistic curves.

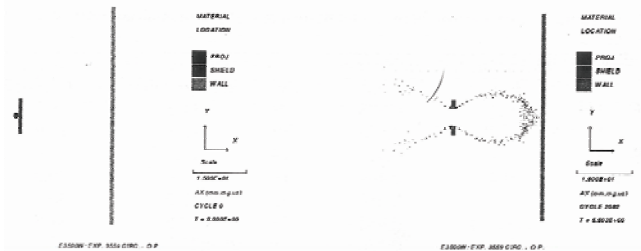


Fig. 12. Initial geometry (left) and debris cloud expansion (right) for case 21W.

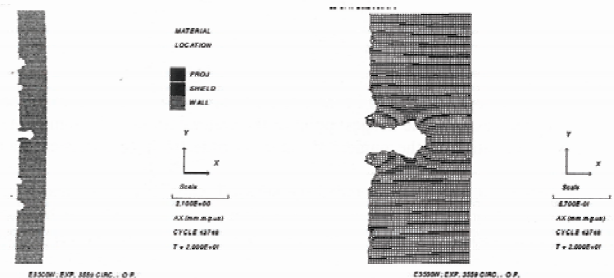


Fig. 13. Craters on the back wall and detail of the deepest crater (EWS).

HVIS 2003, Noordwijk, Netherlands



Eric P. Fahrenthold (Univ. of Texas),
Hybrid Particle Element

Table 6. Parameters of JSC test number B536

Projectile mass (aluminum sphere)	1.0 g
Bumper thickness (aluminum)	0.16 cm
Nexel areal density	0.600 g/cm ²
Kevlar areal density	0.192 g/cm ²
Wall plate thickness (aluminum)	0.48 cm
Total standoff	11.4 cm
Projectile velocity	6.86 km/s
Impact obliquity	15 degrees

David Palmieri et al. (Italy) & ESTEC,
AUTODYN

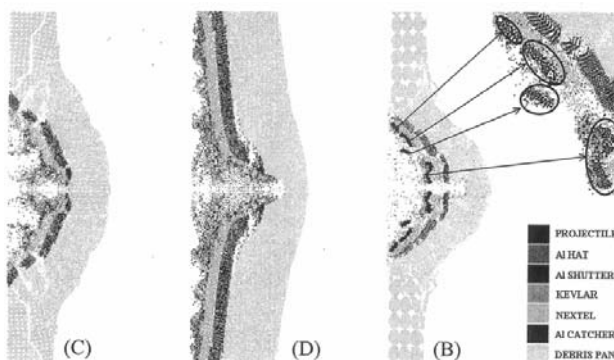


Fig. 4. Impact of fragments on the debris pane for options C, D and B.

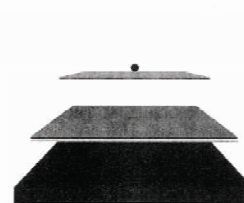


Fig. 7. Element plot of the initial configuration.

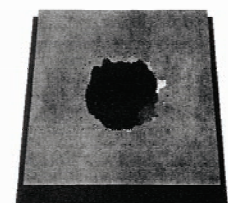


Fig. 8. Element plot of the Kevlar shield and wall plate at 150 microseconds after impact.



Fig. 9. Element plot of the simulation results at 75 microseconds after impact (front view).

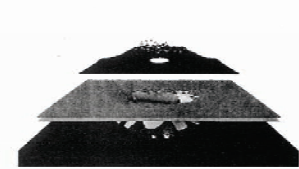
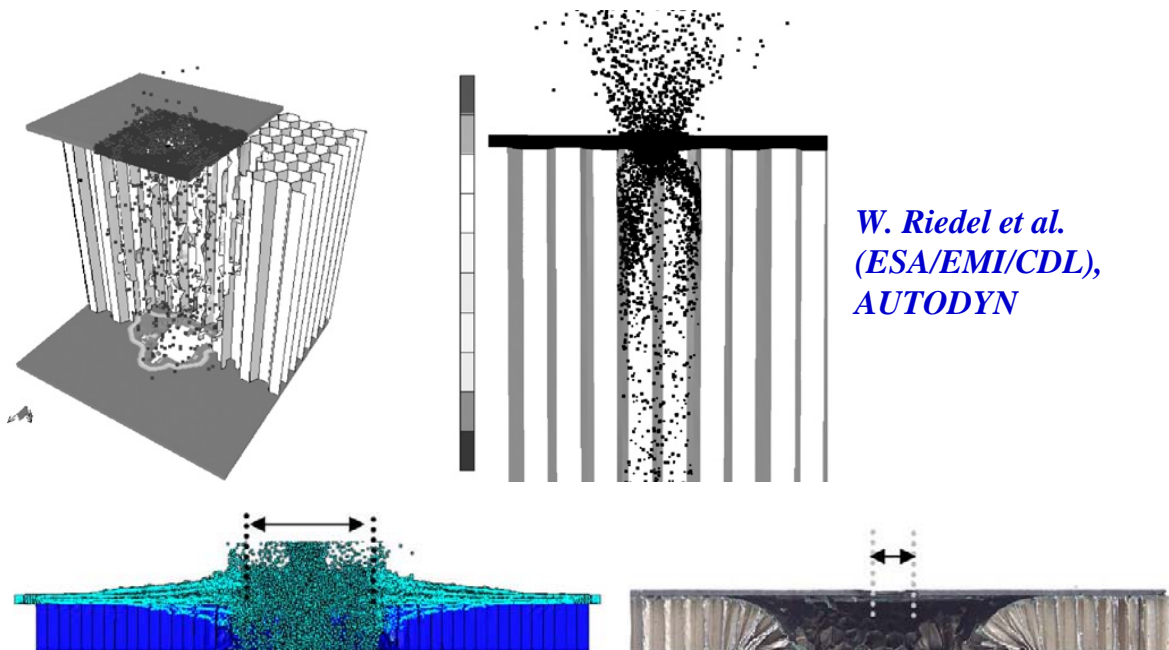


Fig. 10. Element plot of the simulation results at 75 microseconds after impact (rear view).

HVIS 2005, Lake Tahoe, CA



*W. Riedel et al.
(ESA/EMI/CDL),
AUTODYN*

Comparison of front CFRP face-sheet impact damage locality of EF-3 and SF-3 (5 mm, 6.7 km/s, 0°), $d_{h,front}$ marked.

S. Ryan et al. (ESA/EMI), AUTODYN

CONCLUDING REMARKS



1. Hypervelocity Impact Symposium is the most important and predominant conference in the community of space debris protection researchers.
2. Each proceeding of HVIS includes around 60 to 90 papers subjected to the format of the International Journal of Impact Engineering.

NB: Symposia on Shock Waves in Japan
 International Astronautical Congress
 APS Topical Conference on Shock Compression of Condensed Matter
 International Symposium on Ballistics
 Aeroballistic Range Association
 Electromagnetic Launch Technology Symposium

2-3 超高速衝突後の二次デブリ雲の挙動とモデル化

赤星 保浩(九州工業大学),

Motion and Model of Secondary Debris Cloud after Hypervelocity Impact

Yasuhiro. Akahoshi (Kyushu Institute of Technology)

Key Words: Mass Distribution, Velocity Distribution, Behind-Target Debris

いよいよ国際宇宙ステーションの日本モジュール（きぼう）が今年打上げられる予定である。これにより日本も独自の有人宇宙施設を軌道上に有することになり、日本の宇宙開発の歴史を大きく前進させるものとして期待される。この日本モジュールのメイン構造物には、宇宙ごみに対する防御構造が採用されている。この防御構造は、基本的には二重壁構造をしており、一枚目の薄板により宇宙ごみを粉砕し、二枚目の厚板でこの粉砕された宇宙ごみを受け止めるという構造をしている。この粉砕された宇宙ごみを二次デブリ雲と呼んでおり、防御壁構造の性能はこの二次デブリ雲の挙動によって決まる。二枚目に二次デブリ雲が衝突する際に二次デブリ雲中の個々の破片が有している運動エネルギーならびに破片形状と衝突時の姿勢が防御性能に大きく影響する。本講演では二次デブリ雲の質量分布、速度分布の実験における計測方法について紹介し、さらに、2005年に Lake Tahoe で開催された Hypervelocity Impact Symposium において Schaefer らが提案した二次デブリ雲モデルについて紹介する。この二次デブリ雲モデルは破片群に対して質量保存、運動量保存、エネルギー保存を満足するように、質量分布、速度分布を求めるものである。このモデルでは軸対称系を仮定しているため、本来は垂直衝突に対してしか適用できない。しかし、飛翔体由来の破片と薄板（バンパー）由来の破片とを分離して扱い、飛翔体由来の破片は弾道軸方向に飛散し、バンパー由来の破片はバンパーの法線方向へ飛散すると仮定することで、Schaefer らが提案している二次デブリ雲モデルを斜め衝突問題に拡張することができる。本講演ではこの拡張方法についても紹介する。

超高速衝突の二次デブリ雲の挙動とモデル化 Motion and Model of Secondary Debris Cloud after Hypervelocity Impact

九州工業大学 工学部 機械知能工学科
Kyushu Institute of Technology

赤星 保浩

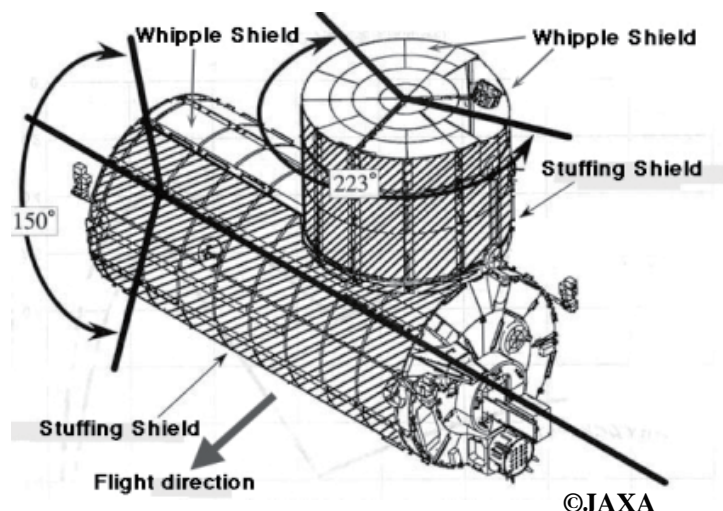
Yasuhiro AKAHOSHI

Strategy against debris impact in ISS

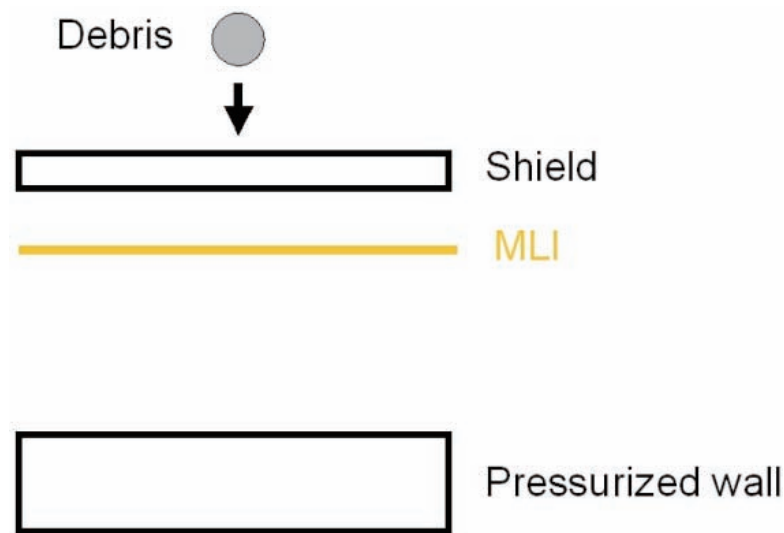
$D > 10\text{cm}$ Maneuver before impact



$D < 1\text{cm}$ Protection



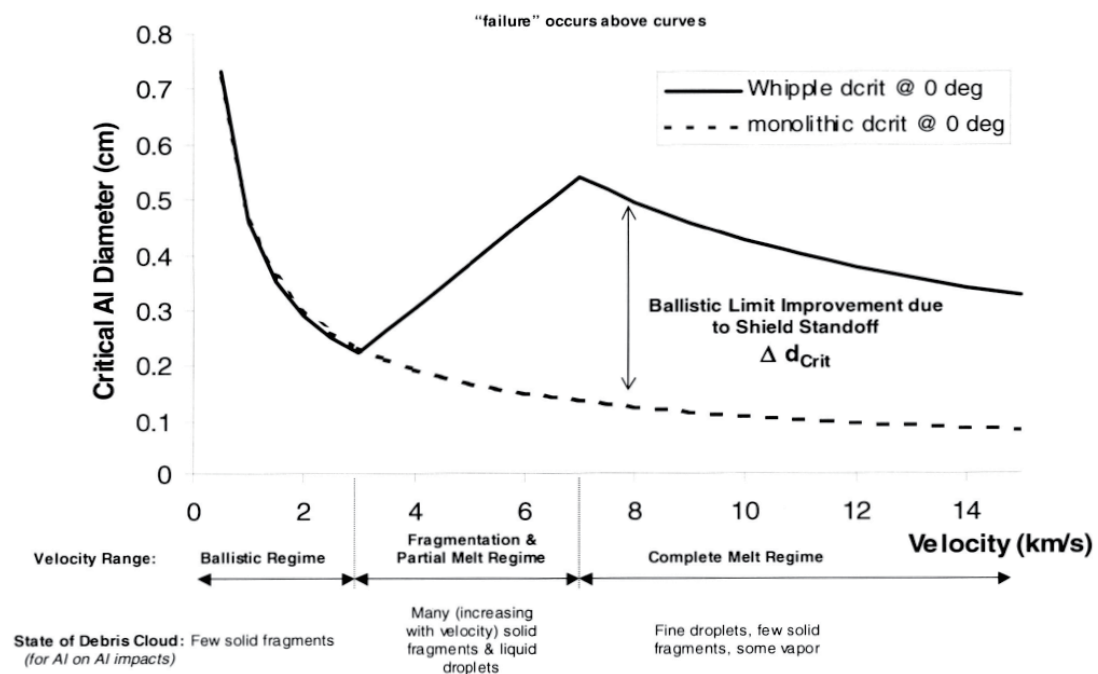
Whipple Bumper



Double Wall System

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Ballistic Limit Curve



3/47

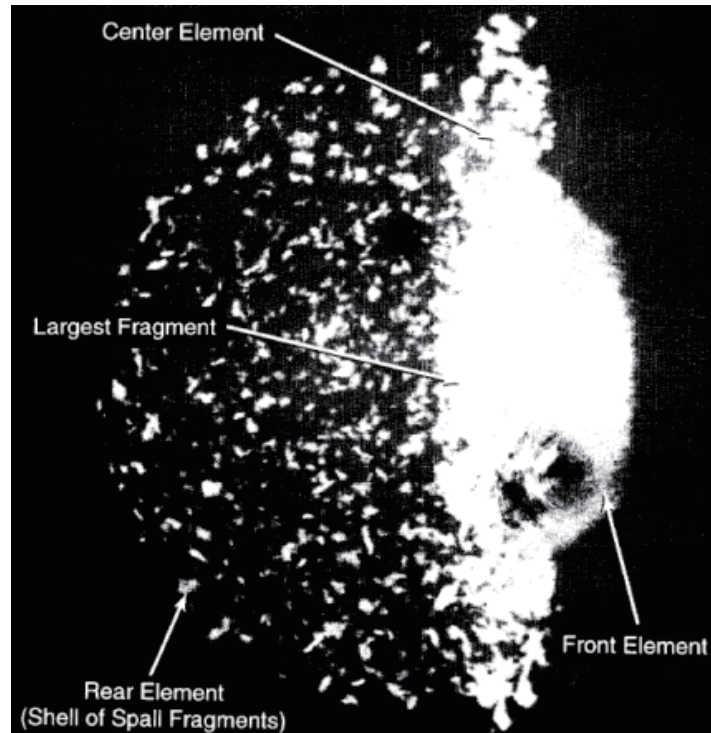
Debris Cloud Study by A.J.Piekutowski

**Flush X-ray
image of Debris
Cloud**

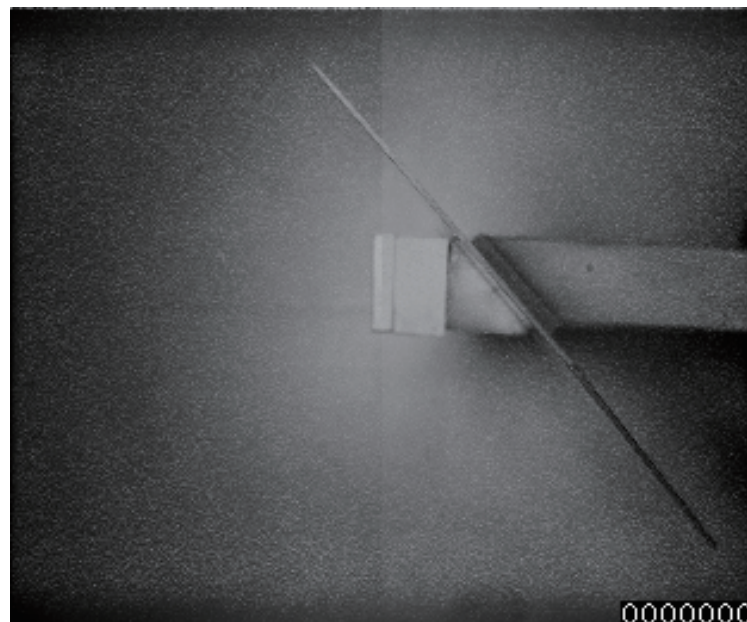
V=6.26km/sec

D=12.7mm

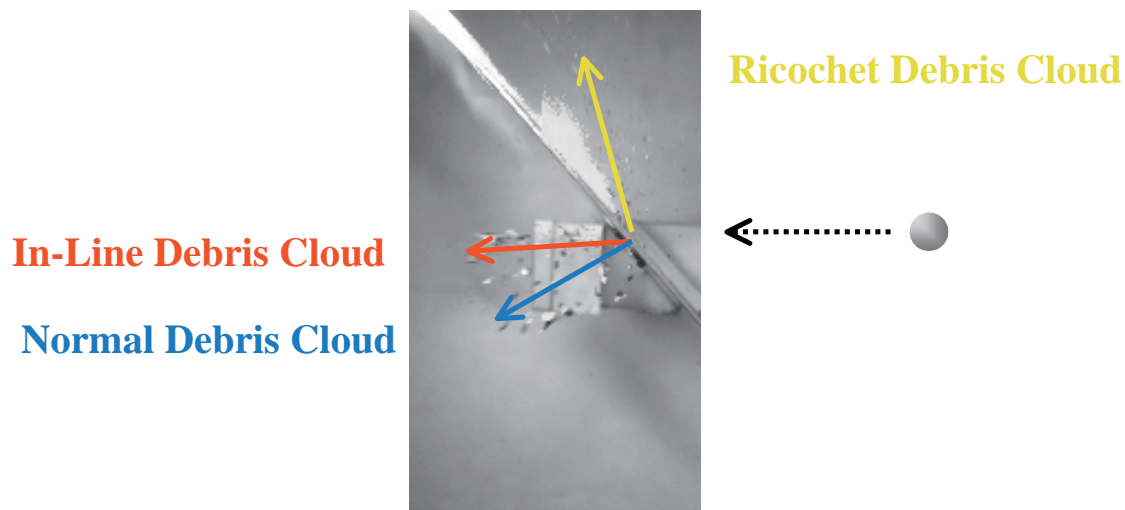
T=0.59mm



Video of Oblique Impact



Debris Cloud Study by W.P.Schonberg



Focus on mass of largest fragment and velocity of leading fragment

6/47

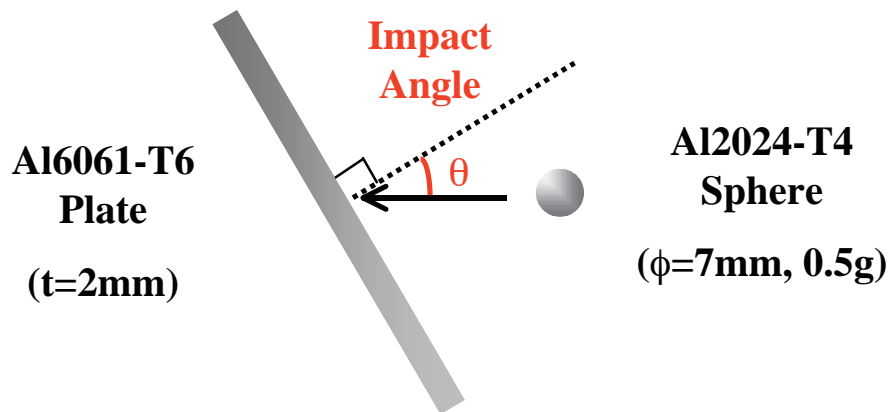
Hypervelocity Impact Test Facility



Two-Stage Light Gas Gun in KIT

7/47

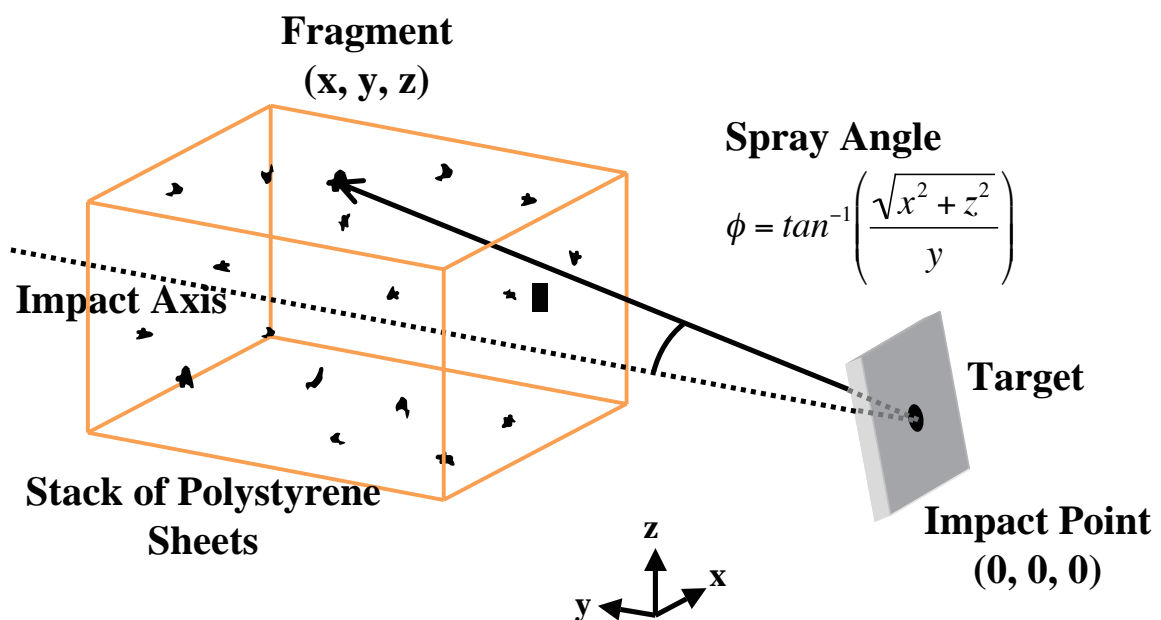
Oblique Impact



Impact Velocity: 2km/sec

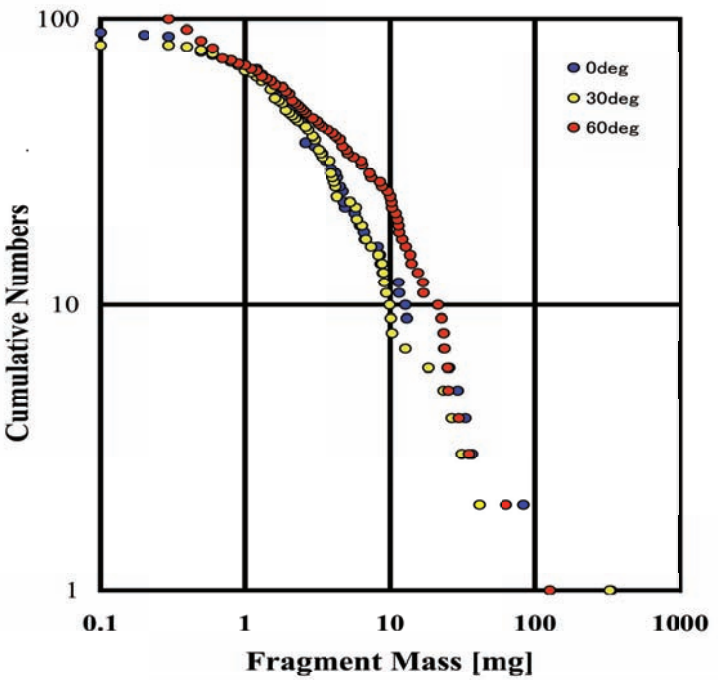
8/47

Soft Recovery of Fragments in Debris Cloud



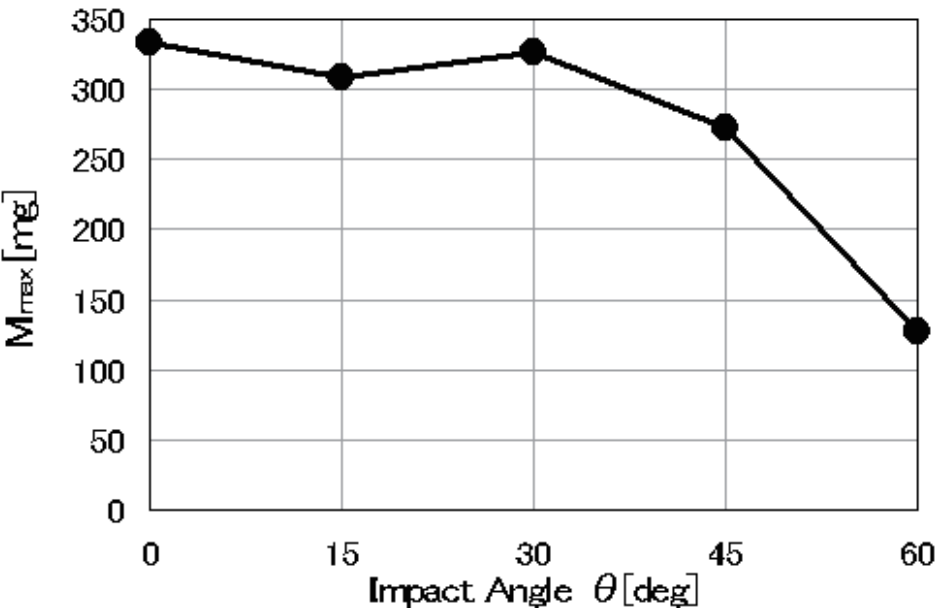
9/47

Mass Distribution



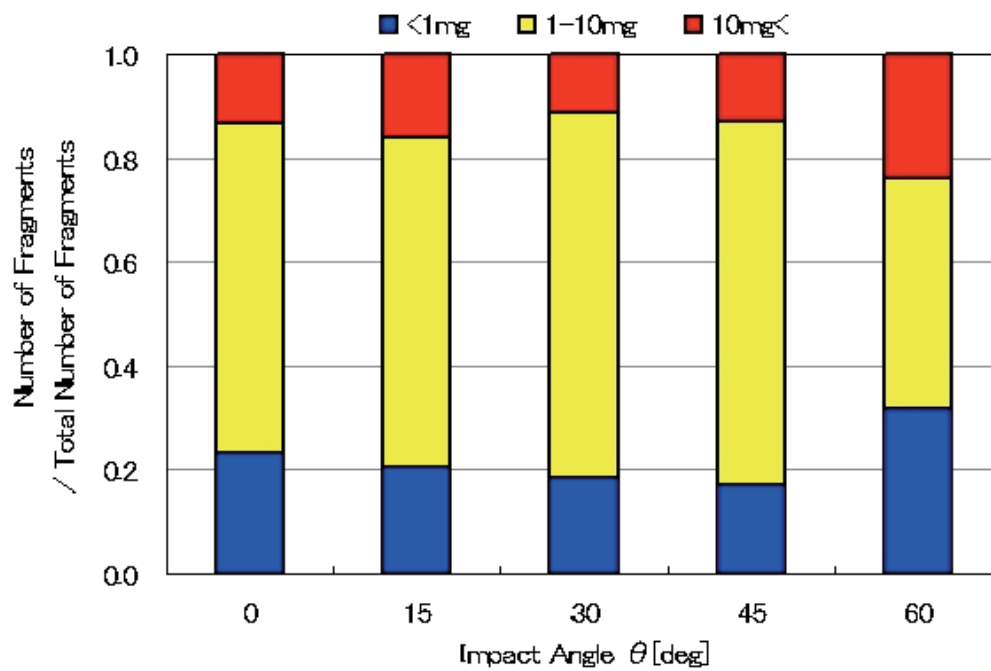
10/47

Residual Projectile (Largest Fragment)



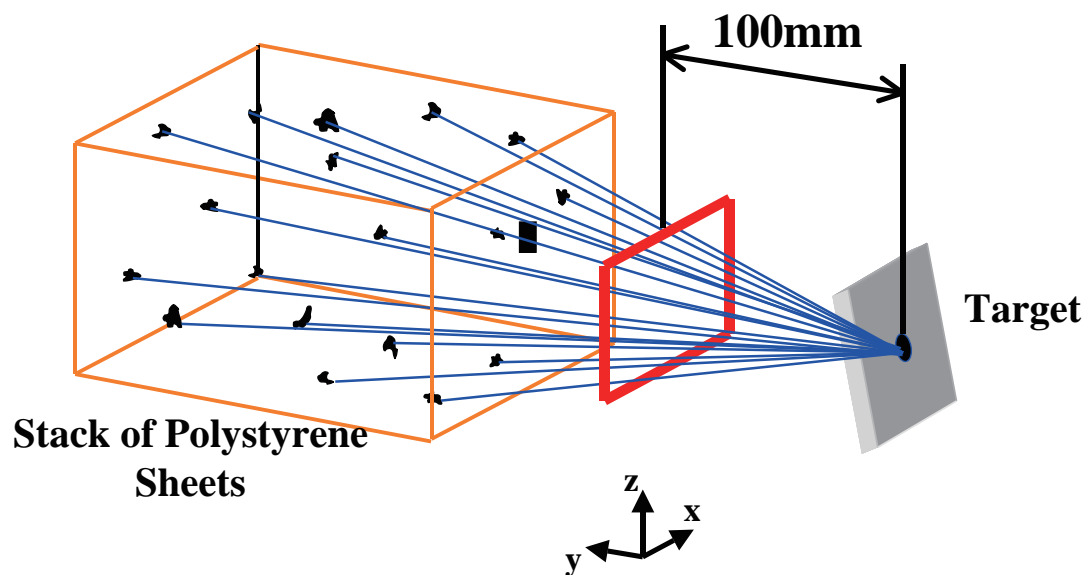
11/47

Distribution of Mass of Fragments



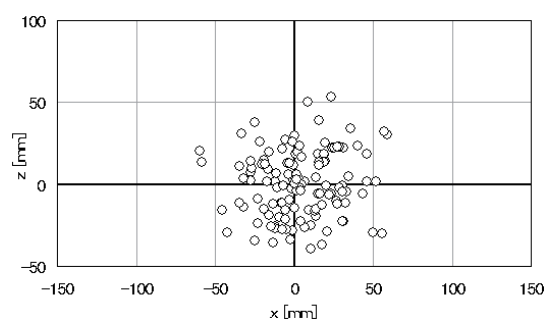
12/47

Definition of Spatial Distribution

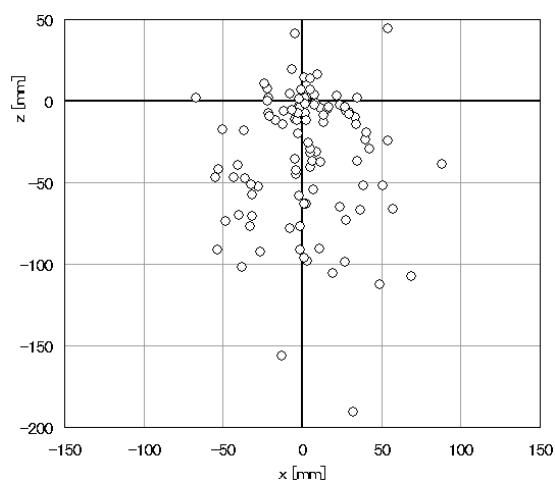


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Spatial Distribution



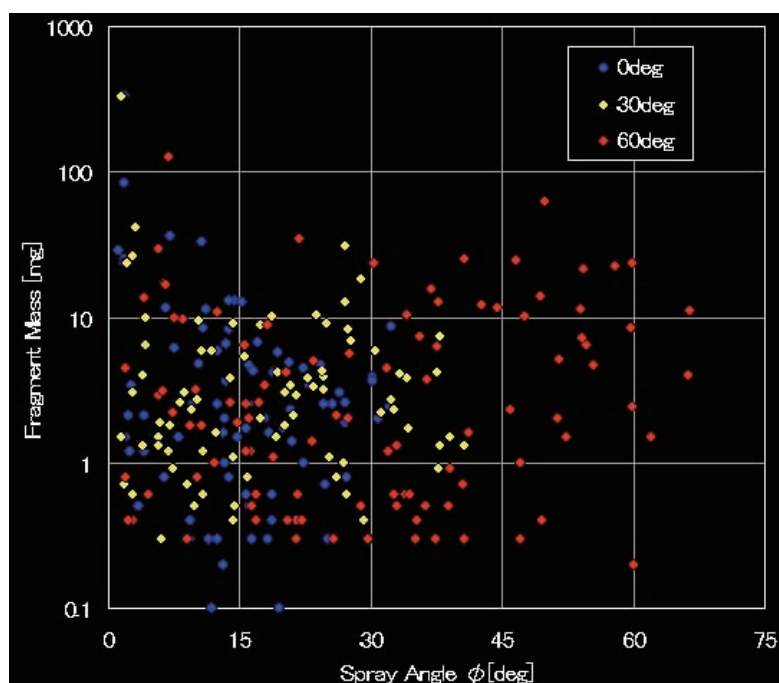
$\theta=0\text{deg}$



$\theta=45\text{deg}$

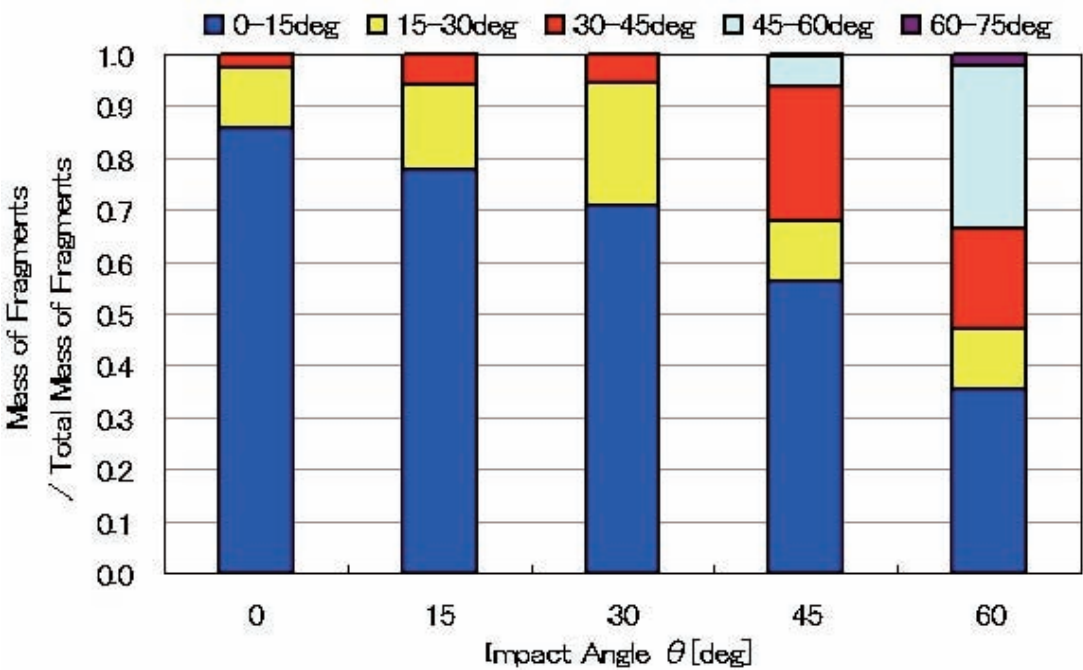
14/47

Distribution of Spray Angle



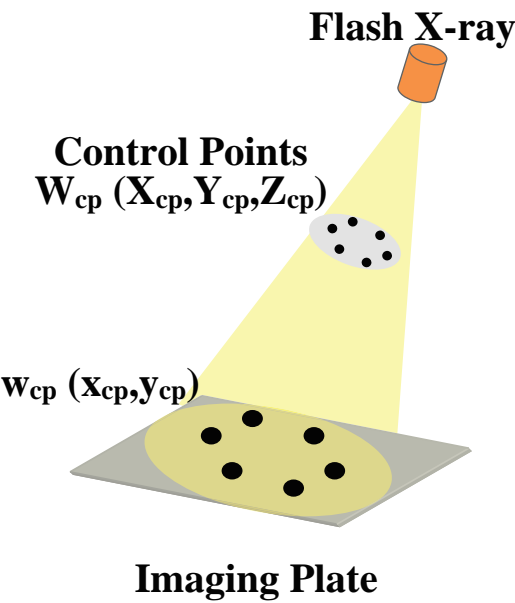
15/47

Distribution of Spray Angle



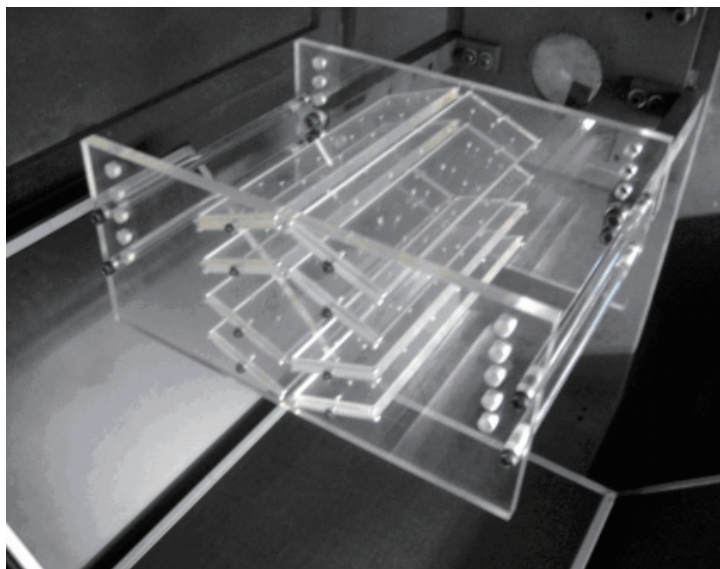
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Direct Linear Transformation Method



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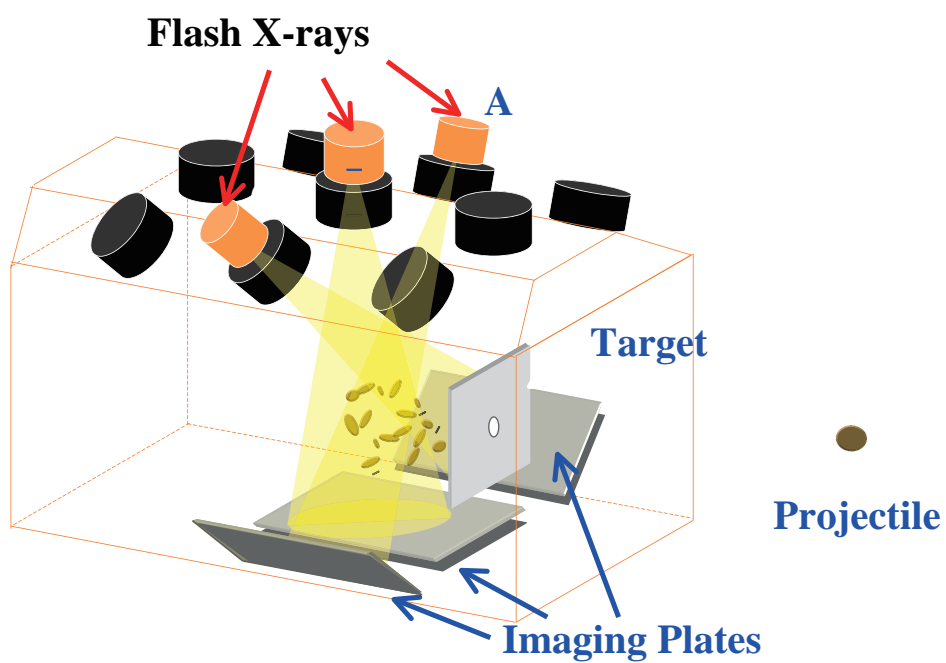
Control Points



80 points are used.

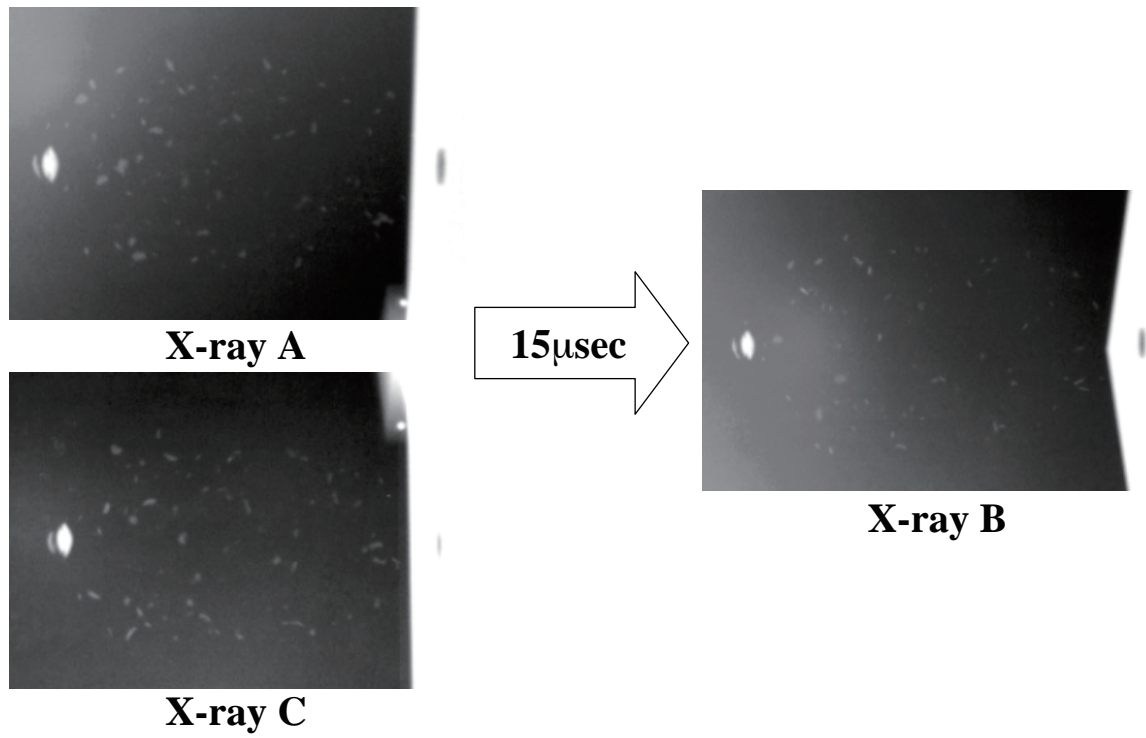
18/47

Measurement using Flash X-ray



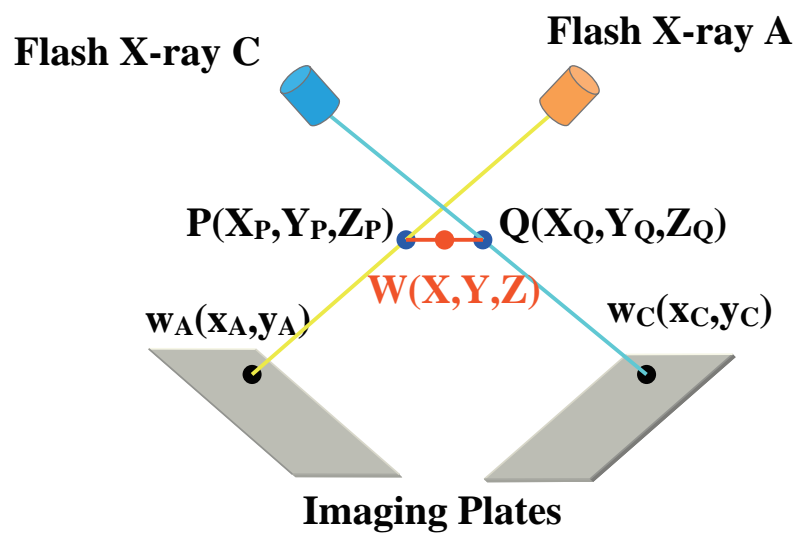
19/47

X-ray image ($\theta=0\text{deg}$)



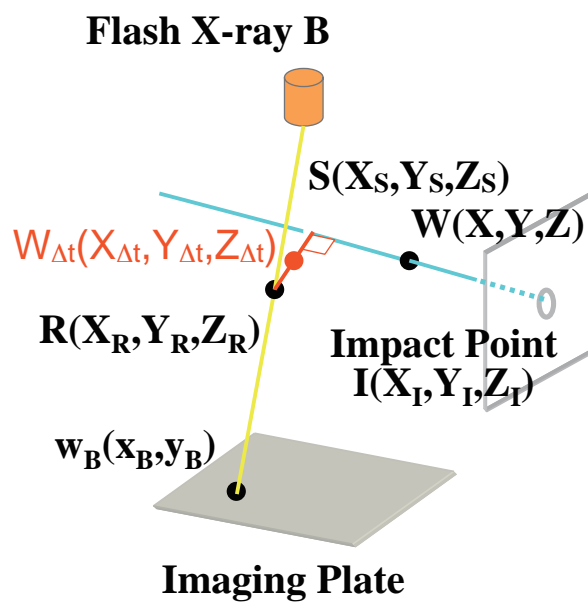
20/47

Estimation of Position of each Fragment



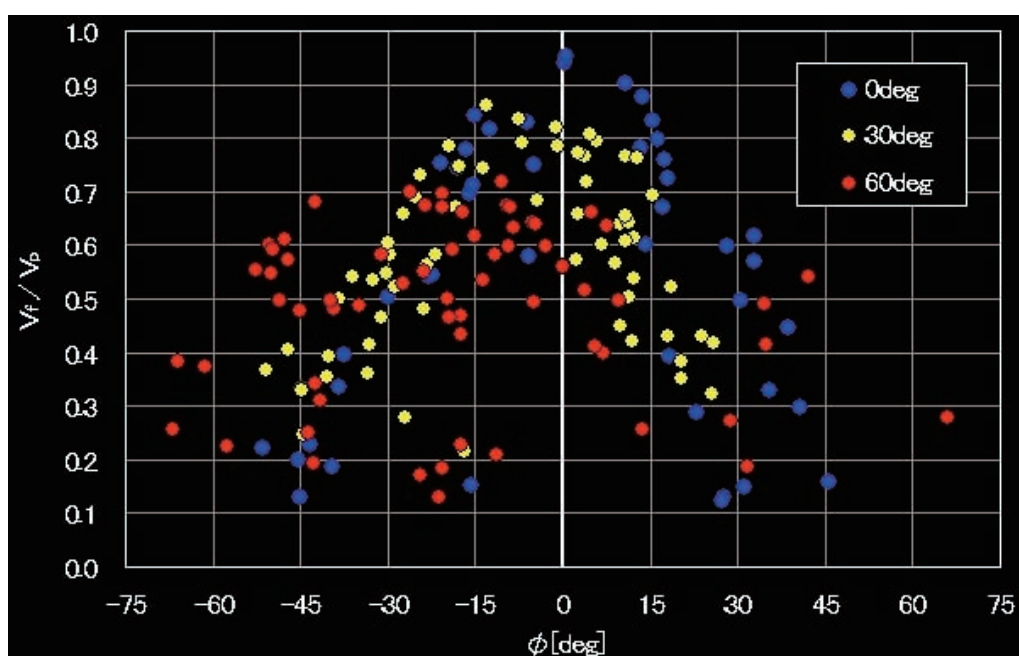
21/47

Estimation of velocity of each fragment



22/47

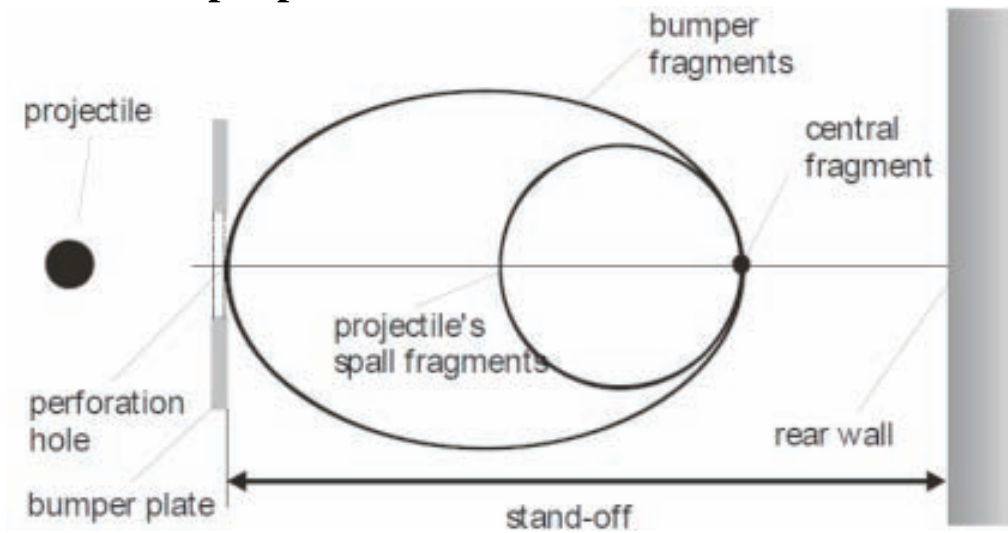
Velocity Distribution



23/47

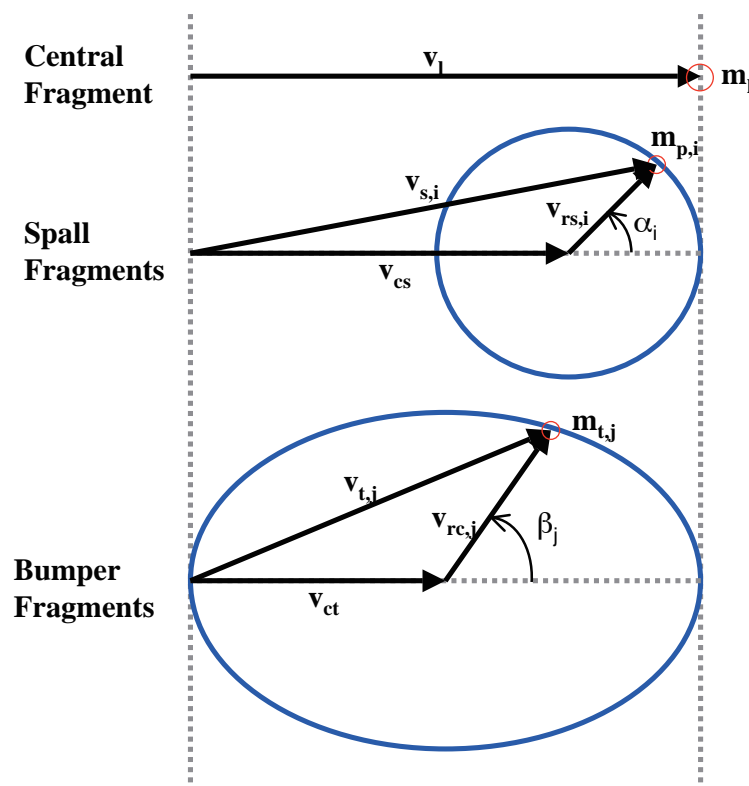
Schäfer Model

- Axi-symmetry
- Fragments are uniformly distributed on curves.
- All fragments are generated from a point on bumper plate.

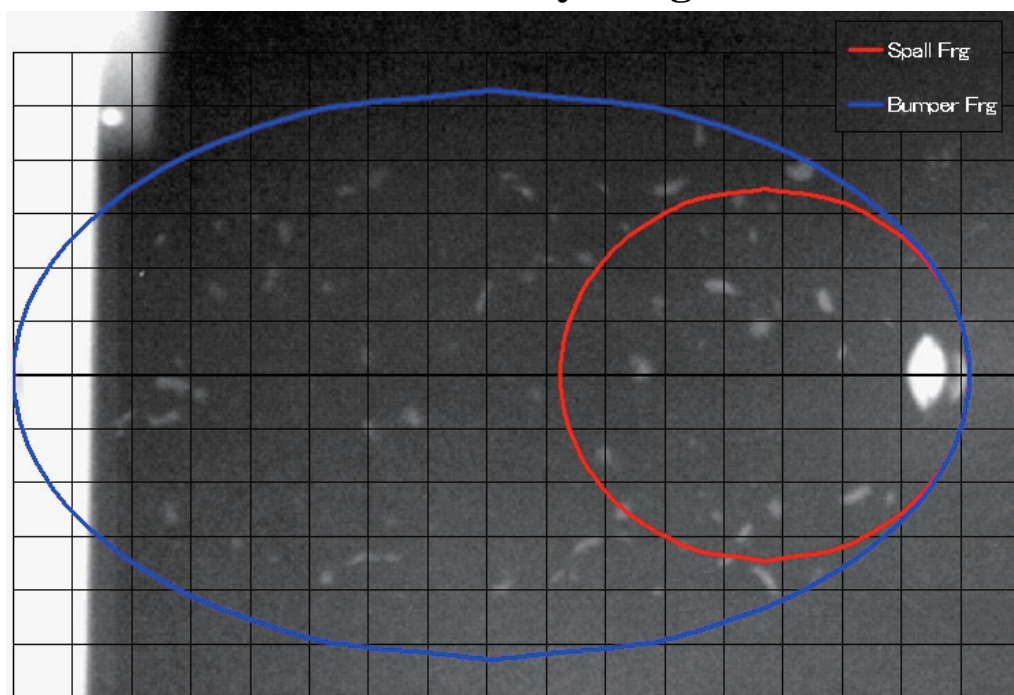


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Velocity Distribution in Schäfer Model

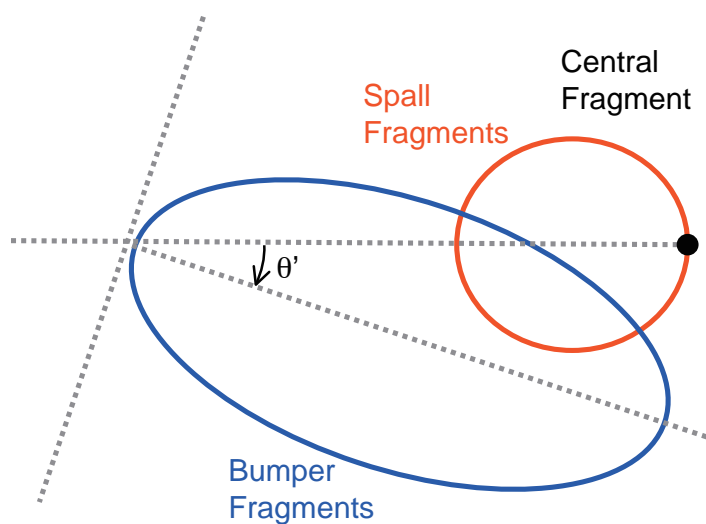


Comparison of space distribution between model and flash X-ray image



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Engineering model for oblique impacts



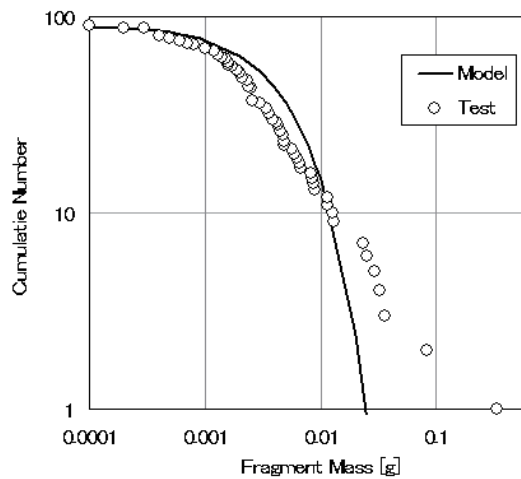
Bumper Fragments

$$\theta' = f_{\text{rot}} \theta$$

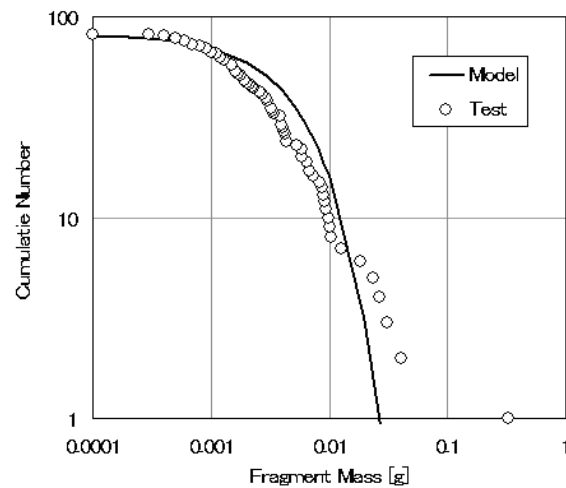
$$v'_a = (2 - f_v) v_a$$

$$v'_b = f_v v_b$$

Mass distribution (Spall Fragments)



(a) $\theta=0^\circ$



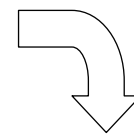
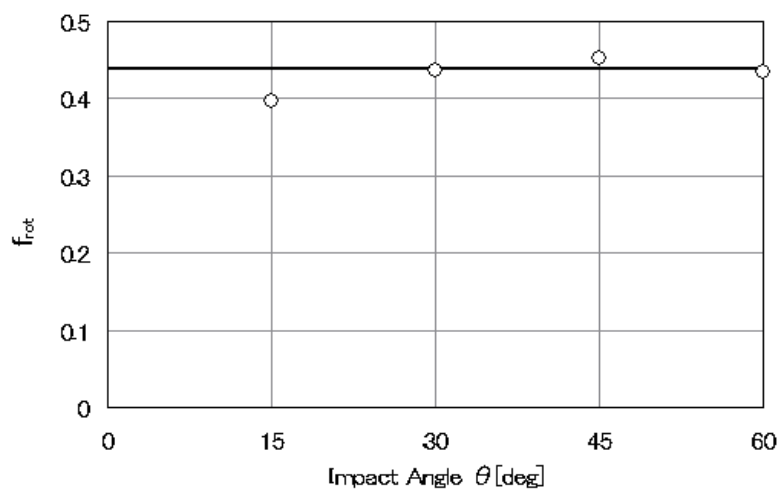
(b) $\theta=30^\circ$

Based on Schäfer model

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Estimation of f_{rot}

f_{rot} is calculated from position of leading bumper fragment.

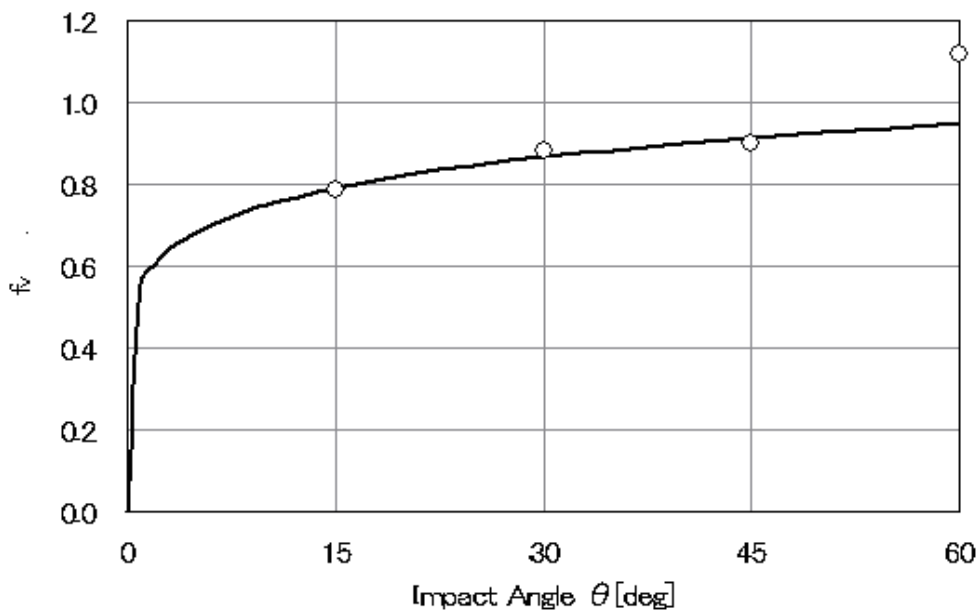


$$f_{\text{rot}} = 0.439$$

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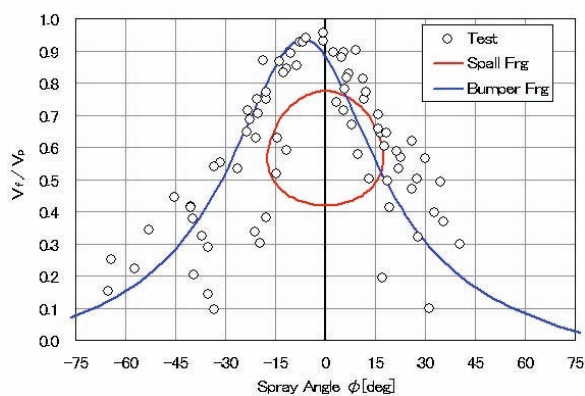
Estimation of f_v

f_v is calculated from leading velocity of bumper fragments.

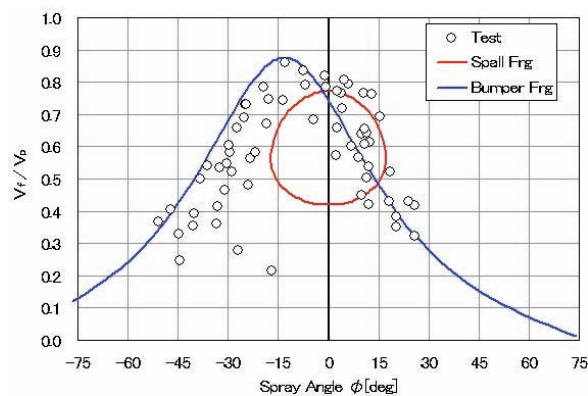


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Comparison between proposed model and experimental results



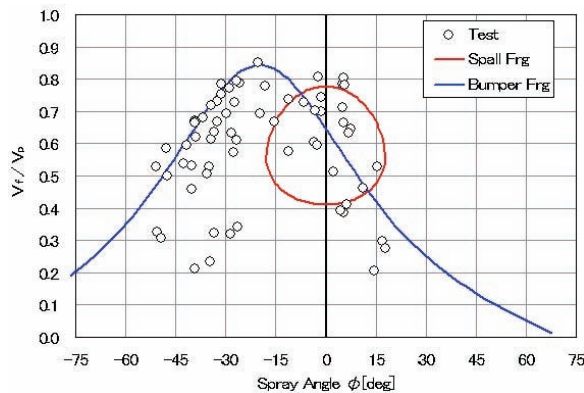
$\theta = 15\text{deg}$



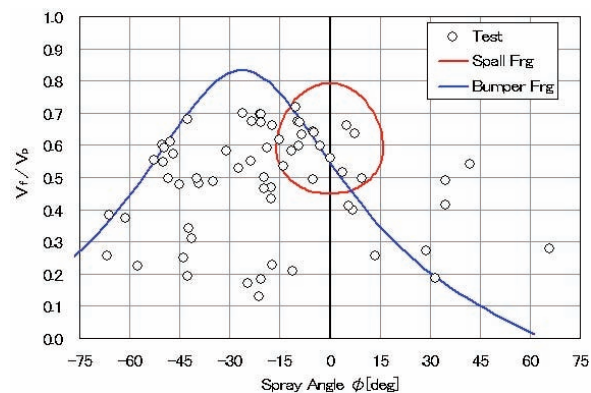
$\theta = 30\text{deg}$

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Comparison between proposed model and experimental results



$\theta = 45\text{deg}$



$\theta = 60\text{deg}$

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Closure

- Mass distribution of secondary debris cloud can be obtained by soft capture system of fragments.
- Velocity distribution of secondary debris cloud can be created by flash X-ray equipment and direct linear transformation method.



Both of mass and velocity of each fragment will be measured by combination between double exposure soft X-ray system and PIV method.

- Schaefer engineering model of secondary debris cloud is useful and this model can be expanded to oblique impact under some additional assumption and simple empirical models of rotation for bumper fragments.

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Ⅳ. セッションー3 デブリ低減対策

3-1 宇宙環境保全ビジネスモデルとデブリ回収計画

○峰 正弥（日本航空宇宙工業会（SJAC）／次世代宇宙プロジェクト推進委員会）

Business model for the space environment maintenance and demonstration plan for the debris removal system

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

Key Words: Debris, Business model, Space environment maintenance, Demonstration plan

概要

「スペースデブリ低減」についての議論は、レーガン大統領が 1988 年に国家宇宙政策（省庁間政策第 9 条）として発表したときからみても 既に 20 年を経過している。この間、米国、日本、フランス、ロシア等の各国毎の議論、欧州のような連合国としての議論、国際的な意見統一としての試み等々になされ、昨年 ようやく、国連宇宙空間平和利用委員会において「スペースデブリ低減ガイドライン」が採択されたというところである。しかし、同じ環境の問題である「地球温暖化政策」の議論のような一般世論を巻き込んだ形での大きな流れまでには至っておらず、「スペースデブリ低減」即ち「宇宙環境保全」が具体的に大きく動き出すかについては、これからの国際的な視点での舵取りにかかっている。

先ず、「大きな流れ」即ち「力強い流れ」にするためには、「地球温暖化対策」の場合と同様に 一般世論を動かすことが必要であるが、それと併行して、「宇宙環境保全」を実際に行うための資金源をどのように論理的に集めるのかについて、国際的な合意を得ることが重要である。

通信・放送衛星、観測・監視衛星、気象衛星、GPS 衛星等々、宇宙環境を利用することのメリットは非常に大きく、これを利用する「権利」については 世界各国に対して平等に与えられている。従って、各国が 積極的に宇宙環境利用を推進することについての問題はないのだが、利用後にそれを綺麗にする、即ち、宇宙環境を保全する「義務」についても、共通な認識として持つように導くことが重要である。この視点に立てば、公平性のある「受益者負担」による資金源の徴収といった形が議論出来る。これは 宇宙環境の「利用度」に応じて宇宙環境の「保全料」を徴収するという考え方である。尚、「宇宙環境保全」即ち「スペースデブリ低減」を行うのであるから、「スペースデブリを発生させるリスクを低減させる」という「リスク低減」のための資金徴収という考え方やスペースデブリ事故に対する「保険」と言う考え方を取っても良い。また、このような方向で合意が出来ていけば、「宇宙環境利用」と「宇宙環境保全」とはペアーな問題であり、かつ 公共性・公益性を有することから、公共事業的な観点で宇宙環境保全という事業を運営することも可能となる。

この「宇宙環境保全」では 「スペースデブリ低減」を推進していくことになるが、その有益な方法のひとつとして、寿命の尽きた衛星を粉砕される前に早期に回収・除去することが考えられる。この方法は、昨年の中国の気象衛星「風雲 1 号（FY-1C）」の破壊実験の結果からも有効であると考えられる。これを行うためのデブリ回収（除去処理）衛星は、軌道上にある寿命の尽きた衛星に近づき、その軌道からその衛星を逸脱させることを行うが、そのための基本的技術については、1997 年に我が国が打ち上げた ETS-VII において実証されており、その技術の延長線上でデブリ回収（除去）衛星の構築が可能である。この技術実証として、軌道上にある衛星 ADEOS を対象とした計画を提案する。

宇宙環境保全ビジネスモデル と デブリ回収計画

Business model for the space environment maintenance
and demonstration plan for the debris removal system

2008年 1月21日

次世代宇宙プロジェクト推進委員会

副委員長 峰 正弥

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

Summary

～ International recognition of debris problem and current will ～

- ❑ In 1995, NASA enacts NSS1740.14 "Guidelines and Assessment Procedure for Limiting Orbital Debris", and in 2000 the US Government implements "Orbital Debris Mitigation Standard Practices".
- ❑ In 1996, NASDA enacts STD-18 "Space Debris Mitigation Standard". (Revised as JMR-003 following JAXA integration.)
- ❑ CNES enacts "Safety Requirements - Space Debris" in 1999. In 2004, ESA along with UK, France, Germany and Italy decide on "European Code of Conduct for Space Debris Mitigation" in line with CNES standards. CNES is first to sign this agreement.
- ❑ In June 2007, "Space Debris Mitigation Guidelines" are adopted by UN Committee for Peaceful Uses of Outer Space (UNCOPUOS).

Although national government and expert level recognition of the importance and necessity of space debris mitigation has been achieved, it has not been a common sense.

However, with continued use of space there is a pressing need to create concrete measures for space environment preservation.

Therefore, we want to promote Japan-led, concrete space environment preservation initiatives that is supported by the public opinion.

Summary

Suggestion: the promotion of the Japanese expression
"space environment preservation"

-
- **Permeating public opinion**
 - Educating the public thru industry and government forums
 - Public outreach thru media, print, DVD (story comics), etc.
 - Promoting the initiative thru Internet, on-line communities, blogs
 - **Japan's suggestions to UNCOPUOS**
 - Codification of the idea of "debris" into the legal framework of Outer Space Treaty's Article 9 "contamination"
 - ***Suggestion and establishment of "organization" to undertake space environment preservation and "cost of operation/business model"***
 - "Space environment preservation" idea promotion thru economic and social organizations, international summits, earth summits, etc.
Earth environment preservation ⇒ Great benefits of earth observation from space ⇒ coupling of space use and space environment preservation
 - **Japan's suggestions for ISO standards and business models**
 - Balanced standardization between advanced and developing countries
 - Standardization not to hinder the benefit of industry and economic development
 - ISO standards-based Business model, such as conformity assessment cost for space environment preservation
-

2

Summary

Suggestion: the promotion of the Japanese expression
"space environment preservation"

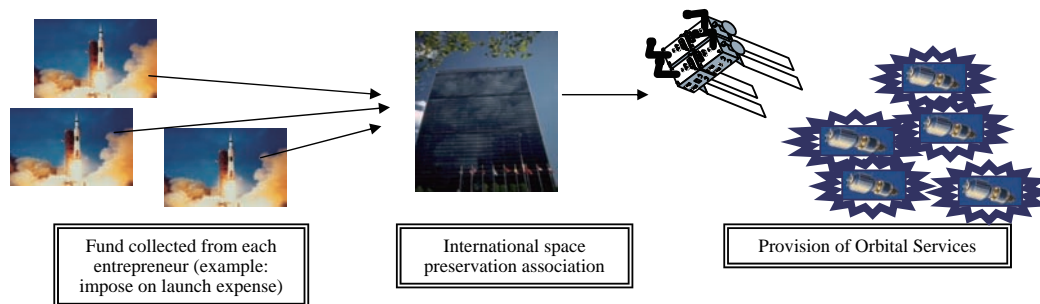
-
- **Establishment of space environment preservation organization in Japan**
 - Working with international partners, Japan to establish an integrated space environment preservation organization
 - Organization to couple the concept of the use of space with idea of space environment preservation
 - This organization would be responsible for the overall space environment preservation project and various systems involved (such as CAM)
 - Organizational responsibilities would include public awareness announcements on importance of the space debris problem (example: announcements by astronauts on the problem's severity).
 - ***Japan's space debris mitigation spacecraft***
 - ***Space debris removal satellite demonstration: debris removal proof-of-concept and Japan technology demonstrator***
 - ***Proposal of debris removal satellite system based on demonstration results***
 - **Debris observation by Japan**
 - Japan's role for debris observation activity and establishment of observation network
 - **Establishment of think-tank to support concrete realization of above objectives**
 - Concrete strategic policies to lead the international project
-

3

Review of Business Model

• International space preservation association & its management

- As "debris recovery/removal" enterprise will generate public interest what is called "space environment preservation" and need immense initial investment, **it should be managed as public utilities and the beneficiary charge system should be applied impartially.**
- It is hard for one country to promote this enterprise, and so it is indispensable of **international frameworks (U.N. resolution etc.)**
- Service offered to the debris which each entrepreneur generated should not be proportional to the burden charge collected from each entrepreneur. **The fund raised from the entrepreneur who will produce future debris can be spent on the cost to recover/remove an existing debris.** (Refer to the following figure.)
- **Both of the system not to generate a debris and (international) standardization is institutionalized.**
- This association performs authorization of a product which does not produce a debris, and that authorization charge is collected.



4

Business Model (Organization's Structure)

Organizations to operate "debris recovery/removal" enterprise (staffing descriptions omitted)

- **Organization 1: Space Environment Preservation Planning (Debris Mitigation Project)**
 - Debris mitigation planning based on current debris conditions and debris forecasting model established by Organization 2 (below)
 - Concrete action plans are formulated based on debris mitigation planning (establishing WBS/SOW)
 - Project management for implementing action plans
 - Effective use of organizational funding
- **Organization 2: Debris Observation & Modeling**
 - Reorganization of current debris conditions based on US, Europe, etc. debris observation network report and in-orbit observation
 - Establish and maintain debris forecasting model
 - Monitor new launches and satellites (are there non-reported satellites, etc.?)
 - In-orbit observation planning and to order observation system to manufacturers
- **Organization 3: Debris Removal**
 - Working in coordination with Organization 1, debris removal planning and to order removal satellite system to manufacturer
- **Organization 4: Establishing ISO Debris-related Standards**
 - Organization 1, 2, and 3 work jointly on establishing debris-mitigation ISO standards applicable for satellite design

5

Business Model (Organizational Funding)

□ Funding Sources

Proposal Plan (Note1)(Note3)(Note5)	General Evaluation	Fairness	Transparency / Evaluation	Comments
Flat Rate	×? (Note4)	×? (Note4)	○	Benefits to advanced/utilizing space countries. Negative impact on developing countries. (Note4)
Proportional to Price	○	○	△	Difficult to Price evaluation?
Proportional to Launch Opportunity	○	△	○(Note2)	Launch Opportunity can be monitored on the ground Debris observation network
Proportional to Mass	○	○	△(Note2)	Debris size can be monitored on the ground Debris observation network

Note1: Above proportional rate is based on the number of launcher + satellite

Note2: Declaration can be evaluated by comparing the data obtained by Debris observation network

Note3: Funding from individual countries collected on basis that space is a shared resource
(i.e., shared terrestrial resources)

Note4: US, Europe, etc. should maintain debris observation infrastructures to supply observation data and the maintenance cost will serve as counterbalance to the flat rate advantage.

Note5: Impartial funding considering the exchange rate

□ Funding Method

- Funding provided by final user (operator)
- "consumption tax" or "insurance fee"-type funding considered (see attached)

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Business Model (Organizational Funding) ~ Insurance-type Consideration ~

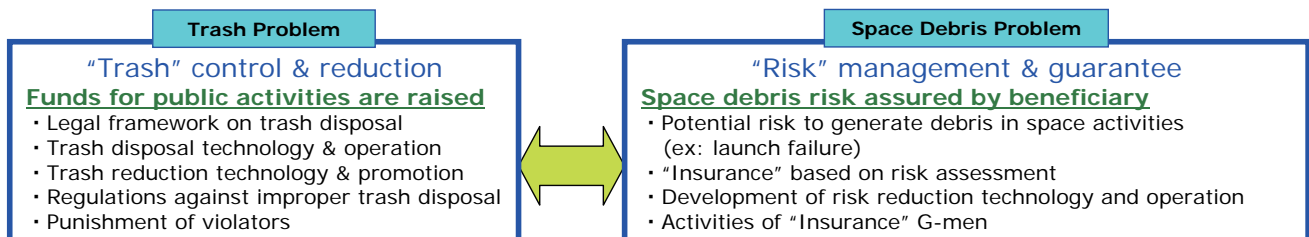
Necessary Base-Line Approach

- Funding for a "space debris policy" must be based on clearly established organizational responsibilities and scope of work.

Definition: towards what are we working?

Points to be clarified: "Are we merely a control group?" "Do we enlighten the way to prevention?" "Do we manage and remove debris, as well?"

- How do we approach the issue of funding when people do not feel "debris" problem as an urgent crisis.



Greenhouse gas effects severely and directly on our life and so it should be considered a "trash" problem. However influence by "space debris" is indirect and uncommon, so its risk should be controlled.

As far as we try to control "space debris" risk, we can discuss "space debris" overall as public acceptance, including the following issues, costs involved, previous satellites and launches, risk assessment, necessary technology to develop, the risk to the ground.

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Business Model (Organizational Funding)

~ Insurance-type Consideration ~

Establishing a risk control regime and its scope

- Organization or entity is based on international treaty. Participating country obligates its establishment cost. Treaty includes terms of the country's unlimited liability regarding launch failure and its damages. (example: an organization under the (initial) auspices of UN, an organization same as the initial INTELSAT, etc.)
- To collect insurance premiums and to pay benefits, and to develop debris mitigation technology and to operate it.
- Risk assessment and evaluating insurance premium. (Commercial entities may act as representatives.)
- Current space technology has been based on past space activities and it will be applied to future satellites and launchers. So, cost to current debris risk control will be assigned to future satellites and launchers as well as current satellites and launchers.
- Space surveillance, debris observation and debris cataloguing carried by each country will be take over by the international organization.
- Establishment of evaluation standards and technology development as necessary for risk assessment and diffusion.

Risk control regime funding (insurance basis)

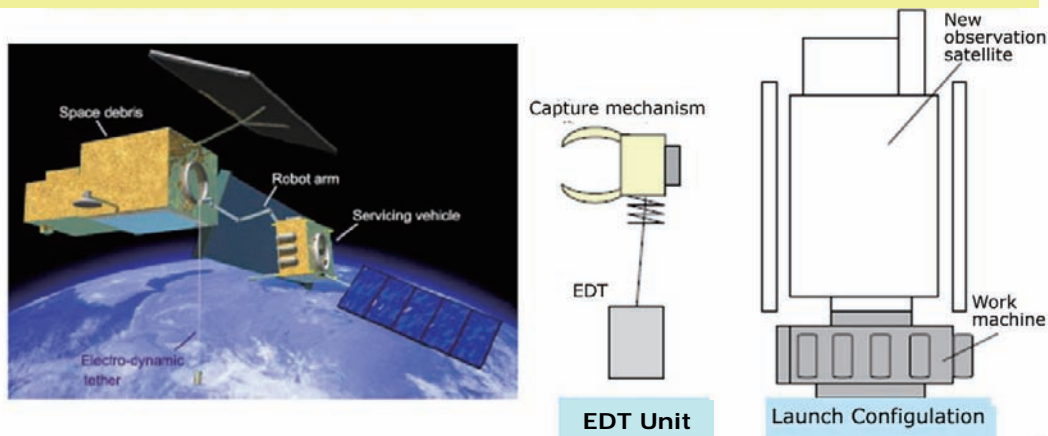
- Participating countries contribute to the capital base. Additional funding can be obtained by insurance premiums covering launch.
- Insurance premiums collected for each launch (LEO, GEO, interplanetary, etc.).
- Evaluating "insurance premiums" based on the following items,
 1. Risks associated with satellite and launcher (reduced fees in case of mitigating debris)
 2. Risks associated with past satellites and launches
 3. Costs associated with removing past satellites
 4. Organizational operating costs and costs related to new technology development
 5. Terrestrially-related risks, etc.
- Reduction in accordance with respective country's degree of contribution.

8

The concept of debris recovery / removal system

Plural Debris Remover

- Plural EDT unit carried in the middle class satellite
- Attaching EDT unit in capturing, extending tether and releasing
- Shifting between orbits, removing more debris sequentially



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Concept of debris recovery / removal system

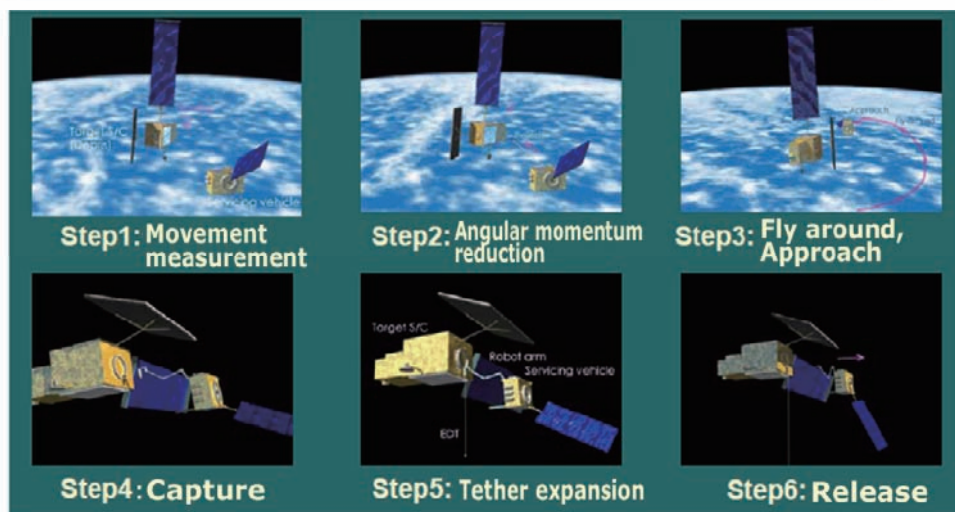
Plural Debris Remover

Subsystem	Mass (kg)	Power consumption (W)	Remarks
EPS/PDL	90~110	50~70	2-axis drive PDL
C&DH	40~50	90~100	S-band
TCS/STR	100~200	80~120	Cone type central cylinder
AOCS	60~80	120~140	3-axis stabilized
RCS	350~700	10~20	Propellant: 300kg~600kg
MISSION	250~360	120~150	10 EDT Units Robotic Arm Imaging sensor
TOTAL	890~1500	470~600	—

10

Concept of debris recovery / removal system

Satellite Removing Scenario : Plural Debris Remover



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Key Component Technologies of a Debris Removal System

■ Electro Dynamic Tether (EDT)

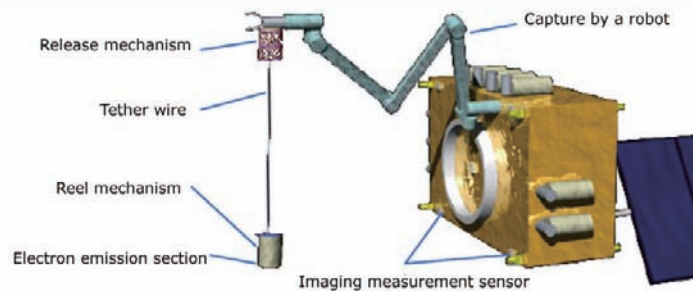
Tether wire, Reel mechanism, Release mechanism, Electron emission section

■ Imaging measurement

Rendezvous sensor for non-cooperative, Debris motion measurement

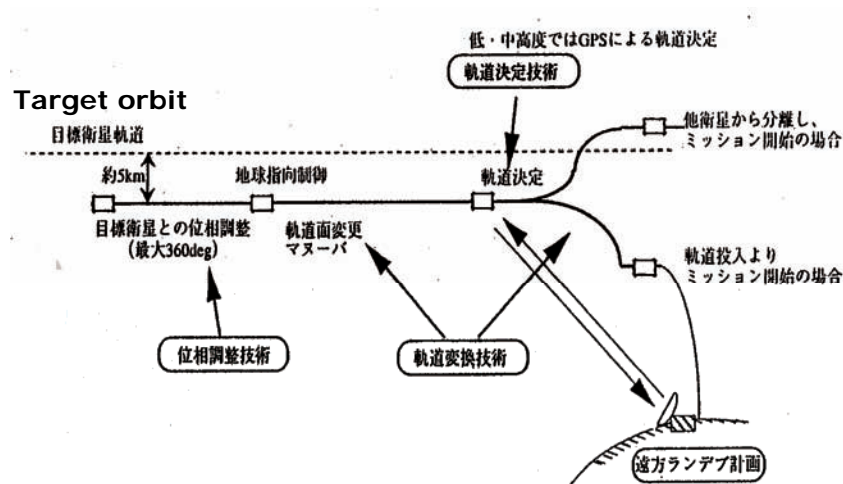
■ Capture technology

Capture by a robot (Compliance control, Dumping control, Capture mechanism)



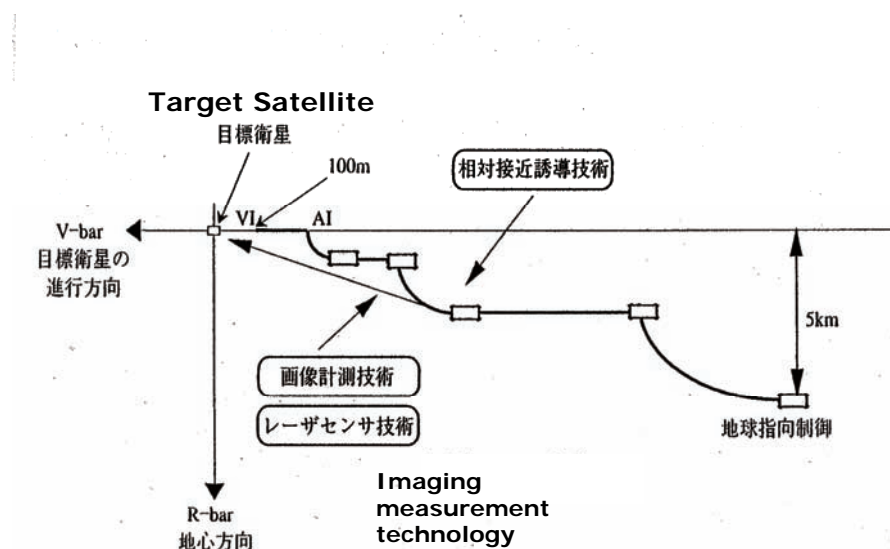
12

The operation profile in an approach phase



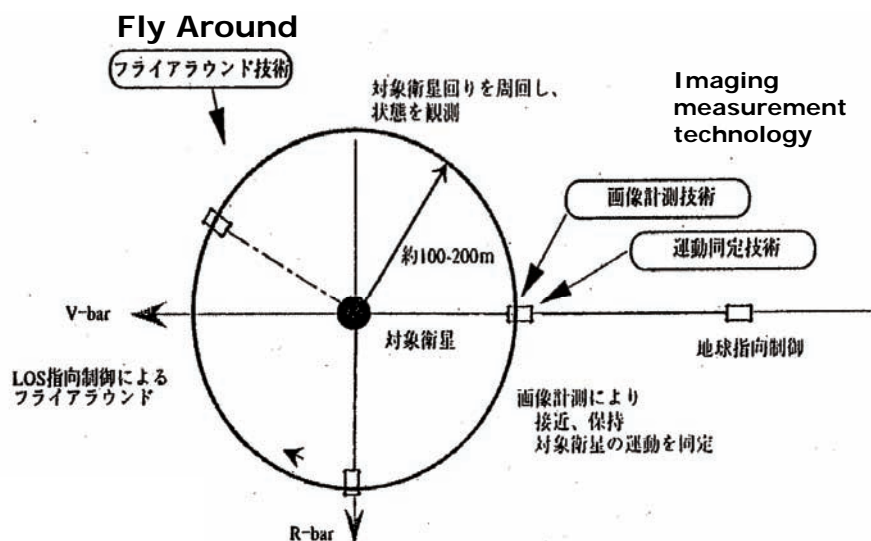
13

Adjacent Rendezvous Operation Profile



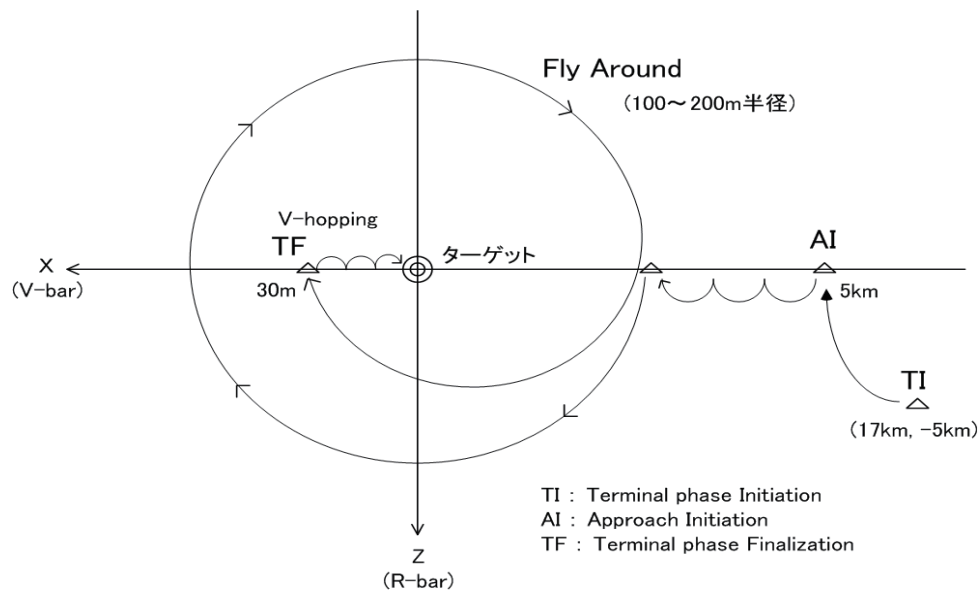
14

Fly Around Observing by Circular Orbit Pattern



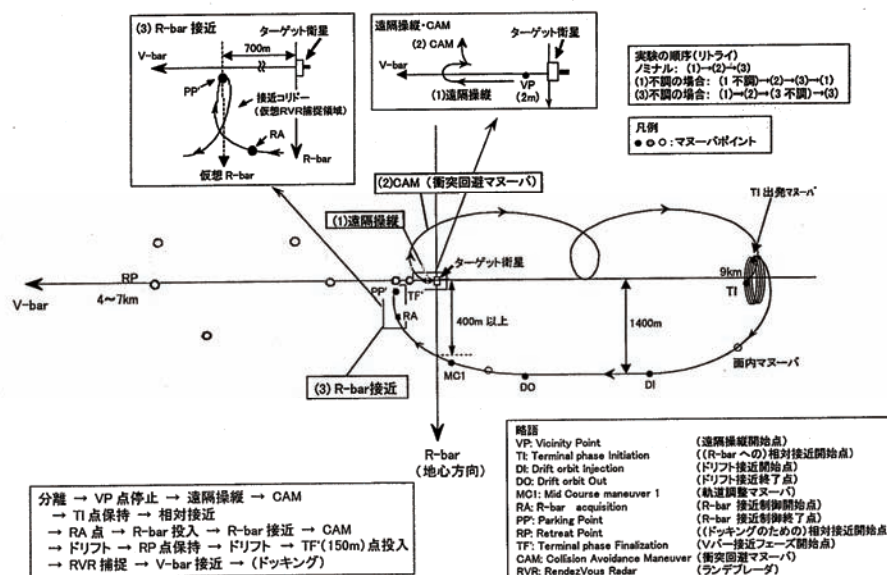
15

Final Approach to Target



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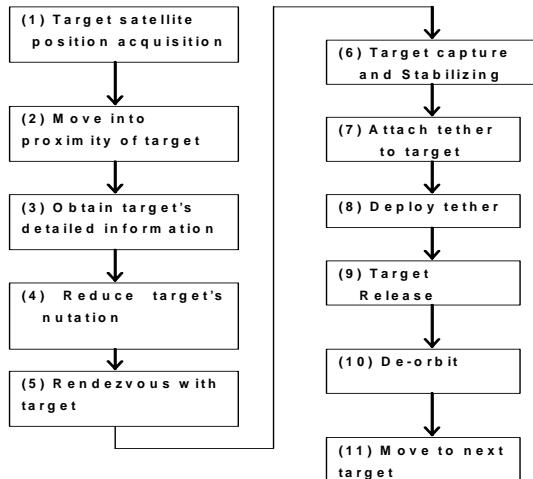
Development technology by ETS-VII



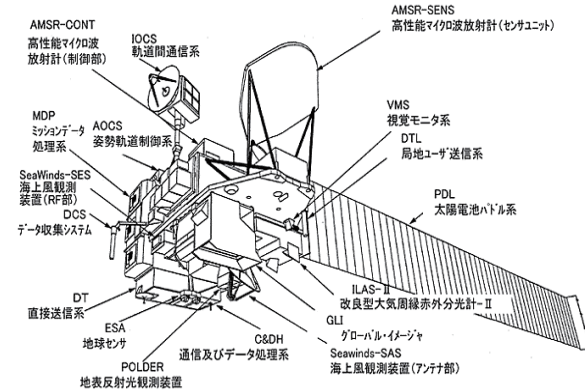
17

Study of ADEOS Removal ~ Japan's debris removal proof-of-concept plan ~

Demonstration recovery plan encompasses targeting Japan's non-operational, in-orbit satellites (example: ADEOS)

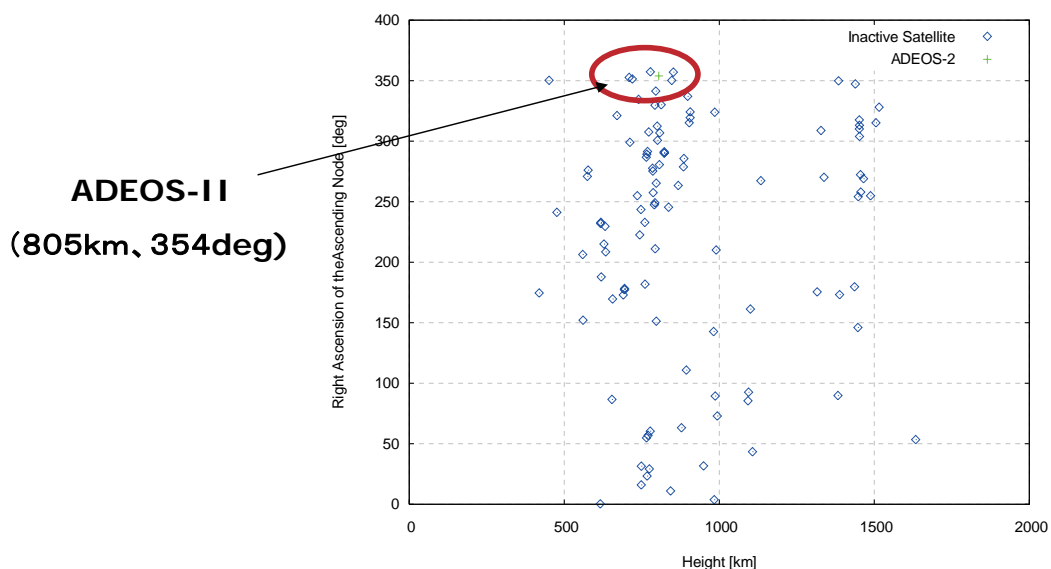


みどりⅡの軌道上外観図 Midori II



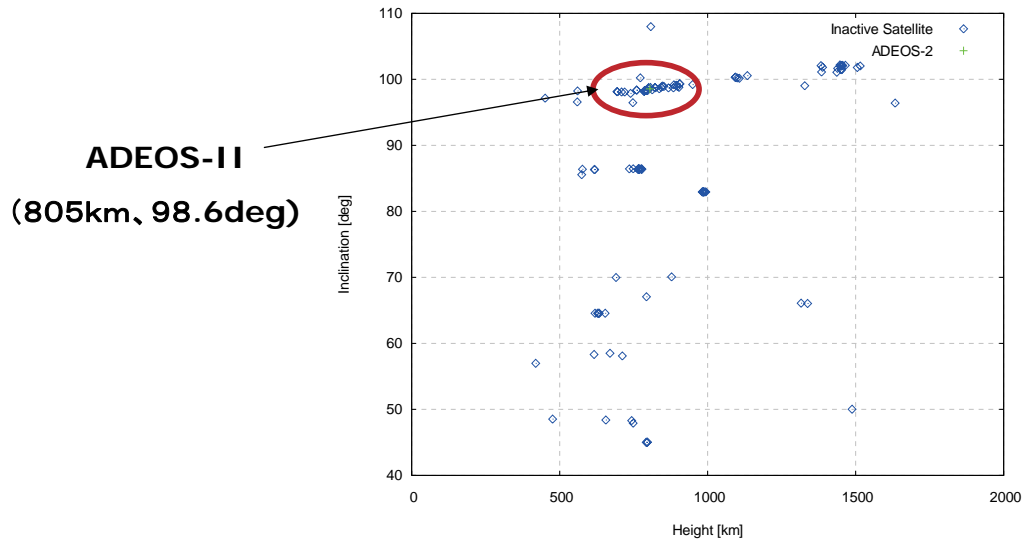
18

Orbital altitude vs Right ascension of the Ascending-node (Inactive Sat)



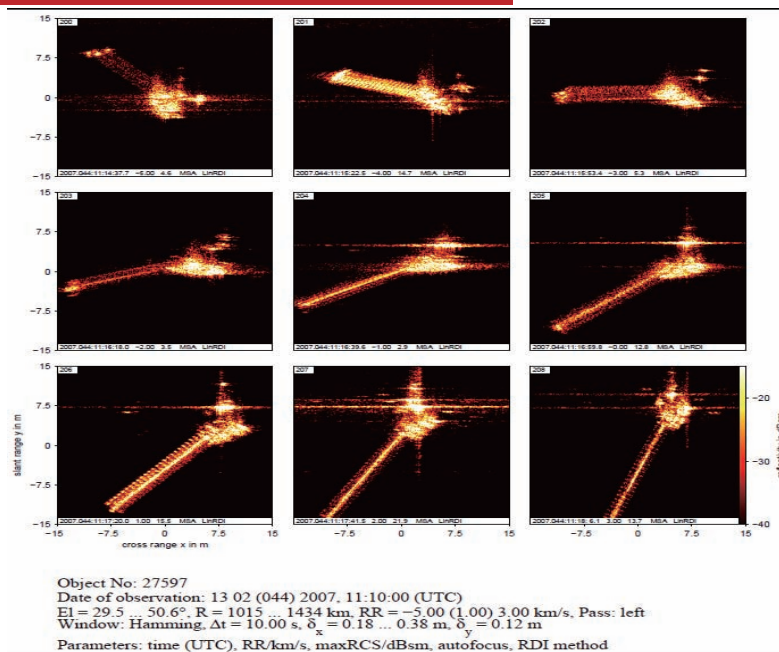
19

Orbital altitude vs Orbital inclination (Inactive Sat)



20

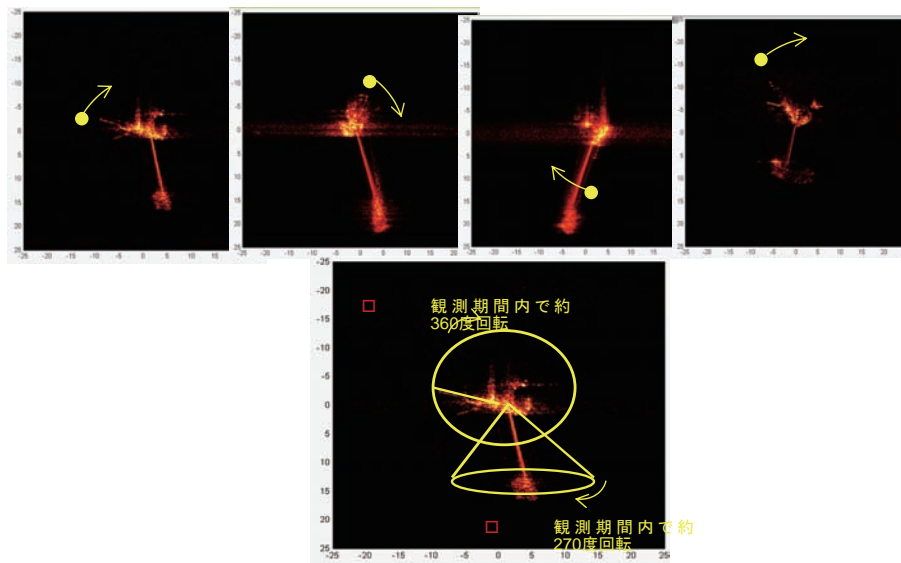
Behavior of ADEOS- II (Observing duration: 3min.28sec.)



21

Behavior of ADEOS

(Rotates of 360 degrees in estimated 6 minutes duration)

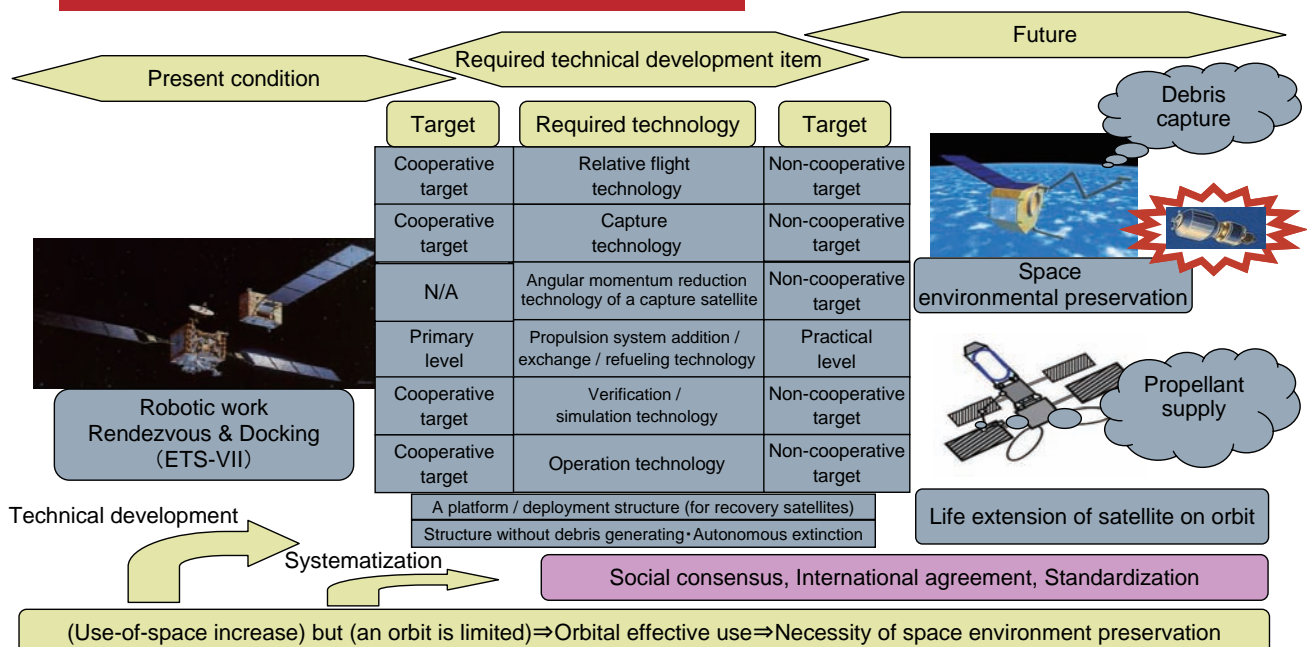


□ ADEOSの回転状況

□ (@2007.02.13.16:24:00 近辺、durationは推定6分間)

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Technical Road Map (Debris Recovery / Removal System)



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3-2 デブリデオービット用導電性テザーシステムのキー要素技術

大川恭志、河本聡美、西田信一郎、北村正治
(宇宙航空研究開発機構 総合技術研究本部 宇宙先進技術研究グループ)

Key Technologies of Electrodynamic Tether Systems for Space Debris Removal

Yasushi Ohkawa, Satomi Kawamoto, Shin'ichiro Nishida, and Shoji Kitamura
(Advanced Space Technology Research Group, Institute of Aerospace Technology, JAXA)

Key Words: Debris de-orbit, Electrodynamic tether

概要

JAXA 総合技術研究本部では、デブリ除去システムへの適用を目指し、導電性テザー推進技術の研究開発を進めている。導電性テザー推進は、軌道上で伸展した km 級のテザーに電流を流し、その電流と地磁気との干渉により発生するローレンツ力を推力として利用する推進系である。軌道高度を下げる方向に推力を発生する場合には、テザーに沿って生じる誘導起電力によりテザー電流を駆動できるため、原理的には推進剤および電力が不要であり、将来のデブリ除去システムの軌道変換用推進系の有力な候補となる。

宇宙用テザー技術に関する研究はこれまでも行われてきており、軌道上での 20 km 級テザーの伸展や誘導起電力の発生、テザー電流の確認などは米国および日本を中心に報告されている。しかし、導電性テザーによる推力発生（軌道変換能力）はこれまでに確認されたことが無く、デブリ除去システムへの適用のためには、軌道変換能力を実証するための軌道上実験が必要である。この軌道上実験の実施に向け、JAXA 総合技術研究本部では、以下に示す導電性テザーのキー要素技術の研究開発を行っている。

1) リール

伸展前のテザーを収納。軽量・高信頼性の両立が必要。テザー収納用の固定リールと制動リールの2段構成で試作・試験を実施。

2) ベアテザー

誘導起電力発生、宇宙プラズマからの電子収集、ローレンツ力の発生、という3役を担う。機械的強度、熱光学性能、電子収集性能、耐デブリ衝突性能が必要。組紐テザーおよび網テザーを試作・試験。

3) エンドマス放出機構

リールを格納したエンドマスを放出。十分な放出速度と高信頼性が必要。2重コイルばねを利用した放出機構の試作・試験を実施。

4) 電子源

電流ループを形成するために宇宙プラズマに電子を放出。小電力・軽量・簡素が求められる。新規開発中の電界放出型電子源に加え、ホローカソードの適用も検討中。

各要素それぞれにおいて技術課題はあるものの、後述のように研究開発は順調に進んでおり、早期の軌道上実証機会の獲得を目指し、開発を継続中である。

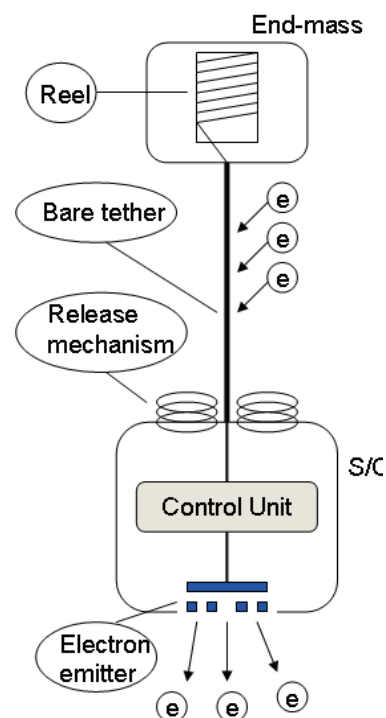


図1 導電性テザーの主要構成



3rd Space Debris Workshop, January 2008

Key Technologies of Electrodynamic Tether Systems for Space Debris Removal

デブリデオービット用導電性テザーシステムのキーテクノロジー

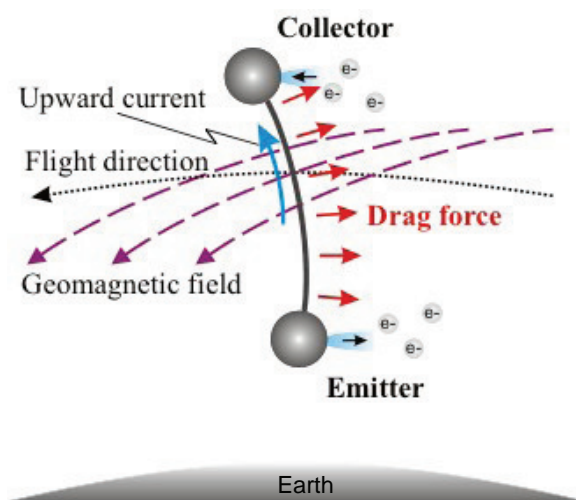
Y. Ohkawa, S. Kawamoto, S. Nishida, and S. Kitamura
Advanced Space Technology Research Group, IAT / JAXA

大川恭志、河本聡美、西田信一郎、北村正治
JAXA 総合技術研究本部 宇宙先進技術研究グループ



Electrodynamic Tether (EDT)

- Electrodynamic Tether
 - High-efficient propulsion system using electromagnetic force
- Thrust Generation
 - EMF by orbital motion
 - $E = (v \times B)L$
 - Electron emission and collection
 - Electric current through tether
 - Lorentz force by electromagnetic interaction
 - $F = (J \times B)L$



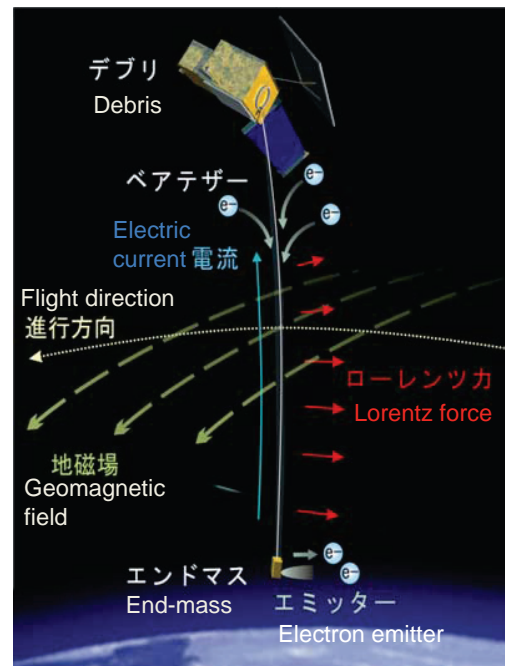
Lowering orbital altitude without propellant and power



EDT for Space Debris Removal

We plan to develop EDT system for space debris removal.

- 1st step
 - Demonstration of **Thrust Generation** on orbit
- 2nd step
 - Demonstration of **Debris De-orbit**
- 3rd step
 - Development of **Debris Removal System**



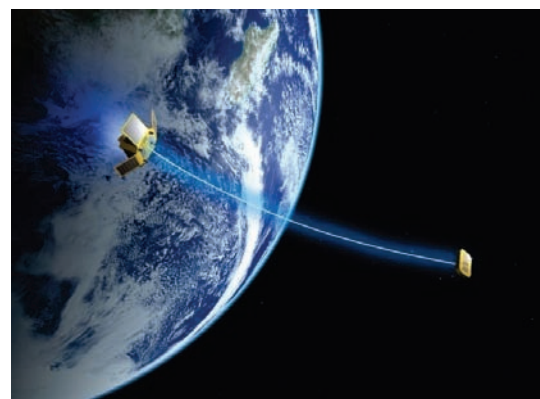
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Why R&D of EDT ?

- Attractive performance
 - Almost no propellant required
 - Almost no electric power required
- We need on-orbit demonstration as 1st step
 - The first thrust generation by EDT in the world
 - Technological difficulties
 - Tether deployment
 - Tether dynamics
 - Electron collection and emission

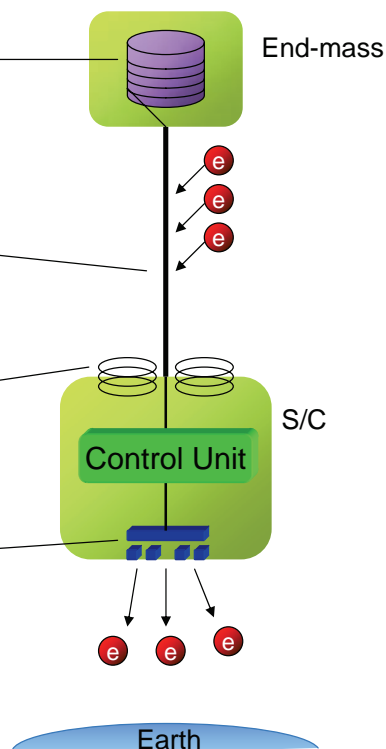
R&D of Key Components
for Demonstration Flight





Key Components of EDT System

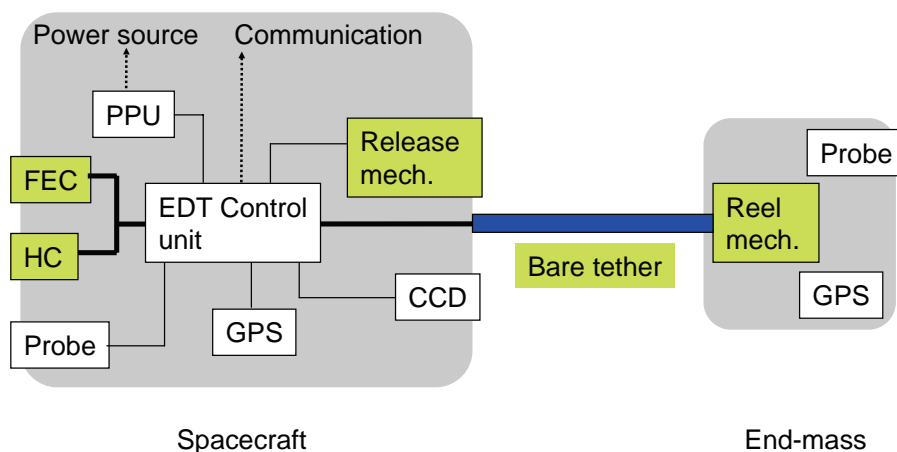
- **Reel**
 - Fixed reel & Braking reel
- **Bare tether**
 - Braided tether
 - Mesh tether
- **Release mechanism**
 - Double helical spring
- **Electron emitter**
 - Field emission cathode (FEC)
 - Hollow cathode (HC)



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EDT System for Demonstration Flight

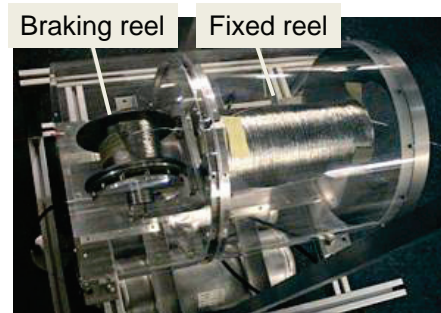
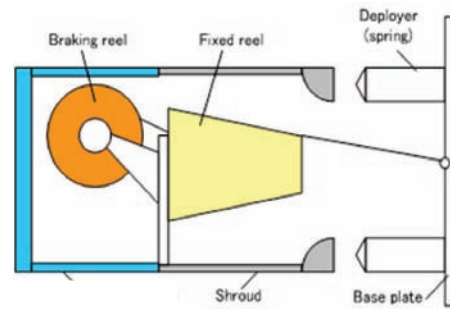


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Reel Mechanism

- Two-stage reel
 - Fixed reel
 - Most part of tether wound
 - Braking reel
 - End part of tether wound for passive braking
- Design & Fabrication
 - Fabricated for 10-km tether (4 kg)
 - Designed for 1-km tether (1.5 kg)
- Testing
 - Deployment drag < 0.2 N
 - Braking force > 2 N

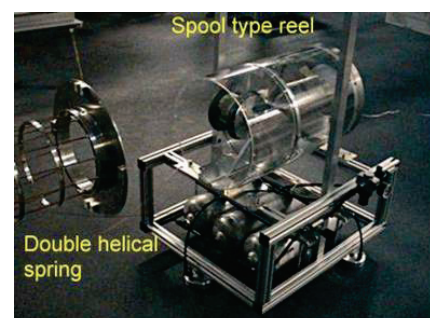
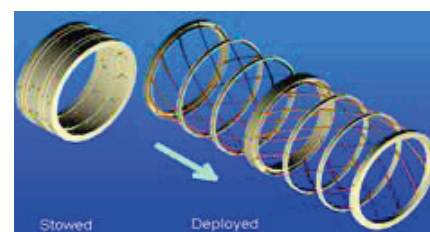


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Release Mechanism

- Spring
 - Double helical spring
 - Light weight
 - High reliability
- Design & Fabrication
 - Fabricated for 20-kg payload with 1-m/s initial velocity
- Testing
 - On air table
 - With the reel mechanism
 - Release velocity ~ 1 m/s



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Bare Tether

- Requirement
 - Strength
 - Electric conductivity
 - Electron collection (Bare)
 - Survivability (Anti-debris-impact)
- Fabrication
 - Braided tether
 - Aluminum wires and carbon fibers braided
 - $\Phi 2$ mm, 2g/m, 350 N
 - Mesh tether
 - Aluminum wires and carbon fibers weaved uniquely
 - For higher anti-debris performance



Braided tether



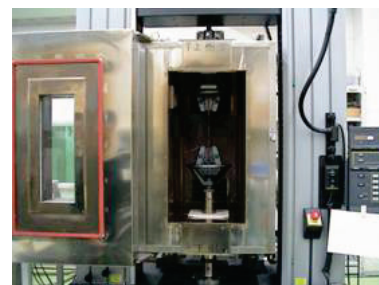
Mesh tethers

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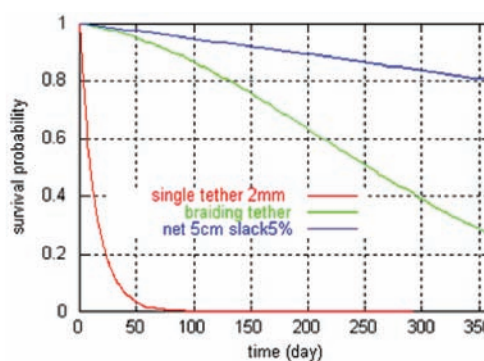


Bare Tether

- Strength test
 - At low (-90°C) and high (300°C) temperature
 - Enough strength obtained
- Estimation of survivability
 - Debris flux model
 - ORDEM2000
 - Cutting judgment
 - 1/3 of tether-diameter damaged
 - Survivability
 - Single line < Braided < Mesh
- * TiPS (4km) survived by 10 years at 1000-km alt.



Strength test at 300°C



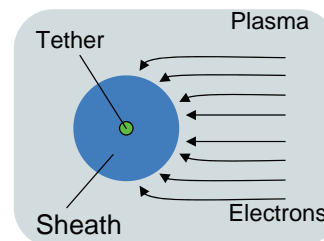
Survival probability

10

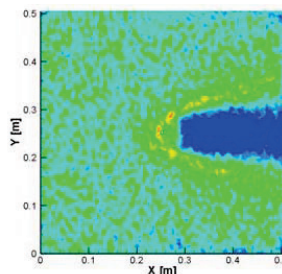


Bare Tether

- Electron collection
 - Positive biased tether collects electrons from space plasma
 - Estimation enabled by experiments and numerical simulation



Plasma simulation chamber



Electron distribution around tether (Calculation)

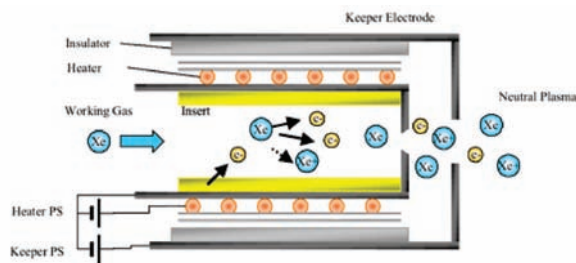
Orbital altitude [km]	Tether diameter [mm]	Tether potential [V]	Tether length [m]	Tether current [A]
300	2.0	50	1000	1.3
800	2.0	50	1000	0.3

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Hollow Cathode (HC)

- Features
 - Ampere-level electron emission with low power
 - Flight-proven technology for ion engines
 - Working gas required (Xenon)
- HC for EDT
 - Short-term development based on matured technologies



Hollow cathode



HC neutralizer for ion engines

Specification of HC for ETS-VIII ion engines (Reference)

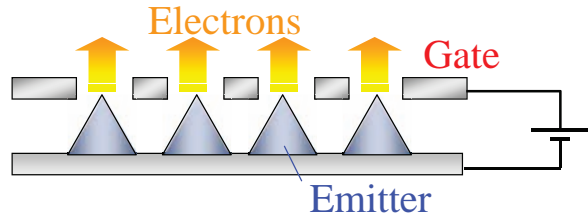
	Emission current	Required power	Xenon flow
Discharge cathode	> 3A	15 W	2 cc/min
Neutralizer cathode	> 400 mA	10 W	1 cc/min

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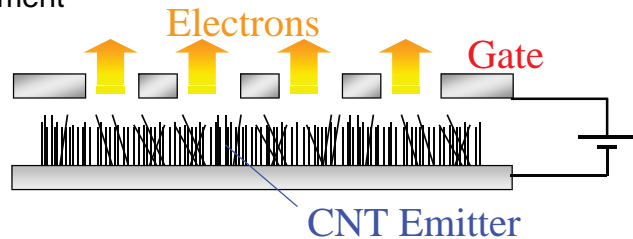


Field Emission Cathode

- Field Emission Cathode (FEC)
 - Electrons are extracted from sharp-edge cathode by strong electric field
 - Low power & simple structure



- Carbon Nanotube (CNT) Cathode
 - Thin nanotubes are used as electron emitter
 - High e-field concentration
 - High tolerance to ion impingement

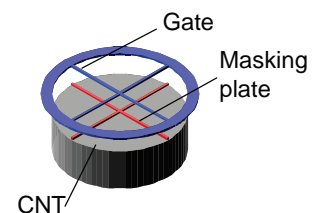


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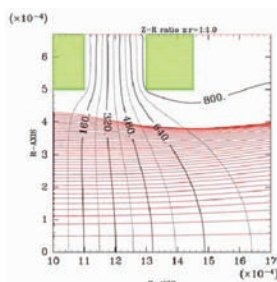


Field Emission Cathode

- Design & Fabrication - *Model A*
 - 7 array of 4-mm-diameter CNT emitter
 - Masking plate for trajectory control
 - 12-mA emission at 3.2-kV gate
 - Emission current density of 100 A/m²



Emitter schematic



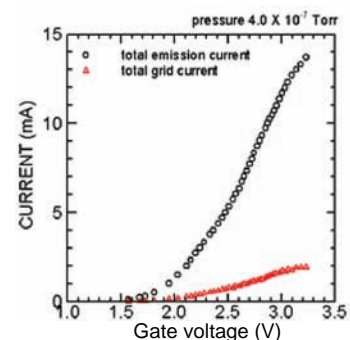
Electron trajectories



Single emitter



7 arrayed emitters



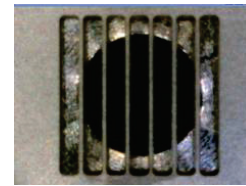
Emission characteristics

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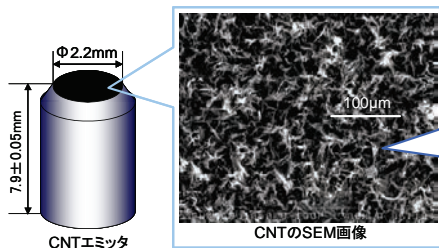


Field Emission Cathode

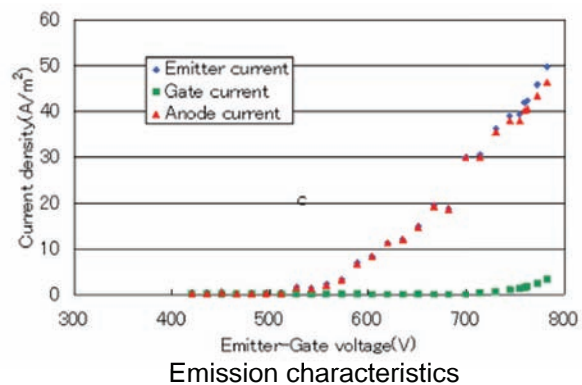
- Design & Fabrication - *Model B*
 - 2-mm-diameter CNT emitter
 - Masking plate
 - 0.2-mA emission at 0.8-kV gate
 - Emission current density of 50 A/m²



CNT emitter with gate



CNT emitter



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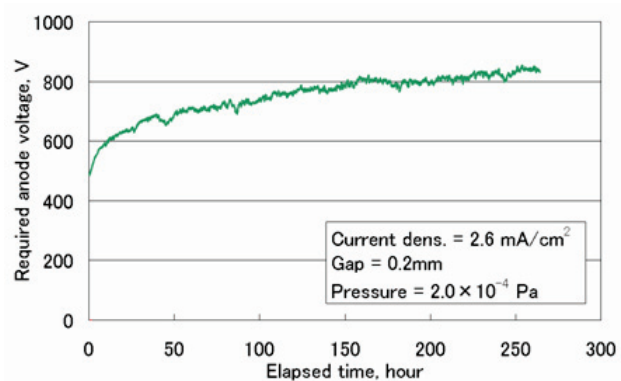


Field Emission Cathode

- Endurance test
 - Long-term operation of CNT cathode in oxygen environment
 - Not atomic Oxygen
 - Higher pressure
 - 250-hour continuous operation at 26 A/m²-emission
 - Emission capability deteriorated as time, however, the trend was saturated



Space chamber



Endurance performance of CNT cathode. Voltage required for constant current emission.

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Summary

- Key technologies of electrodynamic tether systems for space debris removal are under development in IAT/JAXA
- Key technologies
 - Reel
 - Release mechanism
 - Bare tether
 - Electron emitter
 - Hollow cathode
 - Field emission cathode
- We plan to demonstrate these technologies on orbit in near future

3-3 産業界から見たデブリ問題

池内 正之（NEC東芝スペースシステム）

Space Debris in Question of Industry

Masayuki Ikeuchi (NEC Toshiba Space Systems)

Key Words: Space Debris, Survivability, Mission Assurance, DCI, Failure Mode, Risk, Safety

1. 目的および背景

宇宙デブリ緩和要求（宇宙デブリの増加を現状より緩和する要求）は、国際的なテーマであり、ISO 宇宙標準でも、2003 年からこの課題を取上げ議論が続いている。この背景には表 1 に示す宇宙利用とその対応に関する変化があると思われる。この様な状況で、衛星に関する共通認識として宇宙デブリ（SD: Space Debris）の問題について紹介する。

2. デブリ問題とその対応案

①Expected SD Environment around Spacecraft

衛星に対しどの程度の SD 環境要求を想定するか？
直径 2mm 程度以下を対象として推定した。地上から観測できないので、衛星に防護等対応が必要である。

②Survivability for Mission Assurance

SD に関わる寿命要求をどう定義するか？SD の衝突により構造・部材は損傷を受けるので、故障や性能の劣化が発生しない様に考慮する信頼性設計の他に、必要であれば損傷許容設計を考慮して、ミッション達成に要するサバイバビリティ S（信頼度と同様の値）を定義する。

③Debris Critical Item (DCI) & expected Failure Mode

故障形態は何を対象とし想定不具合を設定するか？

対象を選択する考え方として DCI を定義する。故障形態としては、損傷メカニズムと、衝突で損傷する構造・部材の構成物質の状態変化が基本となる。

④Risk Evaluation & PDCA process

リスク判定基準と改善方法をどうするか？システム残留リスク = $1 - \Pi S_i$ （式は直列系を仮定。Si は個別 DCI の S、 Π はその累積）を定義して、これを減らす様に PDCA を回すことにより改善する。

⑤Safety and Failure Mode confirmation in reality

考慮した故障形態を発生する事象と対照できるか？
デブリによる事故か他の不具合かを識別できるか？
今後の課題が数多くあるが、試験と設計解析によりリスク低減を検証することが先決課題である。

⑥System Eng. for Mission Assurance & SD mitigation

衛星システムに対してミッション保証とデブリ緩和をどの様に要求して両立させるか（質量等の配分）？
SD 防護やシールド、損傷許容設計、及び安全で加工しやすく軽量な材料が必要である。

3. おわりに

SD 問題の共通認識により、各種分野の研究の交流、プロジェクトとの連携と成果継承、各種標準の活用等の活動が益々活発になれば幸いである。

表 1 宇宙デブリ緩和要求の背景

視 点	宇宙分野の課題	推測する変化・傾向
需 要	衛星利用ニーズ、ミッション	地球環境問題等から LEO の観測衛星利用ニーズは国内外ともに増加する傾向。
環 境	宇宙デブリ緩和と環境利用に関する国際的な枠組み	デブリ緩和として宇宙環境や他の衛星を省みる国際的な要求の高まり。IADC、ISO、国内委員会等。
要 求	衛星のミッション期間中のサバイバビリティ要求	ミッションを保証する技術的な裏付け強化による信頼性向上の課題。
リスク	残留リスクを評価するための技術基準	第三者や審査会によりリスクを判定できる基準（メトリクス）の整備。
安全性	事故の未然防止と発生時の事故・不具合識別	標準的な故障形態の識別と未然防止。 デブリによる事故か他の不具合かの識別に関する従来の限界と技術的な改善可能性。
開 発	デブリ緩和の付加価値・コスト	ミッション保証とデブリ緩和の両立に向けた付加価値とコストに関する一層厳しい評価。

3-3 産業界から見たデブリ問題

Space Debris in Question of Industry

2008年1月21日

NEC東芝スペースシステム

池内 正之

NEC Toshiba Space Systems

Masayuki Ikeuchi

1 2008/1/21 3rd Space Debris Work Shop in Japan

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1. Introduction

2. Expected SD Environment

3. Major Requirements

4. SD Risk Evaluation

5. SD Safety

6. Implementation

SD: Space Debris

2 2008/1/21 3rd Space Debris Work Shop in Japan

Space Debris in Question of Industry

Introduction (1/2)**Background of SD mitigation Requirement**

Scope	Theme or Question	Change or Tendency
Demand	Spacecraft needs & its mission	Increase of observation mission from LEO for Earth environment etc.
Environment	International activity for space environment & SD mitigation	Considering space environment and other spacecraft by IADC, ISO and SD workshop etc.
Requirement	Survivability for spacecraft mission assurance	Technical evidence requested for mission assurance
Risk	Technical metrics for evaluating residual risk	Common metrics for DR or IV&V
Safety	Preventive action Discrimination of anomaly by SD impact	Standard Failure Mode about SD impact Improvement of discrimination between SD impact and other anomaly
Development	Value added or cost increase for SD mitigation	Severe evaluation for mission assurance and SD mitigation

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Space Debris in Question of Industry

Introduction (2/2)**Scope****Expected SD Environment around spacecraft**

衛星に対し、どの程度のSD環境要求を想定するか？

Survivability for Mission Assurance

SDに関わる寿命要求をどう定義するか？

Debris Critical Item (DCI) & expected Failure Mode

故障形態は何を対象とし想定不具合を設定するか？

Risk Evaluation & PDCA process

リスク判定基準と改善方法はどうするか？

Safety and Failure Mode confirmation in reality

考慮した故障形態を発生する事象と対照できるか？

デブリによる事故か他の不具合かを識別できるか？

System eng. for Mission Assurance & SD mitigation

衛星システムに対してミッション保証とデブリ緩和をどの様に

要求して両立させるか(質量等の配分)？

本稿は、ISO国際宇宙標準メンバによる1スタディである。

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Space Debris in Question of Industry

Expected SD Environment (1/3)

衛星に対し、どの程度のSD環境要求を想定するか？

→ 高い精度で要求定義・検証に使える解析モデルに期待。

<u>SD class</u>	<u>Velocity</u>	<u>against what ?</u>	<u>(Energy)</u>
AI ~500 μ m	<15 km/s	exposed harness	(~20 J)
AI ~2 mm ϕ	<15 km/s	primary structure	(~1280 J)
<i>within 1? kg/m² increase</i>			

Space debris (SD) or Orbital debris consist of artificial objects orbiting the Earth, which are not functional, both accidentally and on purpose, for examples, entire spent rocket stages or spacecraft, fragments, paint flakes, dust and slag from solid rocket motors, and other particles. Those objects can generate secondary debris by other collision.

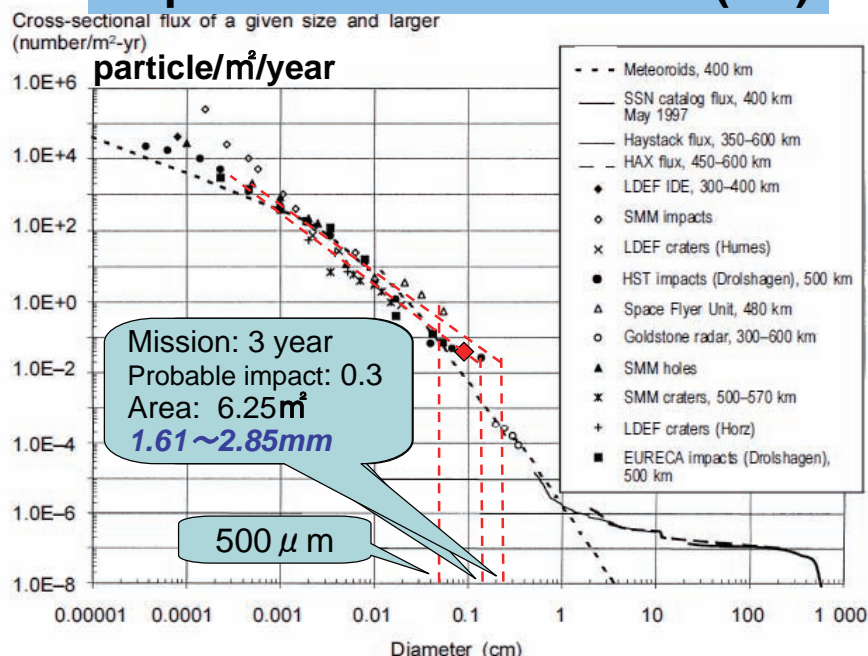
Because there is no equipment to predict the SD impact of mm - class diameter so far, each spacecraft have to prepare shield or protection by itself.

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Space Debris in Question of Industry

Figure I. Approximate measured debris flux in low Earth orbit,

Expected SD Environment (2/3)

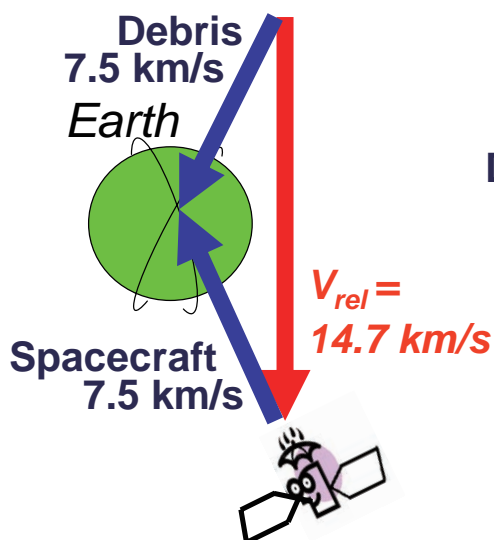
Technical Report on Space Debris

1999 United Nations 国際連合宇宙空間平和利用委員会

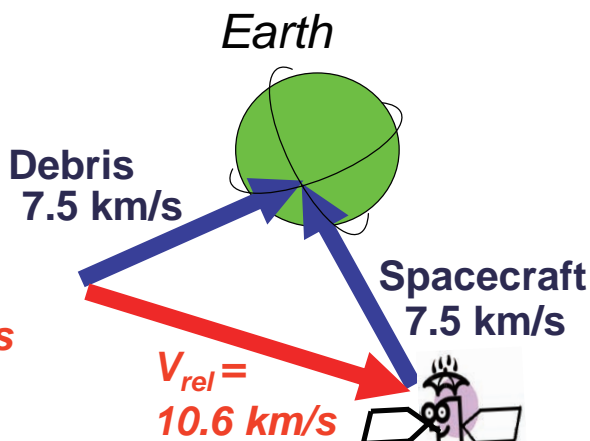
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Expected SD Environment (3/3)**Expected max. relative speed of debris**

Polar spacecraft vs. polar debris
極軌道衛星と極軌道デブリの衝突速度



Polar spacecraft vs. low inclination debris in LEO
極軌道衛星と直行する軌道上デブリの衝突速度

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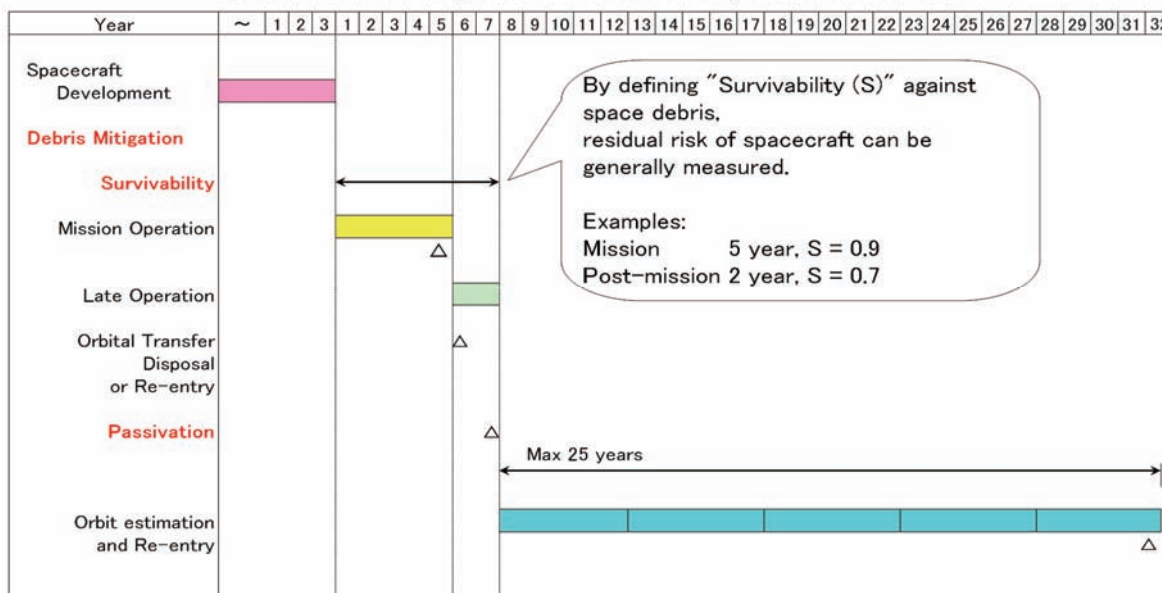
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Space Debris in Question of Industry

Major Requirements (1/4)

Survivability for Mission Assurance

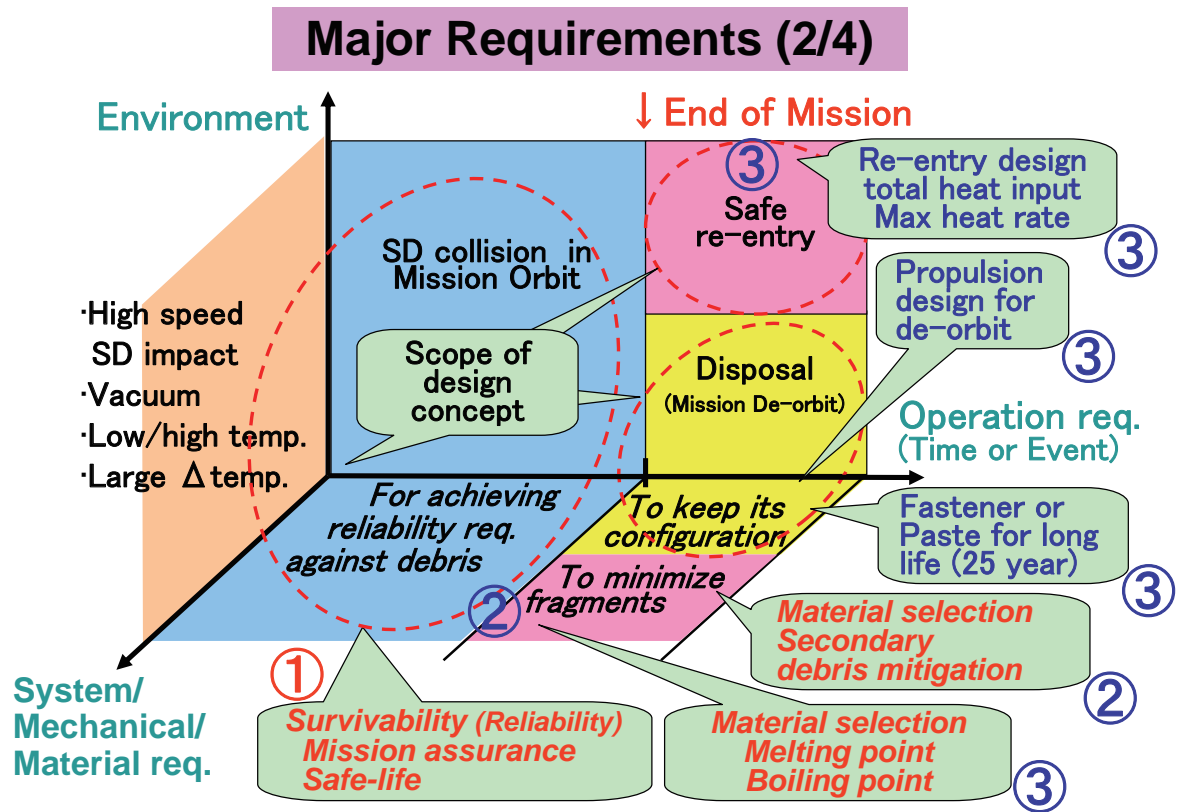
SDに関わる寿命要求をどう定義するか？

Space Debris Mitigation – Survivability and Passivation

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Space Debris in Question of Industry



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Space Debris in Question of Industry

Major Requirements (3/4)

Three major requirements derived from SD mitigation.

① Survivability requirement (~Mission assurance)

Spacecraft shall maintain necessary function against SD during mission, even if its structure is damaged by SD with certain maximum size and velocity,

② Secondary debris mitigation

Secondary debris shall be minimum, which, even if some SD brakes solar array panel, for an example, no secondary debris is expected to emerge, or the energy of secondary debris or ejecta should be minimum, even if penetrated, and

③ Post-mission requirement

Spacecraft itself shall not be debris after mission on operational (useful) orbit.

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Space Debris in Question of Industry

Major Requirements (4/4)

① *is the theme of this presentation.*

② and ③ *include conditions to attain ①.*

① Survivability requirement and
② Secondary debris mitigation
may need high melting point,

but may *contradict* the requirement ③

③ Post-mission requirement,
which will lead to such a plan that
spacecraft in LEO shall be dropped
into the atmosphere
to melt after mission.

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Space Debris in Question of Industry

SD Risk Evaluation (1/4)**Debris Critical Item (DCI) & expected Failure Mode**

故障形態は何を対象とし想定不具合を設定するか？

What is *DCI (Debris Critical Item)* as risk ?

DCI candidates (Subsystem and Components)

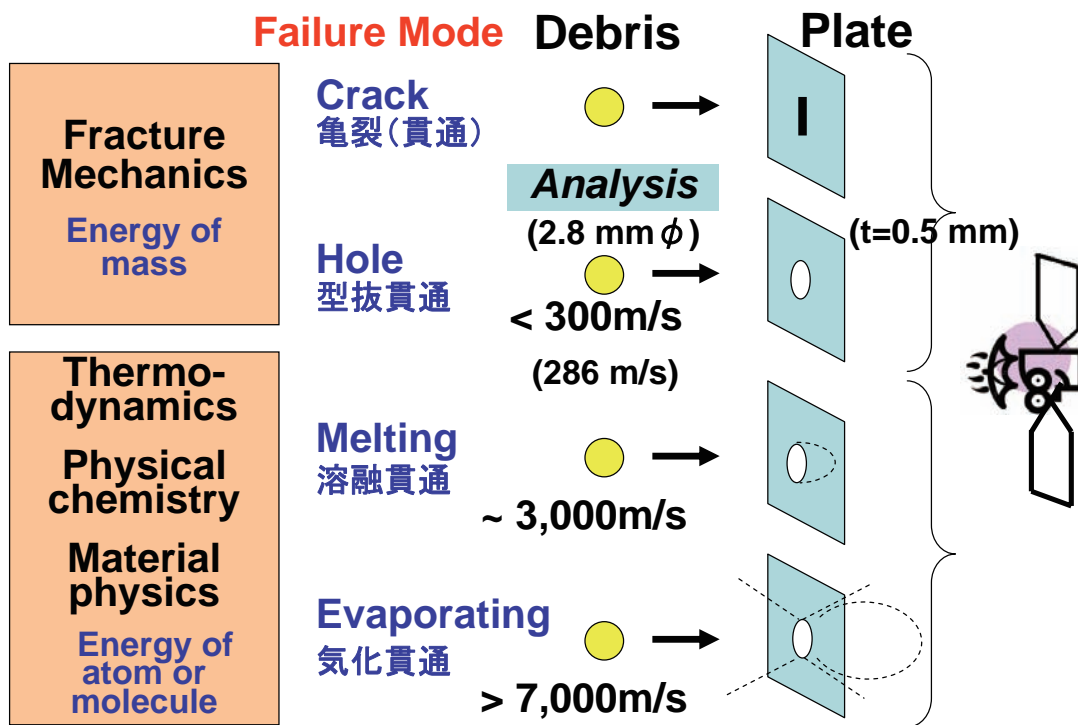
1. Exposed harness on solar array etc.
2. Exposed equipment
3. Exposed long tether for long period
4. Membrane or mechanical parts (e.g., Fastener, Tape)
under cyclic stress (e.g., thermal cyclic stress)
5. Pressure vessel, pressurized structures
6. Pressure components
7. High speed flywheel rotor
8. Refrigerator (cryogenic etc.)
9. Optical sensor, lens, or thin mirror
10. Spring with stress

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Space Debris in Question of Industry

SD Risk Evaluation (2/4)



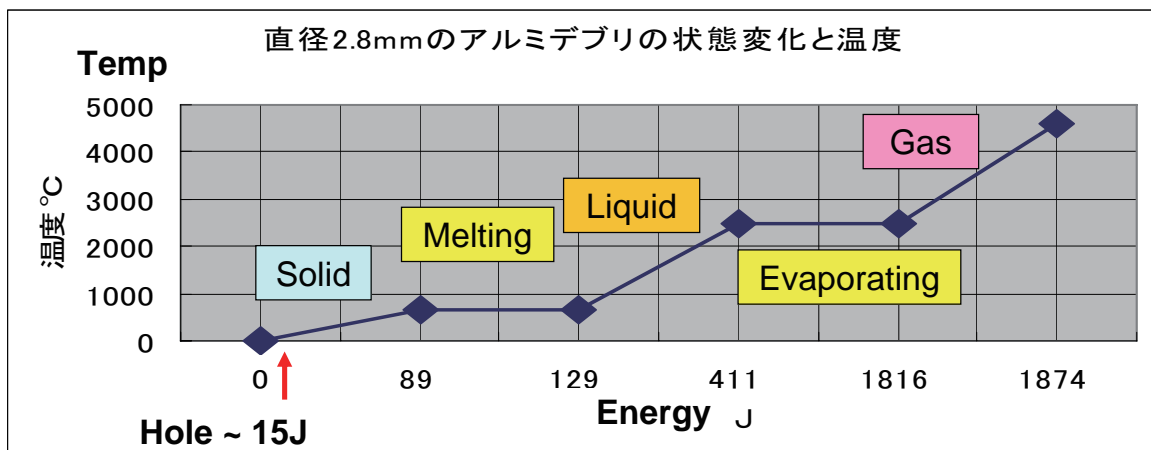
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Space Debris in Question of Industry

SD Risk Evaluation (3/4)

Failure Mode: Phase example of aluminum Debris



Analysis-1:

Aluminum Debris: d=2.8mm, velocity=11km/s

Aluminum plate: t=5.9mm

Assumption:

Temperature increased by whole kinetic energy (1874 J).

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SD Risk Evaluation (4/4)

Risk Evaluation & PDCA process

リスク判定基準と改善方法はどうするか？

SD risk rating

1. To define each Debris Critical Item (DCI) as SD risk.
2. To analyze **survivability S_i** and/or test **damage** for each DCI.
3. To multiply $\prod S_i$ to compare with reliability R .
4. To calculate **Residual risk of all DCI = $1 - \prod S_i$** .

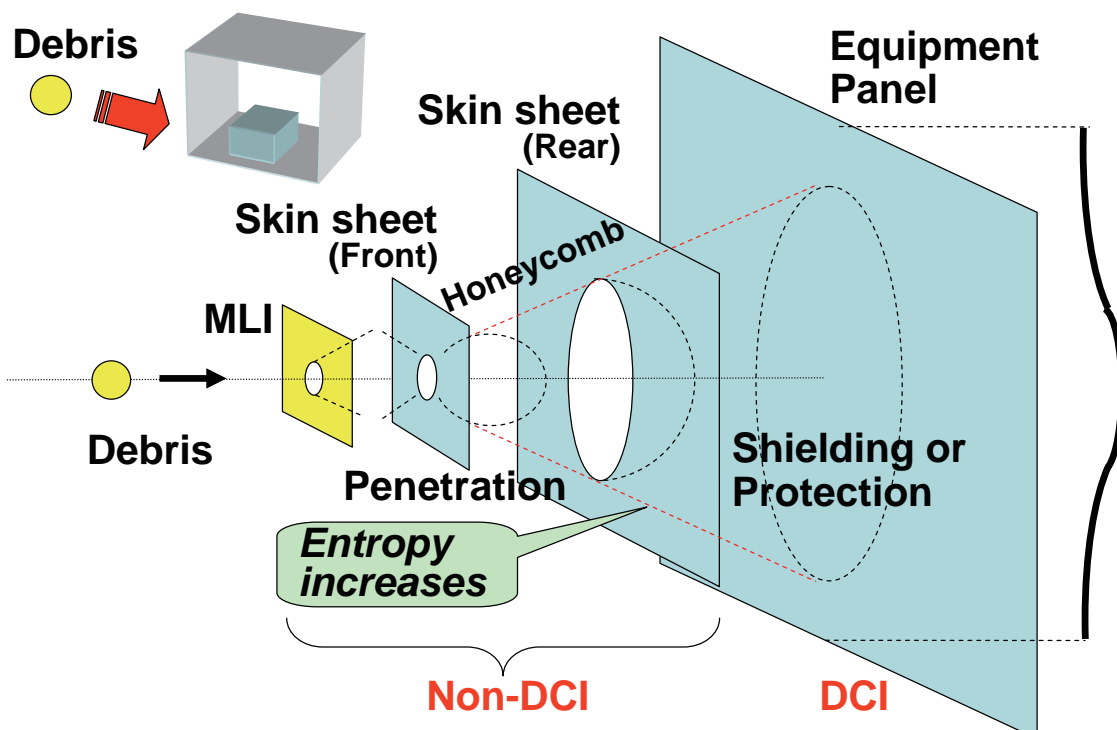
PDCA process to decrease residual risk

5. To take counter measures to attain required $S = \prod S_i$.
 - Systematic protection or shielding of DCI by Non-DCI elements during mission or post-mission
 - Damage tolerance design or Redundant design
 - Increase of S for each DCI as much as possible

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SD Safety (1/4)



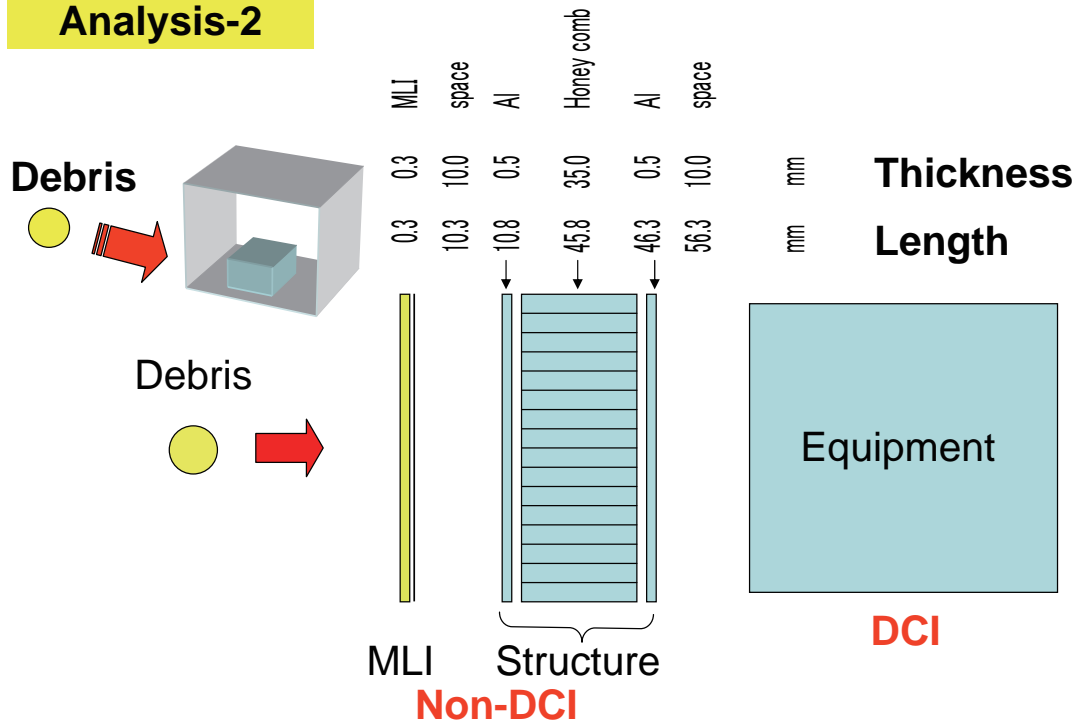
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Space Debris in Question of Industry

SD Safety (2/4)

Analysis-2



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Space Debris in Question of Industry

SD Safety (3/4)

Analysis-2

	Thickness (Diameter)	Dist	Angle	Hole	Area	Mass	Vel.	Time	Crack	Fract	Kinetic	Therm	Loss	Rad	Temp	Phase					
	(mm)	(mm)	(°)	(mm)	(mm ²)	(g)	(m/s)	(μs)	(J)	(J)	(J)	(J)	(J)	(J)	(°C)	(J)	(J)	(J)	(J)	(J)	
	t	L	α	d	S	m	v	t	Cr	Fr	E	ΔE	ε1	ε2	T	Solid	Melt	Liquid	Vapor	Gass	
Debris	2.830	—	0	2.83	6.29	0.032	13000	—			2708	—	—	—	—	—	—	—	—	—	
m0	2.830	—	0	2.83	6.29	0.032	13000	—			2708	0	0.0	0.0	0	0	0	0	0	0	
m1: MLI Al mesh front	0.300	0.0	0	2.83	25.16	0.004	0	0.00			—	301	—	—	—	21	11	58	392		
m0+m1 (Effect of mesh)	0.059	0.3	0	2.94	6.80	0.036	11557	0.03			2407	301	0.0	0.0	2486	280	269	211	-182		
m2: Al front skin sheet	0.500	10.0	0	2.94	27.21	0.037	11557	0.87			—	1215	—	—	—	42	23	118	792	542	
m0+m1+m2	0.500	0.5	0	3.72	10.87	0.073	5723	0.09			1192	1516	0.0	0.0	3467	1474	1451	1334	541	0	
m3: Honeycomb core (4)	0.025	0.0	0	3.72	140.00	0.009	5723	0.00			—	137	—	—	—	47	26	133	895	552	
m0+m1+m2+m3	0.025	35.0	25	19.39	295.39	0.082	5065	6.91			1055	1653	0.0	0.0	3370	1606	1580	1447	552	0	
m4: Al rear skin sheet	0.500	0.0	25	19.39	1181.55	1.595	5065	0.00			—	1003	—	—	—	959	522	1176			
m0+m1+m2+m3+m4	0.500	10.0	25	15.02	177.19	1.677	248	40.27	12	36	52	2656	0.0	0.0	1447	1697	1175	-1			
m5: Equipment structure	3.000	0.0	25	15.02	708.78	5.741	248	0.00			—	40	—	—	—	2701					
m0+m1+m2+m3+m4+m5	3.000	20.0	25	26.25	540.99	7.418	56	356.19	213	668	12	2696	0.0	0.0	414	-5					

Purpose: To control *impact energy* on DCI structure *lower than crack level and melting point*.

Result: *Surviving criteria** proposed to confirm safety.

Accuracy for design to be validated.

Method: Simple rocket propulsion theory for landing.

***Terminal Condition: No fracture and no melting point**

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SD Safety (4/4)

Failure Mode confirmation in reality

考慮した故障形態を発生する事象と対照できるか？
デブリによる事故か他の不具合かを識別できるか？

• Survey or analysis of anomaly caused by SD impact

Statistic approach of past anomaly

→ 目的をもった過去の衛星データの蓄積

• Feasibility of validation from telemetry on the ground

What will be possible for onboard equipment to detect or measure SD impact?

Candidates

- Angular rate: Rate sensor
- Acceleration: Accelerometer, MEMS sensor
- Light: CCD Camera, Phototube
- Electric current: Ammeter, Voltmeter

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Implementation (1/4)

System eng. for Mission Assurance & SD mitigation

衛星システムに対してミッション保証とデブリ緩和をどの様に要求して両立させるか(質量等の配分)？

A. SD protection or shielding mechanism by non-DCI like thin sheets, blankets, and brackets,
will improve some survivability of conventional onboard equipment against SD.

B. Damage tolerance design considered

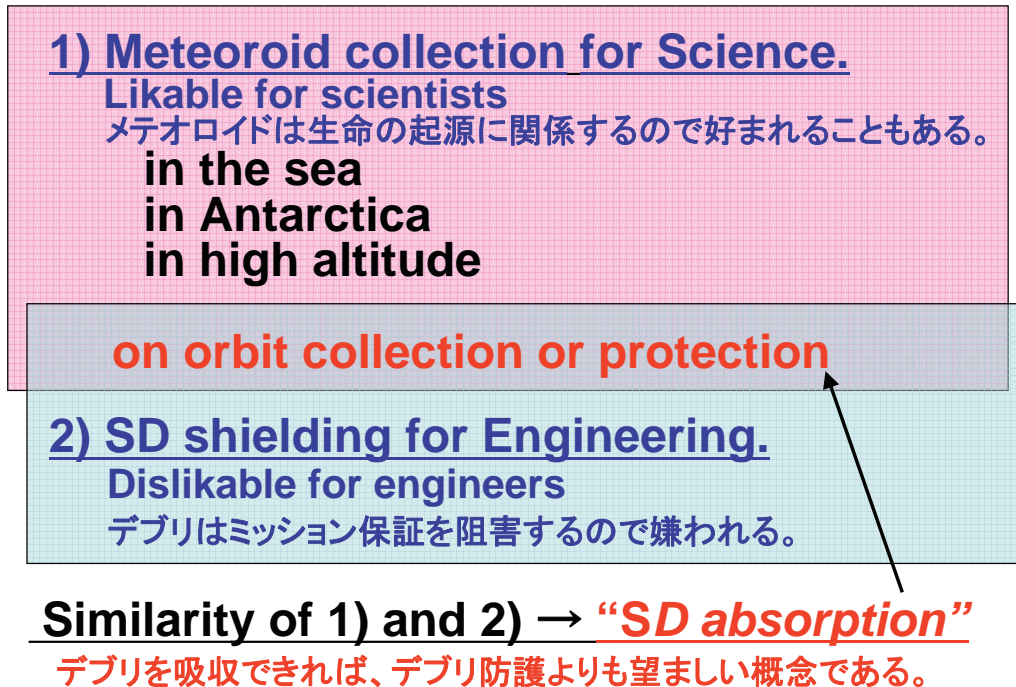
C. Safe and light-weight materials

It seems to be difficult for spacecraft to have heavy SD bumpers.

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Implementation (2/4)



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Implementation (3/4)

1. Survivability (Reliability)

- To achieve required reliability against SD energy
- To shield or protect SD smaller than defined threshold

1.1 Layout of equipment

- To shield or protect at least locally by predicting high velocity SD
- Not to attach mount plates of critical equipment in SDIP
- To put (critical) equipment as far as possible from SDIP

1.2 Safety and mass property allocation

1.3 Damage tolerance design

- To take redundant or dispersed design etc.
- To protect crack growth after SD impact or penetration
- To exclude the effect of large thermo-elastic loads

Remark SDIP: SD Impacting Planes

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Implementation (4/4)

2. Secondary debris mitigation

(Minimum generation of secondary debris)

- To prevent SD from penetration
- To select such material that generates minimum or smaller secondary debris

3. Post-mission requirement

- To design system passivation
- To design for long life de-orbit and its material selection
or
- To select those material easily melted during re-entry (drop)
- To design re-entry trajectory for providing environment condition to melt spacecraft
(max. heat rate and total heat input)

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Change & Challenge

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3-4 USERS サービスモジュールの大気圏再突入消滅について

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(（財）無人宇宙実験システム研究開発機構)

The Disposition of the Service Module of the Unmanned Space Experiment Recovery System Spacecraft(USERS/SEM) after the Completion of the Mission Operation

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(Institute for Unmanned Space Experiment Free Flyer (USEF))

Key Words: USERS/SEM, Debris, Re-entry,

概要

次世代型無人宇宙実験システム(USERS : Unmanned Space Experiment Recovery System)は、軌道上で実験を行う機器を搭載し実験終了後地上に帰還するカプセル(REM)と、REM にリソースとサービスの提供するサービスモジュール(SEM)から構成される。USERS は 2002 年 9 月 10 日に種子島宇宙センターより打上げられ、約 6 ヶ月間にわたり超電導材料製造実験を実施した後 REM を分離し回収した。残った SEM は高度約 580km の軌道へ上昇し 2005 年 1 月 31 日まで各種実験を実施して全ミッション運用を終了した。ミッション運用終了後 SEM は廃棄フェーズを経て自然落下を続け、2007 年 6 月 15 日に大気圏に再突入して消滅した。本報告では SEM に対して廃棄フェーズで施された種々の処置および再突入・消滅時に至るまでの対応について述べる。

ミッション運用を終了した SEM に対して、(1) 衛星の停止・非活性化処置、(2) スペースデブリ低減処置、を実施した。特に後者についてはスペースデブリ低減ガイドラインに従って地球大気へ再突入させ落下・消滅を図るという方針をとり、それに関連して、(3) 地上安全性検討／地上汚染防止、の検討を行った。検討に当たっては、① 目標とする廃棄軌道に投入するに必要な推薬量があるか、追跡管制・軌道上運用が可能かどうか、また軌道変更中に他衛星やデブリ物体との衝突の可能性はあるかどうかという軌道投入の成立性を検討する、② 軌道寿命の計算を行い、デブリ低減ガイドラインに従って最長で 25 年以内に再突入するような軌道とする、③ 再突入の際の空力加熱により衛星が溶融して消滅してしまうかどうか溶融解析を行う、④ ③の解析で何らかの部品が溶融・消滅しきれずに地上に達するならば、地上安全性を評価するため傷害予測数の計算を実施する、を総合的に考慮して離脱軌道を決定した。

その結果に基き、ミッション運用終了後の約 1 ヶ月間に数度の面内制御を行って軌道高度を現追跡局で運用可能な約 465 km まで降下させ、その上で軌道高度を変化させない面外制御を行って推薬を消費させた後に衛星の停止・非活性化処置を施し停波した。なお、SEM の姿勢をなるべく長く維持するための工夫として太陽電池パドルを常時適度な電力を供給する配置とした。

廃棄処置後は再突入・消滅に至るまで NORAD からの軌道情報に基き SEM の軌道状態を監視し、また 5 回にわたり再突入予測解析を行って再突入時期・領域に関する最新情報を取得した。得られた情報は適宜公開した。SEM は 2007 年 6 月 15 日 18 時 16 分（日本時間）頃、ブラジル北東部沖合に再突入し消滅したと推定されている。

3 - 4

USERSサービスモジュールの大気圏再突入消滅について

The Disposition of USERS/SEM after the Completion of the Mission Operation

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Atsuo USHIKOSHI, Shuji NAKAMURA, Koichi IJICHI, Hiroshi KANAI

Jan 21, 2008

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Institute for Unmanned Space Experiment Free Flyer (USEF)

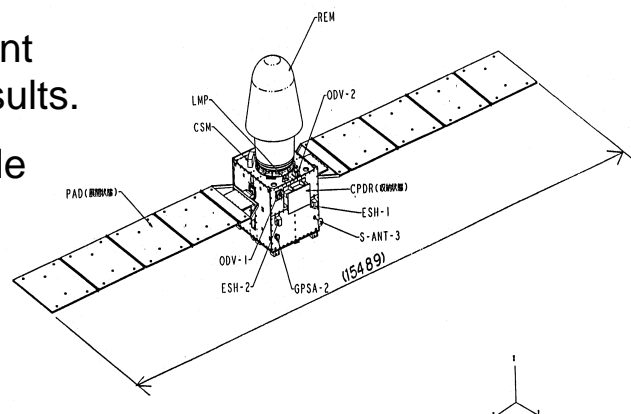


USERS (Unmanned Space Experiment Recovery System)



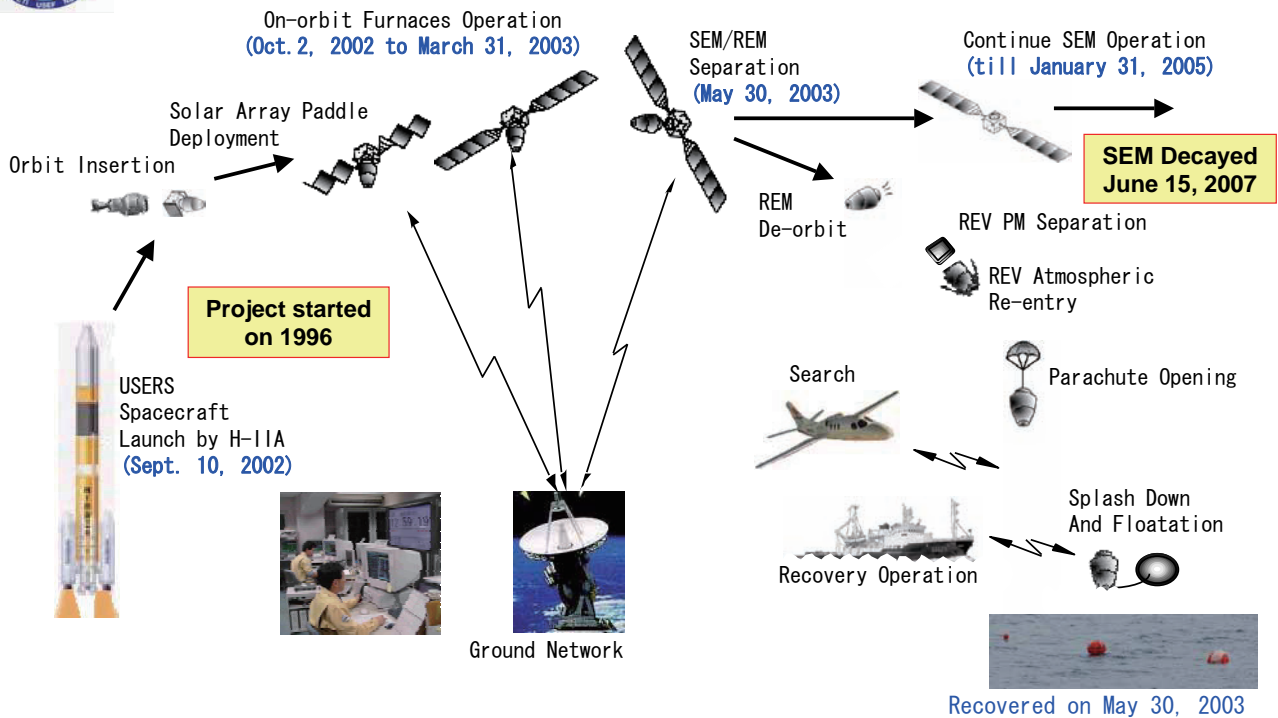
Objectives of the USERS project

- 1) To establish the unmanned space experiment system with self return capability.
- 2) To perform Super-conductor Material Processing Experiment on the orbit, and return the results.
- 3) To verify commercially available parts and technologies on the low earth orbit.





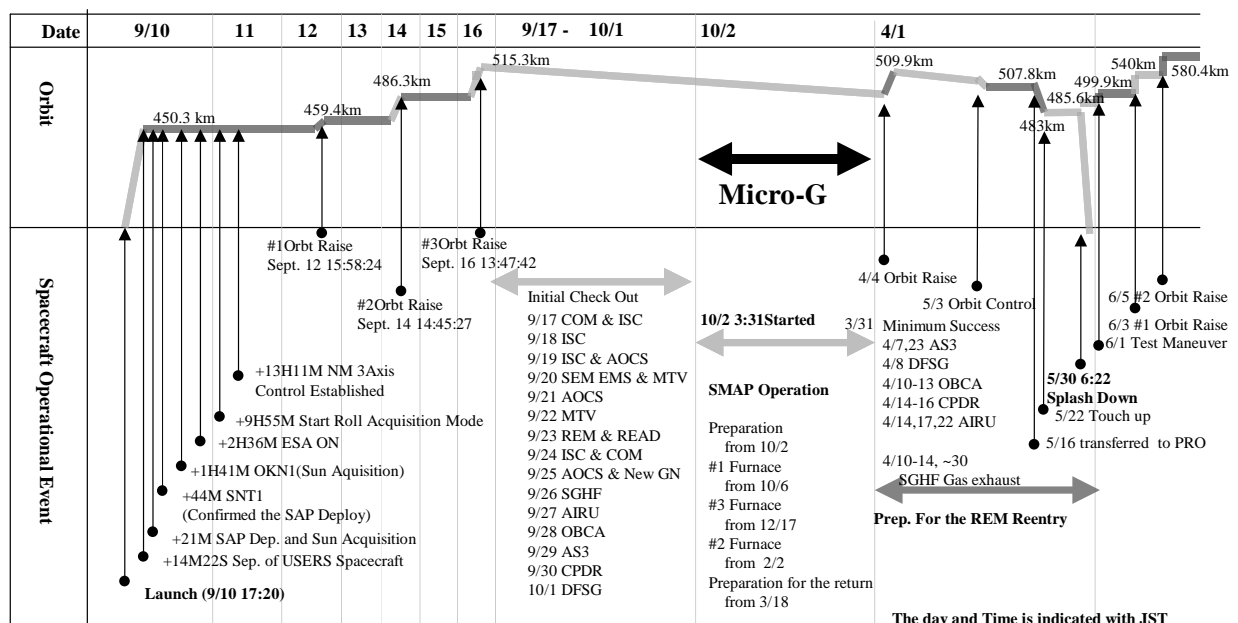
Outline of the USERS Mission Operation



2



USERS On-Orbit Operation : Altitude



3



Action Plans during Disposal Phase and Decay



◆ Mitigation of Space Debris/ Ground Safety Analysis

- Considering the IADC Space Debris Mitigation Guideline as much as possible, take an effort not to make space debris.
- De-orbit from the useful LEO region to avoid the interference with other spacecrafts in operation and put USERS/SEM to decay at most within 25 years naturally.
- Make survivability analysis to assure the possibility not to injure mankind on the ground nor to contaminate the ground environment. If the analysis shows high casualty or high-level contamination, we must consider another action plans (such as controlled re-entry, mere re-orbit/de-orbit from the useful space region, retrieval by space shuttle etc.)

◆ Termination of the Spacecraft activities /Deactivation

- Turn off most of devices onboard the spacecraft, actions for de-activation.

◆ Monitor of the Spacecraft, Announcement

- Monitor the orbit status of the spacecraft until its decay and estimate the decay time.
- Announce these informations in public.

4



De-Orbit Strategy



◆ Selection of the Target Orbit

- Have sufficient propellant needed for injection into the target orbit.
- Possible on-orbit operation.
- Possibility to collide with another spacecraft or debris during orbit change.

◆ Calculation of Decay Time

Calculate the decay time of USERS/SEM so that it decays **at most within 25 years**.

◆ Survivability Analysis

Analyse whether USERS/SEM will survive due to the heating by air drag force. If it survives, we need to assess ground safety.

◆ Assessment of Ground Safety (Expected Casualty Number)

Calculate the expected value of casualty due to parts of USERS/SEM which survive and reach on the ground. If it becomes more than 1/10,000 person, we need to change the target trajectory or to take another method to remove this thread such as controlled re-entry.

[De-Orbit Planning Scheme](#)

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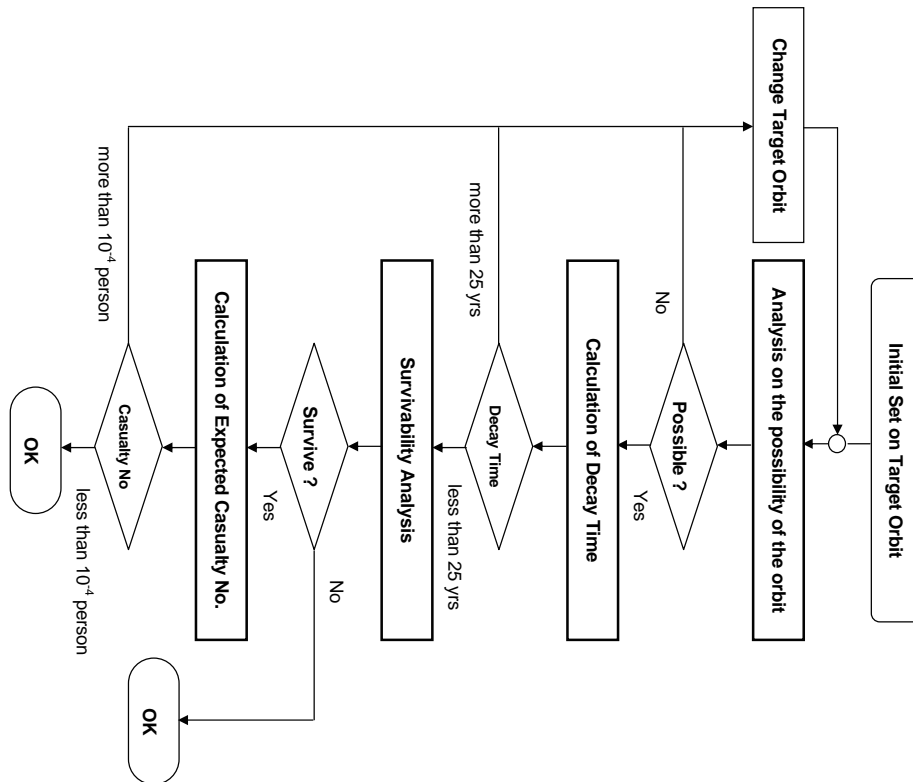


Fig De-Orbit Planning Scheme

S-1



Orbit Disposition of USERS/SEM



◆ Orbit disposition trade off

No.	Case	Orbit Change	Decay Time	Cnsmd Prop	Ope. Span	Remarks
1	Raise the orbit above 2,000 km	1,430 km ascent	N/A	N/A	N/A	Insufficient propellant
2	Stay the present orbit and natural re-entry	none	-3σ > 30 years 0 > 30 years $+3\sigma$ > 30 years	0 kg		
3	Descend the orbit just enough for less than 25 years	100 km descend	-3σ 24 years 0 12 years $+3\sigma$ 6 years	19 kg	9 days	residual propellants should be consumed by out of plane control
4	Descend the orbit as much as possible	291 km descend	-3σ 93 days 0 52 days $+3\sigma$ 28 days	all (54kg)	21 days	Ground Network could not track such low orbits
5	Controlled re-entry	–	N/A	N/A	N/A	Insufficient propellant

◆ Collision probability with S/C, debris during orbit change

- 3 objects are applied, but shows collision probability are very low



Survivability/Ground Safety

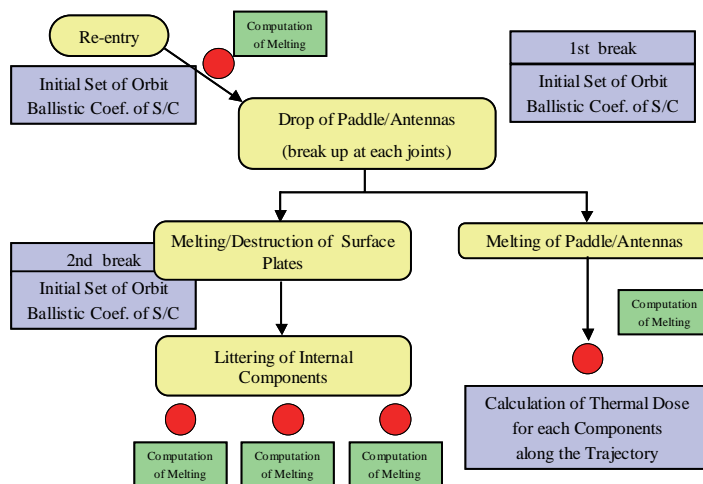


◆ Survivability Analysis

- Several parts of SEM have some possibilities to survive (parts of PDM, IRU, propellants tank, EMS)

◆ Ground safety Analysis

- Casualty :
 $0.54/10,000 < 10^{-4}$ person
- satisfy :
 - NASA Safety Std. 1740.14
 - JAXA Space Debris Mitigation Std.



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Orbit Descent and Propellant Exhaustion Operation



- ◆ 3 burns for orbit descent : 571 km \Rightarrow 465km
53.4 kg \Rightarrow 34.7 kg
- ◆ Propellant exhaustion burns : 34.7 kg \Rightarrow 18.4 kg

Date(JST)	Events	Orbit (before)	Orbit (after)	Residual propellant
Feb 1, 2005	(Start of the orbit disposition operation)			53.4 kg
Feb 2, 2005	Test burns	570.7 km	559.7 km	50.9 kg
Feb 4, 2005	Descent burns #1	559.6 km	510.5 km	41.7 kg
Feb 12, 2005	Descent burns #2	510.6 km	465.1 km	34.7 kg
Feb 21, 2005	Propellant exhaustion burns (Out of plane burns)	465.0 km	464.0 km	18.4 kg



Termination/Deactivation of USERS/SEM



System	Guidelines	USERS/SEM
Battery System	- full discharge - stop charging - FDIR(Fault Detection, Isolation and Reconfiguration) : OFF	- open discharge lines/consume battery energy by active devices - stop charging - FDIR(Fault Detection, Isolation and Reconfiguration) : OFF
Solar Array Paddle	- cut off power supply	- set SAP configuration to be able to supply solar electric power continually
Attitude Control System	- all device : OFF/disable	- SAM(Sun Acquisition Mode) : supply electric power from SAP
Propellants	- should be depleted as thoroughly as possible	- deplete residual propellants by go decent (in-plane maneuvering) - deplete residual propellants by RCS control (rotation of SEM)
Data Handling System	- should be disabled	- enable (not affect safety guidelines)
Communication System	- transmitter/receiver : OFF	- same as on the left
Payloads	- power SW : OFF - fault SW : OFF (deactivation)	- same as on the left



Removal of Stored Energy for Break-ups Prevention



◆ Energy stored in USERS/SEM

① Propellants ② Batteries ③ Reaction wheel/Magnetic Torque

◆ Propellants

- Decent of orbit (in-plane maneuvering)
- Out of plane maneuvering
- Automatic attitude control after completion of mission in SAM configuration

◆ Batteries

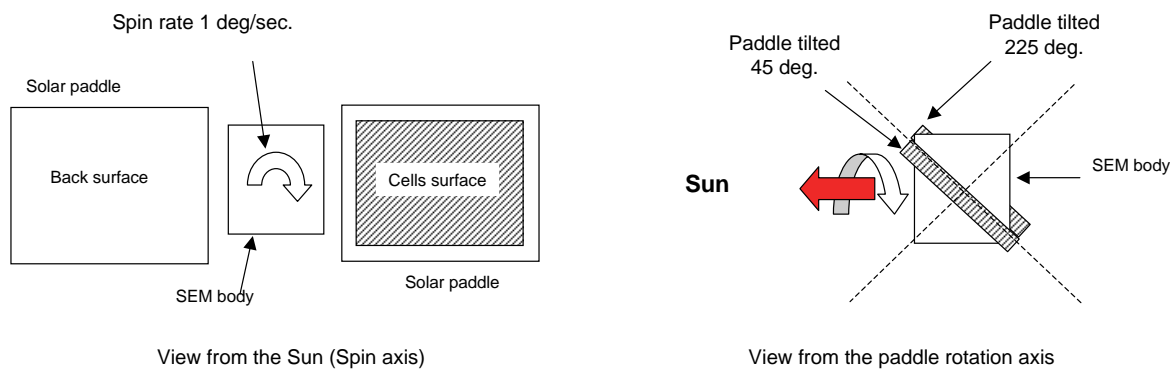
- Stop discharge / keep open discharge circuits
- Automatic switching over to BCCU-B, UVC detection etc. : disable

◆ Reaction Wheel, Magnetic Torque

- SW OFF and dissipate energy by frictional resistance



Solar Paddle Configuration at end of the Mission



Purpose of this configuration is to generate minimum power necessary to maintain the attitude as much as possible even if the attitude become uncertain toward the Sun

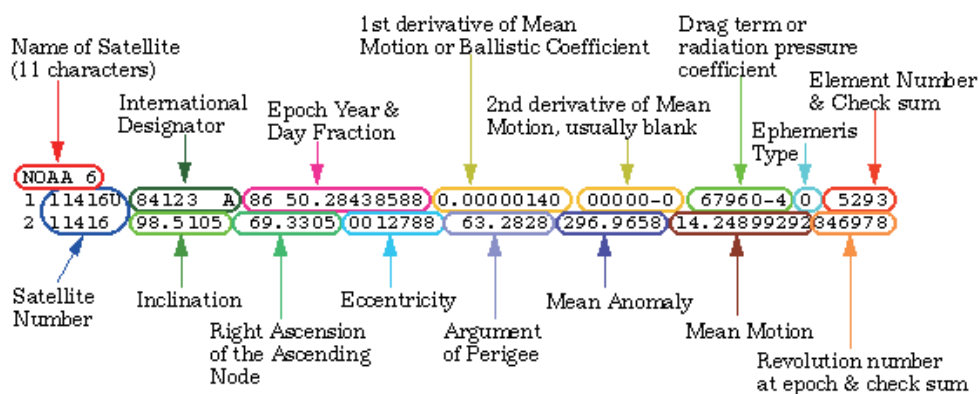
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Monitor of USERS/SEM Orbit



- ◆ Monitor the USERS/SEM orbit status by NORAD TLE (Two Line Elements)

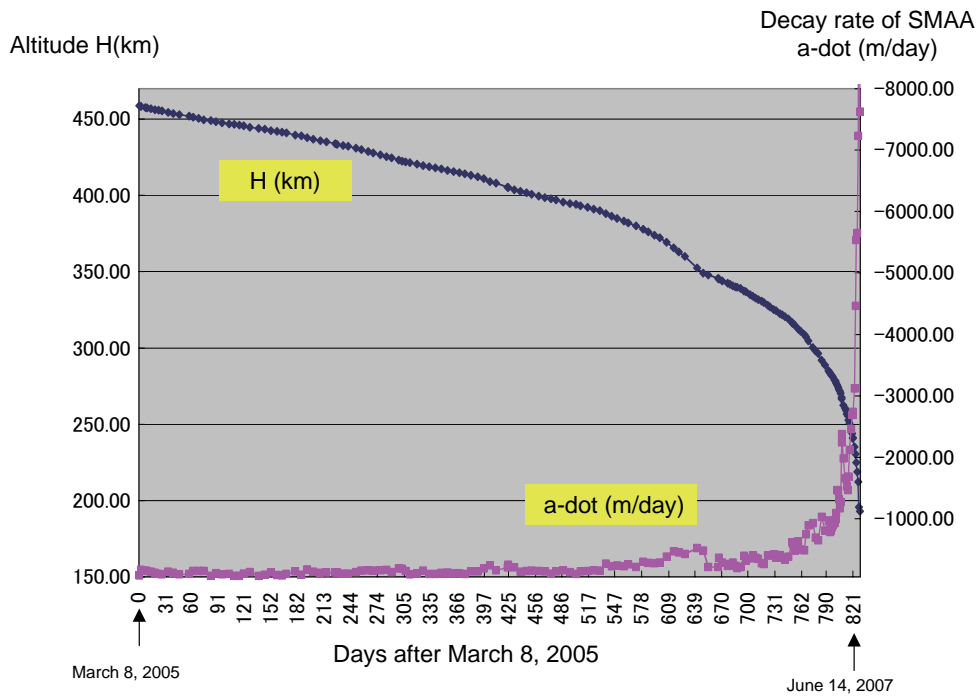


- ◆ Estimation of Decay time

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The USERS SEM Orbit Decay History



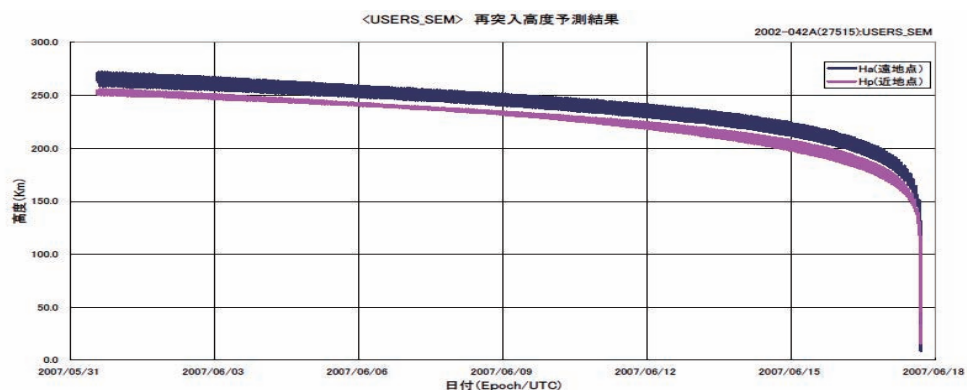
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Estimation of USERS/SEM Re-entry Time



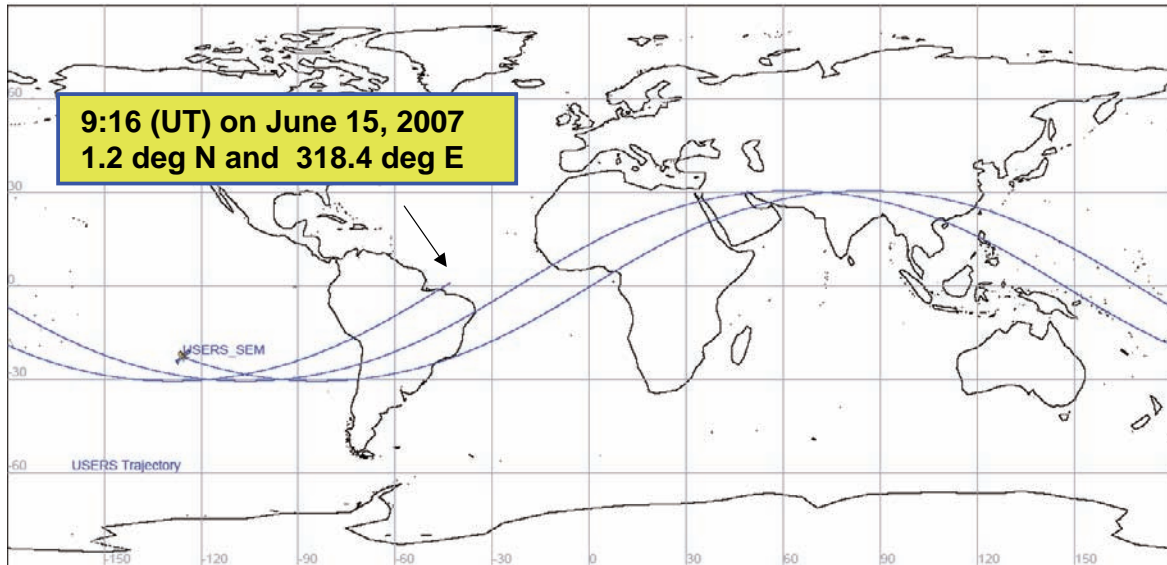
No.	Epoch (UTC)	Estimated Re-entry Time (UTC)			Error (days)	
		nominal	+20 %	-20 %	+20 %	-20 %
1	2006/02/10 21:17:49.4	2007/03/18 21:13:23	2007/01/08 05:13:26	2007/06/23 02:35:25	-69.7	96.2
2	2007/01/16 08:48:56.5	2007/06/19 08:13:58	2007/05/16 05:40:48	2007/07/20 13:09:49	-31.1	34.1
3	2007/04/25 20:05:34.5	2007/06/13 13:25:29	2007/06/04 20:48:24	2007/06/26 23:20:01	-8.7	13.4
4	2007/05/31 13:25:57.3	2007/06/17 16:59:56	2007/06/14 19:40:35	2007/06/22 02:23:53	-2.9	4.3
5	2007/06/14 06:48:38	2007/06/15 12:49:34	2007/06/15 07:42:33	2007/06/15 20:18:41	-0.2	0.3



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Estimated USERS/SEM Decayed Location and Time



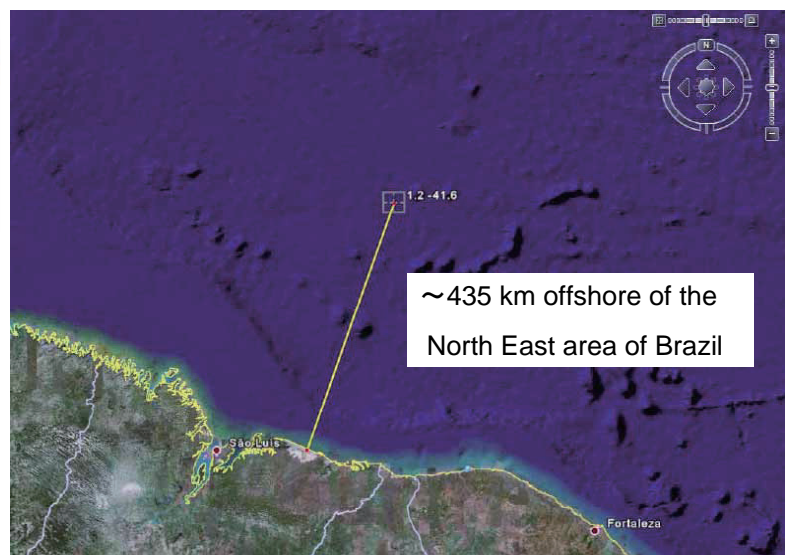
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Estimated USERS/SEM Decayed Location



Report Date/Time	2007-06-28 15:15:00 GMT
Predicted Decay Time	2007-06-15 09:16:00 GMT +/- 2 Minutes
Predicted Decay Location	1.2° N, 318.4° E
Direction	ascending
Inclination	30.4°
Revolution Number	26678
High Interest Object	N
	Final Report



Along the track : ± 850 km (± 2 min)

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Announcement



- ◆ 3 times announcement in public via press release and each Homepages
(before : June 6 and 15, 2007 / after : June 18, 2007)
- ◆ Prepare correspondence procedure to relevant organizations for the case of emergency



USEF HP (www.usef.or.jp)



METI HP (www.meti.go.jp)

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Closing Procedure



- ◆ Delete spacecraft registrations :
 - COSPAR(Committee On SPACe Research)
 - ✧ ISES(International Space Environment Service) via NiCT, GFSC
 - MEXT/UNCOPUOS
 - ✧ “Convention on Registration of Objects Launched into Outer Space” Article 4
- ◆ Spacecraft ID for CCSDS protocol
 - CCSDS(Consultative Committee for Space Data Systems) via JAXA
- ◆ Hand back the licenses of radio stations used to MIC

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Conclusions



- ◆ The disposition of USERS/SEM was properly planned and executed, and that contributed to the reduction of the space debris.
- ◆ Valuable experience of the LEO spacecraft disposition has been obtained throughout this operation, that will benefit the coordination about space debris mitigation rules and the establishment of the international agreement for the guideline.
- ◆ The discussion toward the public acceptance of the risk due to the spacecraft re-entry, which is in fact far less than that of natural disasters, may be necessary.

USERS Project has been promoted by the Ministry of Economy, Trade and Industry(METI) and the New Energy and Industrial Technology Development Organization (NEDO), and developed and operated by the Institute for Unmanned Space Experiment Free Flyer(USEF)

3-5 デブリ対策標準の適合性審査の状況

○関田 隆一（宇宙航空研究開発機構／安全・信頼性推進部）

System Safety Review Board for Space Debris Mitigation Standard

Ryuihci Sekita (Safety & Mission Assurance Department (S&MA) / JAXA)

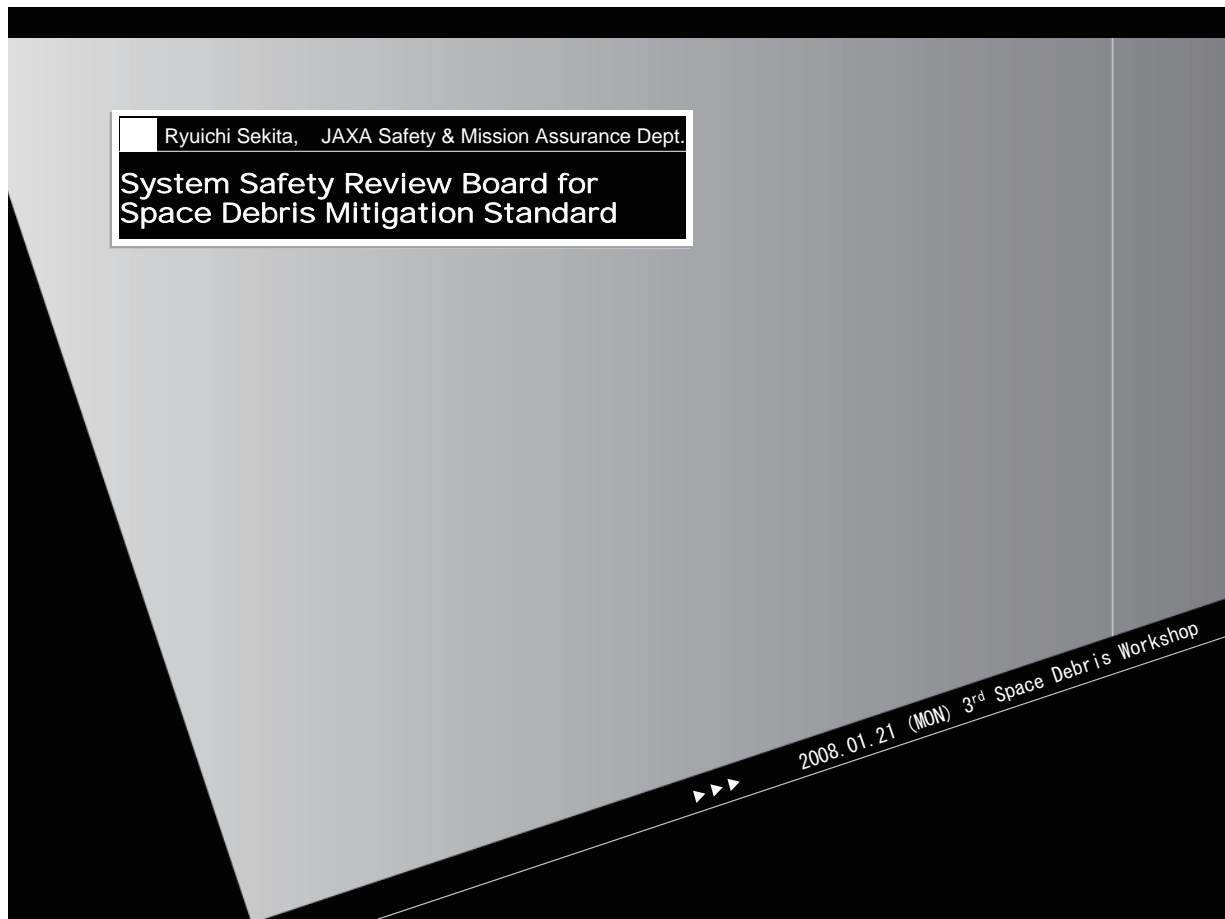
Key Words: Debris, Safety Review

概要

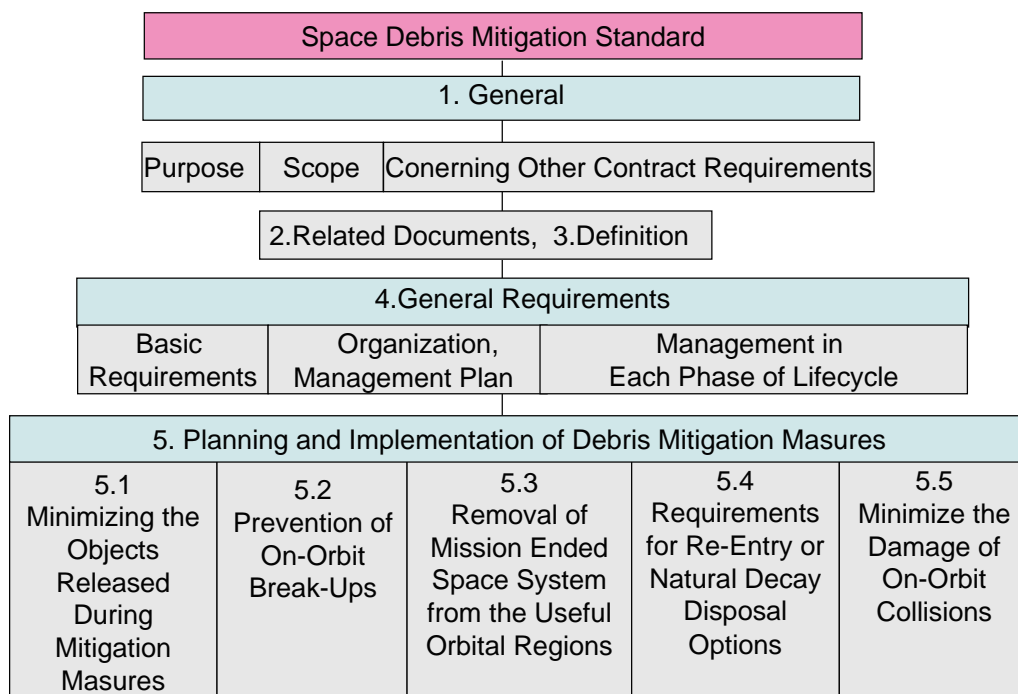
宇宙航空研究開発機構（以下 JAXA）では、ロケットによる宇宙機の打上げ、軌道投入、軌道上運用、運用終了後の各段階において発生するスペースデブリを最小限に抑制する目的で、ロケット、宇宙機の計画、設計及び運用段階で考慮すべき技術事項を規定したスペースデブリ発生防止標準（JMR-003A）を発行している。この JMR-003A について最新技術動向を踏まえた維持・改訂業務は安全・信頼性推進部が行っている。

JAXA におけるロケット、宇宙機の研究・開発プロジェクトは、すべて JMR-003A に従ったスペースデブリ発生防止活動を実施しているが、その実施状況については各段階の設計審査と同じ時期に行っているシステム安全審査部会で客観的に審議している。安全・信頼性推進部はこのシステム安全審査部会実施の事務局業務と審査部会前の各宇宙機プロジェクトとの技術調整業務も行っている。

本報告では、JMR-003A の要求概要とシステム安全審査部会での審査内容を説明し、最近の宇宙機について実施した審査結果をまとめる。更に安全・信頼性推進部が各プロジェクトのスペースデブリ発生防止活動を確実なものとするために行っている再突入溶融解析ツールの改修業務とエンジニア育成教育業務についても報告する。



#001 Space Debris Mitigation Standard (JMR-003A) Requirements



#002 Space Debris Mitigation Standard (JMR-003A) Requirements

■Purpose (1.1)

The following six measures are requested essentially

- (1) Preventing the on-orbit break-up of a space system

In order to preserve the GEO environment

- (2) Transferring a spacecraft that has completed its mission in GEO into higher orbit
- (3) Reducing the time during which the orbital debris left in GTO can interfere with GEO
- (4) Minimizing the number of objects released in orbit during operation
- (5) Reducing the time during which a space system that has completed its mission can interfere with useful LEO.
(A goal of the time is 25 years)
- (6) Minimizing damage posed by on-orbit collision



1~4 JMR-003A Requirements	5.6 About Safety Review Board	7 LEO Satellites	8 GEO and Science Mission Satellites	9 Reentry Analysis Tool	10 Education	2
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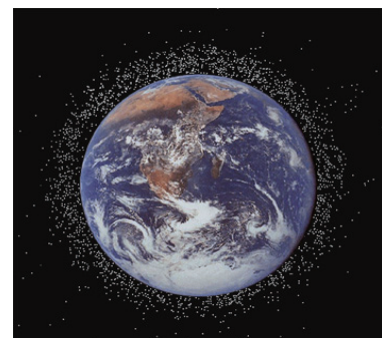
#003 Space Debris Mitigation Standard (JMR-003A) Requirements

■Basic Requirements (4.1)

The following activities should be included to minimize debris generation:

- (1) Considerations for debris mitigation measures in studying the development plans of both space systems and related ground systems.
- (2) Efforts to minimize the generation of debris in the design and manufacturing phases.
- (3) Efforts to minimize the generation of debris during the launch and orbital injection of space systems.
- (4) Efforts to minimize the generation of debris during the orbital operation phase and the disposal phase on mission completion.
- (5) Efforts to minimize the generation of debris, even in the event of failures during the on-orbit operation phase.

Establishment and improvement of the management system to reflect the efforts requested by the above paragraphs (1) through (5).

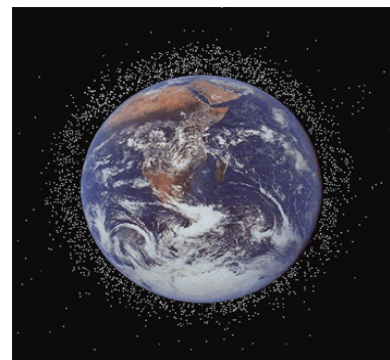


1~4 JMR-003A Requirements	5.6 About Safety Review Board	7 LEO Satellites	8 GEO and Science Mission Satellites	9 Reentry Analysis Tool	10 Education	3
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#004 Space Debris Mitigation Standard (JMR-003A) Requirements

■ Space Debris Mitigation Management (4.2)

- (1) Project and contractors shall assign a responsible organization or individual that has responsibilities to study, plan, implement and review the effective measures to ensure space debris mitigation management.
- (2) Project should develop a feasible Debris Mitigation Plan after tailoring the requirements of this standard in coordination with the Safety and Mission Assurance Department.
- (3) The plan may be incorporated into the System Safety Program Plan. The plan should be offered to the System Safety Review Board for review.
- (4) Contractors should also prepare a Space Debris Mitigation Management Plan which complies with the Debris Mitigation Plan presented by JAXA. The plan should be submitted to JAXA for its approval.



1~4 JMR-003A Requirements

5,6 About Safety Review Board

7 LEO Satellites

8 GEO and Science Mission Satellites

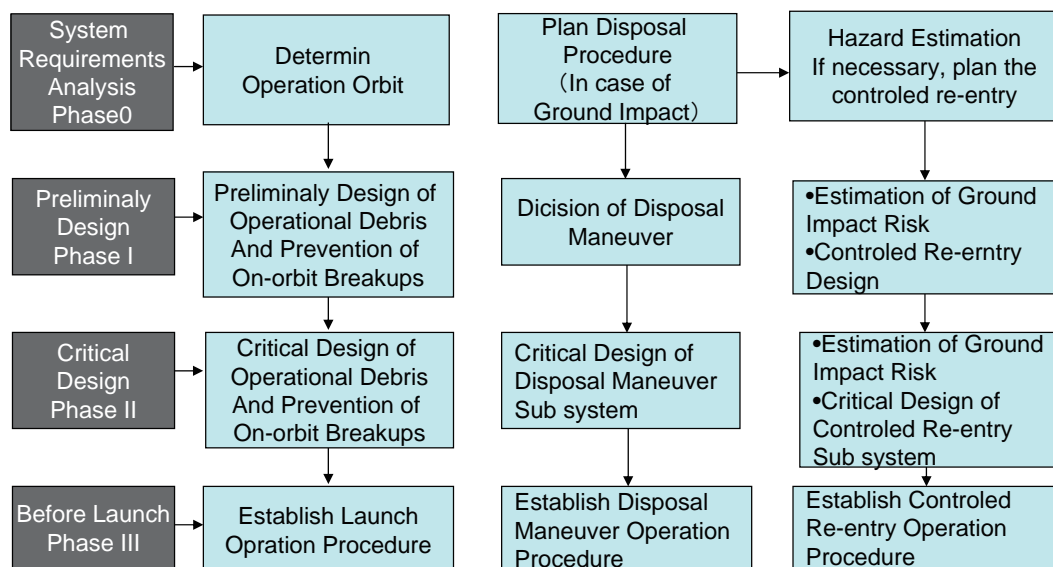
9 Reentry Analysis Tool

10 Education

4

#005 System Safety Review Board

■ Engineering Study in Each Phase



1~4 JMR-003A Requirements

5,6 About Safety Review Board

7 LEO Satellites

8 GEO and Science Mission Satellites

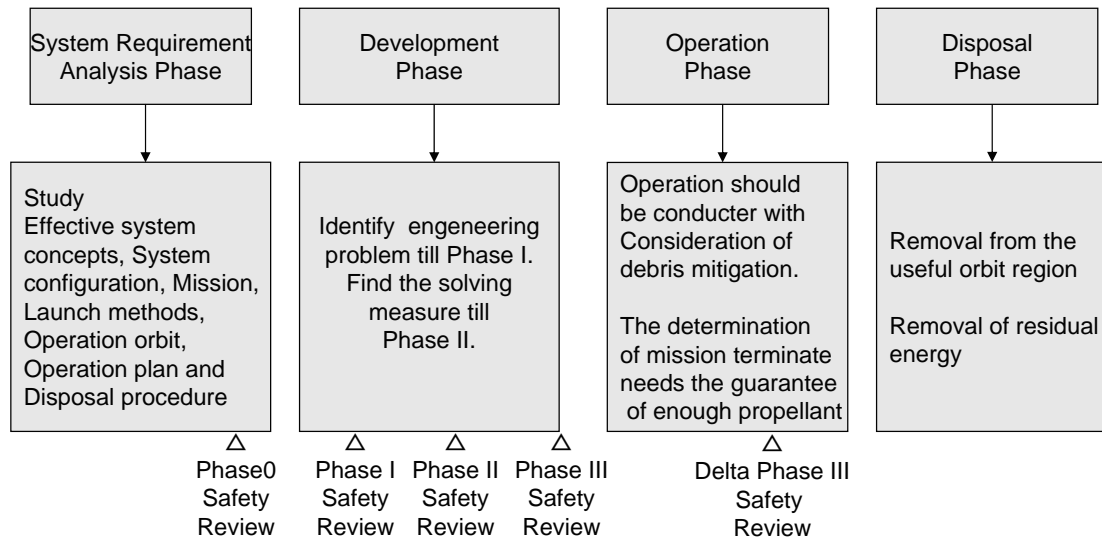
9 Reentry Analysis Tool

10 Education

5

#006 System Safety Review Board

■System Safety Review Board in Each Phase



1~4 JMR-003A Requirements

5,6 About Safety Review Board

7 LEO Satellites

8 GEO and Science Mission Satellites

9 Reentry Analysis Tool

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#007 Review for LEO Space Systems

1 Review Process

- System Safety Review Board which is lower branch of JAXA Safety Review Committee
- Every Development Phase
- Engineering Discussion using Compliance matrix, drawing and engineering data

Every Development Phase!

2 Main Topics

If orbital decay within 25 years due to atmospheric drag can be expected, mission-terminated space systems can simply be left in their operational orbit. JMR-003A 5.3.3(2)

→Every space system decay within 50 years due to atmospheric drag. GOSAT will change the orbit the end of lifetime in order to agree the 25 years decay requirement.

In case that the value of "the Expected Number of Casualties" would exceed 1×10^{-4} [human / event], the best effort to conduct controlled reentry into safe impact zone should be made with consideration of state-of-art and attitude of foreign space organizations. JMR-003A 5.4.1(1)

→Maximum Expected Number is 0.9×10^{-4} human/event

3 Compliance

Every space systems except OICETS agree every JMR-003A requirements. It was almost the end of development that OICETS adopted JMR-003A in the development.

OICETS released 4 pieces of small wires when OICETS deployed the Solar Array Panel.

Good Point!

2004 FY

OICETS System Safety Program Plan
DPR System Safety Program Plan

2005 FY

OICETS フェーズ III
GOSAT System Safety Program Plan and Phase0
ALOS Phase III
ASTRO-F Phase III

2006FY

SOLAR-B Phase III
DPR Phase 0
GCOM-W1 System Safety Program Plan

2007FY

GOSAT Phase I/II
DPR Phase I

1~4 JMR-003A Requirements

5,6 About Safety Review Board

7 LEO Satellites

8 GEO and Science Mission Satellites

9 Reentry Analysis Tool

10 Education

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#008 Review for GEO and Deep Space Mission Sateellites

1 Review Process

- System Safety Review Board which is lower branch of JAXA Safety Review Committee
- Every Development Phase
- Engineering Discussion using Compliance matrix, drawing and engineering data

Just Same as Review for LEO

2 Main Topics

Space systems should be designed not to release parts (such as fasteners) that could possibly stay in Earth orbit, unless either serious technical or economical problem would result. JMR-003A 5.1(1)

→Every space systems are designed not to release any part.

The necessary amount of propellant needed to perform planned orbit changes should be estimated in spacecraft design. JMR-003A 5.3.1(2)

→ Every space systems are designed to keep enough amount of propellants for 250~300km ascending.

3 Compliance

Every space systems agree every JMR-003A requirements.

Good Point!

2004FY

None

2005 FY

MTSAT-2
Phase-III

2006 FY

Mercury Magnetic Observation
System Safety Program Plan and
Phase0

ETS-VIII Phase-III

SELENE Phase-III

2007 FY

WINDS Phase-III

PLANET-C(Venus Mission)
System Safety Program Plan and
Phase 0/I1~4 JMR-003A
Requirements5,6 About Safety
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7 LEO Satellites

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Mission Satellites9 Reentry Analysis
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#009 Object Reentry Survivability Analysis Tool

1 Objective

Assess the reentry risk of impact of objects that survive re-entry.

2 About ORSAT-J

ORSAT-J (Orbital Reentry Survivability Analysis Tool of Japan)
Modified from NASA-ORSAT ver4.0

Estimate the hazard caused by ground impact of objects
surviving atmospheric re-entry.

In case of Ground Impact, Calculate the following Parameters
Casualty Area, Impact Energy, Penetration Depth Limit

3 Improvement Results and Plan

Results

- Improvement of re-entry trajectory analysis
- Introducing the controlled re-entry analysis
- Addition of multi object analysis function
- Addition of graph output function
- Addition of a formula to predict radiant heat transfer
- Improvement of User Interface

Future Plan

- Further Improvement of User Interface
- Preparing CFRP property data
- Add CFRP objects destructive mode
- Add 3 dimensional analysis for Spheres



Delta II second stage propellant tank found in Texas, 1996

1~4 JMR-003A
Requirements5,6 About Safety
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7 LEO Satellites

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Tool

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#010 Education

1 Target

JAXA and Contractors
Engineer for
System design, Structure design, Propulsion Design,
System safety, Mission Assurance

JAXA and Constructor Engineers!

2 Scope

- To develop highly motivation for preserve space orbital environment
- To understand the importance of JMR-003A requirements
- To take space debris mitigation measure into the development from the begining of the project

3 Special Feature

- Provide the point of JMR-003A engineering requirements
- Both JAXA and contractor can get common engineering basis for space debris mitigation

Good Point!

2004 FY

October 27, 2004
JAXA Tsukuba Space Center
Launch Vehicle and Spacecraft
12 engineers,
and 1 University student

2005 FY

March 1, 2006
JAXA Tsukuba Space Center
Launch Vehicle and Spacecraft
10 engineers

2006 FY

March 19, 2007
JAXA Nagoya Office
H-IIA and HTV Contractor
5 engineers

2007 FY

June 14, 2007
JAXA Tsukuba Space Center
GOSAT Project 4 engineers

February 12, 2008 (Plan)
JAXA Tsukuba Space Center
Joint program with Institute of
Space Technology and Aeronautics

1~4 JMR-003A
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V. 国際セッション—2

I2-1 デブリ環境モデルの問題点と JAXA の研究

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 五家 建夫 (宇宙航空研究開発機構／総合技術研究本部),
 桜井 晃((有) Q P S 研究所), 八坂 哲雄((有) Q P S 研究所・九州大学),
 船越 国弘((有) Q P S 研究所),
 花田 俊也 (九州大学), 松本 晴久 (宇宙航空研究開発機構／総合技術研究本部),
 野口 高明 (茨城大学), 山中 理代, 木本 雄吾, 鈴木 峰男 (宇宙航空研究開発機構／総合技術研究本部)

*: 宇宙航空研究開発機構／総合技術研究本部客員、同／宇宙開学研究本部受託研究員、情報通信研究機構特別研究員

Current Problems of Debris Environment Models and Related Studies of JAXA

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 Yasuhiro Akahoshi (Kyushu Institute of Technology), Tateo Goka (JAXA/IAT),
 Akira Sakurai (iQPS Inc.), Tetsuo Yasaka (iQPS Inc. and Kyushu University), Kunihiro Funakoshi (iQPS Inc.),
 Toshiya Hanada (Kyushu University), Haruhisa Matsumoto (JAXA/IAT), Takaaki Noguchi (Ibaraki University),
 Riyo Yamanaka, Yugo Kimoto, Mineo Suzuki (JAXA/IAT)

*: Guest researcher of JAXA/IAT and NiCT, Visiting researcher of JAXA/IASA

Key Words: Debris, Environment model, In-situ measurement, Debris sensor, Debris collector, ISO, MPAC&SEED

宇宙航空研究開発機構(JAXA)の ADEOS-II (「みどり」2号)の運用異常に対し、宇宙開発委員会は「今後の対策」を提言している(平成16年7月26日宇宙開発委員会調査部会)。その提言では、「宇宙環境等軌道上データの蓄積」及び「設計基準の整備」が必要であること、特に、微小なスペースデブリとの衝突については、衝突確率と影響度の評価が必要であることが勧告されている。この提言に基づき、宇宙機設計基準の改訂・体系化の一環として、「宇宙環境標準」(JERG-0-022「一般環境標準」の「宇宙環境」の部分に相当)の見直しを行っており、「マイクロメテオロイドとスペースデブリ(MMOD)」環境についても、全面的に見直しを行っている。しかし、MMOD 環境の軌道上データは日本では十分には取得されておらず、国内で宇宙機設計に適用可能な「環境モデル」は未だ構築されていない。そのため、欧米の代表的な3つの MMOD 環境モデルを宇宙機設計に適用することを想定し、環境モデルの比較評価を行った。その結果、3つの MMOD モデルでは「スペースデブリ」の FLUX 値(単位時間あたりの宇宙機への衝突回数)に最大2桁に上る差異がみられることが判明した。特に高度 800 km~1000 km の極軌道における大きさ 100 μ m~数 mm のデブリでその差が最も顕著である。これは太陽同期軌道の衛星に対するスペースデブリ衝突の影響評価に大きな不確定性を残すこととなる。現在、JAXA は関連各機関と協力の下、設計基準における MMOD 環境モデルの適用ガイドラインの宇宙環境標準への反映と ISO 化活動、及び、モデル間で差異の大きいデブリ(粒径 100 μ m~数 mm)の計測にターゲットを絞り、多重検出線を利用した方式(QPS 方式)による衛星搭載用スペースデブリ計測センサの研究を行っている。また、JAXA が 2001 年から 2005 年に渡って国際宇宙ステーション(ISS)のロシア・サービスモジュール(SM)に搭載し、宇宙空間に曝露した「微小粒子捕獲実験装置及び材料曝露実験装置」(SM/MPAC&SEED)の分析は、ISS の高度が約 400km と低いものの、全く同じ設計の装置3式を曝露期間のみを変えて、曝露期間の影響度合いを明確に比較評価するという世界にも類例をみない実験であること、またシリカロジェルの利用により、捕獲した微小なスペースデブリ(やその断片)の材質の分析、及び速度や到来方向の凡その推定が可能なことから、今後の ISS の運用や実験へのデータ提供のみならず、材質や発生原因が不明確な微小なスペースデブリの評価に有効に活用できると考えられる。

I2-1 デブリ環境モデルの問題点とJAXAの研究

Current Problems of Debris Environment Models and Related Studies of JAXA

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松本 晴久(JAXA/総合技術研究本部),
野口 高明(茨城大学), 山中 理代, 木本 雄吾,
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Y. Kitazawa*(IHI Corporation), S. Fukushima, M. Uchino, Y. Akahoshi (Kyushu Institute of Technology),
T. Goka (JAXA/IAT), A. Sakurai(iQPS Inc.), T. Yasaka(iQPS Inc. and Kyushu University),
K. Funakoshi (iQPS Inc.), T. Hanada (Kyushu University), H. Matsumoto(JAXA/IAT),
T. Noguchi (Ibaraki University), R. Yamanaka, Y. Kimoto, M. Suzuki (JAXA/IAT)

*:Guest researcher of JAXA/IAT and NiCT, Visiting researcher of JAXA/IASA

- Contents -

1. Background
2. Objective of this presentation
3. Comparison of debris environment models
4. Basic study of new type active debris sensor
5. Overview of Passive Debris Experiment
(SM/MPAC&SEED)
6. Summary

1. Background(1/2)



ADEOS - II (Midori- II)

Dimension	Main Body: 6m x 4m x 4m Solar Array Paddle: 3m x 24m
Total Mass	3.68 ton
Designed Life	3 years
Orbit	Sun-synchronous Sub-recurrent
Altitude	803 km
Inclination	99 degree
Period	101 minutes

ADEOS-II was a Japanese (JAXA, formerly NASDA) Earth environmental observation satellite, launched on 14 December, 2002, had observed valuable Earth's global data operationally, however stopped observation suddenly on 24 October, 2003. Telemetry data from the spacecraft showed that the electrical power generated by the solar array dropped.

Cf.

The FTA indicated that it was probable that the short or open circuit failure occurred on Solar Array Paddle or Solar Array Paddle Harness. For the latter, the laboratory test verified that the sustained arc between harnesses could destroy the bundled power lines.

1. Background(2/2)

The Space Activity Commission (SAC) of MEXT * analyzed ADEOS-II's failure, and reported several important recommendations on future spacecrafts designs and developments. (July 28, 2004)

Two of the SAC's recommendations are followings.

- Maintenances and developments of spacecraft design standards
- Many actual orbital environment data should be acquired.

(ex. Space environment data)

Especially the evaluation of collision probability of micro space debris and the evaluation of debris collision effects are necessary.



Based on SAC's recommendations, JAXA has been revising (refining) "Space Environment Standard" and has been studying micro debris environment.

*:Ministry of Education, Culture, Sports, Science and Technology

2. Objective of this presentation

Introductions of current problems of debris environment models and related studies of JAXA

(1) Comparison of debris environment models

- clarification of current model issues

(2) Basic study of new type active debris sensor

- development the in-situ debris measurement devices to detect the size range of hundred micrometers to several millimeters.

(3) Overview of Passive Debris Experiment on ISS

-Status report of SM/MPAC&SEED mission.

3. Comparison of Space Debris Environment Models

JAXA's "Space Environment Standard" (a part of JERG-0-022 "General environment standard") does NOT include debris environment.



Although Japan has high study activity of debris environment (especially in the field of orbital dynamics of debris), Japan has not enough observation data of space debris. And Japan has not original space debris environment model.



In present status, JAXA planed to refer NASA's or ESA's debris environment model for JAXA's standard.

Major three space debris environmental models;

- ORDEM^{*1}-2000
- MASTER^{*2}-2001
- MASTER^{*2}-2005

Which model should be adequate ?

⇒ Comparison of models was performed

*1: ORDEM(Orbital Debris Engineering Model) *2: Meteoroid and Space Debris Terrestrial Model

Model description ~ Model characteristics ~

		ORDEM2000	MASTER2001	MASTER2005
Size range		> 10 μm	> 1 μm	
Altitude range		LEO	LEO - GEO	
Time range		1991 - 2030	1960 - 2050	1957 - 2055
Debris source terms	TLE background	all sources together	O	
	Fragments		O	
	SRM dust/slag		O	
	NaK droplets		O	
	Paint Flakes		O	
	West Ford Needles		O	
Modeling approach		Fit measurement data	semi deterministic including some measurement data	

Parametric studies

Comparison of debris flux

Debris environment models

ORDEM2000, MASTER2001, MASTER2005

Parameters

debris diameter; > 10 μm , > 100 μm , > 1 mm, > 1 cm, > 10 cm, > 1 m

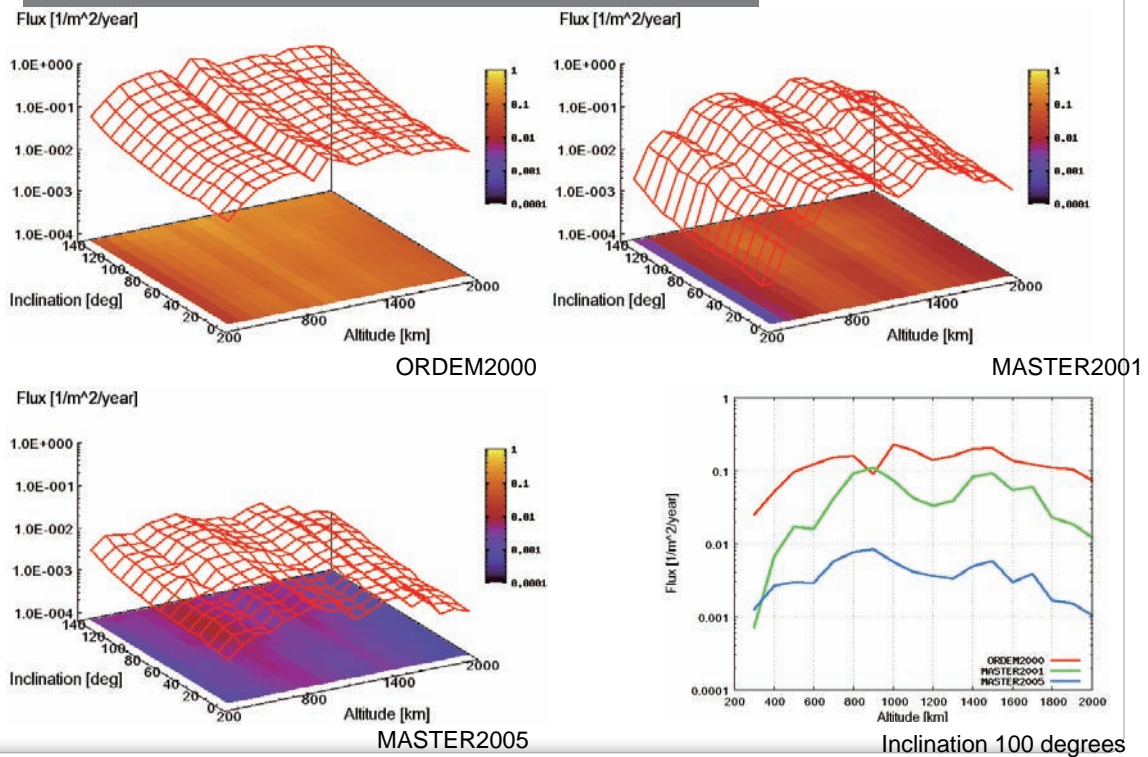
Altitude; 300 ~ 2000 km

Inclination; 0 ~ 140 deg

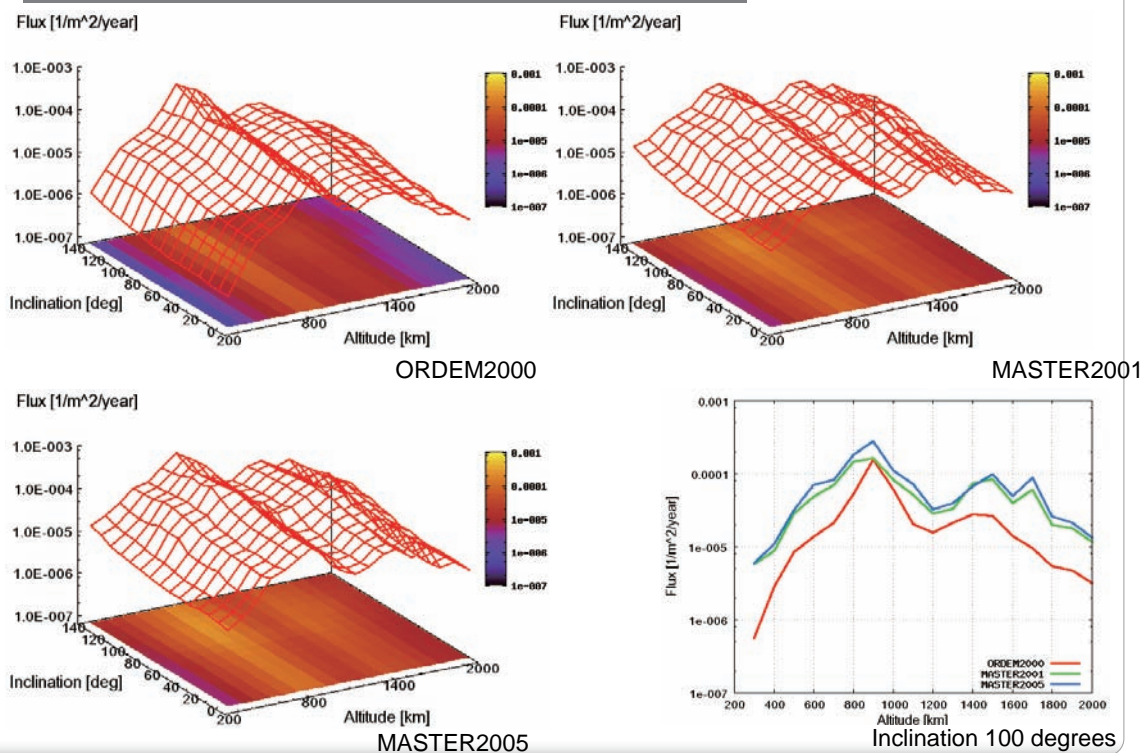
Detail Results

Fukushige *et al.*, ; Comparison of Debris Environment Models;
ORDEM2000, MASTER2001 and MASTER2005", IHI Engineering
Review, Vol.40, No.1, 31-41, February 2007.

Parametric studies ~ Object diameter > 1 mm ~

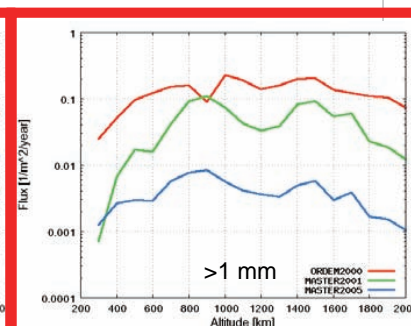
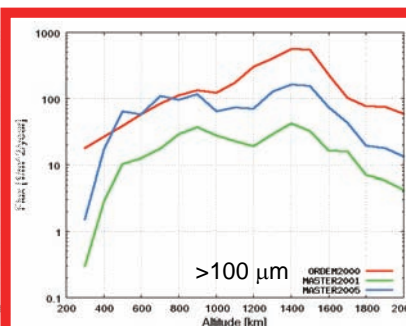
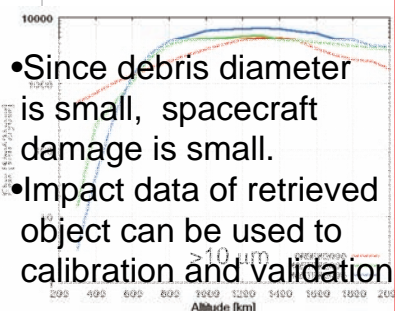


Parametric studies ~ Object diameter > 1 cm ~

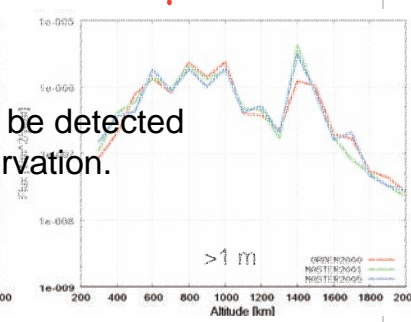
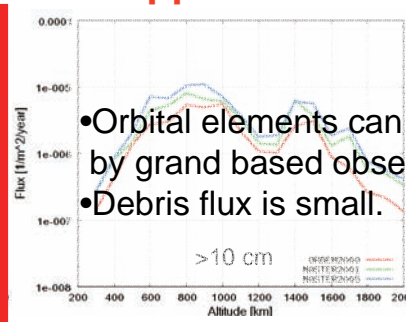
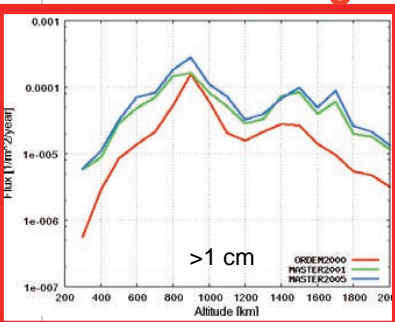


Model description ~ Inclination 100 degrees ~

- Since debris diameter is small, spacecraft damage is small.
- Impact data of retrieved object can be used to calibration and validation



Difference among models appeared between 100 μm and 1 cm.



- Orbital elements can be detected by ground based observation.
- Debris flux is small.

Orbit case studies ~ Orbit to be investigated ~

Examples of calculated results of debris fluxes

ALOS (DAICHI)

Perigee x Apogee 694 x 695 km

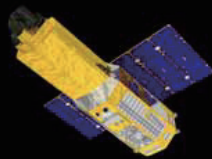
Inclination 98.2 deg.



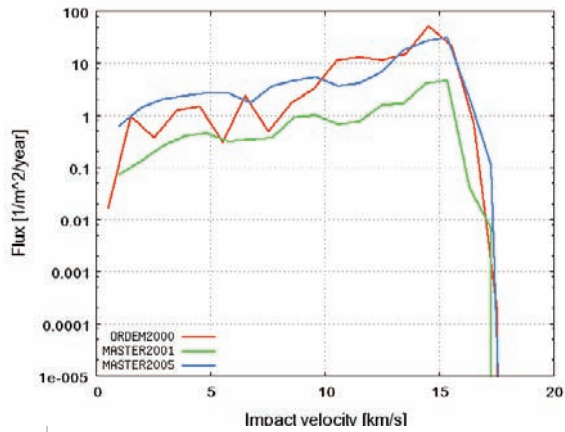
Astoro-E2 (SUZAKU)

Perigee x Apogee 561 x 572 km

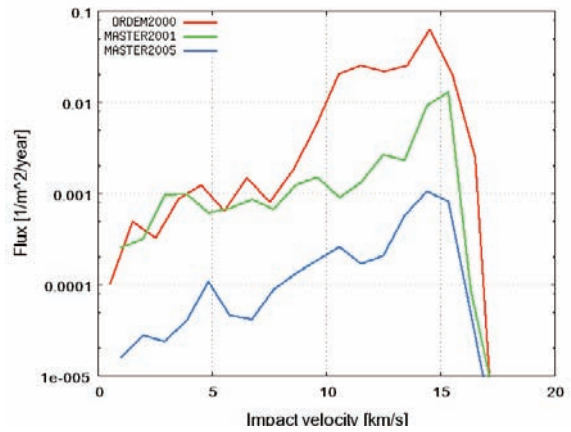
Inclination 31.4 deg.



Orbit case studies ~ ALOS ~

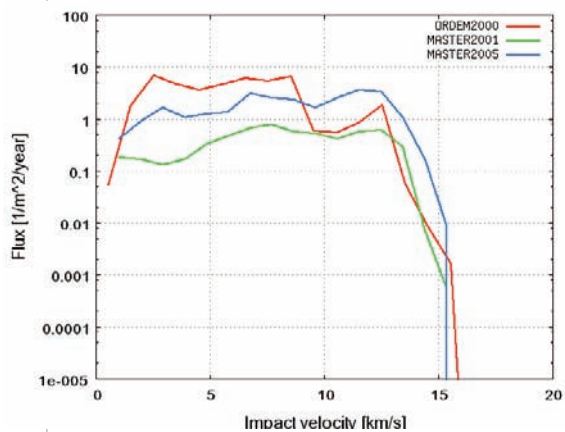


Object diameter > 100 μm

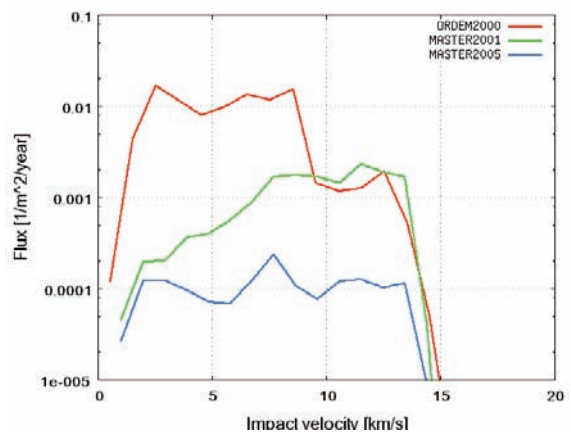


Object diameter > 1 mm

Orbit case studies ~ SUZAKU ~



Object diameter > 100 μm



Object diameter > 1 mm

Current Model Issues

Model comparison results suggest;

- (1) In present status, it is difficult to specify one model for risk assessment of debris impacts for spacecraft designs.

JAXA standard can NOT define "one standard model".

The standard should include "implementation procedures of models".

- (2) Measurement of small debris ranging from a hundred micrometers to several millimeters is important for the establishment of the environment model.

Ground observation systems can not detect small size debris.

In-situ observation data are important.

(1) Revised JAXA's "Space Environment Standard" includes the following "implementation standard (process-based standard)".

(Extract)

1. Implementation of Models to Spacecraft Designs and Operations

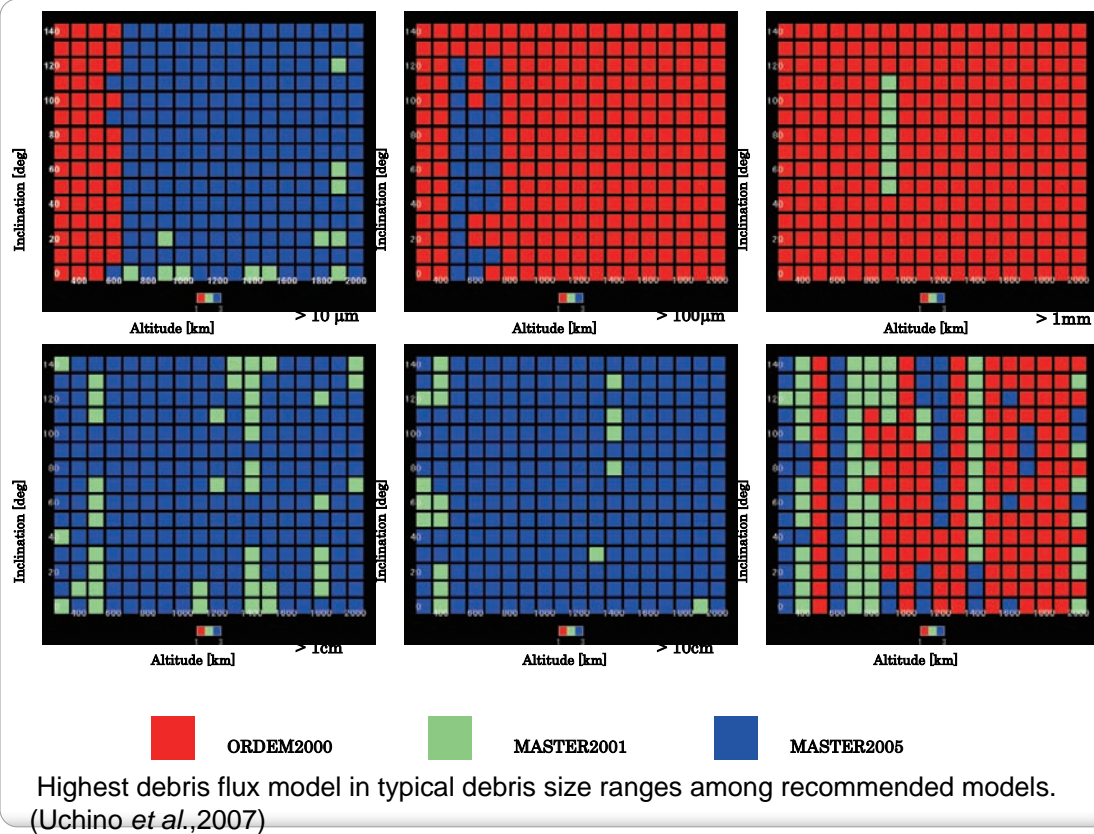
The highest collision flux value should be selected in three recommended models.

NOTE: Use of models other than the recommended model is NOT restricted.

2. Assurance of Traceability

When risk assessments of meteoroid and space debris impacts are required, **following items shall be recorded in each design phase** of the spacecraft. And the contents of the items are evaluated by reviewers.

- **Reasons of the model selection which are used for risk assessments for the spacecraft.**
- **All input parameters and all output parameters.**
- **Assumptions of input parameters on the design and reasons of the assumptions.**
- **When output parameters are corrected, the reason and the assumption of the correction and details of correction methods and correction results. (ex. Consideration of effects by the ASAT,2007)**



ISO's Recommendation

ISO/TC20/SC14(Spacecraft Design and Operations Comity)/WG4 (Space environment working group) recommended JAXA's standard (the process-based standard) should be proposed as ISO standard.

ISO/TC20/SC14/WG4's resolution No.193(extract)

The experts of WG4 having heard a presentation by Dr. Yukihiro Kitazawa on the possibility of development of a process based meteoroid and debris environment standard, recommend that the experts of Japan propose a NWI (New Work Item) on the assumption of obtaining strong cooperation with Japanese national agencies (for example, JAXA, METI).

- Japan could perform neutral evaluation of environmental models as a user's position.
- Japan has experience of post flight analysis for debris environment. (SFU and MFD/ESEM)
- Japan (JAXA) had performed meteoroid and debris passive measurement experiments on ISS (from 2001 to 2005).

(2) Measurement of Micro Debris

Ground observation

It is difficult to measure debris flux of the size range of hundred micrometers to several millimeters

Passive Sensor (sample return of small debris)

- Ability to know material data of debris (information of debris origin)

But

Only applicable to retrievable spacecrafts

- Restricted orbit. - Restricted flight opportunity. - Not able to get real time data

Surface inspection of retrieved spacecrafts

Only applicable to retrievable spacecrafts

- Restricted orbit. - Restricted flight opportunity. - Not able to get real time data.
- Difficult calibration.



In-situ measurement by active sensors

Applicable to all spacecrafts

- Not restricted orbit. - Easy to get flight opportunity -Real time detection

4. Basic study of new type active debris sensor

IQPS (Institute for QPS Inc.) and JAXA started the basic study to develop the in-situ debris measurement devices to detect the size range of hundred micrometers to several millimeters.

Importance of in-situ and real time micro debris measurement

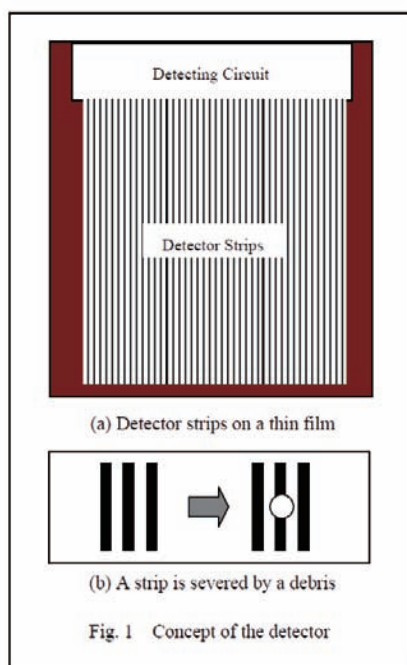
- 1) Verification of a debris environmental model
- 2) Verification of a debris environment evolution mode
- 3) Real time detecting of unexpected events, such as explosions on an orbit. (Ex. ASAT)

It does not yet succeed in systematic observation of the micro debris. Simple in-situ micro debris detection becomes very important to monitor debris environment. And it can complement Space Surveillance Network (SSN).

Especially change of micro debris environments is more sensitive than large size debris environment.

If ASAT or Brake-up happen, the real time flux measurement of micro debris environment gives not only detection of the event but also estimate intensity of the break-up.

A New Debris Sensor* by IQPS



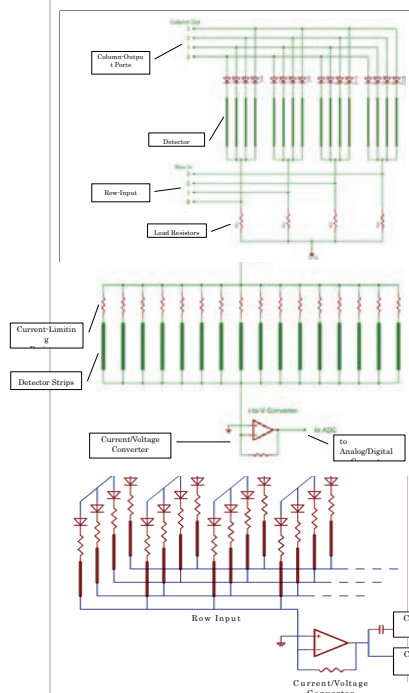
Multitude of thin, conductive strips are formed with fine pitch on a thin layer (film) of nonconductive material.

Debris impact is detected when one or more strips are severed by the impact hole.

It is simple to produce and use and requires almost no calibration as it is essentially a digital system.

* Patent Pending

Candidates of Detecting Circuits



Digital

- strips are represented as a matrix and the state of each strips is checked successively
- Impact position and the number of severed strips are detected

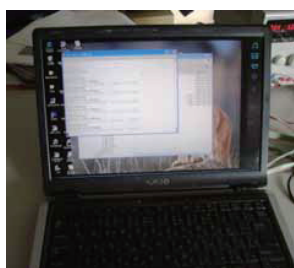
Analog

- impact is detected by the current decrease through all the strips
- impact time and the number of severed strips are detected

Hybrid

- combination of both
- impact time, its position, and the number of severed strips are detected

An Example of Element Experiments

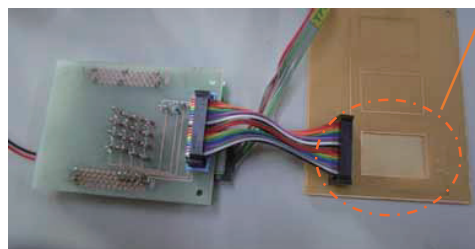


Controller /Data Acquisition



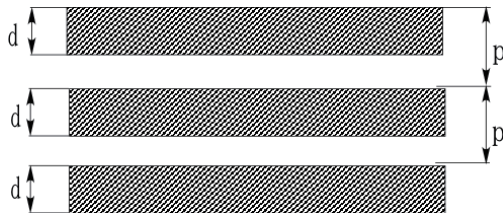
Sensor Surface

Multitude of thin, conductive strips are formed with fine pitch on a thin layer (film) of nonconductive material



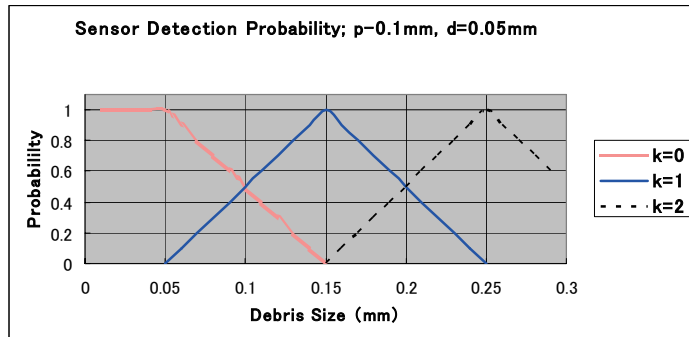
Detecting circuit (Digital)

Sensor Detection Probability



$$D = kp + d \pm p$$

D : size of debris
 k : the number of severed strips.
 d : width of a conductive strip
 p : pitch of conductive strips



An example of sensor detection probability

Calculation conditions

- $p=0.1\text{mm}$
- $d=0.05\text{ mm}$
- (sensor thickness: less than 0.01mm)

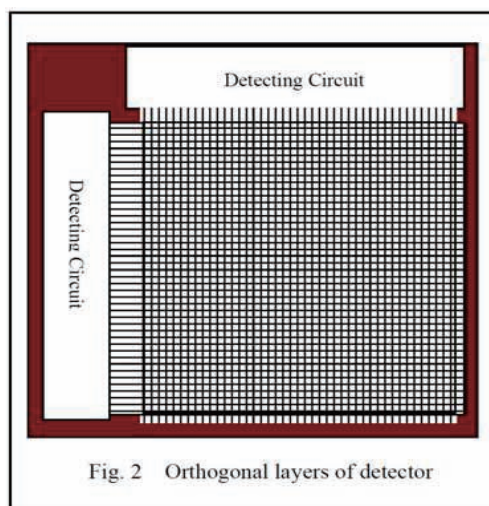


Detecting debris size and measurement error are estimated accurately.

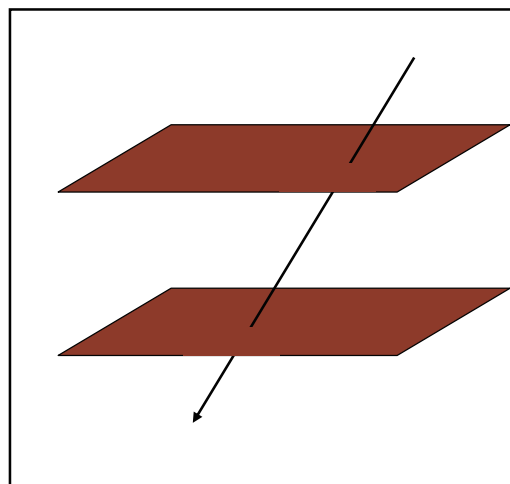
Features of the QPS sensor

- 1) Simple mechanism
- 2) High Reliability (sensing ability)
- 3) Flexible configuration
 - easy to make a large-size sensor. - no restrictions of size and/or form.
- 4) No need to perform many hypervelocity impact experiments (calibration shots)
 - (cf. usual sensors need many calibration shots.)
- 5) Measurement of change of the usable area of a sensor is possible correctly.
- 5) Low weight, low power and low cost
 - (ex. $< 200\text{g}$ and $< 1\text{W}$ per 1m^2 [sensing area])
- 6) Excellent extendibility
 - Additional parameters (impact location, impact velocity and impact (incident) direction) are measured by minor expansions.

Expansion of the concept

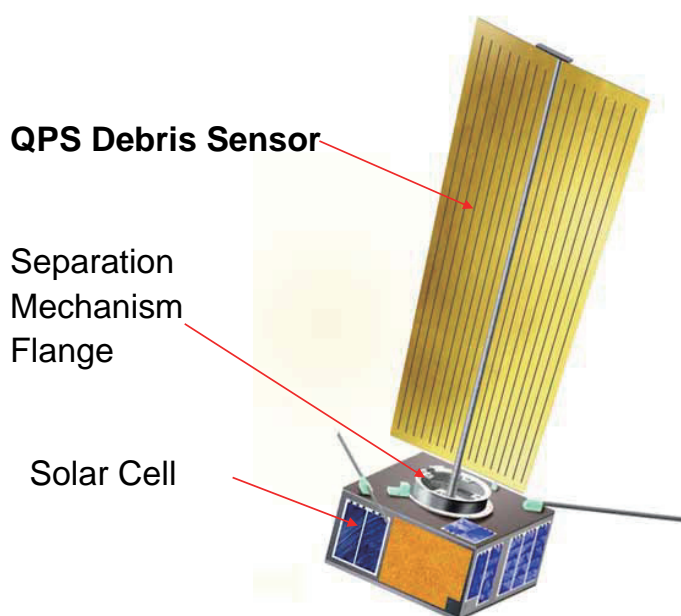


Use of Double Layers to Detect the impact position

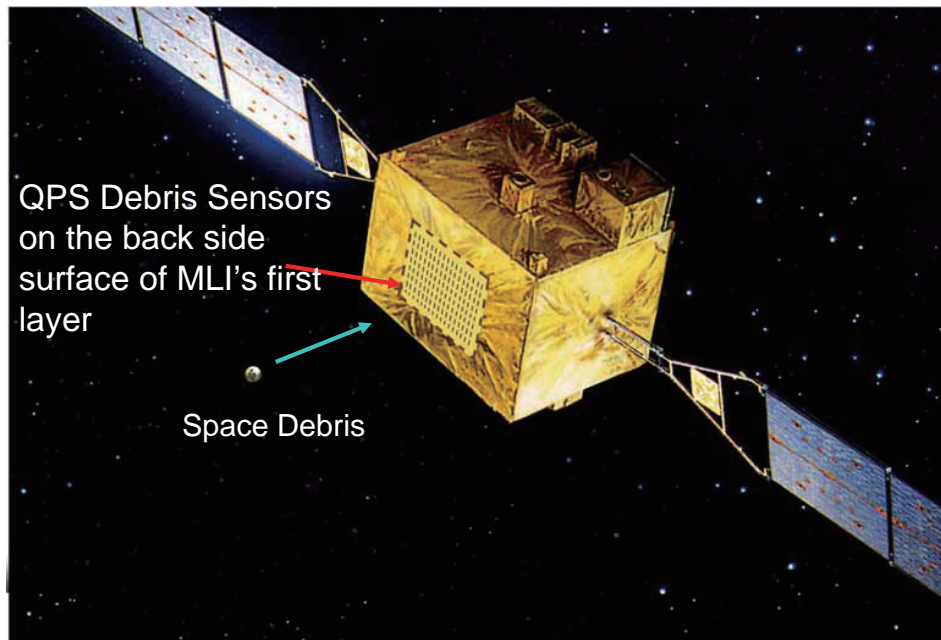


Use of Double Sheets to Detect the impact velocity and impact angle

An Example of Application of QPS Debris Sensor for a Small Satellite (Q-SAT)



An Example of Application of QPS Debris Sensor for a common satellite

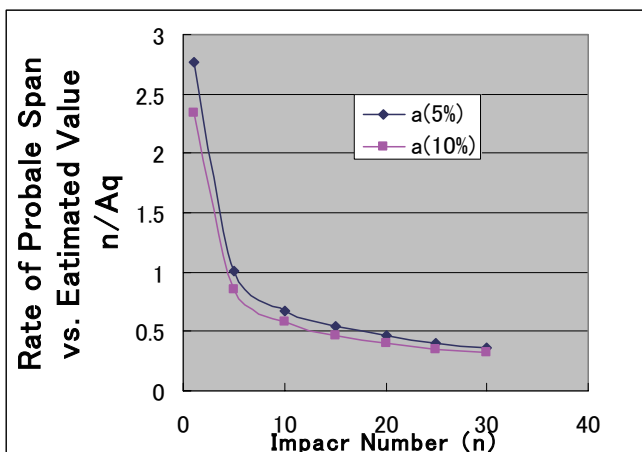


Reliability for Evaluation of Flux Value

$$q = n/At$$

(q : impact flux, A : sensor area, t : measurement duration time, n : impact number)

Since debris impacts follow **Poisson distribution**, the flux can be statistically calculated with arbitrary reliability. Rate of Probability Span was estimated based on T. Yasaka 2003. ("Space Debris Protection: A Standard Procedure in Future?" Acta Astronautica, 53 (2003), pp. 527-531.)



a: significance level

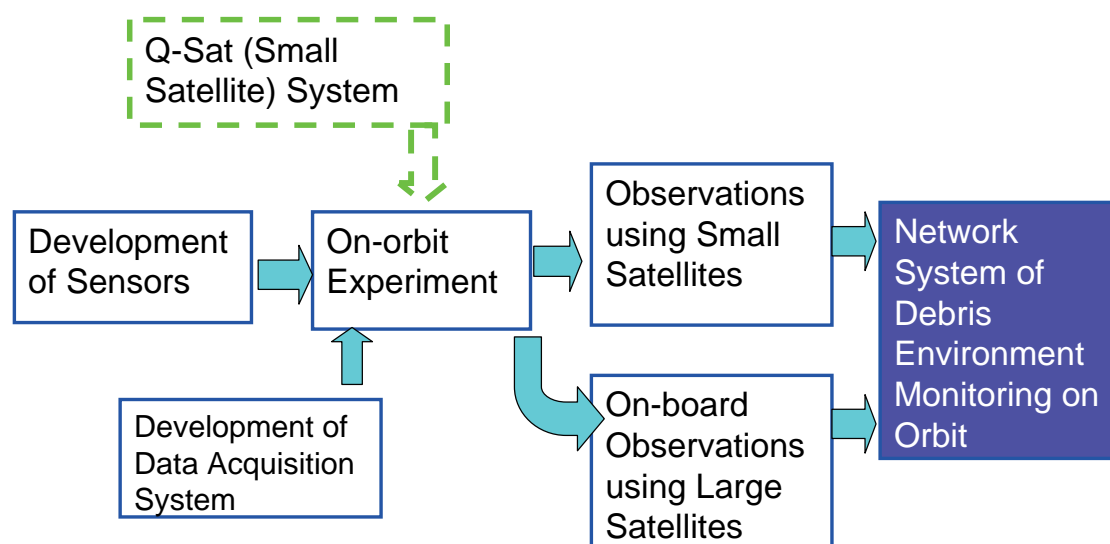
Measured impact number is greater than 10.



Error of the flux is less than 50%

Ex.
For evaluation of Reliability of ORDEM 2000 (altitude: 700km, inclination: 100deg.);
>100μm: Area: 0.1m² Duration 1 year
>1mm: Area: 3m² Duration 3 year

Development and Measurement Plan



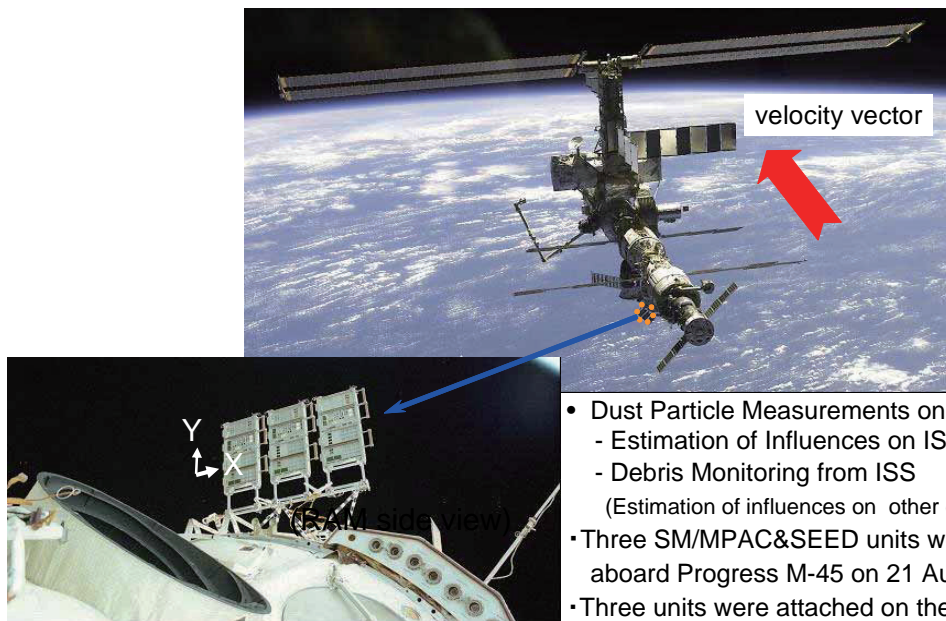
Proposed Study Items in the Next FY

- Manufacturing of Sensor BBM
(Multitude of thin, conductive strips will be attached actual films (ex. MLI) and/or structures.)
- Manufacturing of detecting circuits (digital, analog and hybrid) and performing of trade-off experiments.
- Impact experiments on the BBM

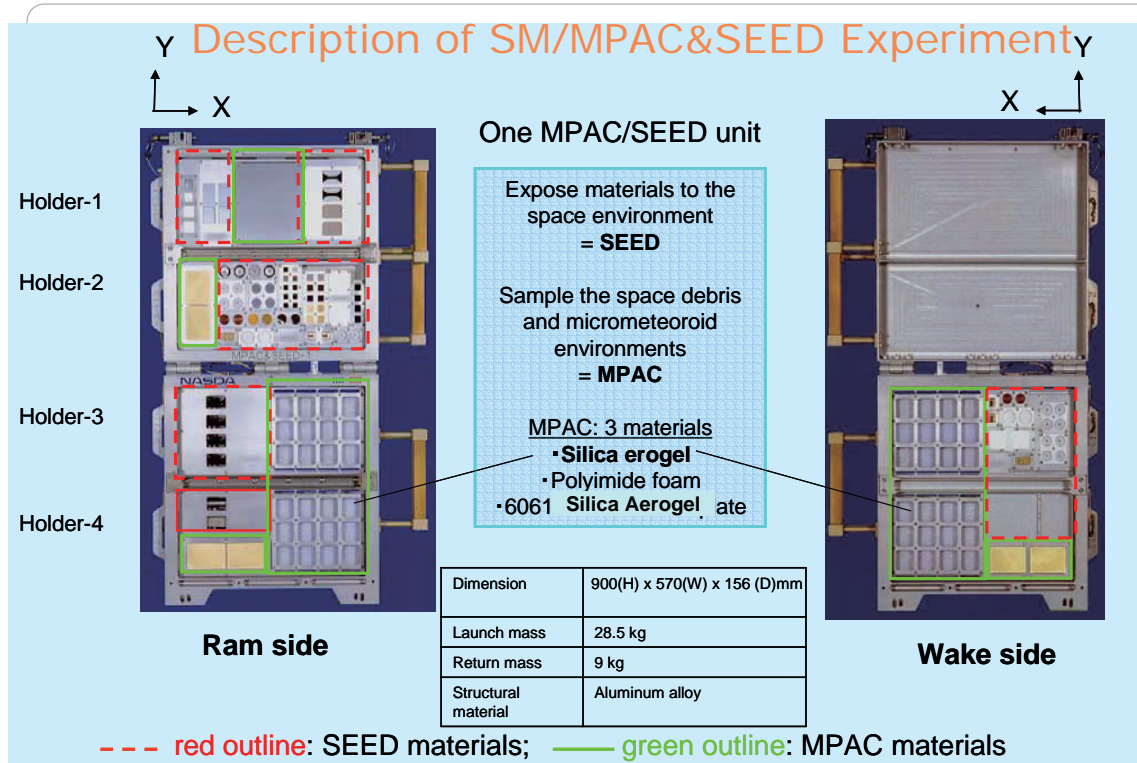
5. Overview of Passive Debris Experiment (SM/MPAC&SEED)

The Micro-Particles Capturer (MPAC) is a passive experiment on ISS, which is designed to evaluate the micrometeoroid and space debris environment, and to capture particles for **getting material information** (by chemical analysis). MPAC is mounted on a frame about 1 m long, which it shares with the Space Environment Exposure Device (SEED), a materials exposure experiment and named as “SM/MPAC&SEED”.

A view of the three SM/MPAC&SEED units during exposure

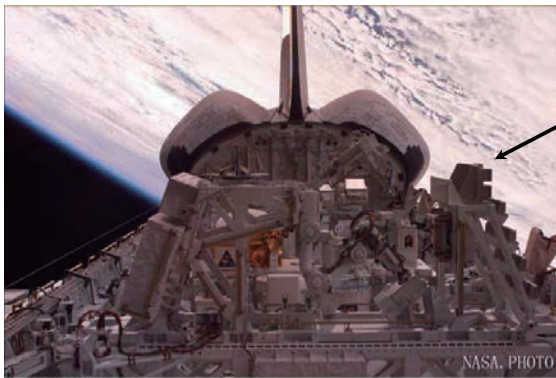


- Dust Particle Measurements on ISS
 - Estimation of Influences on ISS surface
 - Debris Monitoring from ISS
 - (Estimation of influences on other exposed devices)
- Three SM/MPAC&SEED units were launched aboard Progress M-45 on 21 August 2001.
- Three units were attached on the outside of the Russian Service Module.

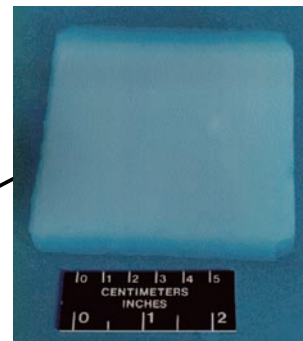


Developments for dust collectors were started in 1995 for focus on mainly measurement of micro debris.

Silica aerogel



Space Shuttle (STS-85), 1997
(Kitazawa et al., 1998).



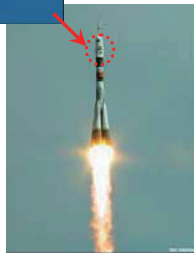
• Characteristics of Silica aerogel

- Very low density ($\sim 0.03 \text{ g/cm}^3$)
→ Effective for Intact capture
- Transparent
→ Easy to locate dust captured in aerogel
- Robust against space environment

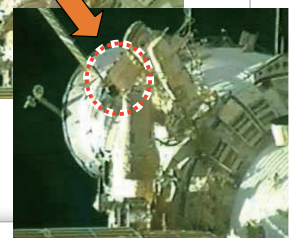
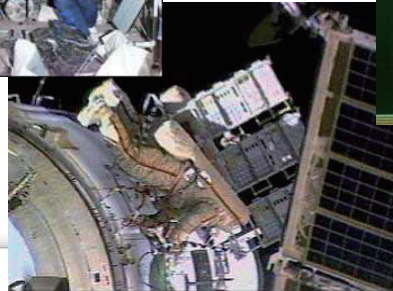
2. Description of MPAC&SEED

Experiment Mission Schedule

Year	2001			2002				2003				2004				2005			
Month	4	7	10	1	4	7	10	1	4	7	10	1	4	7	10	1	4	7	10
No.																			
SM#1																			
SM#2																			
SM#3																			



(21 August 2001)



Main Features of SM/MPAC(&SEED)

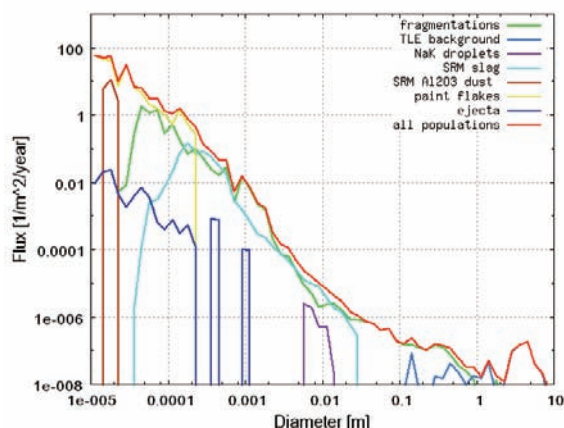
- **The first systematic debris capturing experiments in the world**
Since three units are **complete same structures**, it is able to purely evaluate space environment effects (ex. Impact flux, varieties of chemical data for impact residues) **ONLY** by difference of exposure duration.
- **“Silica-aerogel” are used as dust capturing material.**
Material information of the captured debris, and impact parameters (incident direction, debris diameter, and impact velocity) are estimated.



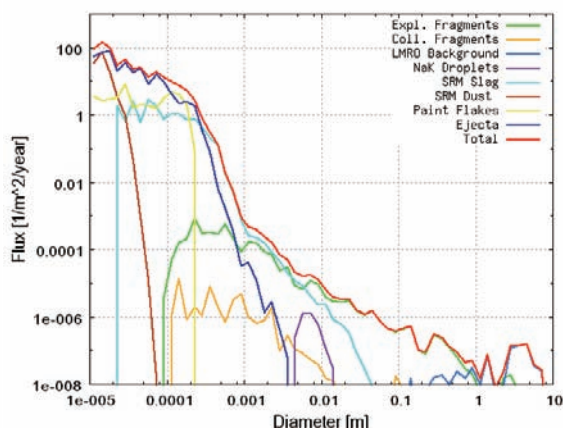
SM/MPAC&SEED mission is important not only as a precursor mission of ISS's exposed experiments, but also as a great opportunity of research of **debris origin through the material information of captured debris.**

Orbit case studies ~ SUZAKU ~

Material distribution of debris revised from MASTER-2001 to MASTER-2005, but there are many uncertainties. Additionally ORDEM-2000 has no material information.

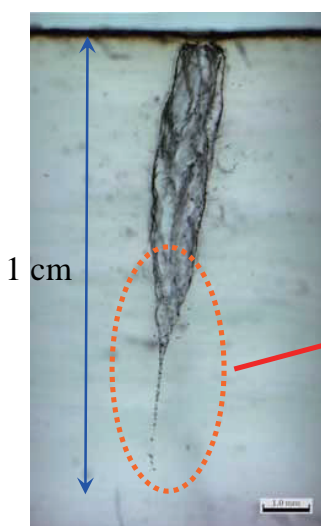


MASTER 2001

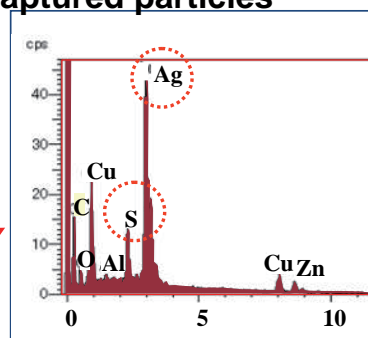
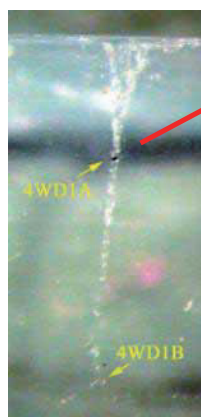


MASTER 2005

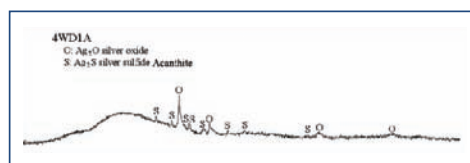
An example of chemical composition of captured particles



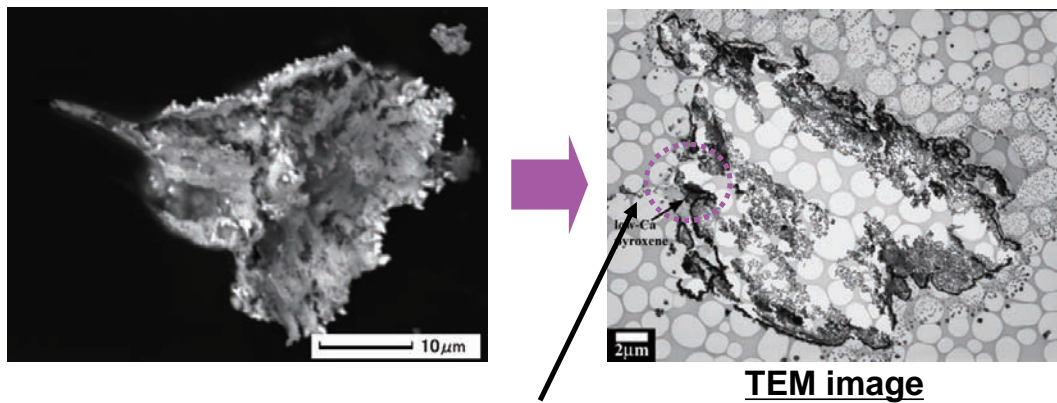
Captured Particles on Wake side
Diameter: about 20 μm each
Estimated Impact velocity: about 5 km/s



Al, C, Cu, Zn:Background



X-Ray Diffraction Chart
(by Prof.T.NAKAMURA, Kyushu Univ.)



Meteoroid particle (Fragment of H-Chondrite?)

The feature of the captured particle;

- The mixture of Ag_2O and Ag_2S .
- The aggregate of a particulate with a size of tens to hundreds of nm.
- The natural grain of about $1\mu\text{m}$ in diameter is included.

Secondary Debris induced by natural meteoroid impact on the surface of the spacecraft.

Near Future Plans of MPAC

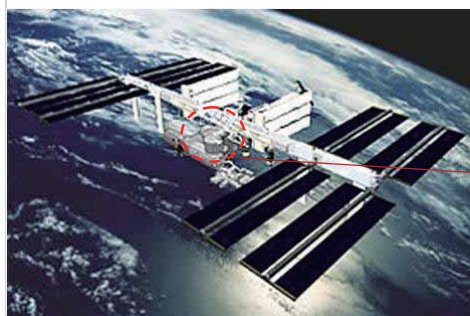
1) Re-start of analysis of MPAC

- Some of detailed inspection of SM#3/MPAC *1 will be carried out.

*1: In quick visual inspections from back sides of aerogels (no contamination), many tracks were founded (ex. more than 20 tracks per one aerogel).

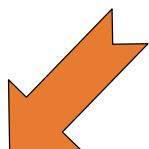
- Data base will be made for sample distributions.

2) An MPAC&SEED experiment is also scheduled for the Japanese Experiment Module (Kibo).



International Space Station

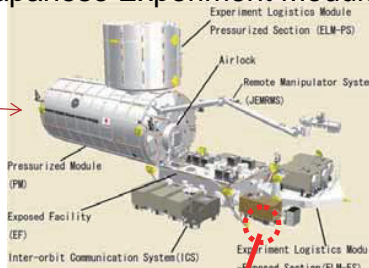
(This figure at the time of completion)



Velocity vector
(=contamination is little)

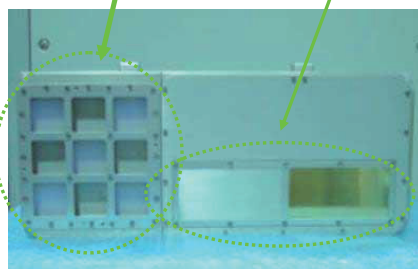
JEM/MPAC&SEED

Japanese Experiment Module (Kibo).



MPAC (Aerogel)

MPAC (Gold Plate)



JEM/MPAC&SEED (Pre flight model)
450(W) × 220(H) × 190(D) [mm]

**Detail results and future plans will be reported in
the international symposium on SM/MPAC&SEED.
(March 10 -11, 2008 at Tsukuba)**

**International Symposium on
"SM/MPAC&SEED Experiment"**
(Service Module / Micro-Particles Capturer &
Space Environment Exposure Device)

Date : March 10-11, 2008
Place : International Congress Center
EPOCHAL TSUKUBA Conference Room 101
<http://www.epochal.or.jp/eng/index.html>
Electronic, Mechanical Components and Materials Engineering Group
Institute of Aerospace Technology (IAT)
Japan Aerospace Exploration Agency (JAXA)
E-mail: mpacseed@jaxa.jp

http://matdb1n.tksc.jaxa.jp/mpac_seed/index.html

Summary

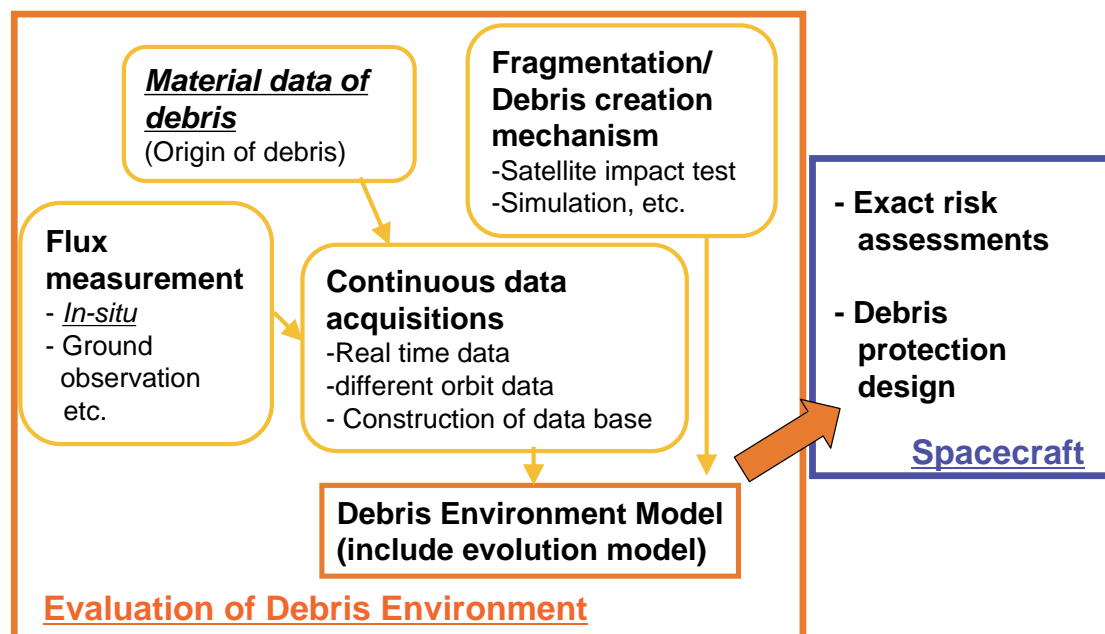
Comparison among the major three debris models, NASA-ORDEM2000, ESA-MASTER2001, and MASTER2005, revealed that the distribution of small debris in LEO differs among those models. Particularly, the size range of a hundred micrometers to several millimeters differs among them.

JAXA has been developing an International Standard entitled "Process-based implementation of debris environment model" under ISO community, not only the **revision** of the JAXA's standard.

IQPS and JAXA has begun a basic study to develop in-situ measurement devices to detect micro debris ranging from a hundred micrometers to several millimeters.

JAXA had performed passive dust collector experiments on the International Space Station. Although the analyses of dust collectors are not completed yet, the analysis results will supply important material information about micro debris.

Concept of Debris Environment Evaluation



I2-2 最近実施した衛星衝突破壊実験の結果について

○花田俊也（九州大学）

Outcome of Recent Satellite Impact Experiments
Toshiya Hanada (Kyushu University)

Keywords: Orbital Debris, Hypervelocity Impact, and Satellite Fragmentation.

Although explosion fragments dominate the current near-Earth orbital debris environment, many models predicted collisions rather than explosions would generate more debris in the future. Therefore, understanding the outcome of both low- and hyper-velocity satellite impacts is key to modeling the future debris environment. As a first step to achieve this objective, Kyushu University and the NASA Orbital Debris Program Office have collaborated on a series of impact tests on micro satellites. This paper summarizes the recent satellite impact experiments completed in late 2005 and in early 2007.

The target satellites used in 2005 were identical, 15 cm by 15 cm by 15 cm in size. The target satellites used in 2007, on the other hand, were also identical, but 20 cm by 20 cm by 20 cm in size, slightly larger than the target satellites used in 2005. They were all composed of five layers (top and bottom layers and three inner layers parallel to the top and bottom layers) and four side panels, and were assembled by angle bars made of an aluminum alloy and metal spacers. The external layers and side panels were made of Carbon Fiber Reinforced Plastics (CFRP), while the three inner layers were made of Glass Fiber Reinforced Plastics (GFRP). The interior of each micro satellite was equipped with fully functional electric devices, such as a wireless radio, lithium-ion batteries, and communication, electronic power supply, command and data handling circuits. The total mass of each micro satellite used in 2005 was approximately 740 grams, whereas that of each micro satellite used in 2007 was approximately 1,300 grams.

All satellite impact experiments were conducted using the two-stage light gas gun at the Kyushu Institute of Technology, in Kitakyushu, Japan. Table 1 summarizes the impact scenarios. The first two experiments were completed in 2005 to compare low- and hyper-velocity impacts on identical target satellites, whereas the last three experiments were completed to compare impacts on identical target satellites in different impact directions with respect to the inner layers. The ratios of impact kinetic energy to target satellite mass for all experiments placed the outcome as catastrophic according to the NASA Standard Breakup Model which defines a threshold of 40 J/g or higher for catastrophic collisions.

All target satellites were completely fragmented after the impact, consistent with the NASA criterion. More than 1,000 fragments collected from each experiments have been weighted, measured and analyzed. The preliminary results have suggested the development of a general-purpose distribution model applicable for a wide impact velocity range and a size-based material density distribution model. The further analysis of fragments is currently in progress. The results will be utilized to improve our understanding of the outcome of hypervelocity impact, and to improve breakup models.

Table 1. Impact parameters of the recent satellite impact experiments.

Shot	M_t [g]	M_p [g]	V_{imp} [km/s]	E_{imp} / M_t [J/g]	Impact Direction [With Respect to Layers]	Number of Fragments Collected
HVI	740	4.03	4.44	53.7	Normal	1,500
LVI	740	39.2	1.45	55.7	Normal	1,500
1	1,300	39.2	1.66	41.5	Normal	1,300
2	1,283	39.2	1.66	42.0	Parallel	1,000
3	1,285	39.2	1.72	45.1	Normal	1,500

M_t = Target Mass, M_p = Projectile Mass

V_{imp} = Impact Velocity, E_{imp} = Impact Energy ($= M_p \times V_{imp}^2 / 2$)

Outcome of Recent Satellite Impact Experiments

Toshiya Hanada
Kyushu University, Fukuoka, JAPAN

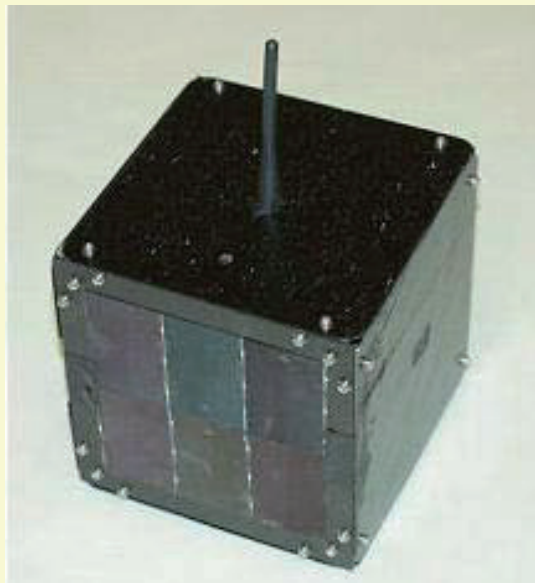
Background and Motivations

- A commonly used model to describe the outcome of satellite fragmentation is the NASA standard breakup model (for explosions and collisions).
- The impact experiments incorporated in the development of the NASA standard breakup model were all hypervelocity impacts.
- The recent satellite impact experiments aim to compare
 - low- and hyper-velocity impacts on identical target satellites (conducted in 2005), and
 - impacts on identical target satellites in different impact directions with respect to inner layers (conducted in 2007).

Satellite Impact Experiments in 2005

– Target Satellites –

- Target satellites are 15 cm × 15 cm × 15 cm in size and 740 grams in mass.
- Main structure is composed of five CFRP layers (top, bottom, and three internal layers parallel to the top and bottom layers) and four CFRP side panels, assembled by aluminum alloy angle bars.
- Each satellite is equipped with fully functional electronic devices.



2008.1.21-22

The 3rd Space Debris Workshop

2

Satellite Impact Experiments in 2005

– Impact Scenarios –

Shot	M_t [g]	M_p [g]	V_{imp} [km/s]	E_{imp} / M_t [J/g]	Impact Direction [with respect to layers]	Video
HVI	740	4.03	4.44	53.7	normal	N/A
LVI	740	39.2	1.45	55.7	normal	Yes

M_t = Target Mass, M_p = Projectile Mass

V_{imp} = Impact Velocity, E_{imp} = Impact Energy ($= M_p \times V_{imp}^2 / 2$)

HVI = Hypervelocity Impact, LVI = Low-velocity Impact

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Satellite Impact Experiments in 2005 – Collected CFRP Layers –



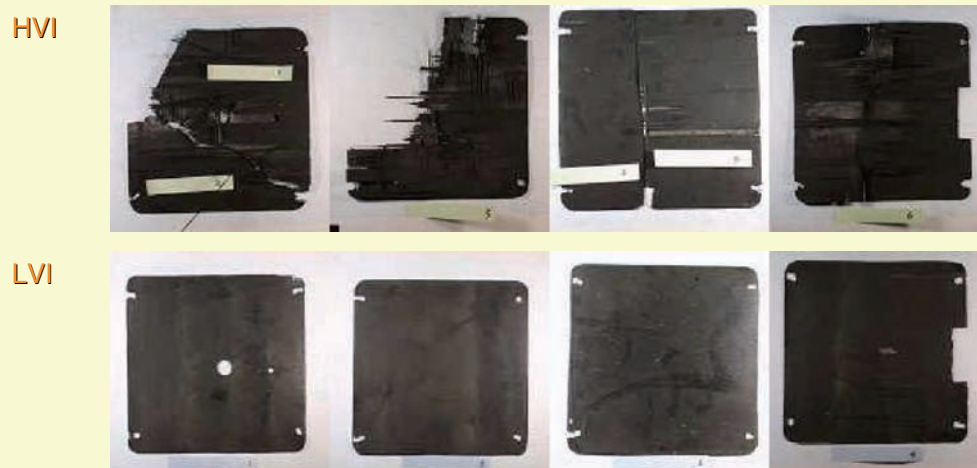
- LVI (lower) projectile penetrated all layers but HVI (upper) projectile was not able to shoot through the bottom layer.

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Satellite Impact Experiments in 2005 – Collected CFRP Side Panels –



- Side panels were damaged in HVI (upper) but not in LVI (lower).

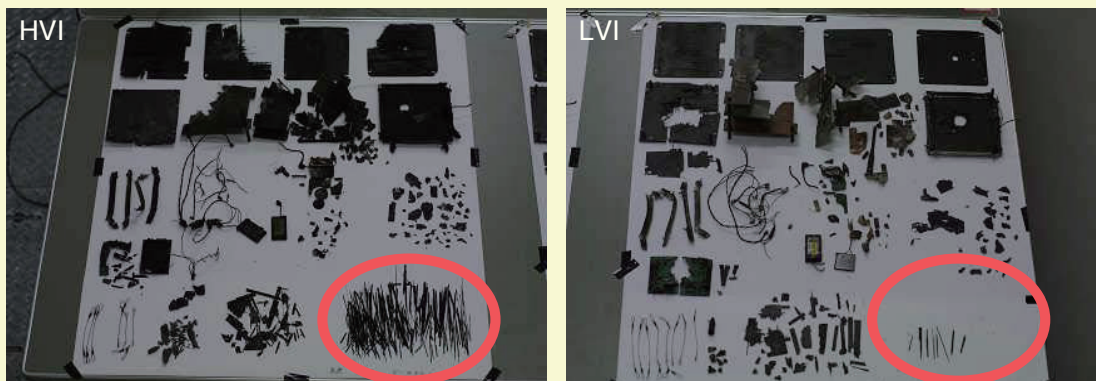
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Satellite Impact Experiments in 2005

– 500 Largest Fragments –



- Overall characteristics of fragments are similar, although some differences exist. For example, HVI (left) produces more needle-like fragments than LVI (right) does. This difference may lead to differences in fragment properties.

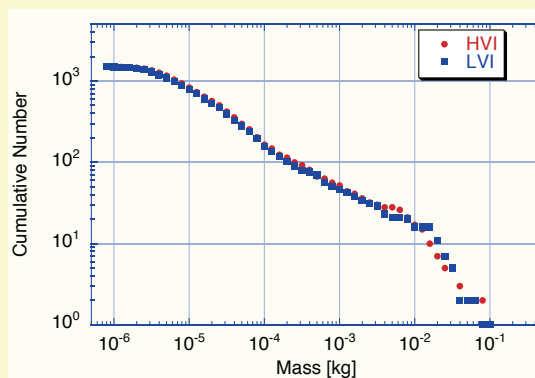
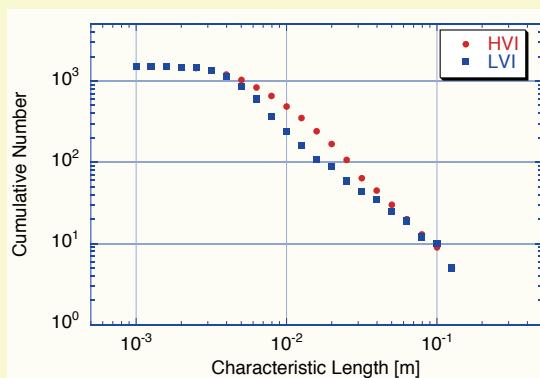
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Satellite Impact Experiments in 2005

– Size & Mass Distributions –



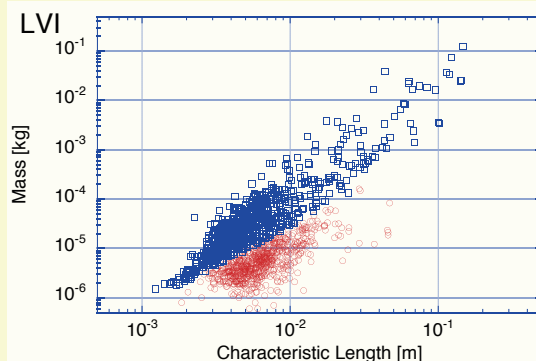
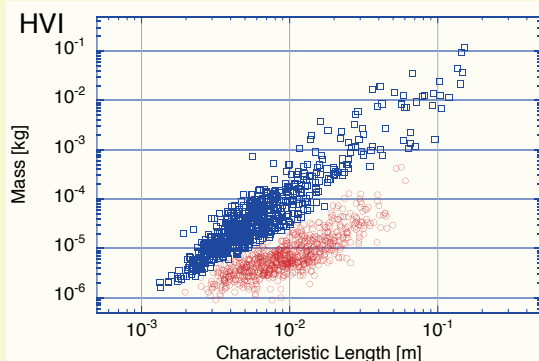
- Two fragments sets have very similar mass distributions (right) but slightly different size distributions (left).
- HVI (red) produces more fragments in the 1 cm and larger size regime than LVI (blue) does.

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Satellite Impact Experiments in 2005 – Size-mass Distribution –



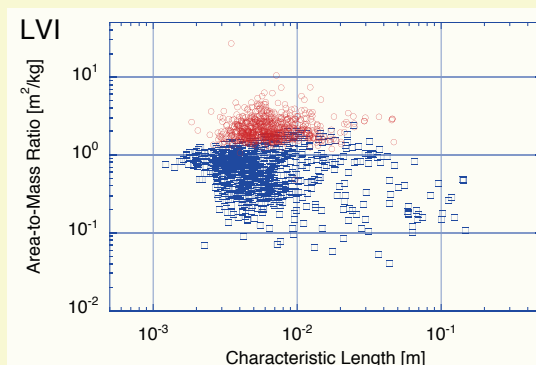
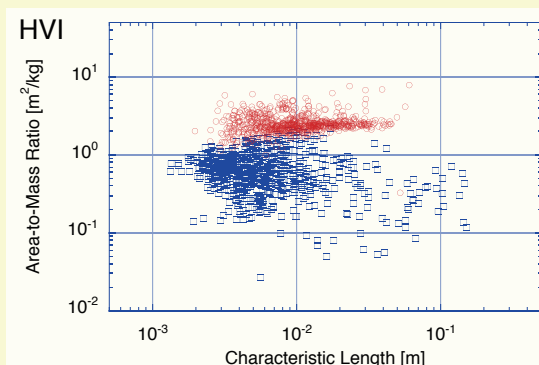
- Fragments can be separated into two groups:
 - one with a higher material density distribution (**blue**), and
 - the other with a lower material density distribution (**red**).
- The criterion for the separation may be given by $M = 0.057L_C^{1.65}$.

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Satellite Impact Experiments in 2005 – Area-to-Mass Distribution –



- **Red** represents fragments with lower material densities, whereas **blue** represents fragments with higher material densities.
- Two fragment sets have similar area-to-mass distributions in the 1 m²/kg and lower regime (**blue**), but slightly different area-to-mass distributions in the 1 m²/kg and higher regime (**red**).

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Satellite Impact Experiments in 2005 – Conclusions (1) –

- This paper has summarized two satellite impact experiments conducted to investigate the outcome of low- and hyper-velocity catastrophic impacts on identical target satellites.
- One was performed with a 39-gram projectile at a speed of 1.45 km/s, whereas the other was performed with a 4-gram projectile at a speed of 4.44 km/s.
- The kinetic energy at impact in the two experiments were approximately the same and placed the outcome as catastrophic according to the NASA criterion.

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Satellite Impact Experiments in 2005 – Conclusions (2) –

- The target satellites were completely fragmented in both experiments, consistent with the NASA criterion.
- Approximately 1,500 fragments collected from each impact experiments have been weighted, measured and analyzed.
- The results shown have suggested the development of
 - a general-purpose distribution model applicable for a wide impact velocity range, and
 - a size-based material density distribution model.

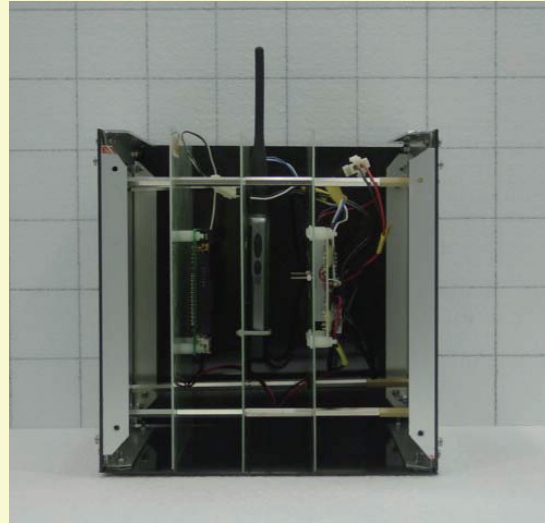
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Satellite Impact Experiments in 2007 – Target Satellites –

- Target satellites are 20 cm × 20 cm × 20 cm in size and ~1,300 grams in mass.
- Main structure is composed of five layers (top and bottom CFRP layers, and three GFRP internal layers parallel to the top and bottom layers) and four CFRP side panels, assembled by aluminum alloy angle bars.
- Each satellite is equipped with fully functional electronic devices.



Inside View of Target Satellite

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Satellite Impact Experiments in 2007 – Impact Scenarios –

Shot	M_t [g]	M_p [g]	V_{imp} [km/s]	E_{imp} / M_t [J/g]	Impact Direction [with respect to layers]	Video
1	1300	39.2	1.66	41.5	normal	N/A
2	1283	39.2	1.66	42.0	parallel	Yes
3	1285	39.2	1.72	45.1	normal	Yes

M_t = Target Mass, M_p = Projectile Mass

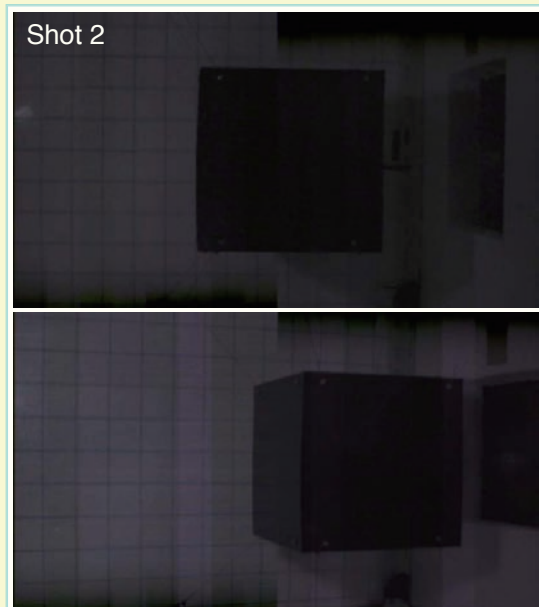
V_{imp} = Impact Velocity, E_{imp} = Impact Energy ($= M_p \times V_{imp}^2 / 2$)

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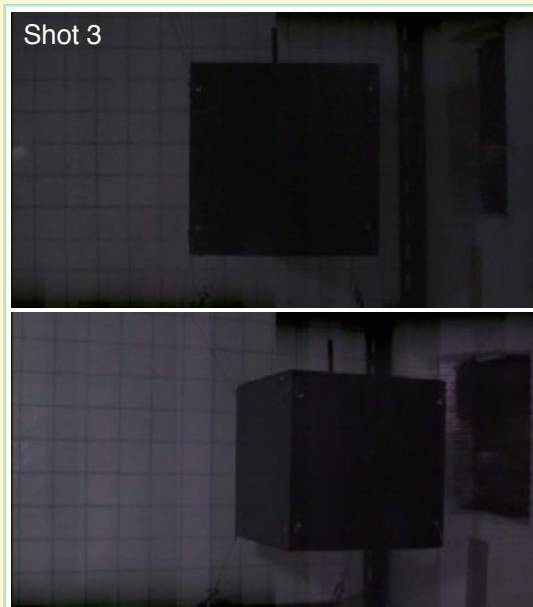
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Satellite Impact Experiments in 2007 – Captured Video –



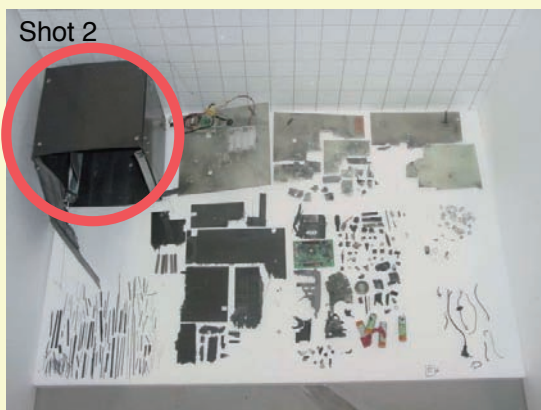
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Satellite Impact Experiments in 2007 – 300 Largest Fragments –



- The main box structure still remained intact in the second shot (left).
- Approximately 1,500 fragments were collected in the third shot (right), whereas only about 1,000 fragments were collected in the second shot (left).

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Satellite Impact Experiments in 2007 – Conclusions (1) –

- This paper has summarized three satellite impact experiments conducted in 2007 to investigate the outcome of catastrophic impacts on identical target satellites in different impact directions with respect to the inner layers.
- Two were performed at a speed of 1.66 km/s but in the different impact directions with respect to the inner layer. The other was performed at a speed of 1.72 km/s.
- The kinetic energy at impact in the three experiments placed the outcome as catastrophic according to the NASA criterion.

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Satellite Impact Experiments in 2007 – Conclusions (2) –

- The target satellites were completely fragmented in all three experiments, consistent with the NASA criterion.
- More than 1,000 fragments collected from each impact experiments have been weighted, measured and catalogued.
- The analysis of fragments is currently in progress.
- The results will be utilized to improve our understanding of the outcome of hypervelocity impact, and to improve breakup model.

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I2-3 The Characteristics and Consequences of the Break-up of the Fengyun-1C Spacecraft

Gene Stansbery, Mark Matney, Nicholas Johnson

Orbital Debris Program Office, NASA Johnson Space Center, Houston, TX 77058, USA

Abstract

The intentional break-up of the 8-year-old, nearly one-metric-ton Fengyun-1C spacecraft on 11 January 2007 via hypervelocity collision with a direct ascent anti-satellite system created the most severe artificial debris cloud in Earth orbit since the beginning of space exploration. The intercept occurred at the relatively high altitude of 850 km at a collision speed of approximately 9 km/sec. By the end of 2007, the U.S. Space Surveillance Network had officially cataloged 2317 debris, and was tracking an additional 200 objects tentatively identified as Fengyun debris. The NASA Orbital Debris Program Office has conducted a thorough examination of the nature of the Fengyun-1C debris cloud, using SSN data for larger debris and special Haystack radar observations for smaller debris. Both the large and small Fengyun-1C debris populations are now assessed to considerably exceed predictions from the NASA standard satellite break-up model for collisions. Much of the debris will be long-lived due to the high altitude of the intercept and will significantly effect the orbital environment for many years to come.

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The Characteristics and Consequences of the Break-up of the Fengyun-1C Spacecraft

**Gene Stansbery
Mark Matney
Nick Johnson**

**NASA Orbital Debris Program Office
NASA Johnson Space Center**

January 2008

National Aeronautics and Space Administration

Outline



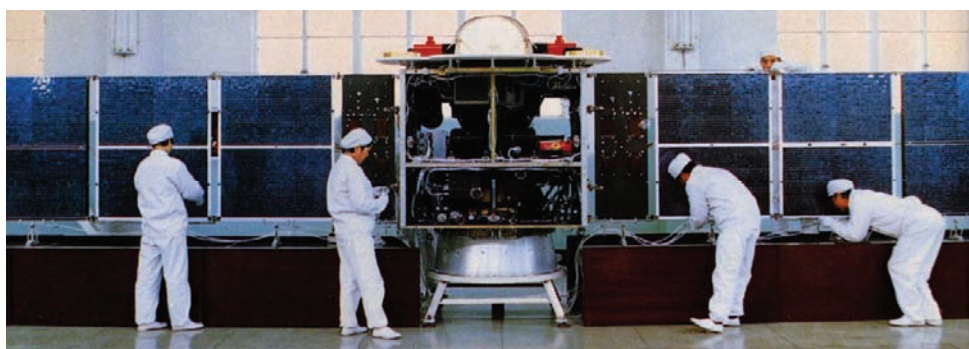
- **Background of Breakup Event**
- **Debris Cloud Characterization**
 - U.S. Space Surveillance Network data
 - Special Haystack radar observations
- **Changes in the near-Earth Environment**
- **Near- and Long-term Collision Effects**
- **Conclusions**

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Breakup Event Summary

- The Fengyun-1C spacecraft (1999-025A, U.S. Satellite Number 25730) was the target on 11 January 2007 of a ground-launched, direct ascent ballistic missile equipped with a kinetic kill vehicle.
- Fengyun-1C orbit: ~ 850 km, 98.6 deg inclination
- Fengyun-1C mass: ~960 kg
- Impact velocity: ~ 9 km/s



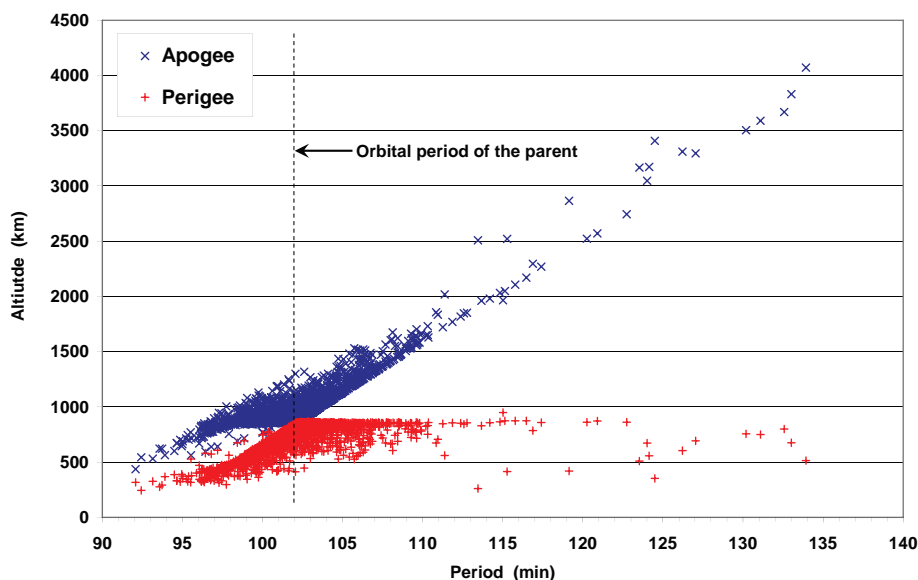
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SSN Observations of Debris Cloud

- Almost 1 year after the breakup, a total of 2317 pieces of debris had been officially cataloged by the U.S. Space Surveillance Network.
 - 22 cataloged objects have reentered the earth's atmosphere
 - ~ 200 additional debris are being tracked but are not yet cataloged.



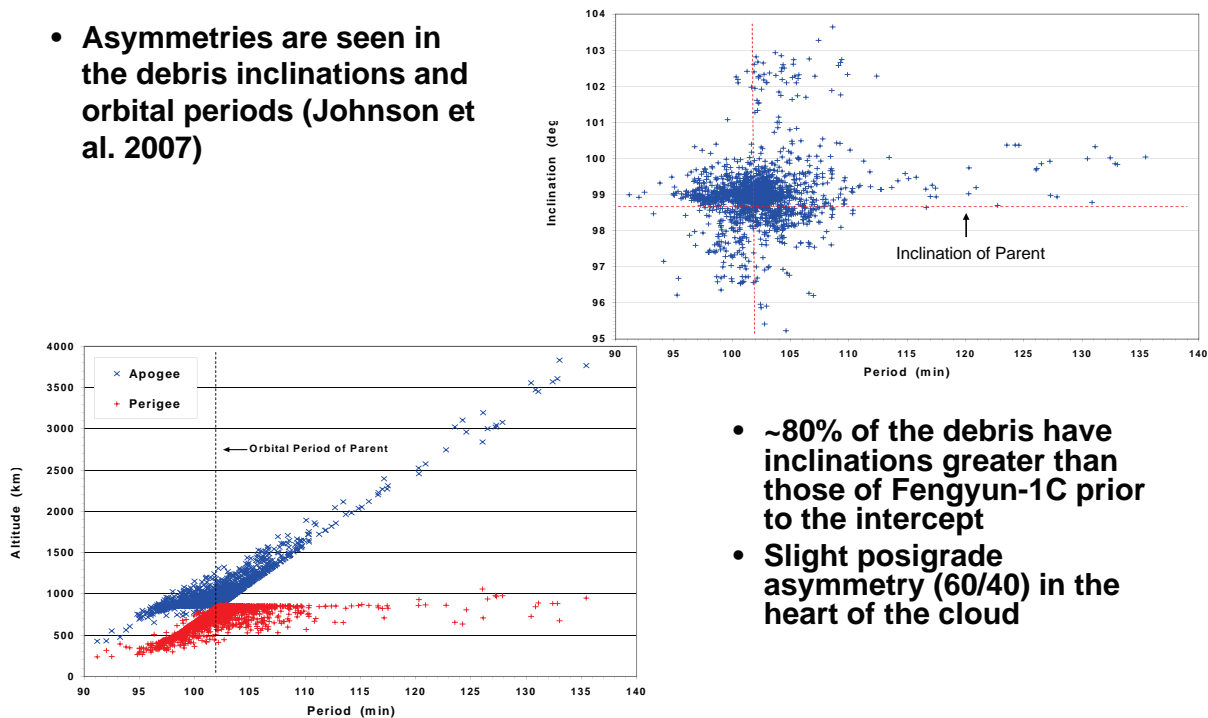
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Asymmetries in Fengyun-1C Fragments

- Asymmetries are seen in the debris inclinations and orbital periods (Johnson et al. 2007)



- ~80% of the debris have inclinations greater than those of Fengyun-1C prior to the intercept
- Slight posigrade asymmetry (60/40) in the heart of the cloud

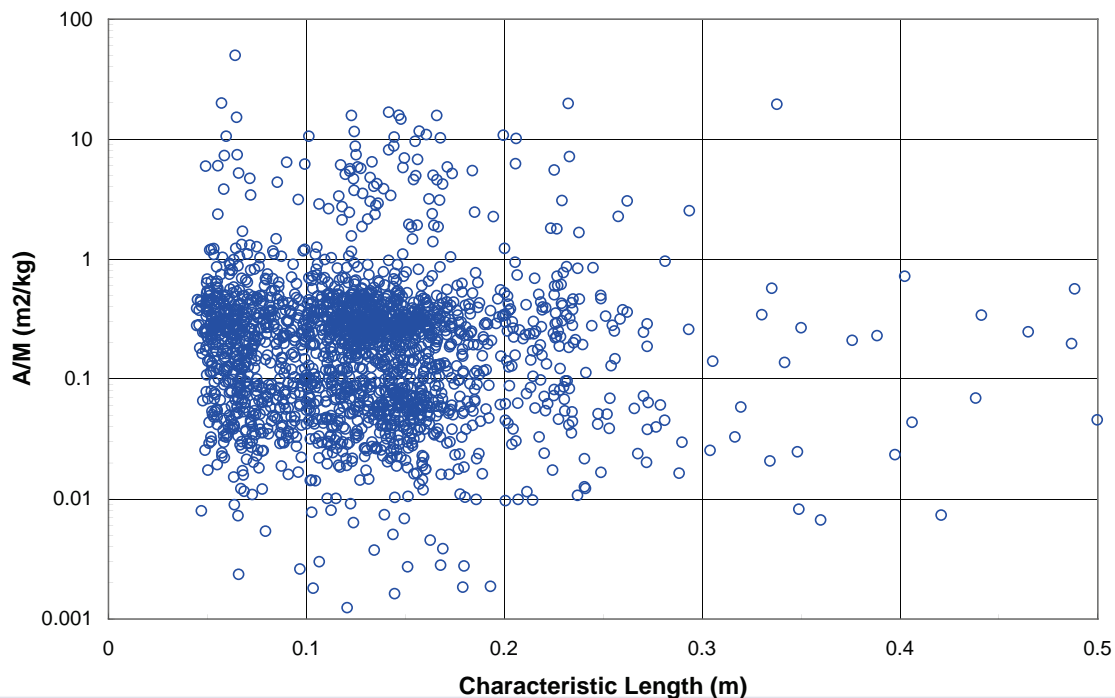
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A/M versus Lc

Fengyun-1C Debris Data (11/11/2007)

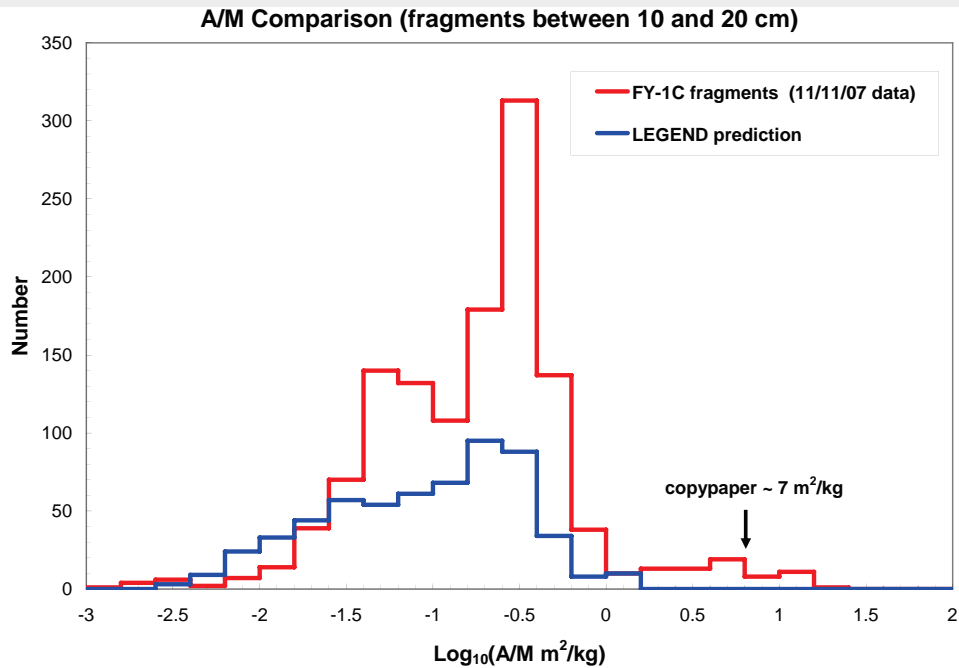


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FY-1C Fragment A/M Distribution (1/2)



- More light-weight fragments (plastic and/or solar panel pieces?) and MLI fragments than the NASA predictions

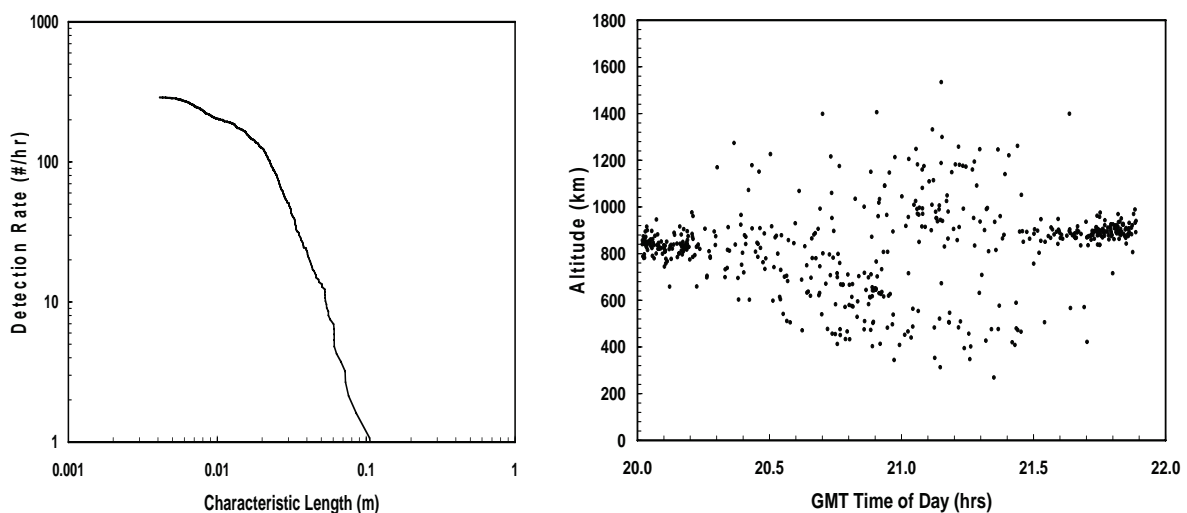
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Haystack Observations of Debris Cloud

- The Haystack radar observed the debris cloud for 1.9 hours in a special “orbit plane tracking” mode ~24 hours after the breakup.
 - Some sub-centimeter debris were observed.



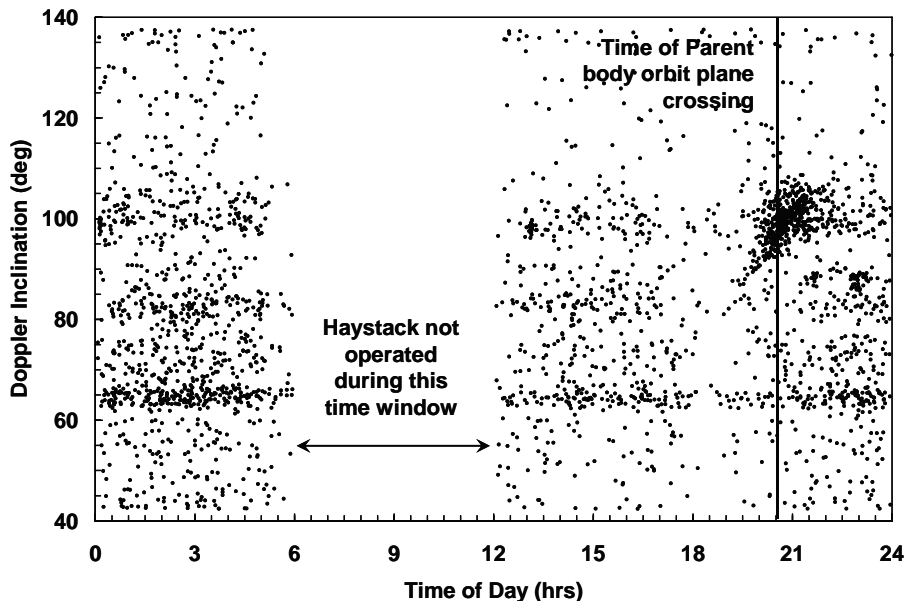
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Haystack Observations of Debris Cloud (continued)



- During January through May, Haystack observed the debris in a normal staring mode for 184 hours.



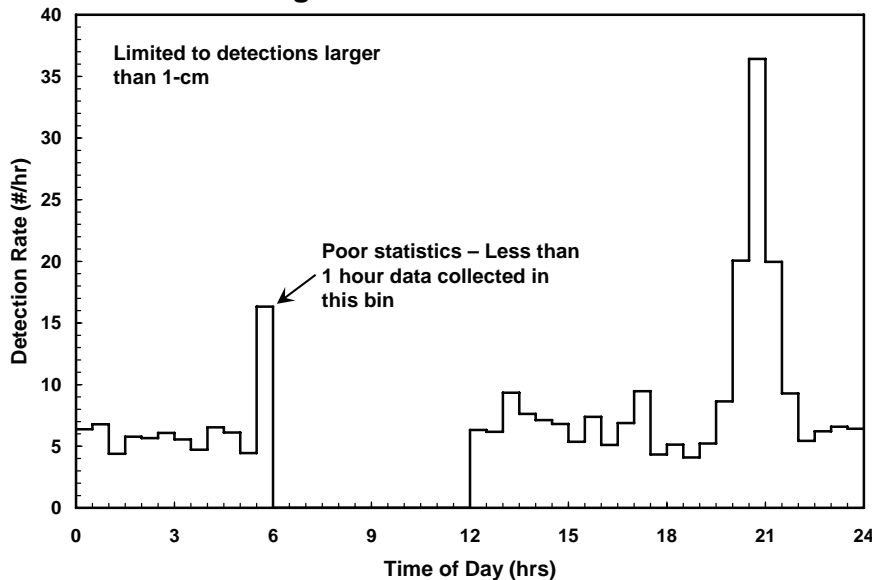
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>1 cm Population from Haystack Data



- The average detection rate for all detections visible to Haystack is 12.4 per hour
- The average detection rate for debris larger than 1 cm is 4.7 per hour
- Model results show that this breakup alone approximately doubled the population of 1 cm and larger debris in low earth orbit

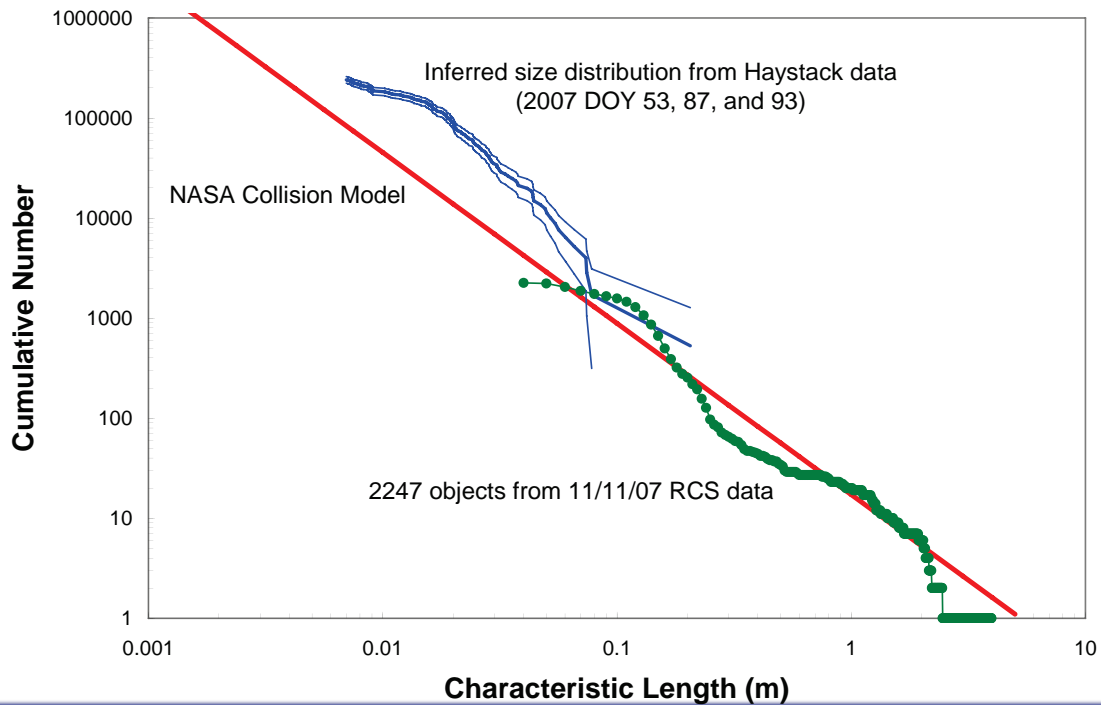


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FY-1C Fragment Size Distribution



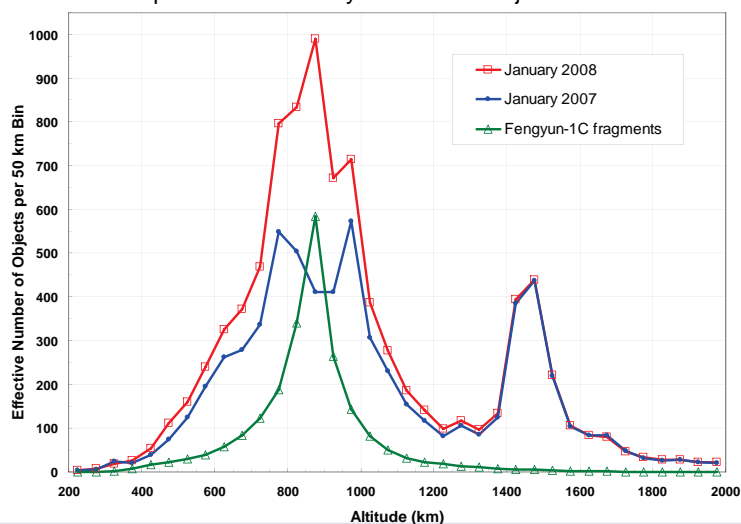
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Changes in the near-Earth Environment

- The number of tracked objects in LEO increased ~ 25% as a result of the breakup of Fengyun-1C.
- The debris now represents a significant portion of conjunction assessments for many operational spacecraft.
 - A least two U.S. spacecraft have maneuvered to avoid very close approaches of tracked debris, and the ISS canceled a planned collision avoidance maneuver when the estimated miss distance increased to an acceptable value shortly before the conjunction.



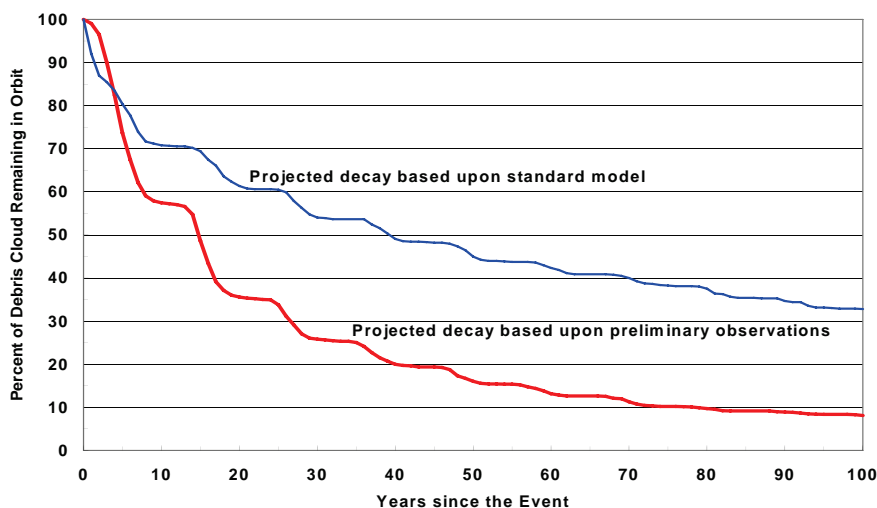
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Projected Debris Decay Rate

- Due to the apparent higher than expected debris area-to-mass ratios, the orbital decay rates will likewise be accelerated. However, the greater than expected number of large debris yields a lifetime large debris collision risk for the cloud of essentially the same magnitude.
 - For smaller debris collision risks may be greater than model predictions.



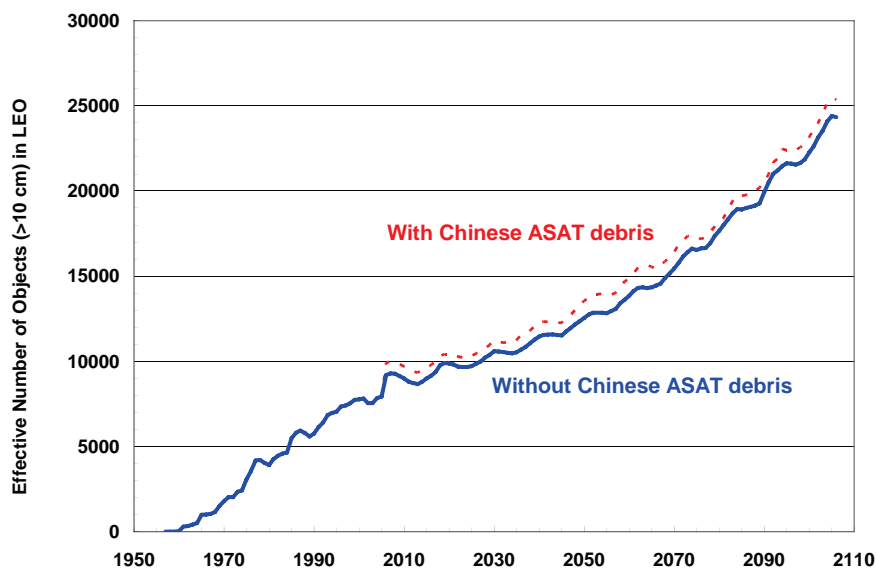
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Long-term Effects on the Environment

- NASA's evolutionary satellite population model LEGEND was employed to predict the possible increase in the long-term large object population resulting from the Fengyun-1C debris cloud.



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Summary

- **The breakup of Fengyun-1C stands as the most severe satellite fragmentation of the space age, and its detrimental effects will be very long-lasting.**
 - Cataloged debris increased by ~ 25 %
 - > 1 cm population increased by ~ 100 %
- **In analyses to date, the number of debris greater than 10 cm produced appears to markedly exceed the number predicted by the NASA standard breakup model for hypervelocity collisions.**
- **Both the IADC Space Debris Mitigation Guidelines and the UN COPUOS Space Debris Mitigation Guidelines explicitly recommend the avoidance of any intentional destruction which would result in long-lived debris.**
 - The test involving Fengyun-1C is non-compliant with those recommendations.

I2-4 スペースデブリ低減策の概観

○西田 信一郎（宇宙航空研究開発機構／総合技術研究本部／宇宙先進技術研究グループ）

Overview of Space Debris Mitigation Measures

Shin-Ichiro Nishida (IAT / JAXA)

Key Words: Debris, Mitigation, Removal, Capture

概要

寿命の尽きた人工衛星が軌道上に放置されたスペースデブリ（宇宙ゴミ）の増加が問題となっている。有人宇宙機や稼働中の人工衛星がスペースデブリやその破片と衝突して致命的なダメージを受ける危険性が年々高まっている。また、スペースデブリ同士の衝突によって破片を生じ、自己増殖的にスペースデブリが増加する「デブリシンδροーム」状況の発生が危惧されている。そこで、JAXAでは、スペースデブリを軌道上から除去するシステムの研究を行っている。

スペースデブリの衝突確率が高く、デブリシンδροームの起源となりやすい軌道として、軌道高度が500～800 kmの地球周回低軌道（LEO）が挙げられる^[1]。この辺りの軌道は、地球観測衛星の軌道として有用な軌道であり、特に高軌道傾斜角の太陽同期軌道に多数の衛星残滓およびロケット上段残滓が残存している。これらの大型の残滓の何割かを軌道上から除去することにより、相互衝突によるスペースデブリの増加を抑えることが可能と考えられる。そこで、新規の地球観測衛星の打上時に相乗り衛星によりスペースデブリを除去するシステムの検討を実施している。

LEOからの除去には、スペースデブリを減速して軌道高度を下げ、大気圏に再突入させて燃え尽きさせる方法が効率的であり、そのための軌道変換アクチュエータとして導電性テザーが有望である。

スペースデブリに接近し、ロボットアームによってスペースデブリを捕獲し、導電性テザーを取り付けることにより、スペースデブリを軌道上から除去することが可能となる。

スペースデブリ除去システムのキー要素技術として、ランデブ・運動計測用の画像センサ、捕獲用ロボットアームと制御方式、導電性テザー装置の研究開発を進めている。

本講演では、スペースデブリ除去システムの概念について述べ、各キー要素技術の研究開発状況につき報告する。



Overview of Space Debris Mitigation Measures

Shin-Ichiro Nishida, Satomi Kawamoto, Yasushi Ohkawa,
Fuyuto Terui, Atsushi Nakajima and Shoji Kitamura

Institute of Aerospace Technology (IAT)
Japan Aerospace Exploration Agency (JAXA)

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Outline

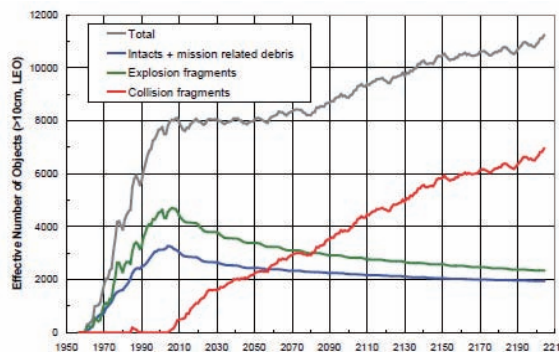
- I. Introduction
- II. Strategy for Removal of Space Debris
- III. R&D of Key Technologies
- IV. Road Map of Debris Removal System
- V. Conclusion



Introduction

Space Debris Syndrome

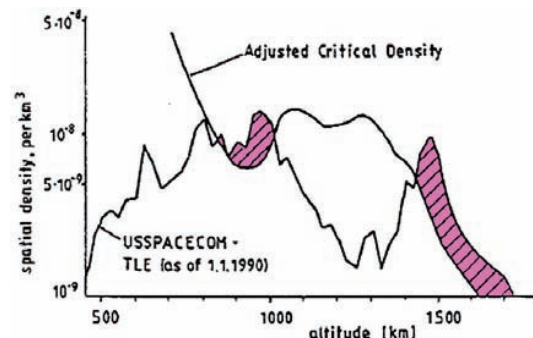
- The number of debris increases by the collision self-proliferating according to the transition forecast of NASA even when any launch are not done after 2005.
- It is necessary **to remove existing space debris**, especially of the height of 800—1000km and 1400—1700km.



Effective number of objects forecasted by NASA (LEGEND):
NASA The Orbital Debris Quarterly News (2006, April)

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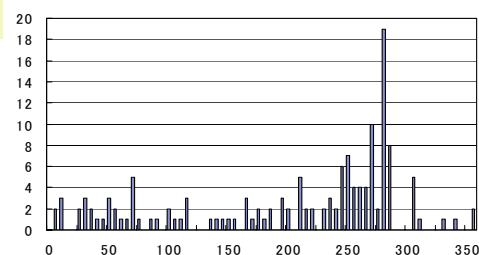
Kessler, Collisional cascading: The limits of population growth in low Earth orbit, Advances in Space Research 11(12):63-66, 1991

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Strategy for Removal of Space Debris

- Sun-synchronous low earth orbits (500—800km) are much useful to earth remote sensing, and many remnants of used satellites and upper stages remain.
- Orbital transformation into an orbit of **near inclination angle** can be carried out with little fuel.
- Dead satellites in near sun-synchronous orbit can be removed at the launch of a new **remote sensing satellite** by using of its **piggyback satellites**.



Histogram of debris around 800km-altitude sun-synchronous orbit
(the horizontal bar is RAAN)

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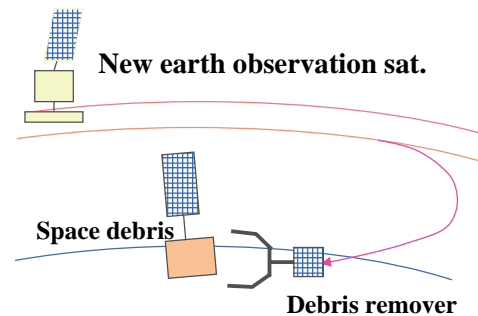
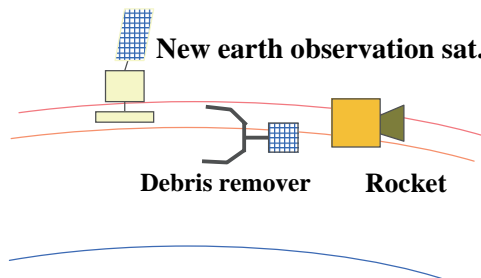
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Strategy for Removal of Space Debris

- Debris remover satellite is launched with a new earth remote sensing satellite into sun-synchronous orbit.
 - Single debris remover: Piggyback small satellite
 - Multi debris remover : Payload adapter satellite
- The debris remover satellite moves to an orbit of a space debris.



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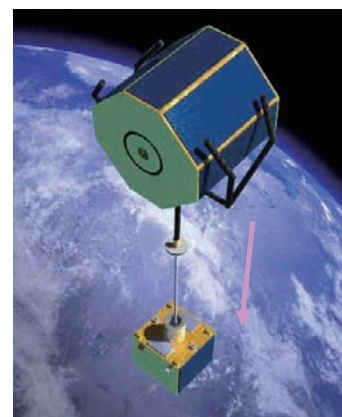
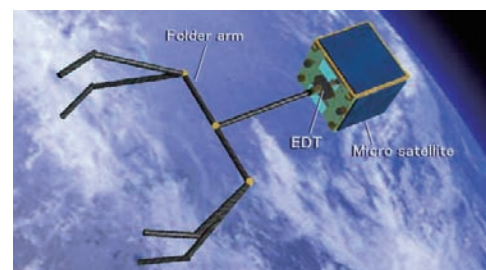
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Strategy for Removal of Space Debris

Space Debris Micro Remover

Items	Characteristics	Remarks
Size	700 × 700 × 600mm	
Weight	140kg	Fuel: 25kg
Power	100W	Average
Attitude control	3 axes control	3 wheels
Thrusters	1N × 8	
Rendezvous Sensors	GPS receiver Star tracker Stereo vision	



Extension of electro-dynamic tether

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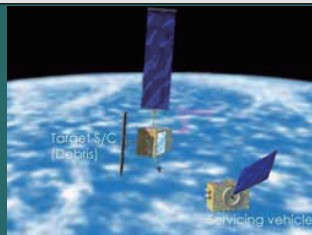
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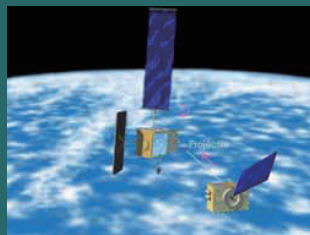


Strategy for Removal of Space Debris

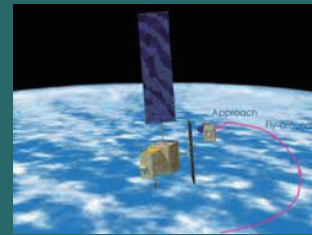
Removal sequence



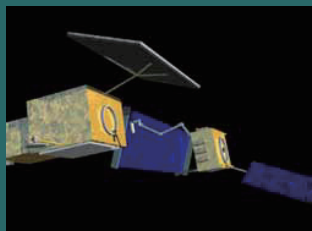
Step1: Motion measurement



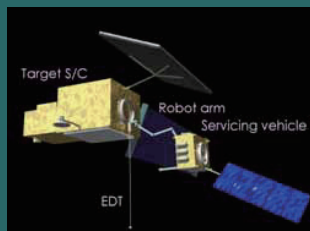
Step2: Momentum reduction



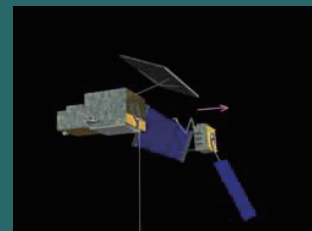
Step3: Fly-around & approach to target



Step4: Capture of target



Step5: Deployment of tether



Step6: Release of target

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Space Debris Remover

Characteristics

- Launch:
Compact shape and low mass to allow a piggyback launch with an earth observation satellite.
- Rendezvous:
Simple rendezvous system consists of a GPS receiver, a star tracker and vision sensors.
- Capture:
Extensible light weight robot arm for debris capture.
- Removal:
Electro-dynamic tether package

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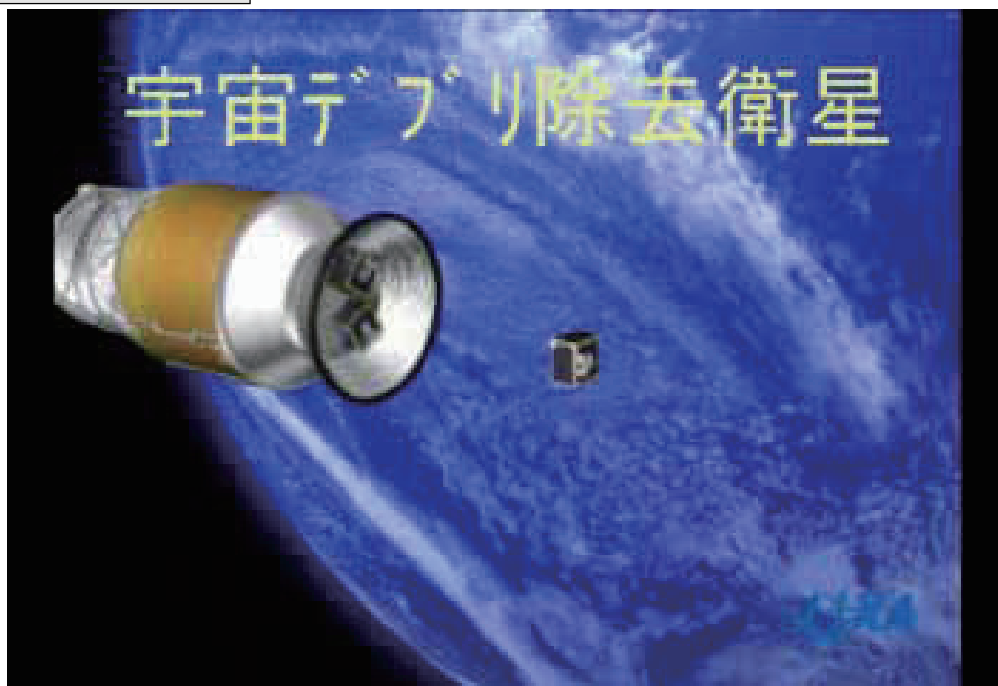
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Strategy for Removal of Space Debris

Removal sequence



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Space Debris Remover

JAXA is doing research and development of the following key technologies,

- Actuator for debris orbit transfer
Electro-dynamic Tether
- Sensor for rendezvous and motion measurement
Motion measurement vision sensor
- Target capture by using of robot arm
High response force controlled robot arm

Prototyping of each hardware/software was furthered.

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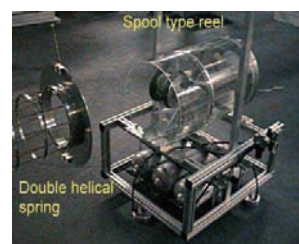
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R&D of Key Technologies

Electro-dynamic Tether

- Tether: A combination of a bare wire as the electron collector and an electric field release type cathode as the electronic emitter is the most suitable for a expendable EDT system.
- Reel: By using a passive non-contact eddy current braking element, stable braking performance was achieved at the end phase of wire extension.
- Release mechanism: A DHS(double helical spring) is suitable because of its compactness in the stowed configuration.



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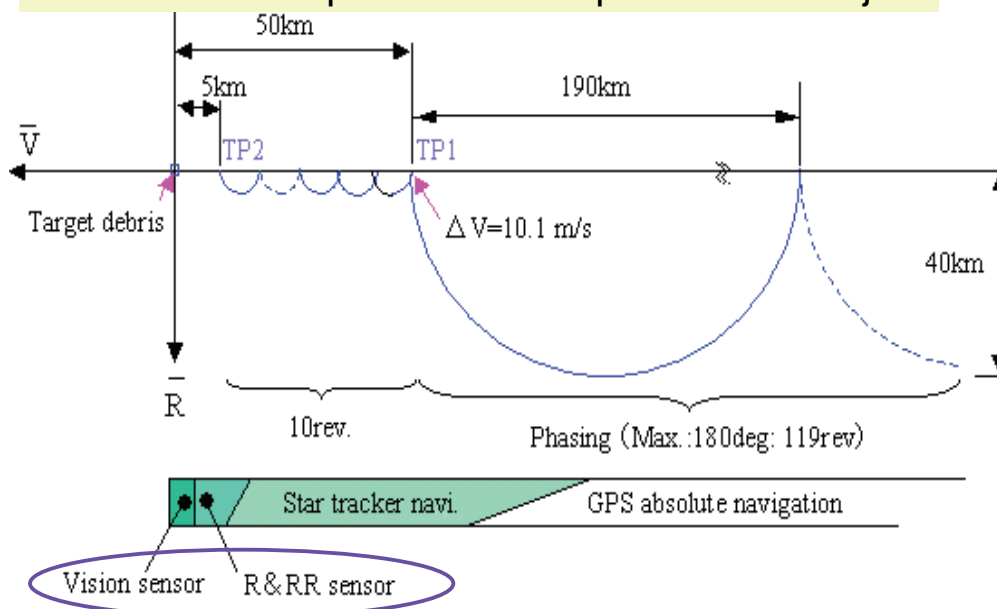
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R&D of Key Technologies

Rendezvous & motion measurement sensor

Rendezvous sequence with a space debris object



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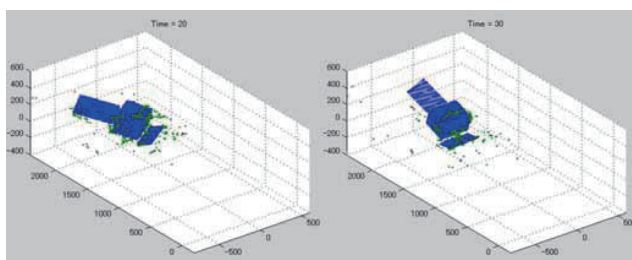
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R&D of Key Technologies

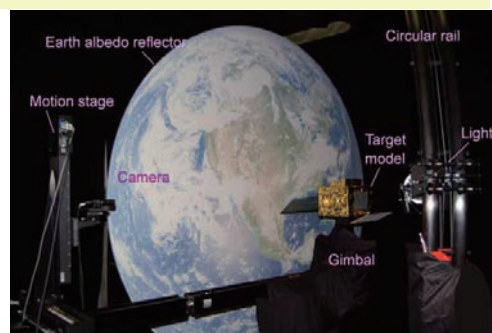
Vision sensor

- An algorithm has been developed for estimating the **motion** (relative position and attitude) of space debris.
- The algorithm uses a combination of **stereo vision** and 3D model matching, applying the **Iterative Closest Point (ICP)** algorithm, and uses time series of images to increase the reliability of measurement.



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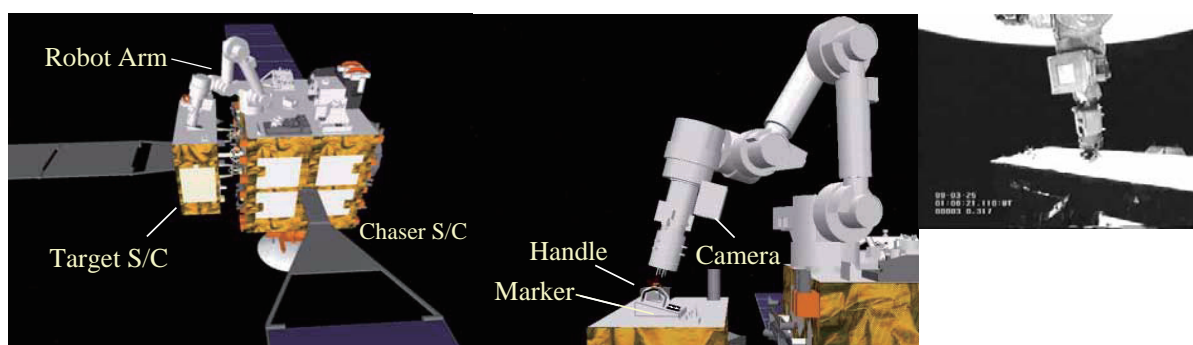
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R&D of Key Technologies

ETS-VII Flight Demonstration on 1998

- **Autonomous target capture experiments** have been conducted successfully on the ETS-VII satellite for the case of a **visual marker** equipped with a **handle** to facilitate grasping by a robot arm.
- **Visual feedback control** and **force control** function were applied to the robot arm. And they worked very good.



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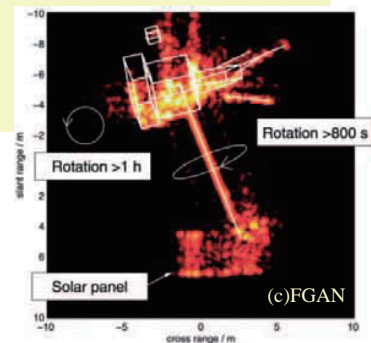
R&D of Key Technologies

Debris capture by a robot arm

■ **Capture** is an essential process for the retrieval of large space debris objects by other spacecraft.

■ It is common for large debris objects to **tumble**, due to angular momentum that remained in their attitude control systems when failure occurred.

■ For example, the **ADEOS** is tumbling in rotating rate around **0.3deg/sec**.



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R&D of Key Technologies

Capture Strategy

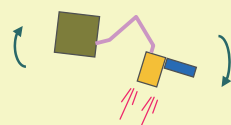
(1) The chaser observes the target's attitude and motion via image processing and begins **tracking** of a point to be grasped.



(2) The target is grasped by the robot arm. **Impact loads due to rate difference/position gap** at the time of capture are relieved by means of arm force/torque control.



(3) After target capture, the robot arm is slowed according to a deceleration profile.



(4) De-rotation of the target and the chaser is done using RCS of the chaser.

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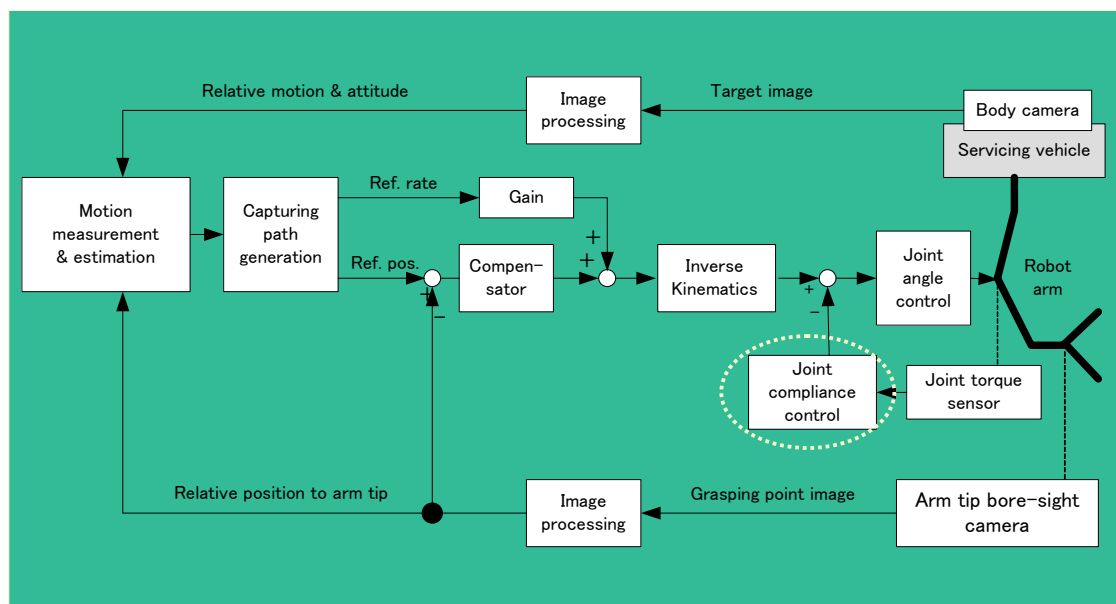
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R&D of Key Technologies

Debris capture by a robot arm

Block diagram of robot arm control system



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R&D of Key Technologies

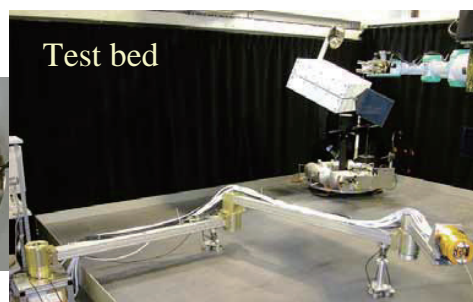
Debris capture by a robot arm

■ As a control system of a robot arm to buffer and braking residual motions of space debris at the time of capture, joint virtual depth control and joint mechanism with torque sensor have been developed.

■ It achieves high response and good control characteristics by the collocation of a torque sensor and an actuator.



New joint mechanism & torque sensor



Test bed



Extensible boom

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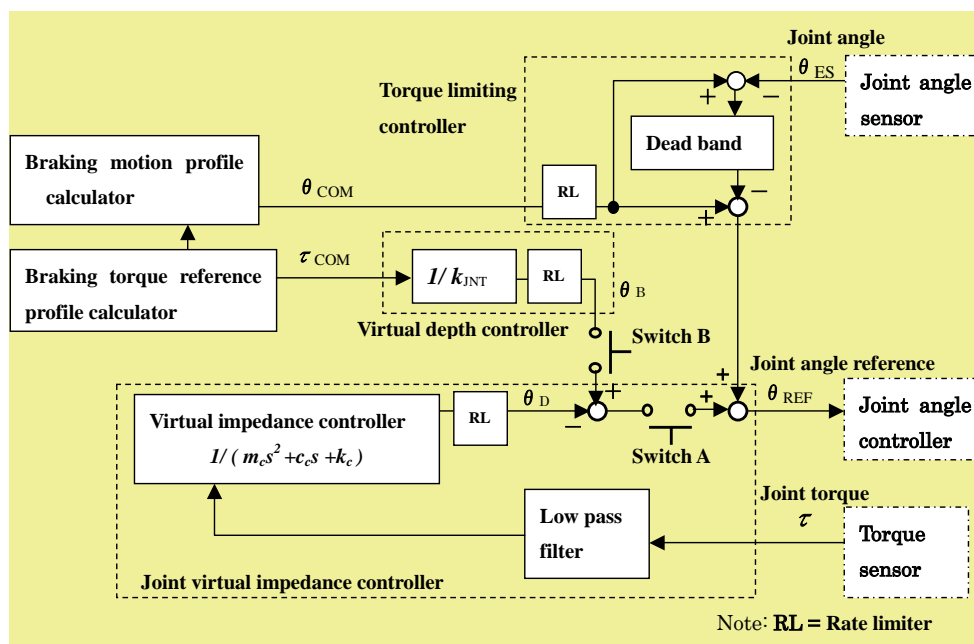
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Joint Virtual Depth Control for debris capture and braking



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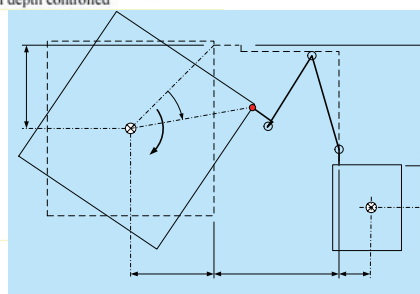
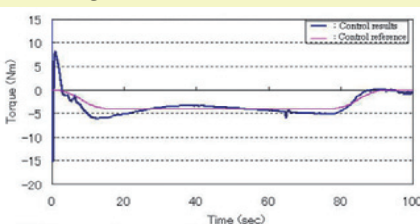
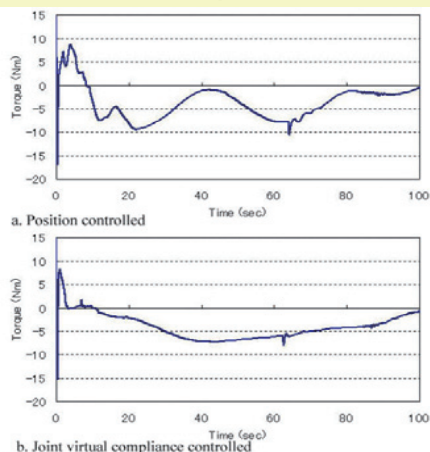
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R&D of Key Technologies

Dynamical simulation results

- Simulation results of three kind of control methods is shown below respectively.
- Braking operation with Joint Virtual Depth control was along with the slowdown profile and the braking was sufficient.



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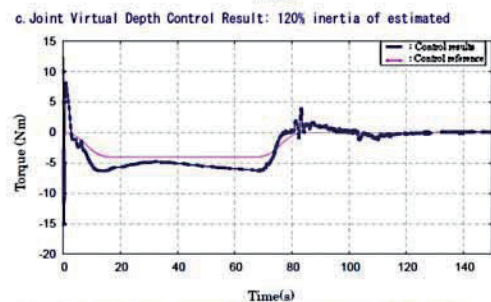
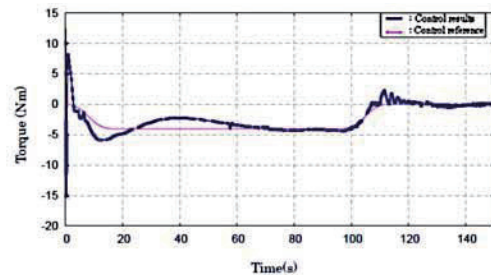
R&D of Key Technologies

Dynamical simulation results

■ Right figure shows simulation results for larger estimation error of target inertia cases.

■ The target inertia is set as 120% and 80% of estimated one respectively.

■ In both cases, braking of target rotation are smoothly accomplished.



d. Joint Virtual Depth Control Result: 80% inertia of estimated

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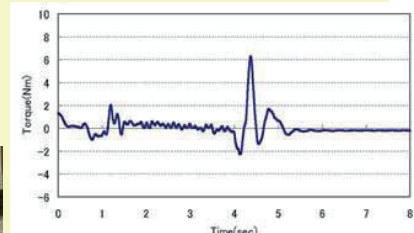
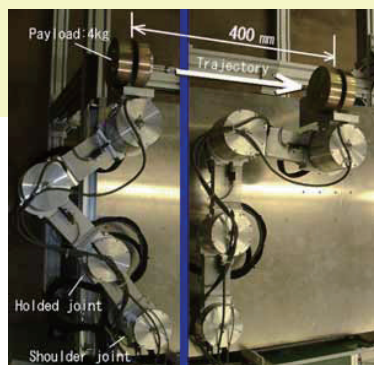
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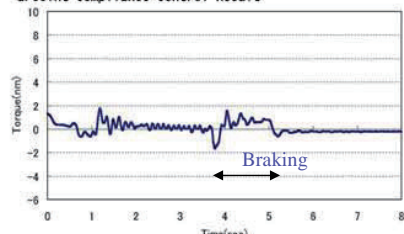
R&D of Key Technologies

Experiment of target motion braking

- An experiment on relieving the braking load was conducted with a 2-dimensional arm.
- Braking/stop operation trials were carried out with Joint Compliance control and Joint Virtual Depth control systems, and the responses were compared.
- In the Joint Virtual Depth control case, there is little oscillation, and the expected braking force is generated.



a. Joint Compliance Control Result



b. Joint Virtual Depth Control Result

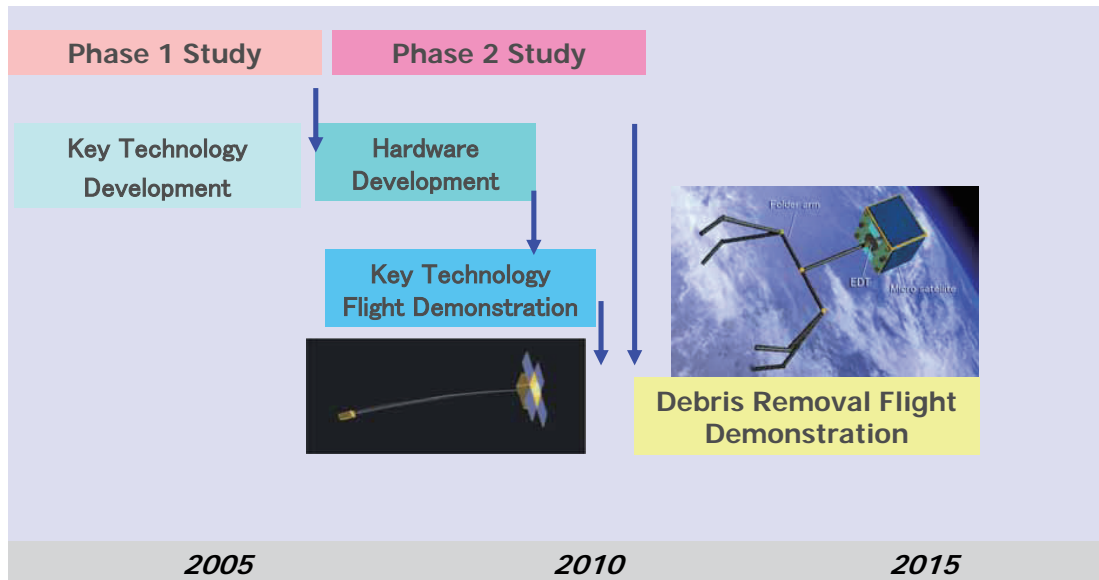
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Road Map of Debris Removal System



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Conclusion

- JAXA is investigating an active space debris removal system using robotic satellite.
- Dead satellites in near sun-synchronous orbit can be removed at the launch of a new remote sensing satellite by using of its piggyback satellites.
- The applicability of electro-dynamic tether technology as its high efficient orbital transfer system.
- The development of the robotic debris capture is also advanced well by the development of various, new control and sensor techniques.
- As the result of these activities, the realization of a new active space debris removal system is becoming more feasible.

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付録・講演プログラム

第3回スペースデブリワークショッププログラム

主催：(独) 宇宙航空研究開発機構 (JAXA) 総合技術研究本部 宇宙先進技術研究グループ

後援：(社) 日本航空宇宙学会

日時：平成20年1月21日(月)～22日(火)午前

場所：日本科学未来館(東京都江東区青海2-4-1) 7階第2会議室

第1日 1月21日(月)

10:00-10:10 開会挨拶

北村正治(IAT/JAXA)

10:10-11:50 国際セッションー1 (使用言語：英語)

Chairperson：T. Nakajima(ISAS/JAXA)

10:10-10:50 **Keynote Address:**

I1-1 R & D Strategy for Space Debris Related Issues

A. Kato (IAT/JAXA)

10:50-11:50 **Invited Lecture:**

I1-2 Orbital Debris Research in the United States

E. Stansbery (Orbital Debris Program Office/NASA JSC)

11:50-13:10 昼休み

13:10-14:50 セッションー1 「観測・モデル化」

司会：五家建夫(IAT/JAXA)

13:10-13:30 **1-1 JAXA 総研本部におけるデブリ光学観測技術の研究**

中島厚、黒崎裕久、柳沢俊史(IAT/JAXA)

13:30-13:50 **1-2 光学望遠鏡を用いた未知静止デブリの軌道決定法の提案**

柳沢俊史、黒崎裕久、中島厚(IAT/JAXA)、梅原広明(NICT)

13:50-14:10 **1-3 JAXA におけるデブリ衝突回避運用の検討**

堀井道明、森 茂博、工藤伸夫、廣瀬史子(OSFO/JAXA)

14:10-14:30 **1-4 JAXA におけるデブリ解析ツールの開発**

河本聡美(IAT/JAXA)

14:30-14:50 **1-5 地球低軌道におけるスペースデブリ環境の推移モデル**

鳴海智博(Graduate Student, Kyushu Univ.)、花田俊也(Kyushu Univ.)、

河本聡美(IAT/JAXA)

14:50-15:10 休憩

15:10-16:10 セッション2 「防御」

司会：北澤幸人(IHI)

15:10-15:30 **2-1 JAXA におけるデブリ防御の研究概要**

永尾陽典(IAT/JAXA)

- 15:30-15:50 **2-2** デブリ防護研究における **Hypervelocity Impact Symposium/Society** の位置付について
片山雅英 (伊藤忠テクノソリューションズ)
- 15:50-16:10 **2-3** 超高速衝突後の二次デブリ雲の挙動とモデル化
赤星保浩(Kyushu Institute of Technology KIT)

16:10-16:30 休憩

16:30-18:10 セッション3 「デブリ低減対策」

司会：西田信一郎(IAT/JAXA)

- 16:30-16:50 **3-1** 宇宙環境保全ビジネスモデルとデブリ回収計画
峰正弥 (SJAC 次世代プロジェクト推進委員会)
- 16:50-17:10 **3-2** デブリデオービット用導電性テザーシステムのキー要素技術
大川恭志、河本聡美、西田信一郎、北村正治(IAT/JAXA)
- 17:10-17:30 **3-3** 産業界から見たデブリ問題
池内正之 (NT スペース)
- 17:30-17:50 **3-4** **USERS** サービスモジュールの大気圏再突入消滅について
牛越淳雄、中村修治、伊地智幸一、金井宏
(財) 無人宇宙実験システム研究開発機構 USEF)
- 17:50-18:10 **3-5** デブリ対策標準の適合性審査の状況
関田隆一(S&MA/JAXA)

第2日 1月22日(火)午前

10:00-12:00 国際セッションー2 (使用言語：英語)

Chairperson：A. Kato (IAT/JAXA)

- 10:00-10:30 **I2-1 Current Problems of Debris Environment Models and Related Studies of JAXA**
Y. Kitazawa(IHI), S. Fukushima, M. Uchino, Y. Akahoshi (KIT), T. Goka (IAT/JAXA),
A. Sakurai (iQPS Inc.), T. Yasaka (iQPS Inc., Kyushu Univ.), K. Funakoshi (iQPS Inc.),
T. Hanada (Kyushu Univ.), H. Matsumoto (IAT/JAXA), T. Noguchi (Ibaraki Univ.),
R. Yamanaka, Y. Kimoto, and M. Suzuki (IAT/JAXA)
- 10:30-11:00 **I2-2 Outcome of Recent Satellite Impact Experiments**
T. Hanada (Kyushu Univ.)
- 11:00-11:30 **I2-3 The Characteristics and Consequences of the Break-up of the Fengyun-1C Spacecraft**
E. Stansbery, M. Matney, and N. Johnson (Orbital Debris Program Office/NASA JSC)
- 11:30-12:00 **I2-4 Overview of the Space Debris Mitigation Measures**
S. Nishida (IAT/JAXA)

12:00-12:10 閉会挨拶

中島厚(IAT/JAXA)

午後：第4回宇宙環境シンポジウムが開会。(1月22日(火)午後-23日(水)夕方)

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