Comparison of Debris Environment Models; ORDEM2000, MASTER2001 and MASTER2005

FUKUSHIGE Shinya : Department of Mechanical Engineering, Faculty of Engineering, Kyushu Institute of Technology
AKAHOSHI Yasuhiro : Doctor of Engineering, Professor, Department of Mechanical Engineering, Faculty of Engineering, Kyushu Institute of Technology
KITAZAWA Yukihito : Doctor of Science, Manager, Science Research & Business Development, Staff Group, Space Development Department, Aero-Engine & Space Operations
GOKA Tateo : Ph. D. of Systems Management, Director of Space Environment Measurement Group, Institute of Aerospace Technology, Japan Aerospace Exploration Agency (JAXA)

An accurate estimation of the impact flux of debris, the relative impact velocity and impact angle is necessary for the design of reliable spacecrafts. Space agencies of some countries have space debris environment models that can estimate debris flux as a function of the size, relative impact velocity, and impact angle in a spacecraft orbit. However, it is known that calculation results of models are not always consistent with each other. In the present, since the result of the influence estimation for debris impact depends on the selection of debris environment model, collective reliability cannot be ensured when a spacecraft is designed. Therefore, an internationally common implementation process for debris environment models is required and the proposal for the international standard is being prepared in Japan. In this paper, as the first step of the international standardization of the implementation process of debris environment models, we compared estimation results of debris impact flux in low Earth orbit calculated by the available three debris environment models, namely NASA's ORDEM2000, ESA's MASTER2001 and MASTER2005. The results display that a large difference in flux estimation appears in size of debris > 100 μm and > 1 mm.

1. Introduction

There are natural meteoroids and space debris which has been generated by space activities in Earth orbit. Meteoroids are created from comets and asteroids. Meteoroids orbit the Sun and rapidly pass by and leave near the Earth, resulting in a fairly continual flux (the number of impact objects per unit area per year) of meteoroids coming into collision with spacecraft. The hazard of meteoroids to spacecraft is low because these are predominantly small particles. Space debris consists of artificial objects that cannot play a useful role now nor in future years. Such space debris consists of non-operational satellites, rocket upper stages, fragments generated by their breakup due to accidental or intentional collision and explosion, aluminum particles from rocket exhaust, etc. Space debris orbits the Earth and remains in orbit until atmospheric drag and other perturbing forces eventually cause their orbits to decay into the atmosphere. Since atmospheric drag decreases as altitude increases, large debris in orbits above approximately 600 km can remain in orbit for tens, thousands, or even millions of years.(1) In recent years, the problem of space debris has become obvious with the advance of space development. The current number of artificial objects in Earth orbit is approximately 10 000 trackable objects(2) of 5 to 10 cm in diameter and over, of which no more than 5% are operational spacecraft(3) as well as 38 000 000 objects including those which have a size in the 1 mm order.(4) Space debris is an environment problem in Earth orbit because space debris has been continually accumulating and most of the debris remains there.

The Inter-Agency Space Debris Coordination Committee (IADC)(5) was founded in April 1993 by ESA (Europe), NASA (USA), NASDA (later: JAXA, Japan), and RSA (later: ROSCOSMOS, Russia) to exchange informations on space debris research activities between member space agencies, facilitate opportunities for cooperation in space debris research, review the progress of ongoing cooperative activities, and to identify debris mitigation options. They were in later years joined by ASI (Italy), BNSC (United Kingdom), CNES (France), CNSA (China), DLR (Germany), ISRO (India) and NSAU (Ukraine). IADC plays a technical support role in the Scientific & Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space (UNCOPUOS) and the Orbital Debris Coordination

Working Group (ODCWG) within the Technical Committee 20 and Sub-Committee 14 of the International Organization for Standardization (ISO TC20/SC14). UN working group is concerned with international policies and ISO working group is engaged on standards.[3]

For the design of reliable spacecrafts, an accurate estimation of the impact flux of debris, the relative impact velocity and impact angle is necessary. Space agencies of some countries have space debris environment models that can estimate debris flux as a function of the size, relative impact velocity, and impact angle in a spacecraft orbit. Representative space debris environment models are ORDEM[6] developed by NASA, MASTER[7],[8] developed by ESA and SDPA[9] developed by RSA. However, it is known that the calculation results of these models are not always consistent with each other.[10] At present, since the result of the influence estimation for debris impact depends on the selection of debris environment model, collective reliability cannot be ensured when a spacecraft is designed. Therefore, an internationally common implementation process for debris environment models is required. ISO TC20/SC14/ODCWG assigned WG4 this project and requested Japan to prepare the New Work Item Proposal (NWIP) for international standardization with respect to the implementation process of debris environment models to design spacecraft entitled "Process Based Implementation of Meteoroid and Debris Environmental Models." JAXA has taken a leading part in this project because JAXA can evaluate those debris environment models on neutral ground and has recorded achievements for the measurement of debris in orbit.[11],[12] In this paper, as the first step of international standardization of the implementation process of debris environment models, we compared estimation results and investigated differences in debris impact flux in low Earth orbit calculated by the available three debris environment models, namely NASA's ORDEM2000, ESA's MASTER2001 and MASTER2005 (an upgraded version of MASTER2001).

2. Debris environment models

Space debris environment models may take two forms: as discrete models, which represent the debris population in a detailed format, or as engineering approximations. These models are applied to risk and damage assessments, predictions of debris detection rates for ground-based sensors, predictions of avoidance maneuvers of operational spacecraft and long-term analysis of the effectiveness of debris mitigation measures. These models are limited by the sparse amount of data available to validate the derived relationships. The models must rely upon historical records of satellite characteristics, launch activity and in-orbit breakups. In addition, there is only a limited amount of data on spacecraft material response to impact and exposure to the orbital environment. Space debris models must be continually updated and validated to reflect improvements in the detail and size of observational and experimental data sets.[13]

The ORDEM and MASTER models can predict the flux of space debris that might strike a spacecraft during its lifetime as a function of debris size and velocity for the orbital altitude and inclination of various spacecraft.[1] ORDEM and MASTER take forms as discrete models, which represent the debris population in a detailed format. These models work with discretized volume elements.[6],[14],[15] The region is divided into volume elements in longitude, latitude, and altitude, respectively. The residence probability of the target can be derived from the share of its total orbital period passed within the volume element. For example, the MASTER model makes use of an analogy with the theory of gas dynamics to calculate impact flux. The spacecraft, crossing a space environment filled with particles, is seen to be equivalent to a surface sweeping through a control volume element filled with a static gas. All objects in the path of the surface at the time of its movement are assumed to make impact. The impact probability can be written as the following equation and flux within the volume element can be calculated by the equation.

$$P_i = \Phi A \Delta t = \rho V P_t$$

- P_i : Impact probability
- Φ : Object flux encountered within the volume element
- A : Target surface area
- Δt : Residence time of target within the volume element
- ρ : Object density contribution of particle within the volume element
- V : Volume swept by target within the volume element
- P_t : Target residence probability within the volume element

The total flux can be obtained by calculation flux in all volume elements that target passes through and cumulating the resulting flux contributions.[15]

2.1 ORDEM2000[6]

ORDEM2000 is an empirical model based on ground-based observation data and surface inspection results of objects retrieved from orbit. The sources of ground-based observation data are the Space Surveillance Network (SSN) catalog data of orbital objects that can be tracked whose orbital parameters are distributed as NASA Two Line orbital Elements (TLE), observation results of the Haystack radar, the Haystack Auxiliary radar and the Goldstone radar. Retrieved objects whose surfaces have been inspected are the Long-Duration Exposure Facility (LDEF), the European Retrieval Carrier (EuReCa), the Hubble Space Telescope solar array, a US Space Shuttle window and radiator, the Space Flyer Unit (SFU), and the exposure package experiment data of Mir space station.

ORDEM2000 has two functions. One is debris assessment along an orbit to design spacecraft and plan missions. The other is observation and estimation of debris from grand-based telescope and radar. ORDEM2000 can calculate spatial density, flux, velocity distribution and inclination distribution for debris. The applicable scope of ORDEM2000 is altitude between 200 km and 2 000 km and debris diameter between 10 μm and 1 m.

2.2 MASTER2001(16)

MASTER2001 is based on semi-deterministic analysis that includes orbit propagation of debris from all major debris sources. Debris generation models in terms of mass/diameter distribution, additional velocity and direction distribution have been developed and the orbit propagation of debris has been simulated in advance. This data is used as reference data for MASTER2001. The debris sources are catalog objects such as spent payloads and rocket upper stages, fragmentations due to collision and explosion, dust and slag generated by solid rocket motor, NaK coolant droplets released from the RORSAT reactor core, surface degradation particles (paint flakes) of spacecraft and rocket body induced by atomic oxygen, radiation and thermal cycle, ejecta created by the impact of small particles on larger surfaces and the release of copper needles (West Ford Needles) for radio communication experiments. MASTER can estimate the meteoroid environment as well as the debris environment. MASTER2001 is composed of the "STANDARD" application to calculate object flux with low CPU cost and the "ANALYST" application for high resolution flux estimation. The difference in calculation results between the "STANDARD" application and the "ANALYST" application is within ±25%. MASTER2001 can calculate flux, velocity and direction distribution with respect to each individual debris source, and spatial density with consideration of future mitigation scenarios. The applicable scope of MASTER2001 is the altitude between 186 km and 38 786 km and impact objects diameter between 1 μm and 100 m.

2.3 MASTER2005(17)

MASTER2005 is an upgraded version of MASTER2001. The "STANDARD" and "ANALYST" applications in MASTER2001 have been integrated. Because of revisions of debris generation models such as breakup model, NaK droplet model, ejecta model, etc., size and velocity distribution of debris differ from MASTER2001. MASTER2005 takes over the function of MASTER2001. In addition, basic damage laws, which were the ballistic limit in aluminum and the conchoidal diameter of the glass surface of solar cells have been implemented. MASTER2005 was released recently. MASTER2005 will replace MASTER2001 as a tool for estimating debris environments for spacecraft design. The applicable scope of MASTER2005 is the altitude between 186 km and 36 786 km and impact objects diameter between 1 μm and 10 m.

Model characteristics of ORDEM2000, MASTER2001 and MASTER2005 are shown in **Table 1**.

3. Comparison of debris environment models

The impact flux of debris without meteoroids was calculated for comparison of debris environment models. The same calculation conditions of the IADC report (IADC-2001-AI19.2.doc)(10) with respect to comparison of debris environment models were adopted in this comparison. The calculation conditions, which are shown in **Table 2**, are altitudes between 300 km and 2 000 km with a stepsize of 100 km, inclinations between 0 degree and 140 degrees with a stepsize of 10 degrees, circular orbit, and an epoch of 2 000.

The calculation results of the cumulative flux of debris > 10 μm in diameter, > 100 μm, > 1 mm, > 1 cm, > 10 cm, and > 1 m as the function of altitude and inclination are shown in **Fig. 1** using 3D graphs. Since changes of flux along altitude are larger than along inclination across the whole size range, the results in inclination of 100 degrees are shown in **Fig. 2** to assist comparison between different models.

The flux of debris > 10 μm shown in high altitude comparatively corresponds; however, the difference in calculation results between the ORDEM2000 and MASTER models is large in low altitude. The reason that the flux result of debris > 10 μm in low altitude is in disagreement between the ORDEM and MASTER models is due to a difference in decay due to atmosphere.

Table 1 Characteristics of debris environment models

Item		ORDEM2000	MASTER2001	MASTER2005
Size range (μm)		> 10	> 1	
Altitude range (km)		200 - 2 000	186 - 38 786	186 - 36 786
Time range (year)		1991 - 2030	1958 - 2050	1957 - 2055
Objects source terms	TLE background	All sources together	Yes	
	Fragments		Yes	
	SRM dust/slag		Yes	
	NaK droplets		Yes	
	Paint flakes		Yes	
	West ford needles		Yes	
	Meteoroids	None	Yes	
Modeling approach		Measurement data	Semi deterministic analysis	

Table 2 Calculation conditions of models comparison(10)

Altitude (km)	300 - 2 000
Inclination (degree)	0 - 140
Size range (m)	10^{-5} - 1
Stepsize*1 (km)	100
Stepsize*2 (degree)	10
Stepsize*3 (log scale)	1
Resulting data	Cumulative flux
Debris	Yes
Meteoroids	None

(Note) *1 : Altitude
*2 : Inclination
*3 : Size range

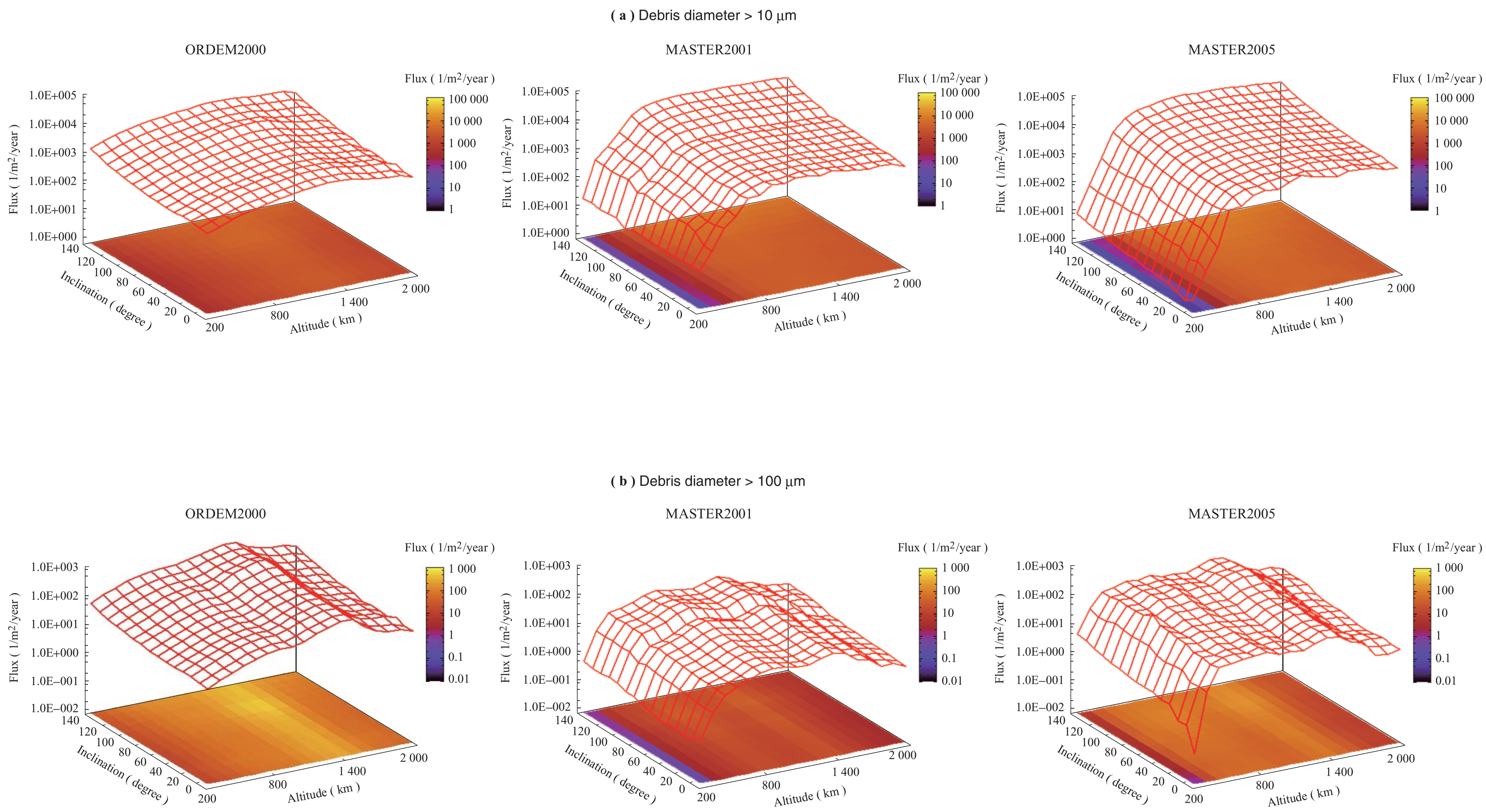

Fig. 1 Flux calculation results of the three models against altitude and inclination (Continued on the following page)

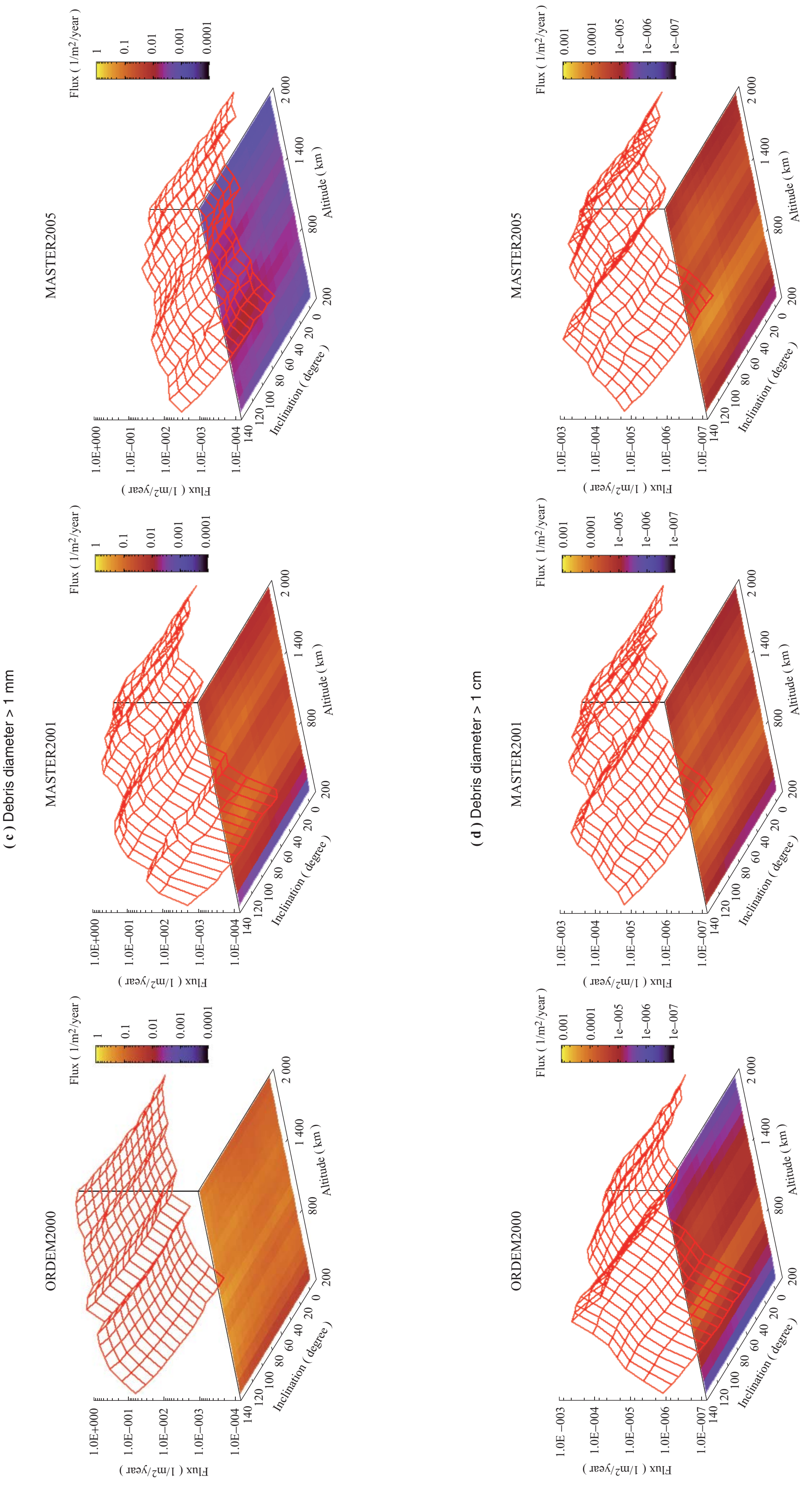

Fig. 1 Flux calculation results of the three models against altitude and inclination (Continued from the previous page)

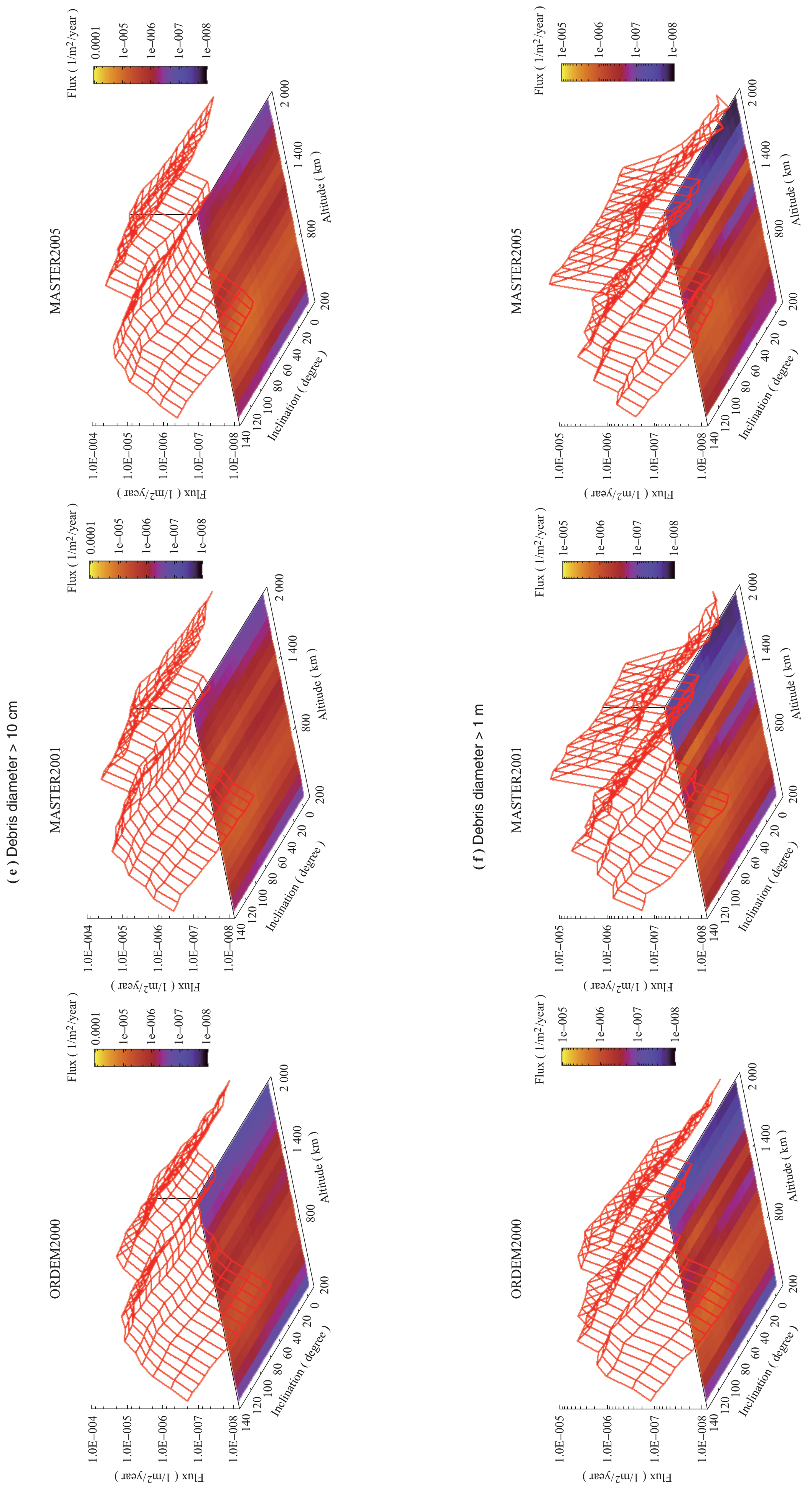

Fig. 1 Flux calculation results of the three models against altitude and inclination (Continued from the previous page)

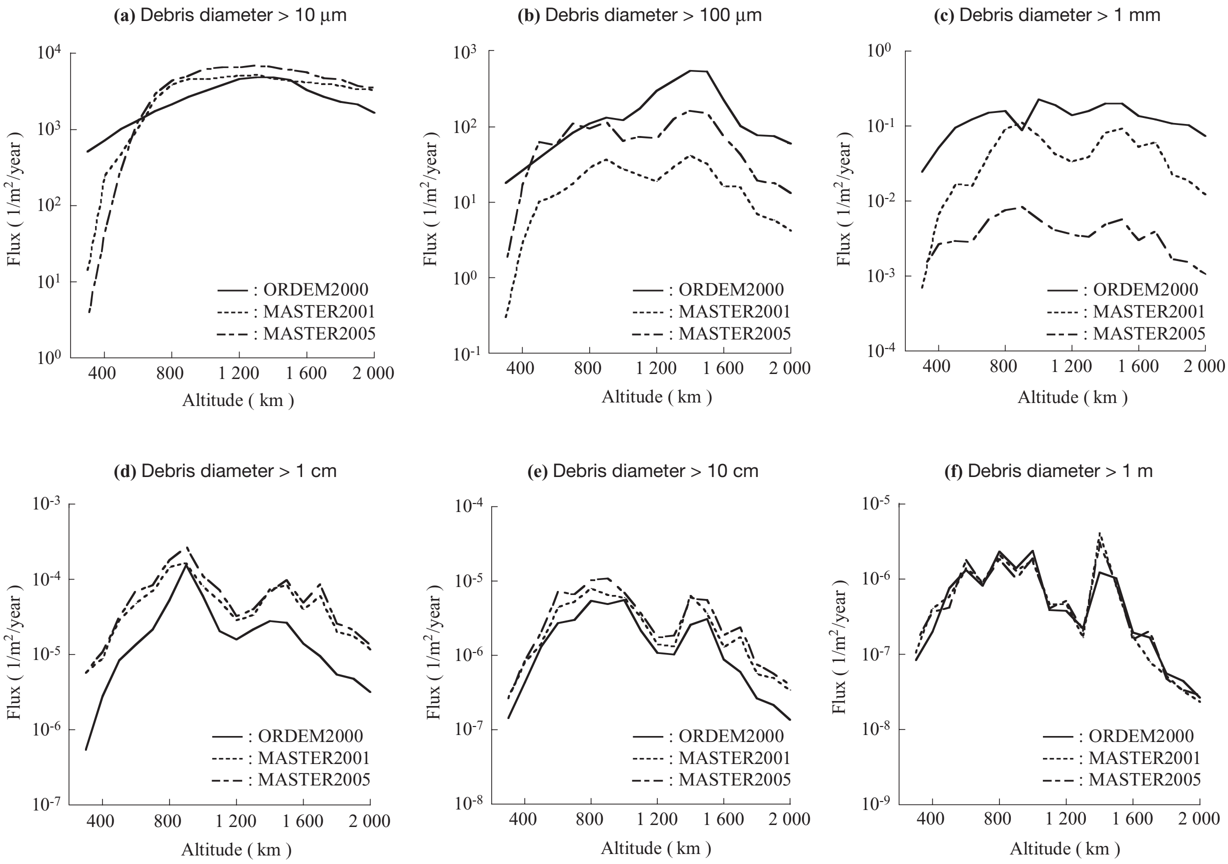

Fig. 2 Flux against altitude at inclination 100 degrees

According to the flux of debris > 10 μm, the impact frequency is large. Therefore, the correction of models using data of the surface inspection of objects retrieved from the orbit is possible in the future.

The flux profiles of debris > 10 cm and > 1 m match well. Since debris > 10 cm can be observed from ground-based radar, the flux of each model prediction in this size range based on grand-based observation data obtains similar results. The peak flux is shown to be in the altitude of approximately 800 km and 1 400 km. At around 800 km, there is a constellation of communication satellites, and sun-synchronous remote sensing and navigation satellites are used at around 900 km. These orbits are used very often and a lot of debris of objects from missions has been generated. The peak at around 1 400 km is caused by breakups of Delta rocket bodies and constellations of communication satellites.(1) Debris > 10 cm does not become a problem for ordinal spacecraft missions because the orbital parameters of these objects can be detectable by ground-based observation and the flux is very small.

Large differences in the calculation results of debris flux are displayed in debris > 100 μm, > 1 mm and > 1 cm, and in particular, the flux of debris > 100 μm shows the largest difference between the results obtained by ORDEM2000 and MASTER2001. The flux of debris > 1 mm shows that the differences between ORDEM2000 and MASTER2001 and between MASTER2001 and MASTER2005 to be at their greatest. It is difficult for debris of 1 cm and smaller to be detected by ground-based observation. Because of the low frequency of debris impact that is 100 μm and greater, the surface inspection of objects retrieved from orbit dose not reveal much data concerning debris in this size range. Therefore, we have no resources to verify the flux results in this size range calculated by each model and cannot judge which model is better. However, the flux of debris in this size range affects the survivability of satellites because the impact of debris > 100 μm can degrade the surface of spacecrafts, damage unprotected components(1) such as optical equipment and sever tethers.(18) Furthermore, debris > 1 mm can cause damage to components, lessen mission execution capability and cause loss of satellites.(1)

4. Application of debris environment models

Debris environment models were applied to the perforation failure risk assessment of a spacecraft for comparison using a specific example.

4.1 Ballistic limit of the satellite body

The perforation failure risk, in the other words, the ballistic limit of the satellite body depends on not only debris size but also relative impact velocity. Frank Shäfer et al. conducted hypervelocity impact tests on the CFRP honeycomb sandwich panel of ENVISAT.[19] The test results show that the projectile of 1-1.5 mm in diameter with the velocity of 5-7 km/s can perforate the CFRP honeycomb sandwich panel. Therefore, in this study, the ballistic limit of the satellite body is defined by the impactor with a diameter of 1 mm and a velocity of 5 km/s.

4.2 Perforation failure risk assessment of debris impact using debris environment model

A perforation failure risk assessment was conducted against two Japanese spacecrafts. One is the Advanced Land Observation Satellite (ALOS) named DAICHI shown in **Fig. 3**, which is in sun synchronous orbit. The other is SUZAKU shown in **Fig. 4**, which is an x-ray satellite. Specifications of ALOS and SUZAKU are shown in **Tables 3** and **4**, respectively. The graph displaying debris flux against size in ALOS and SUZAKU orbits calculated by each model is shown in **Figs. 5** and **6**. There are large differences of flux between the models around the debris size of up to 1 cm. The flux estimation result of ORDEM2000 is on the large side in comparison with MASTER models.

The perforation failure risk of the satellite bodies was estimated according to the supposition that the ballistic limit is the impactor with a diameter of 1 mm and a velocity of 5 km/s. The flux calculation results of debris > 1 mm in ALOS and SUZAKU orbits against impact velocity of each model are shown in **Figs. 7** and **8**, respectively. According to the calculation results of each

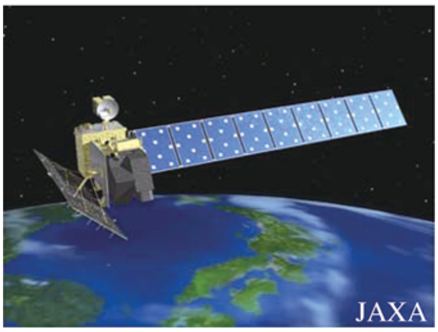

Fig. 3 ALOS (DAICHI)

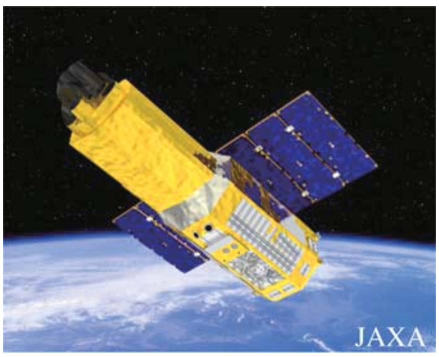

Fig. 4 SUZAKU

Table 3 Specifications of ALOS [20]

Launch	24 January 2006
Lifetime	3–5 years
Size	Satellite body 6.5 × 3.5 × 4.5 (m) Solar array paddle 3 × 22 (m)
Orbit	Sun synchronous sub recurrent Altitude 692 (km) Inclination 98.2 (degree)

Table 4 Specifications of SUZAKU [21]

Launch	10 July 2005
Lifetime	5 years
Size	Satellite body 6.5 × 2.0 × 1.9 (m) Solar array paddle 5.4 (m)
Orbit	Altitude 560 (km) Inclination 32 (degree)

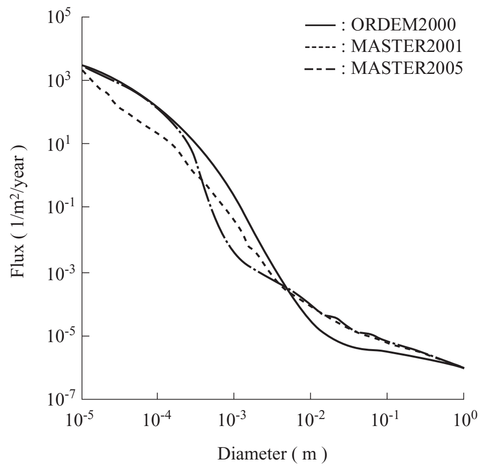

Fig. 5 Flux against diameter in the ALOS orbit

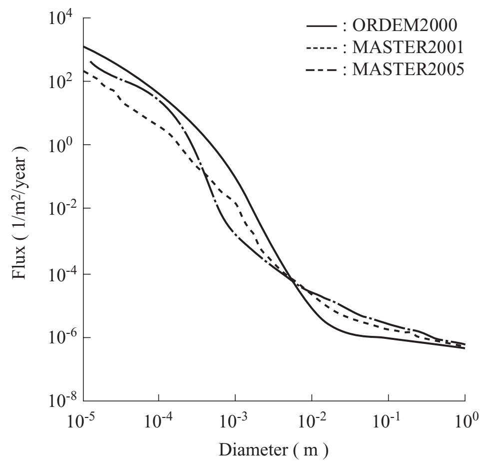

Fig. 6 Flux against diameter in the SUZAKU orbit

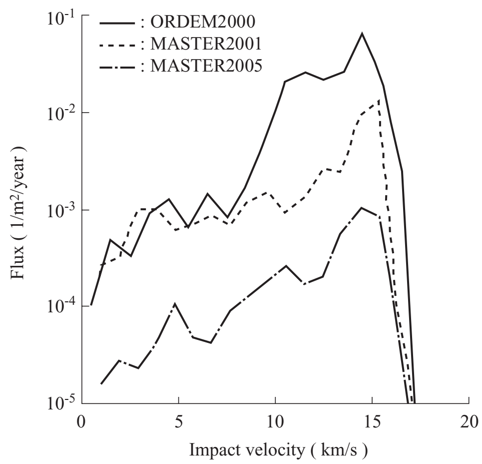

Fig. 7 Flux against impact velocity in the ALOS orbit (debris diameter > 1mm)

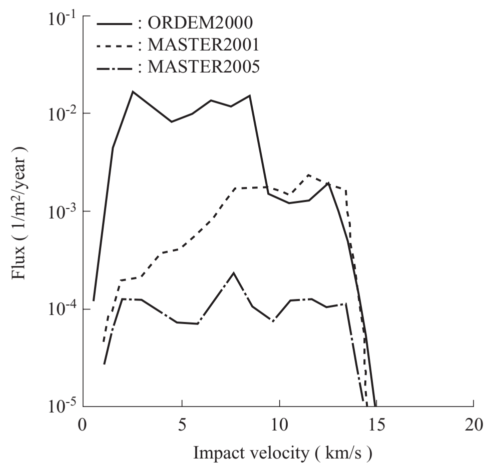

Fig. 8 Flux against impact velocity in the SUZAKU orbit (debris diameter > 1mm)

model, in the case of the ALOS orbit, the cumulative flux of debris > 5 km/s in terms of impact velocity is 1.91×10^{-1} $1/m^2$/year estimated by ORDEM2000, 3.48×10^{-2} $1/m^2$/year estimated by MASTER2001 and 3.67×10^{-3} $1/m^2$/year estimated by MASTER2005, respectively. In comparison with the MASTER2005 result, the flux of ORDEM2000 is 52.0 times larger and that of MASTER2001 is 9.48 times larger. In the case of the SUZAKU orbit, the cumulative flux of debris > 5 km/s in terms of impact velocity is 5.78×10^{-2} $1/m^2$/year estimated by ORDEM2000, 1.42×10^{-2} $1/m^2$/year estimated by MASTER2001 and 1.11×10^{-3} $1/m^2$/year estimated by MASTER2005, respectively. In comparison with the MASTER2005 result, the flux of ORDEM2000 is 52.1 times larger and that of MASTER2001 is 12.8 times larger.

These results demonstrate that the risk assessment result of debris impact for spacecraft depends on which model is adopted. Therefore, it is important to form an international agreement with respect to the process of adoption and application of debris environment models.

5. The comparison of flux calculated by models and recent measurement data on the ISS

We compared impact flux predictions of the three models with the recent measurement data on the International Space Station (ISS) to ascertain the validity of models of recent debris environment. The source of the measurement data is the inspection results of the Micro-Particles Capturer (MPAC) experiment conducted by Kitazawa et al.[22] MPAC units, which is a particle-capture experiment consisting of three identical units (numbered 1 to 3), were launched aboard Progress M-45 on 21 August 2001 and deployed on the exterior of the Russian Service Module (SM) of the ISS on 15 October. The first unit (hereafter SM1) was retrieved after 315 days' exposure. Then SM2 was retrieved after 865 days' exposure and SM3 was retrieved after 1 403 days' exposure. Impact flux estimated by detailed inspection results on the MPAC ram side and the wake side are available. In this comparison, flux values of the ram side were adopted because of low contamination. Impact flux of debris of the ISS ram side calculated by ORDEM2000 and that of debris and meteoroids calculated by MASTER2001 and MASTER2005 against size are shown in **Fig. 9**. The ISS orbit parameters are the altitude of 400 km and inclination of 51.6 degrees. Maneuver effects of the ISS and shielding effects of the ISS structure are not considered in the flux calculations of models. According to the calculation results of the MASTER models, meteoroids are dominant in small size particles and in low altitude orbits like the ISS because debris flux decreases as altitude decreases in near Earth orbit (see **Fig. 1-(a)**). Therefore, impact flux calculated by the MASTER models contains meteoroids and the meteoroids flux of MASTER2001 added to the flux of ORDEM2000 (**Figure 10** shows flux against size in these conditions).

Table 5 shows a comparison between the impact flux of

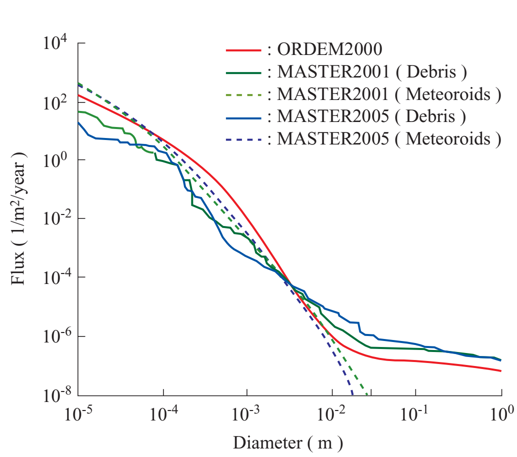

Fig. 9 Debris and Meteoroids flux against diameter in the ISS orbit

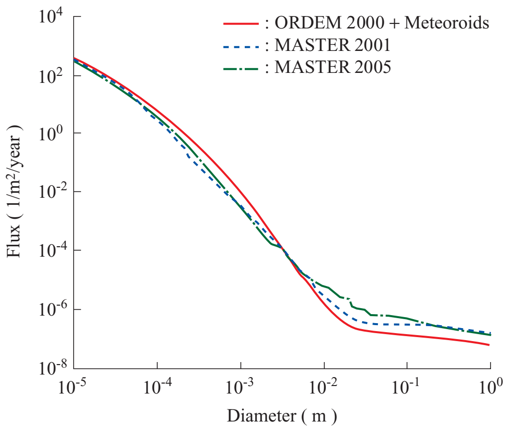

Fig. 10 Total flux Debris and Meteoroids against diameter in the ISS orbit

MPAC and the calculated results of the three models. Although the contribution of debris to flux is different between ORDEM2000 and the MASTER models, the calculation results of flux are consistent with each other. In the flux of particles with a diameter > 10 μm, the inspection results of MPAC are three to four times greater than the calculation results of the models, and in the flux of particles with a diameter > 20 μm, MPAC results are two to four times greater than the results from the models. It is thought that models underestimate flux considering that calculation results did not reflect the maneuver effect and shielding effect of the ISS. More investigation is required to decide upon adequate models to design spacecraft, in particular, in the size range where the difference between models is large, namely particles with a diameter > 100 μm. A Large Area Debris Collector (LAD-C) planed by J.-C. Liou et al. is promising in terms of in-situ measurements and sample return plans for the acquisition of flux data in this size range.[(23)] LAD-C, which is the aerogel and acoustic sensor system on the ISS, has a large enough area of 10 m^2 to obtain flux data of meteoroids and debris in the 100 μm order.

6. Conclusions

The results of the comparison of representative debris environment models, which are ORDEM2000, MASTER2001 and MASTER2005, display large difference in the flux estimation of debris > 100 μm and > 1 mm. This size range is important for spacecraft design. The risk assessment of debris impact over the ballistic limit on a satellite body in two orbit cases demonstrates the calculation probability of critical debris impact depends on which model is adopted. In comparison with the estimation results of the perforation risk of MASTER2005, the flux of ORDEM2000 is 50 times larger and that of MASTER2001 is 10 times larger. Comparison of the impact flux predictions of the three models with the recent measurement data on the ISS indicate a potentiality of underestimating the flux calculated by the models against small particles. Therefore, more measurement data to decide upon adequate models and immediate international standardization that prescribes the process of adoption and application of debris environment models are required to ensure the international collective reliability of spacecraft.

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Table 5 Comparison with impact flux of MPAC and calculated results of three models

(a) Inspection

Particle diameter (μm)	SM #1 (1/m²/year)	SM #2 (1/m²/year)	SM #3 (1/m²/year)
10	1.6×10^3	–	TBD*1
20	6.3×10^2	3.9×10^2	

(note) *1 : Under inspection

(b) ORDEM2000 and Meteoroids

Particle diameter (μm)	SM #1 (1/m²/year)	SM #2 (1/m²/year)	SM #3 (1/m²/year)
10	5.9×10^2	6.0×10^2	6.1×10^2
20	2.2×10^2	2.2×10^2	2.3×10^2

(c) MASTER2001

Particle diameter (μm)	SM #1 (1/m²/year)	SM #2 (1/m²/year)	SM #3 (1/m²/year)
10	4.7×10^2	4.7×10^2	4.7×10^2
20	1.7×10^2	1.7×10^2	1.7×10^2

(d) MASTER2005

Particle diameter (μm)	SM #1 (1/m²/year)	SM #2 (1/m²/year)	SM #3*2 (1/m²/year)
10	3.8×10^2	3.8×10^2	4.1×10^2
20	1.4×10^2	1.5×10^2	1.5×10^2

(note) *2 : Flux calculated in 1 294 days because MASTER2005 cannot estimate particles less than 1 mm after 1 May 2005.

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