B2

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

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

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

Orbital Debris Modeling and Applications

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Orbital Debris Modeling

Orbital debris modeling describes:

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

Applications

<u>Orbital debris modeling</u> can be applied to:

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

Debris Generation

To characterize and predict physical properties of breakup fragments

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

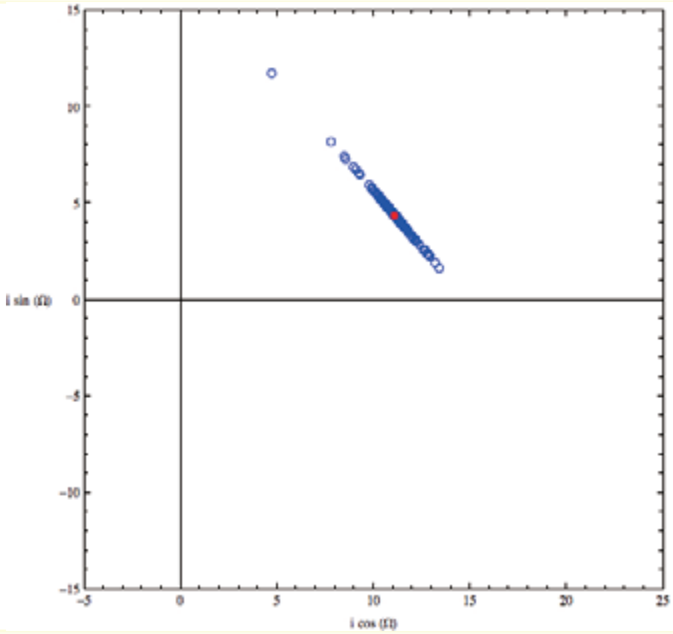
Example and Result of Satellite Impact Fragmentation

Orbit Propagation

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

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

Example of Evolution of Explosion Fragments in the Geostationary Region



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

i = inclination
Ω = ascending node

• = US Titan IIIC Transtage
○ = explosion fragments

2014.12.17-19 The Sixth Space Debris Workshop 6

Future Projections

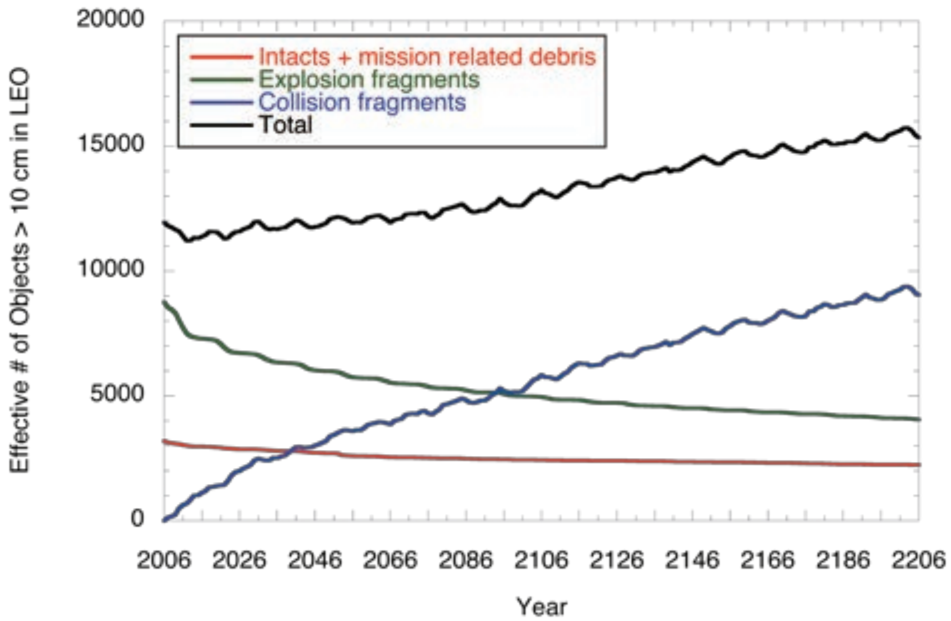
- Orbital debris evolutionary models
  - To investigate the stability of the current or future orbital debris populations
  - To discuss what and how to do for orbital debris mitigation and environmental remediation
- GEODEEM
  - To track objects in the geostationary region (or with eccentricity < 0.2,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

2014.12.17-19 The Sixth Space Debris Workshop 7

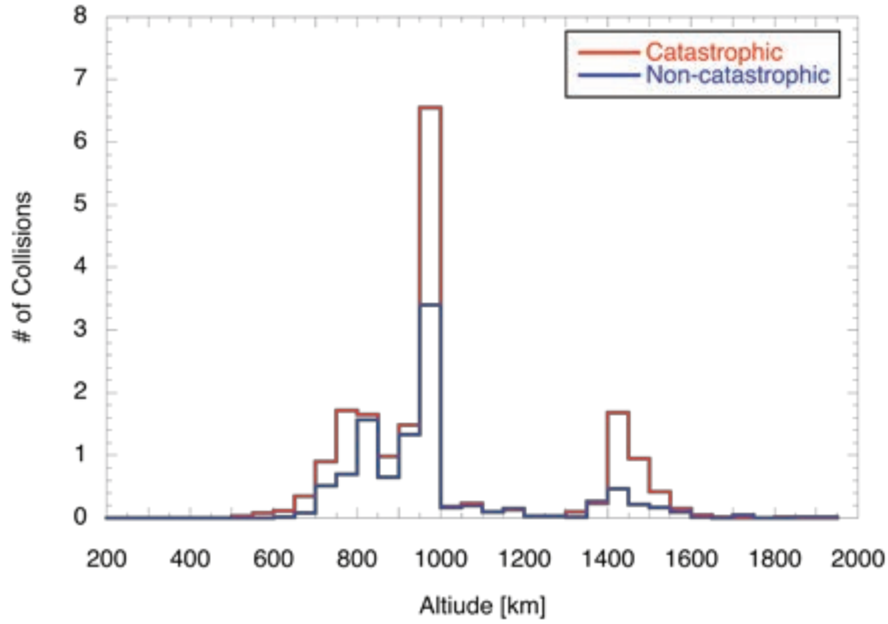
Projection Scenario

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

LEO Population Growth



Collision Locations



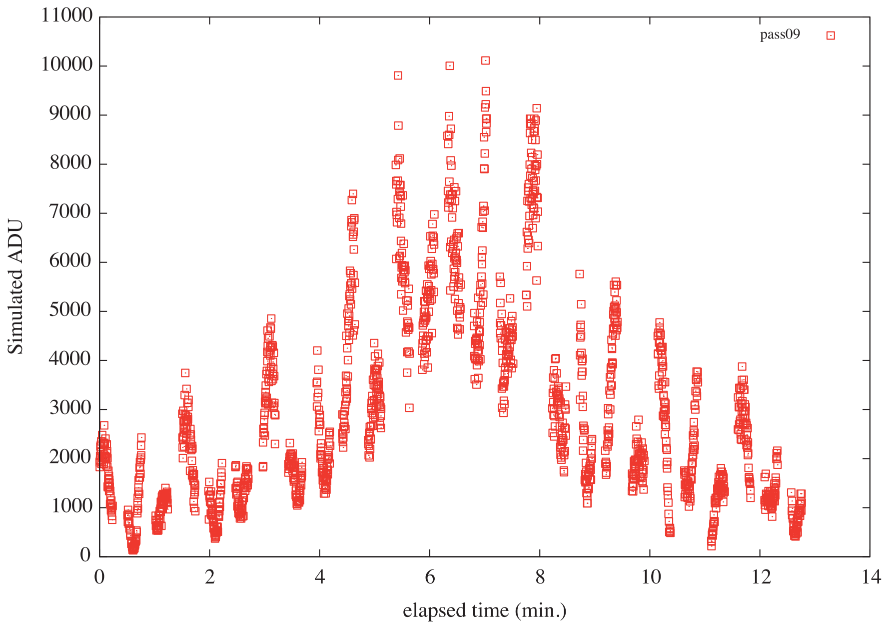
Light Curves

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

Efforts to Be Emphasized

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

Example of Light Curves



Optical Measurements

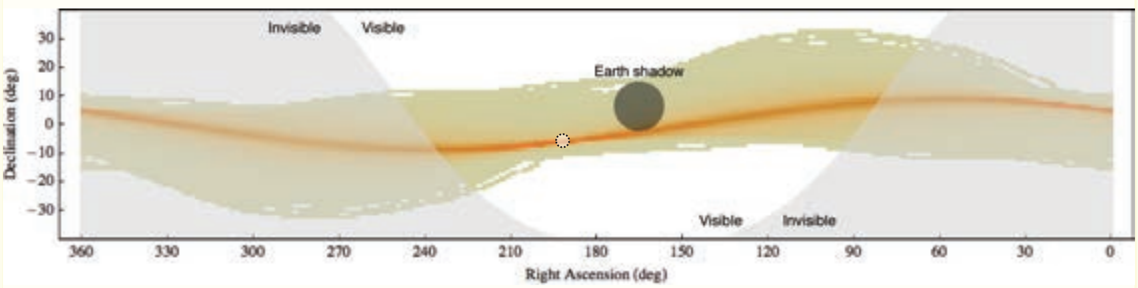
- Four very old Titan IIIC Transtages (1966-053J, 1667-066G, 1973-100D, 1978-113D) have experienced abrupt orbital changes for unknown reasons
  - Orbital changes have been equivalent to ΔV of only **a few meters per second**
  - **No debris clouds** have yet been associated with these Transtages
- ESA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

Issues to Be Solved and Solutions

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

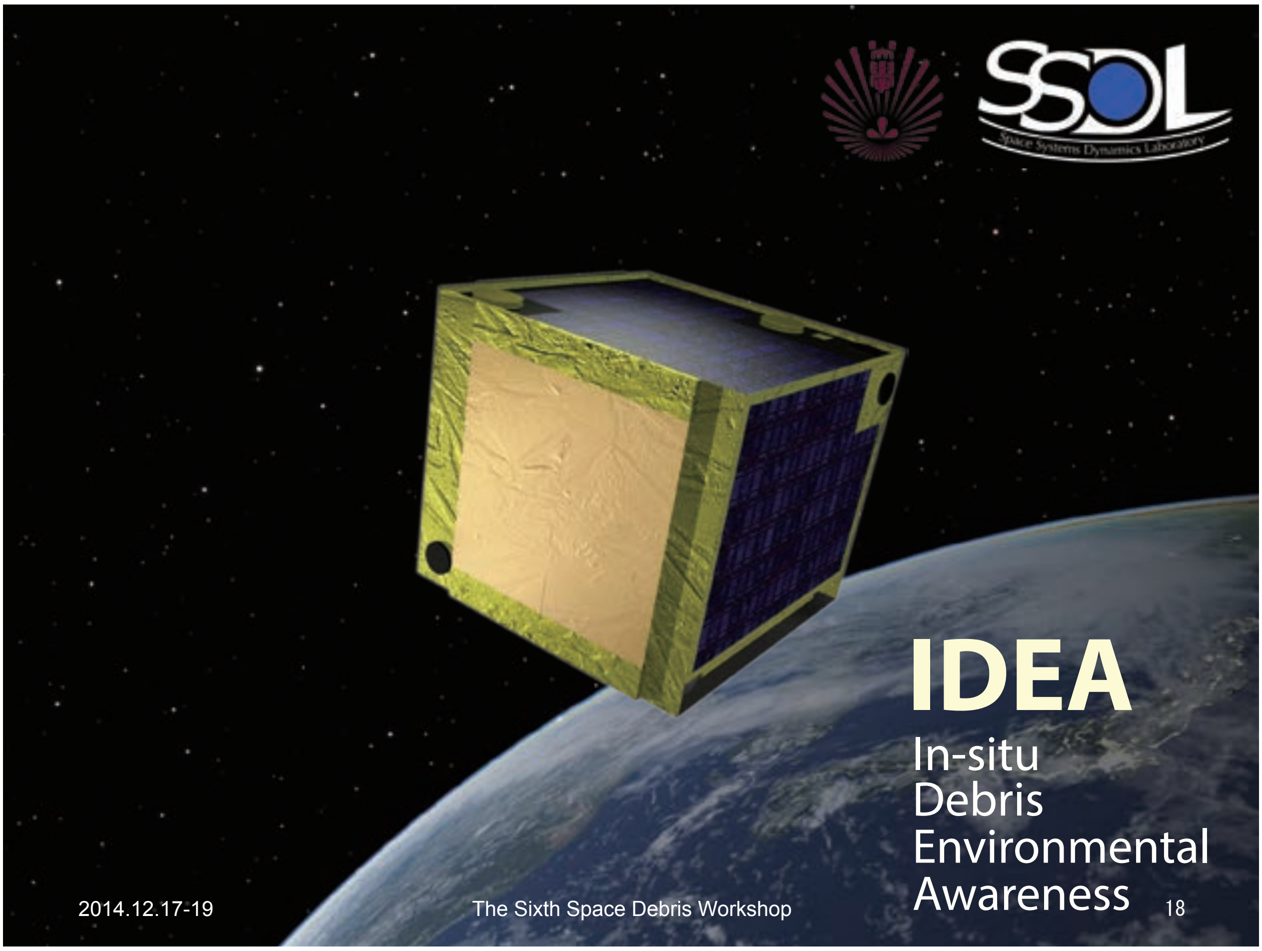
Example of Effective Observation Planning

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



In-situ Measurements

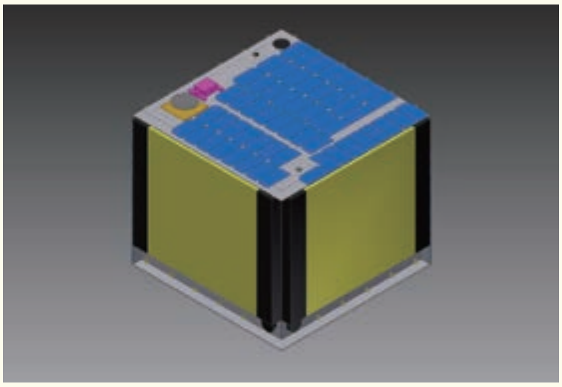
- Current environment has not been defined well because
  - Measurements of micron-size debris are
    - Nearly impossible from the ground
    - **Quite limited** in terms of orbital regimes
    - **Not continuously** available
  - Latest information on micron-size debris may
    - **Not be enough regarding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



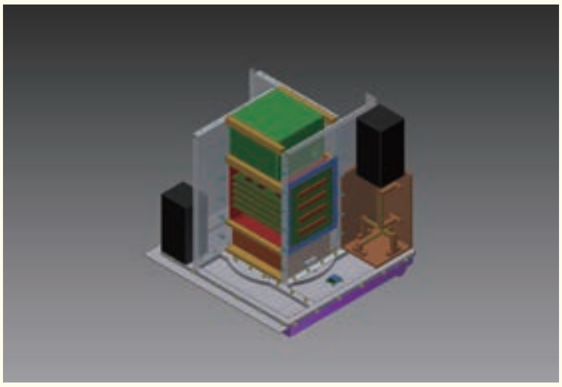
IDEA the project for In-situ Debris Environmental Awareness

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

Schematic Design of IDEA Satellite



External View

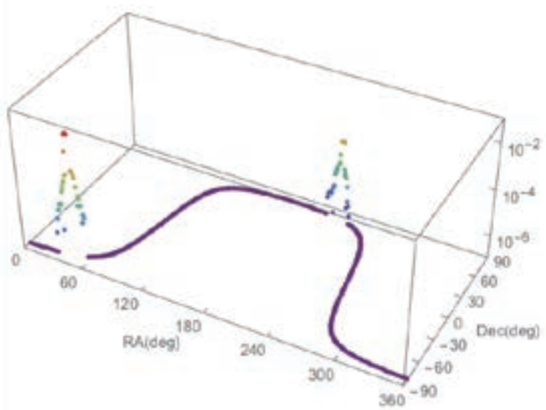


Inner Layout

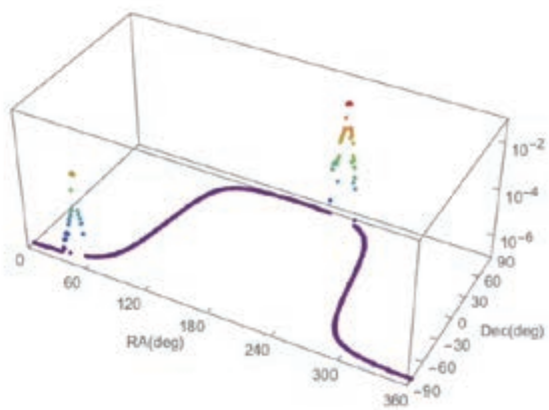
Dimension	**50 cm by 50 cm by 50 cm**
Mass	**25 kg**
Power	**31.5 W**

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

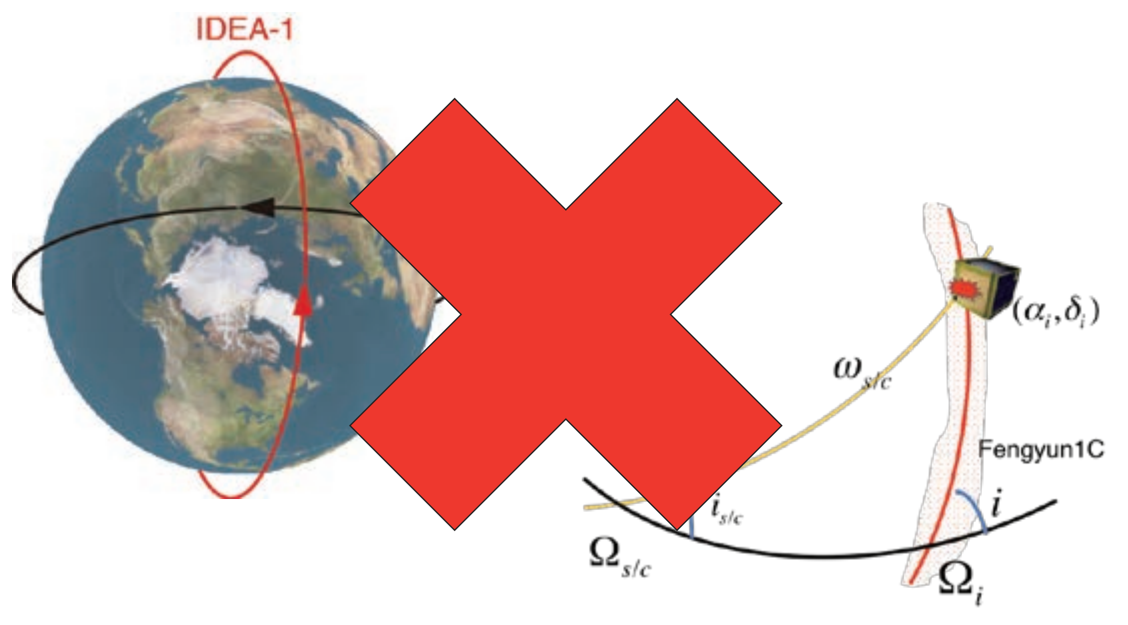
Left Sensor



Right Sensor

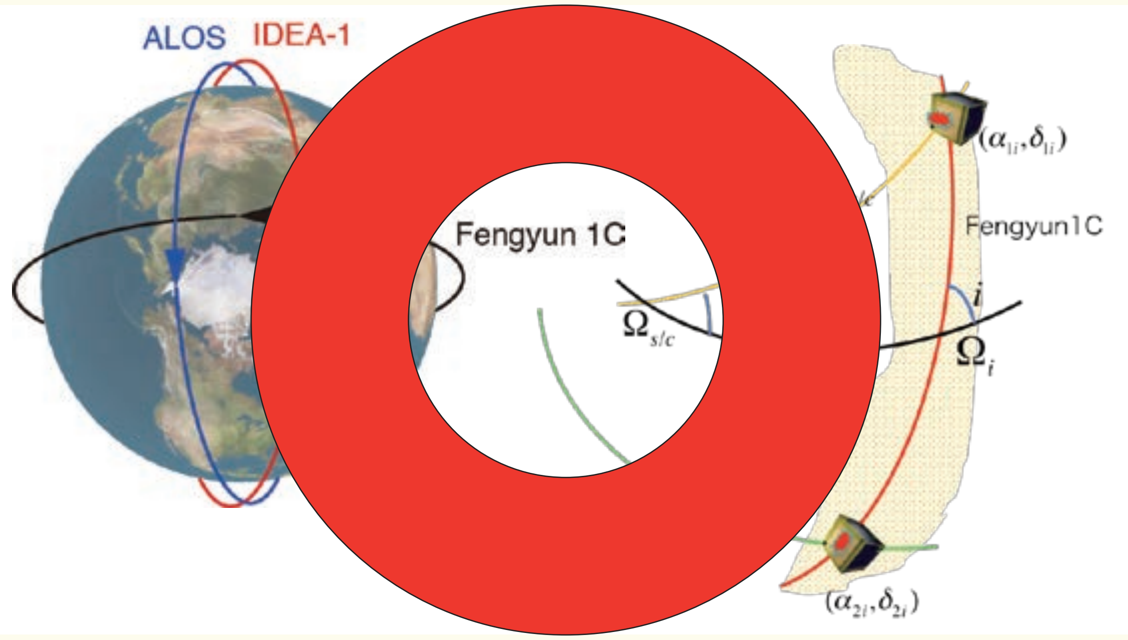


One Measurement Satellite



2014.12.17-19　The Sixth Space Debris Workshop　22

Two Measurement Satellites



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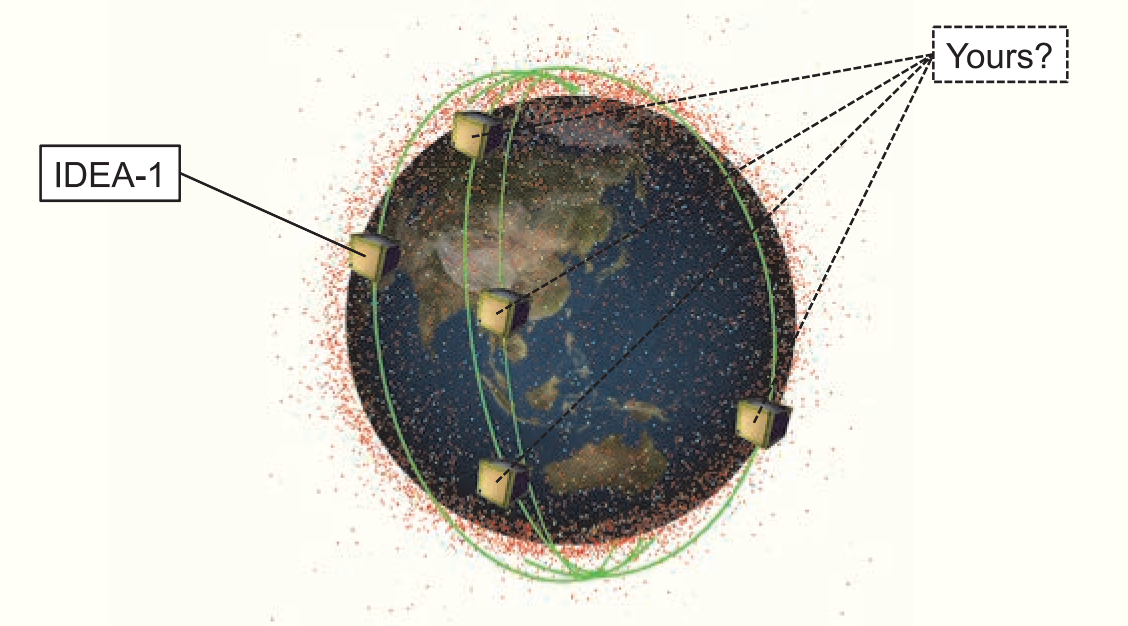
Future Vision of Collaboration Through IDEA



Summary

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