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軌道上観測データを用いた微小スペースデブリの環境推定

Environmental estimation on sub-millimeter-size debris utilizing in-situ measurements

古本政博, 出水澤大悟, 吉村康弘, 花田俊也(九州大学)
Masahiro Furumoto, Daigo Izumizawa, Yasuhiro Yoshimura and Toshiya Hanada
(Kyushu Univ.)

大きさが 2mm 以下の微小なスペースデブリは地上から観測することが不可能であるが, 宇宙機の機能喪失をもたらすような損傷を与え得る. そのため, 微小デブリに対しては軌道上観測を用いた環境把握が不可欠であり, 衛星による微小デブリの軌道上観測計画が各国で進められている. 本発表では, 逐次モンテカルロフィルタおよび観測され得るデブリの軌道力学的特性を利用し, 軌道上観測により得られる微小デブリの衝突データを用いて軌道環境を推定する手法を提案する. また, 本発表では, 円軌道上の観測衛星により得られるデータを用いて本発表で提案する手法が軌道上環境を正しく推定できることを, シミュレーションにより検証する. さらに, 観測衛星の軌道が楕円である場合に必要となる, 楕円軌道上の衛星により観測され得るデブリの軌道力学的特性と本発表で提案する手法の拡張についても述べる.

Space debris smaller than 2 mm cannot be tracked or detected by ground-based observations even though an impact of such small debris can cause a fatal damage on a spacecraft. Therefore, the environment of sub-millimeter-size debris must be monitored utilizing in-situ measurements.
This paper proposes a statistical method to estimate the environment of sub-millimeter-size debris utilizing in-situ measurements. The proposed method consists of a sequential Monte Carlo filter and natures of orbits on which debris may be detected by the satellite. This paper also evaluates that the proposed method can sufficiently estimate the environment utilizing simulated impacts onto the satellite.
Furthermore, this paper describes modifications to apply the proposed method to measurement data obtained by a satellite in an elliptic orbit.

The 8th Space Debris Workshop
3-5 December, 2018, Chofu, Japan

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Masahiro Furumoto
Daigo Izumizawa
Yasuhiro Yoshimura
Toshiya Hanada

Kyushu University, Japan.

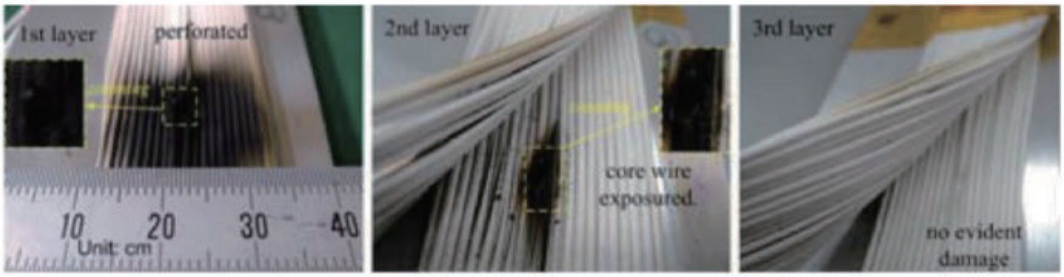
Outline

- Background
  - Sub-millimeter-size debris
  - In-situ measurements
- Estimation Method
  - SMC filter
  - Natures of detectable debris
- Simulation Result
- Model Generalization

Background

Sub-millimeter-size Debris

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



Cables severed by an impact with simulated debris (0.3 mm)

Nitta et. al., 2010

Background

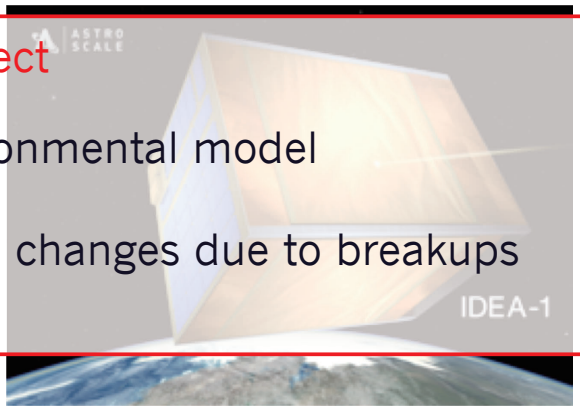
In-situ Measurements

❖ IDEA project (In-situ Debris Environmental Awareness)

- Kyushu University has initiated in 2011
- Satellites record the position and time of impacts
- 1st satellite “IDEA OSG 1” was lost in Nov. 2017

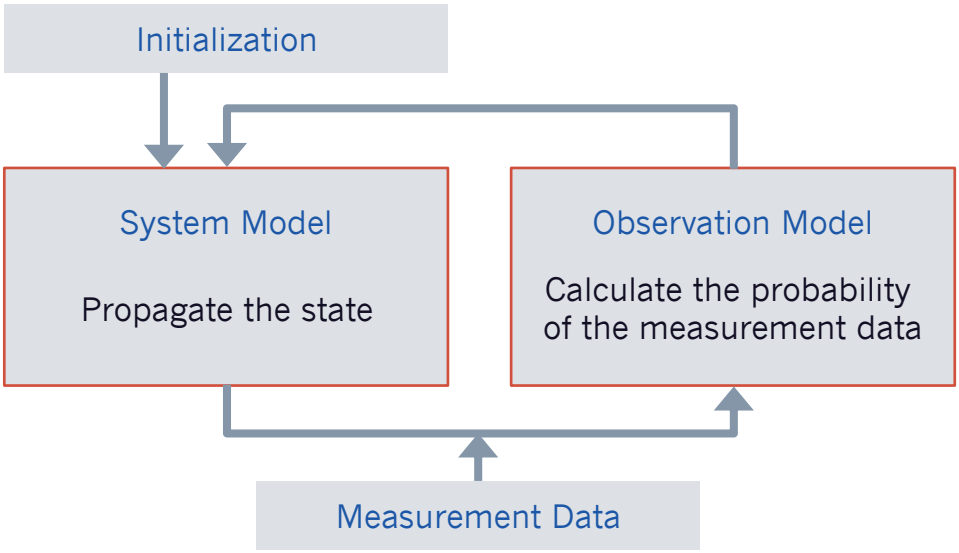
Objectives of the IDEA project

- Develop a dynamic environmental model
- Recognize environmental changes due to breakups



Estimation Method

❖ Dynamic Estimation



❖ Sequential Monte Carlo (SMC) filter
- ✓ Statistical
- ✓ Non-linear

Estimation Method

System Model

❖ Approximation of the environment
- Ensemble of orbits
- Each orbit represents a lot of pieces of debris
- Debris are in circular orbits

➢ State vector: $\boldsymbol{x} = (N_d, \Omega_1, i_1, \Omega_2, i_2, \ldots, \Omega_n, i_n)$

N_d: Number of debris in each orbit

$\Omega_1, i_1, \Omega_2, i_2, \ldots, \Omega_n, i_n$: Orbital plane of each orbit

➢ Propagation

Nodal regression + White noise

$$N_d(t+\Delta t) = N_d(t) + \Delta t v_N$$

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

$$i(t+\Delta t) = i(t) + \Delta t v_i$$

Estimation Method

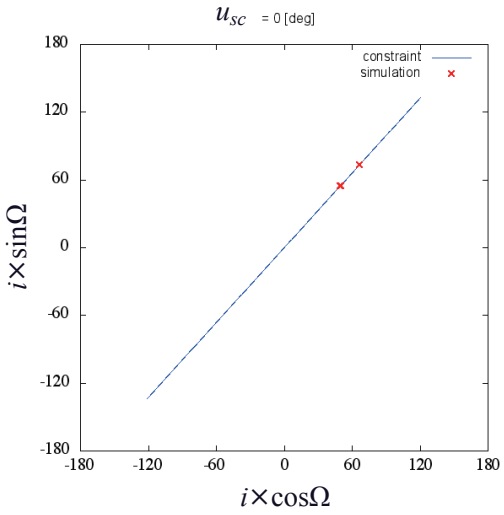
Observation Model

To calculate the probability of the measurement data, the orbital plane on which debris may be detected and the collision flux should be determined

◆Orbital plane constraint

The orbital plane on which debris may be detected by the satellite is constrained by the position of the satellite (Furumoto et al., 2017)

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



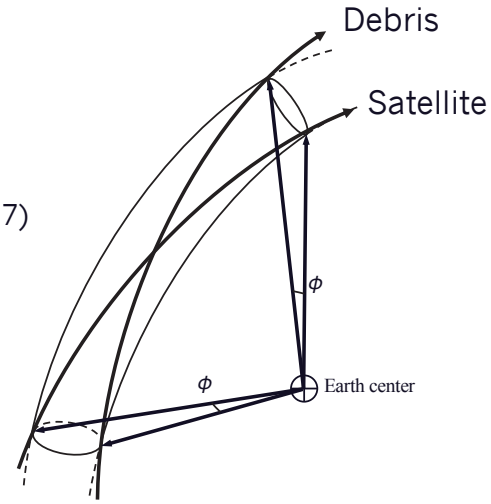
Estimation Method

Observation Model

To calculate the probability of the measurement data, the orbital plane on which debris may be detected and the collision flux should be determined

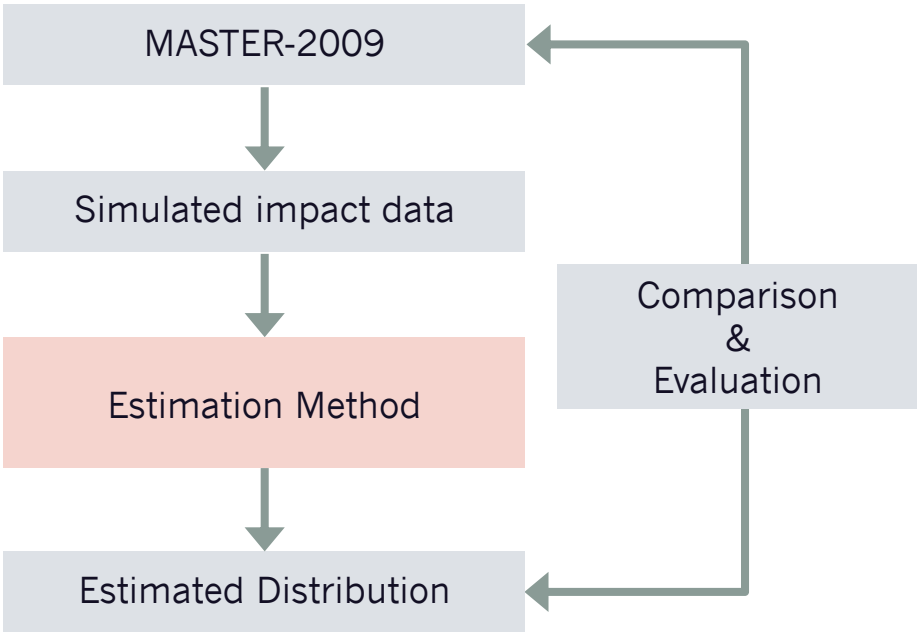
◆Collision Flux

The collision flux between two circular orbits is approximately determined by the torus model (Furumoto et al., 2017)



Torus model

Evaluation Strategy



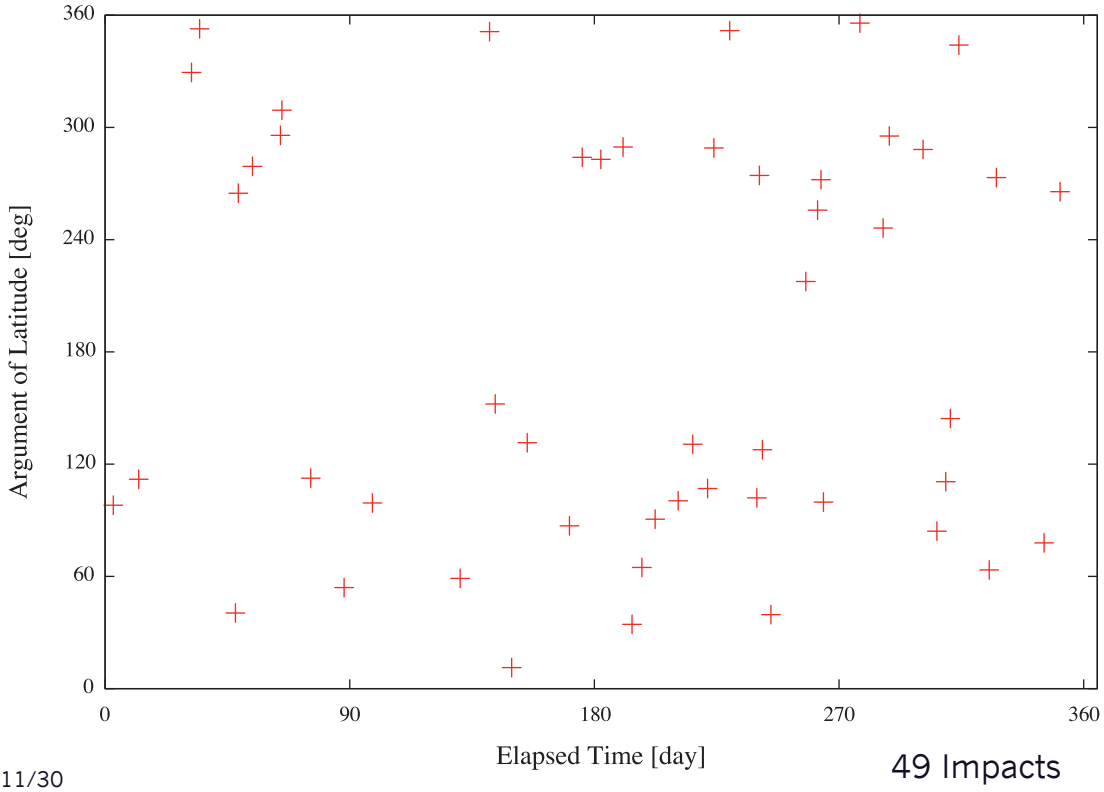
Impact Simulation

condition of the simulation

Initial Epoch	[yyyy/mm/dd]	2007/04/01
Final Epoch	[yyyy/mm/dd]	2008/04/01
Semi-major Axis	[km]	7170.8
Eccentricity		0.0003
RAAN[1] (Ω)	[deg]	267.776
Inclination (i)	[deg]	98.576
Debris size	[mm]	0.1 – 10

[1] Right ascension of the ascending node

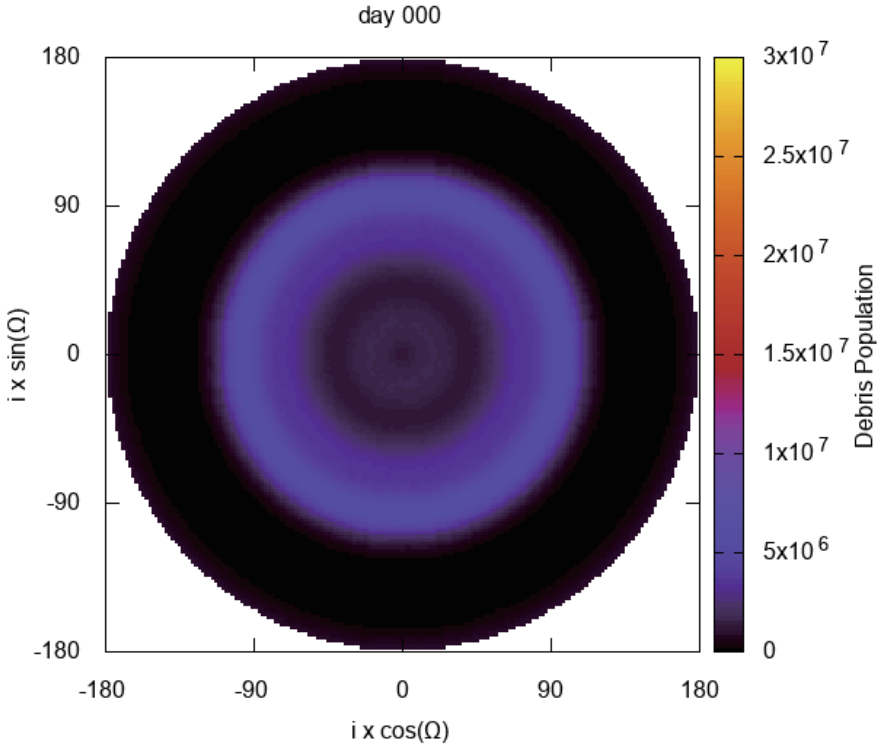
Impact Simulation



49 Impacts

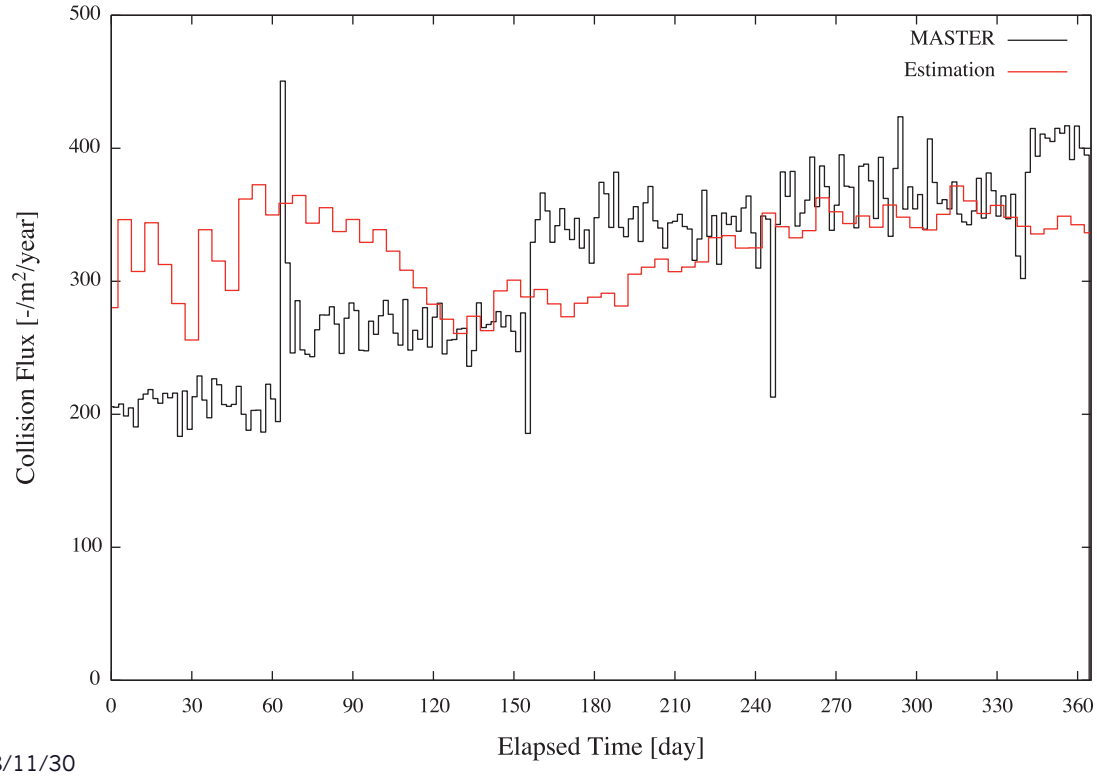
Estimation Result

Inclination Vector Distribution



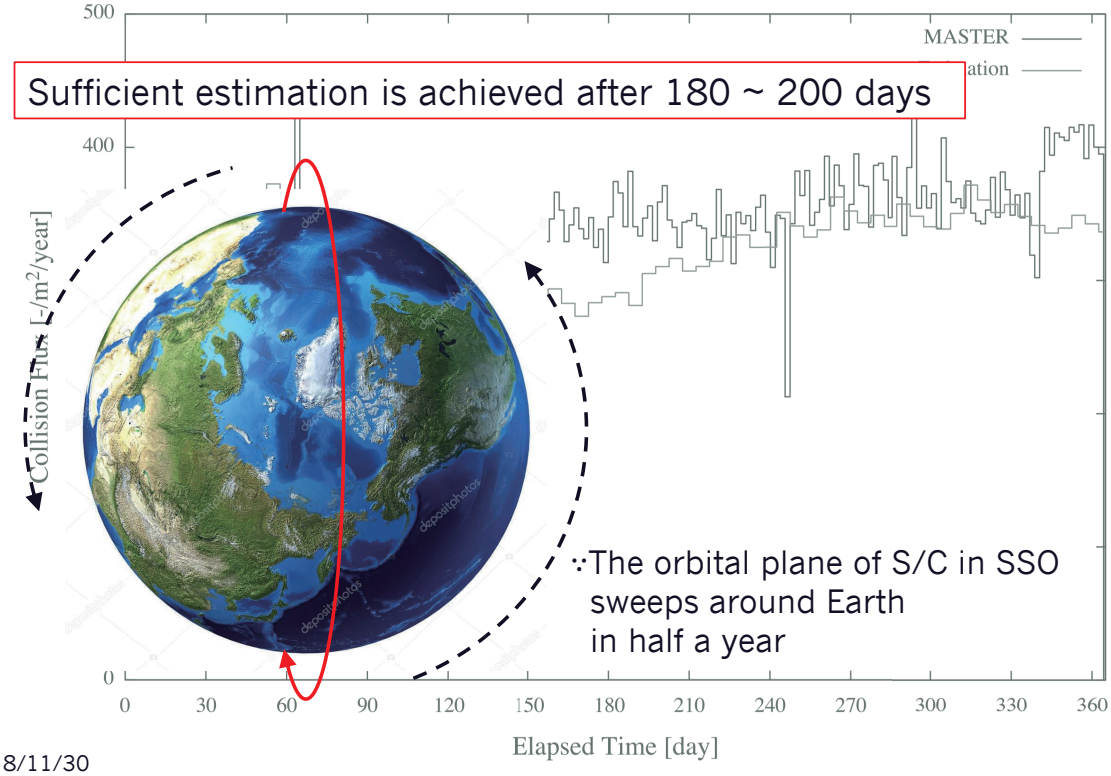
Estimation Result

Estimated Collision Flux



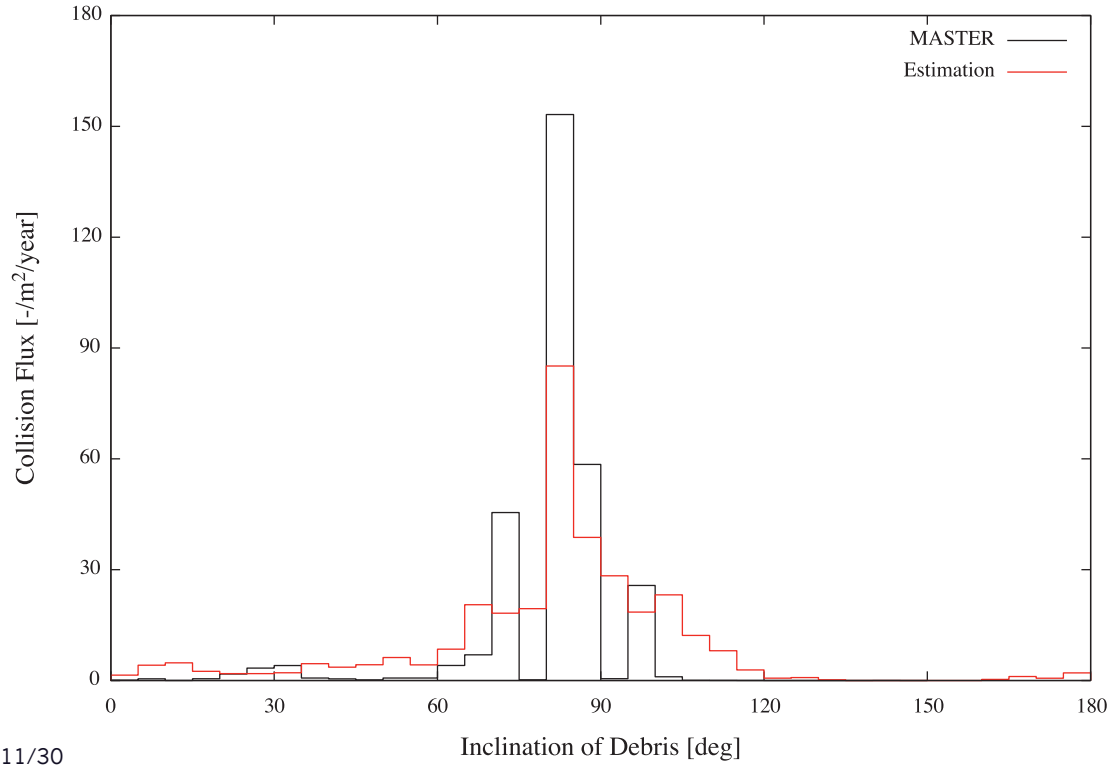
Estimation Result

Estimated Collision Flux



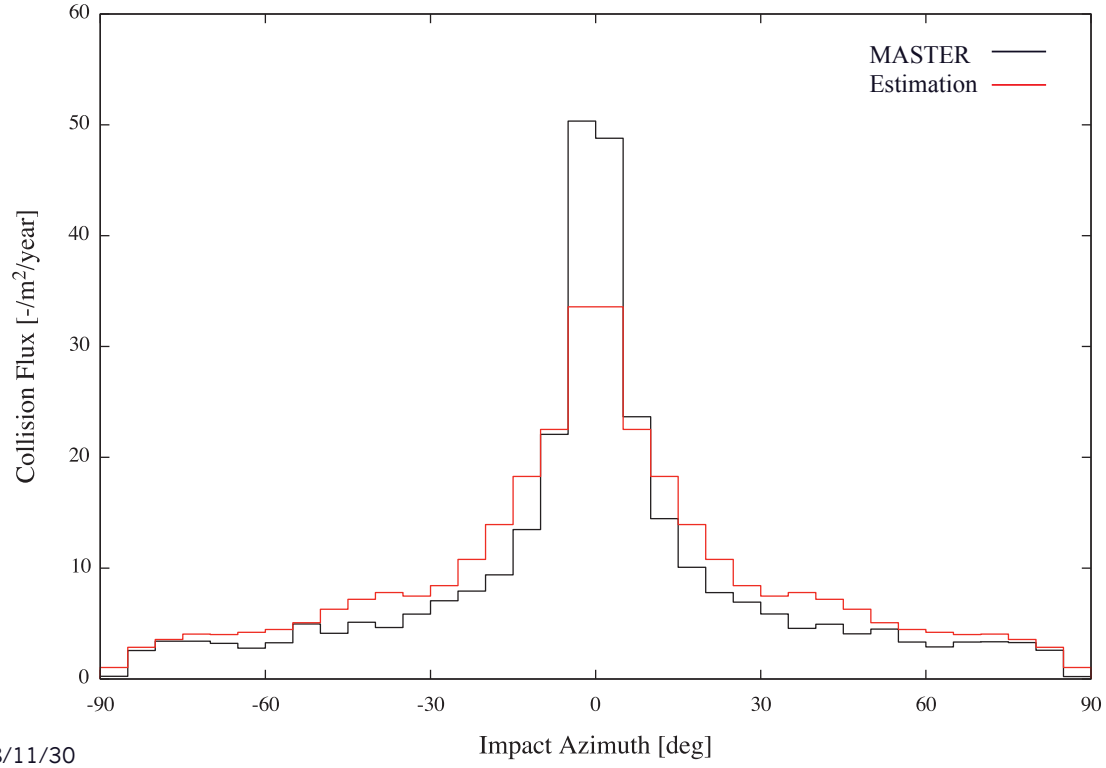
Estimation Result

Estimated Collision Flux



Estimation Result

Estimated Collision Flux



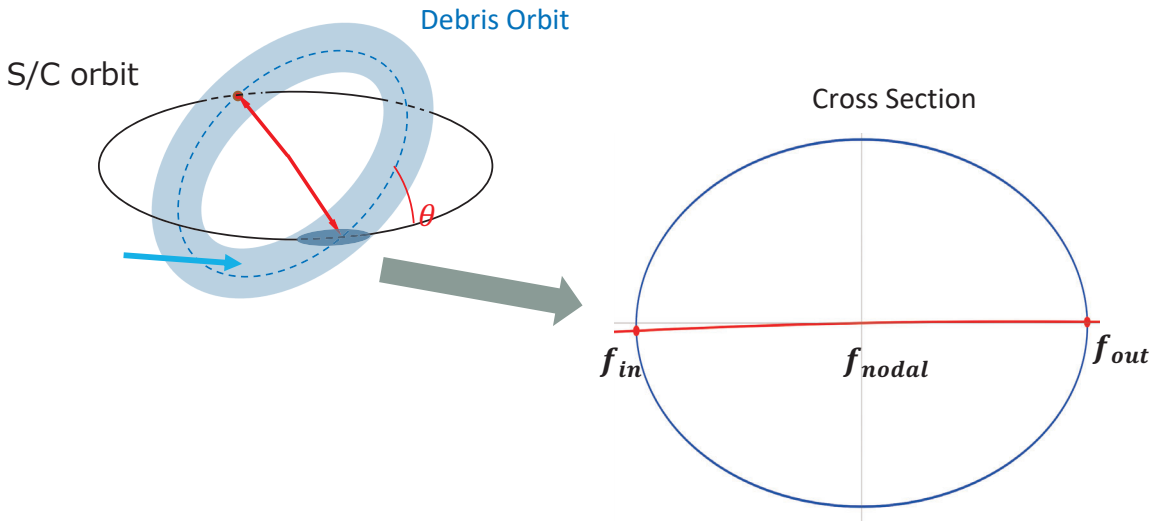
Method Generalization

- Assumption of the current method
  : Both the satellite and debris are in circular orbits

- Generalized method that can be applied to in-situ measurements in elliptic orbits
  - Debris orbits
    → Also assumed as circular orbits
  - Satellite orbit (elliptic)
    → Torus model must be modefied

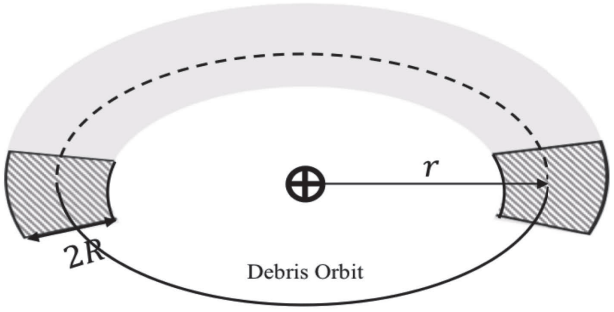
Modification of Torus Model

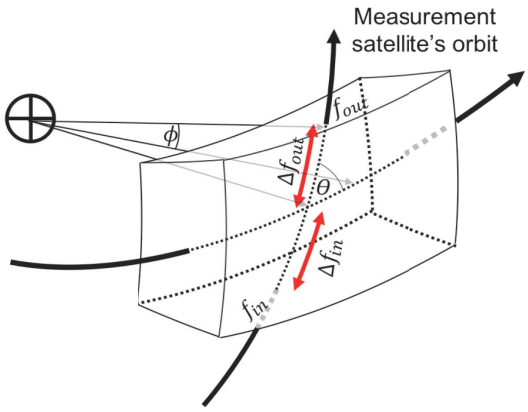
1. Modified Torus
- More similar to original
- Difficult to calculate f_{in} and f_{out}

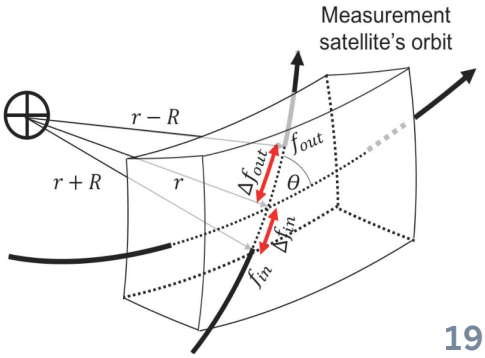


Modification of Torus Model

2. Ring
- Easier to calculate

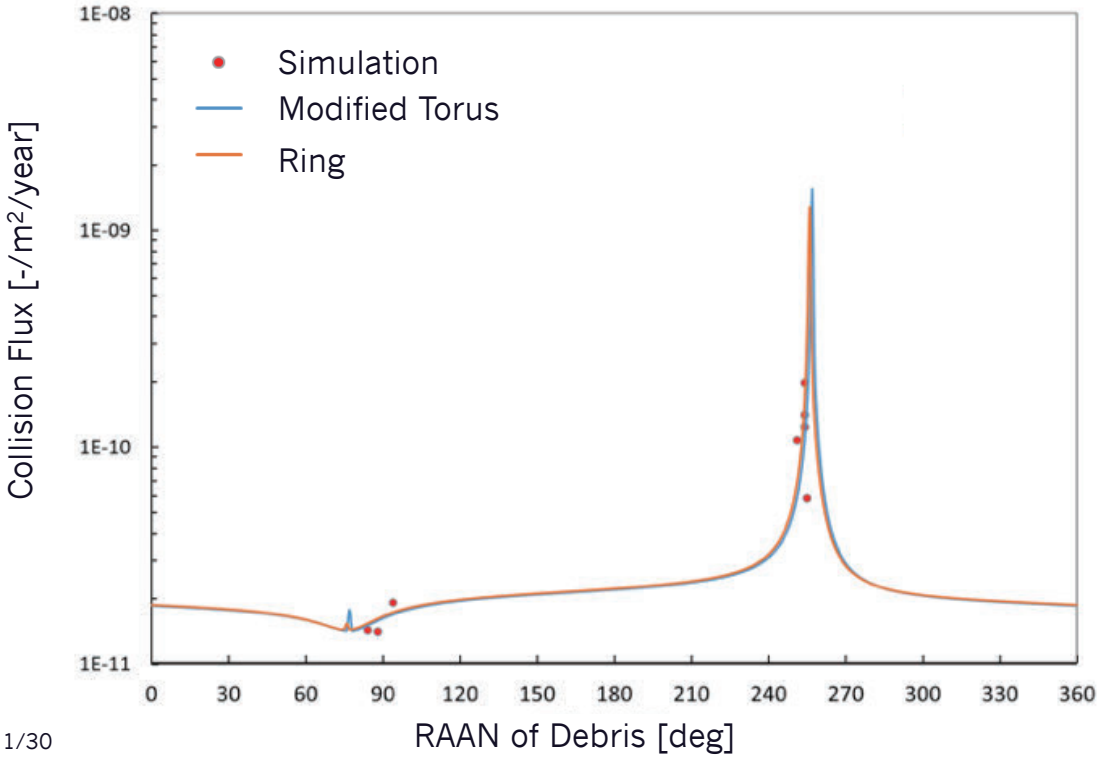






Modification of Torus Model

Evaluation



Conclusion

- This study proposes a statistical method to estimate the environment of sub-millimeter-size debris utilizing in-situ measurements
- The estimation by the proposed model was simulated and evaluated for an in-situ measurement on a circular orbit
- A generalized approximation of collision flux that can be applied to in-situ measurements on elliptic orbits was discussed