ISSN 1349-1121
JAXA-RM-11-020E

JAXA Research and Development Memorandum

Comparison of Space Debris Environment Models: ORDEM2000, MASTER-2001, MASTER-2005 and MASTER-2009

Yuki KANEMITSU, Yasuhiro AKAHOSHI, Tomohiro NARUMI, Pauline FAURE, Haruhisa MATSUMOTO, Yukihito KITAZAWA

March 2012

Japan Aerospace Exploration Agency

Comparison of Space Debris Environment Models: ORDEM2000, MASTER-2001, MASTER-2005 and MASTER-2009*

○Yuki KANEMITSU*1, Yasuhiro AKAHOSHI*1, Tomohiro NARUMI*1, Pauline FAURE*1
Haruhisa MATSUMOTO*2 and Yukihito KITAZAWA*3

Abstract

Hypervelocity impact by space debris on spacecraft is one of the most important issues for space development and operation, especially considering the growing amount of space debris in recent years. It is therefore important for spacecraft design to evaluate the impact risk by using environment models. In this paper, the authors compared the results of the debris impact flux in low Earth orbit, as calculated by four debris environment engineering models—NASA's ORDEM2000 and ESA's MASTER-2001, MASTER-2005 and MASTER-2009. The results reveal large differences in the flux estimation for debris larger than 1 mm and more than 100 μm in diameter.

1. Introduction

There are currently more than 16,000 catalogued objects in Earth's orbit, of which operational spacecraft [1] account for about 5%. Space debris can consist of non-operational satellites, the upper stages of rockets, fragments generated by breakups due to collisions and explosions, dust and slag from Solid Rocket Motor (SRM) firings, and paint flakes from spacecraft surfaces. The relative impact velocity of debris in low Earth orbit (LEO) ranges from 8.7 km/s to 15 km/s. Space debris poses an environmental issue in Earth's orbit because most space debris does not decay and thus continues to accumulate. In addition, debris more than several hundred micrometers in diameter might not penetrate a spacecraft, but could affect its solar array—something that cannot be ignored regarding the threat of partial breakups on reducing power. The study of debris ranging from hundreds of micrometers to several millimeters in size is thus critical for reliable spacecraft design.[2]

The debris impact flux must be accurately estimated for reliable spacecraft design; consequently, space agencies have developed space debris environment models capable of estimating the impact flux for a given orbit. Representative space debris environment models are the ORbital Debris Engineering Model (ORDEM) developed by the National Aeronautics and Space Administration (NASA), and the Meteoroid And Space debris Terrestrial Environment Reference (MASTER) developed by the European Space Agency (ESA). However, the results obtained with these models are not always consistent with each other, and thus the reliability of a given design cannot be collectively ensured.

In this report, the authors compared the debris impact flux results in LEO as calculated by the four models (ORDEM2000, MASTER-2001, MASTER-2005 and MASTER-2009). Sdunnus,[3] Fukushige,[4] and Drolshagen[5] have already compared the results obtained from the ORDEM2000, MASTER-2001 and MASTER-2005 models. This paper compares the results obtained from MASTER-2009 (the latest model released) with those obtained by the other models. From these calculations, differences between the debris environment models could be analyzed as a step toward international standardization of such models.

2. Space debris environment models

2-1. ORDEM2000[6]

ORDEM2000 is an empirical model established as a benchmark for ground-based observations data and retrieved surface inspection results. Its applicable regime is for debris ranging from 10 μm to 1 m in diameter, and at altitudes between 200 km and 2,000 km.

---

* Received 26 January 2012
*1 Kyushu Institute of Technology
*2 JAXA
*3 IHI

Most data on space debris comes from:
・Space Surveillance Network (SSN) catalog;
・Observation results from Haystack radar, Haystack Auxiliary radar, and Goldstone radar;
・Retrieved objects having undergone surface inspection, such as the Long-Duration Exposure Facility (LDEF), European Retrieval Carrier (EuRECA), solar arrays of the Hubble Space Telescope (HST), windows and radiators of the U.S. space shuttle, and the Space Flyer Unit (SFU), along with exposure package experiment data on the Mir space station.

2-2. MASTER-2001[7]

The MASTER-2001 model is based on semi-deterministic analysis that includes the orbit propagation of debris from all major sources of debris. Its applicable regime is for impacting objects ranging from 1 μm to 100 m in diameter, and at altitudes between 186 km and 38,786 km.
The major sources of space debris are:
・Cataloged objects such as spent payloads and the upper stages of rockets;
・170 fragmentation events due to collisions and explosions;
・1033 dust and slag generated by SRM;
・NaK coolant droplets released from reactor core of the Radar Ocean Reconnaissance SATellite (RORSAT);
・Paint flakes or surface degradation particles from spacecraft and a rocket body induced by atomic oxygen, radiation, and thermal cycle;
・Ejecta created by the impact of small particles on spacecraft surfaces;
・West Ford needles (copper needles released for radio communication experiments).

2-3. MASTER-2005[8]

The MASTER-2005 model is an upgraded version of MASTER-2001. Due to the revisions made to debris generation models, such as those pertaining to breakups, NaK droplets, and ejecta model, the size and velocity distribution of debris for MASTER-2005 are different from those of the MASTER-2001 model.
The major revisions are:
・NASA breakup model;
・Event list (203 and SRM 1076);
・Parameter settings for SRM slag/dust, ejecta, and paint flakes;
・User interface.

2-4. MASTER-2009[9]

MASTER-2009 is the latest version of the MASTER model series and was released on June 2011. The MASTER-2009 model includes data collected until May 2009.
The major revisions are:
・Event list (234, SRM 1964, Cosmos-2251 and Iridium-33 collision);
・Multi-Layer Insulation (MLI) fragments;
・Population cloud with code number 25730 as given by the U.S. SSN to identify fragments from the explosion of the Feng-Yun 1C satellite. Note that when this population cloud is included, the value of the right ascension of the ascending node (RAAN) and that of the argument of perigee (AoP) are changed as compared to the input values;
・User interface.

3. Comparison of debris environment models

3-1. Debris environment models' characteristics

In this report, the authors compared four debris environment models (ORDEM2000, MASTER-2001, MASTER-2005 and MASTER-2009) by using the same calculation conditions. Table 1 lists the characteristics of each model.
The debris impact flux was calculated in order to compare the debris environment models. Table 2 lists the calculation parameters for an altitude between 300 km and 2,000 km, a step size of 100 km, inclination of 100 degrees, and a presumably circular orbit.

Table 1. Characteristics of the debris environment models.

Item		ORDEM2000[6]	MASTER-2001[7]	MASTER-2005[8]	MASTER-2009[9]
Source		NASA	ESA		
Modeling approach		measurement data	semi-deterministic analysis		
Applicable regime	Minimum size	> 10 μm	> 1 μm		
	Orbital regime	200 - 2000 km	186 - 36786 km		
	Evolutionary period	1991 - 2030	1958 - 2050	1957 - 2055	
Input parameter		Apo/Peri Altitude Semi-major axis Eccentricity Inclination Argument of perigee	・Target Orbit Scenario Semi-major axis, Eccentricity, Inclination, Right asc. of asc. node, Argument of perigee ・Inertial Volume Scenario Geocentric distance, Right ascension, Declination ・Spatial Density Scenario Lower/Upper alt. limit, Lowe/Upp		
Output data		Flux vs. Size, Orbit position, Altitude, Latitude	・Flux vs. Size, Mass, Semi-major axis, Eccentricity, Inclination, Altitude, Latitude, Impact velocity, Impact declination ・Spatial density vs. Size, Mass, Altitude, Declination, etc.		
Debris source terms	TLE background	all sources together	yes		
	Fragments		yes		
	SRM dust/slag		yes		
	NaK droplets		yes		
	Paint flakes		yes		
	West ford needles		yes		
	MLI fragments		none		yes
Meteoroid	Background	none	Divine-Staubach		
	Streams		Jenniskens-McBride, Cour-Palais		
Primary data source / Validation		SSN catalog, LDEF, Haystack radar, HST-SA, STS window and radiator, HAX radar, Goldstone radar	LDEF, HST(SM1), EuReCa, PROOF2001	LDEF, CME, HST(SM1, SM3B), EuReCa, PROOF2005	LDEF, CME, HST(SM1, SM3B), EuReCa, PROOF2009
Engneering model available for intentional use		yes	yes	yes	yes
Release data		2002	2002	2006	2011

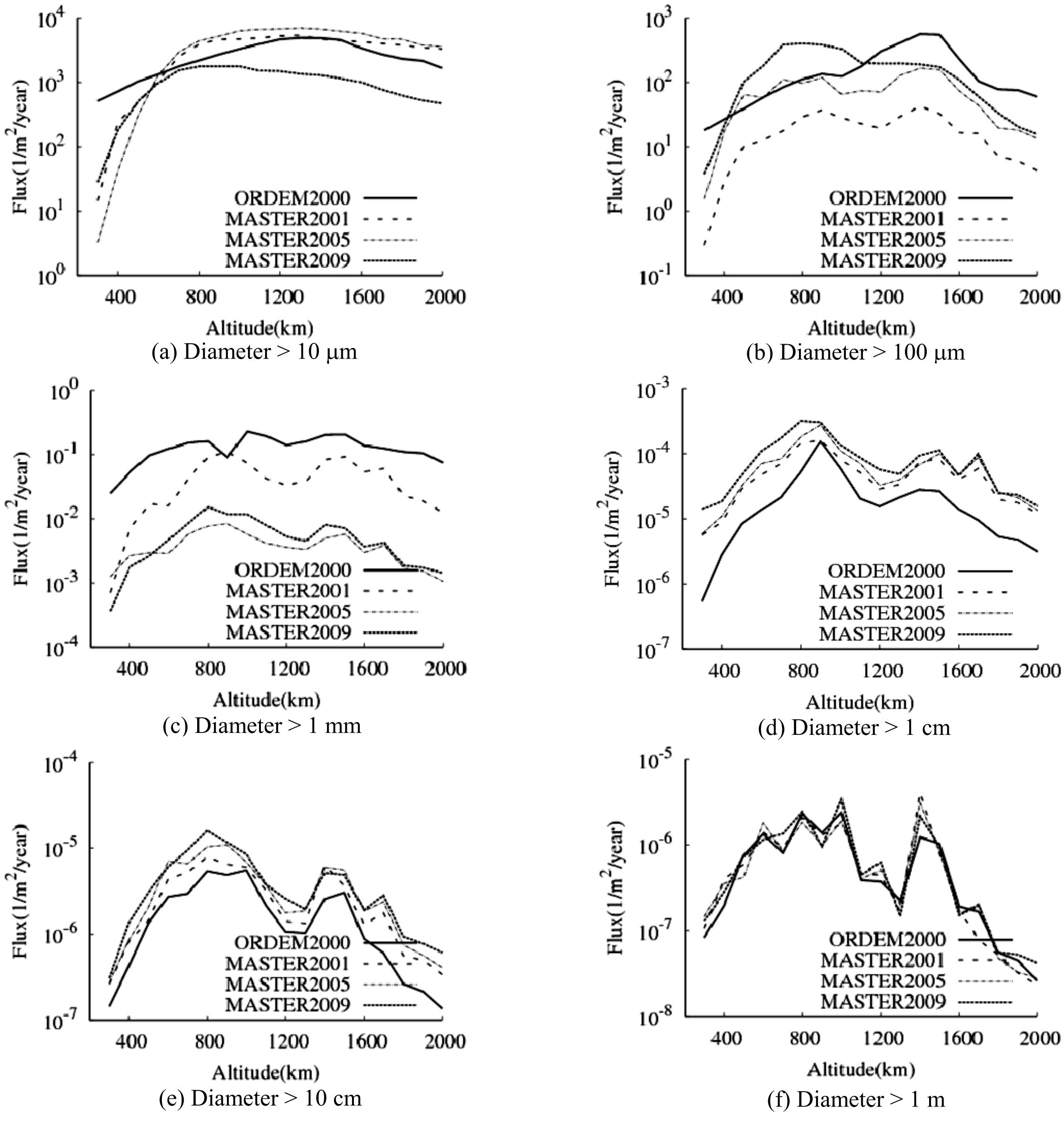
Table 2. Calculation parameters for comparison of the models.

Item	ORDEM2000	MASTER-2001	MASTER-2005	MASTER-2009
Calculation epoch	2000/1/1	2000/5/1	2000/5/1	2009/5/1
Altitude [km]	300 - 2000			
Stepsize [km]	100			
Inclination [degree]	100			
Size range [m]	10^{-5} - 1			
Resulting data	Cumulative flux			
Debris	Yes			
Meteoroids	None			

For ORDEM2000, "January 1, 2000" was selected as the calculation epoch, and with "May 1, 2000 selected for MASTER-2001 and MASTER-2005, and "May 5, 2009" selected for MASTER-2009.

3-2. Comparison for debris with a diameter between 10 μm and 1 m in low Earth orbit

Figure 1 shows the calculation results of cumulative flux as a function of altitude for debris larger than 10 μm, 100 μm, 1 mm, 1 cm, 10 cm, and 1 m in diameter, respectively. Discrepancies appear for debris larger than 10 μm and 100 μm when comparing the ORDEM and MASTER models for low altitudes. For debris larger than 10 μm, the reason is that ORDEM does not consider the decay of space debris involved in air drag in the Earth's atmosphere.[6] For debris larger than 100 μm, the difference between both models can be explained by the fact that MASTER-2009 considers the latest breakup events, such as the Anti-SATellite (ASAT) weapon test on the Chinese weather satellite Feng-Yun 1C in 2007 and the collision between Cosmos-2251 and Iridium-33 in 2009.[9] On the other hand, the impact flux profiles for debris larger than 10 cm and 1 m are similar for both models since debris larger than 10 cm can be tracked by ground-based observations. Even though debris larger than 10 cm can be tracked, there are still differences between the models, and almost the same differences observed with 1 cm debris. At altitudes around 1,500 km and for debris larger than 1 m, there is a noticeably large discrepancy between the ORDEM and MASTER models. Finally, large differences in impact flux profile can also be observed for debris larger than 1 mm and 1 cm, as ground facilities cannot track debris in this size range, and because not enough surfaces were retrieved for conducting statistical analysis. Consequently, the results given by the ORDEM and MASTER models vary significantly.



(a) Diameter > 10 μm

(b) Diameter > 100 μm

(c) Diameter > 1 mm

(d) Diameter > 1 cm

(e) Diameter > 10 cm

(f) Diameter > 1 m

Figure 1. Debris flux against altitude at inclination of 100 degrees for different debris

3-3. Detailed comparison of debris 100 μm to 1 mm in diameter and in low Earth orbit

As mentioned before, there is a lack of data on debris smaller than 1 mm, given the difficulty of observing such small debris from ground-based facilities, and because not enough surfaces were retrieved to conduct proper statistical analysis. Therefore, the debris impact flux for different classes in this size range was calculated under the same conditions as for the previous calculations. Figure 2 shows the results.

From these calculations, the ORDEM model apparently shows a larger debris impact flux value than the MASTER model, except for debris larger than 100 μm and 200 μm (Figure 2 (a) and (b)) at altitudes near 700 km. There are large differences between each debris impact flux, including some on an order of 100 or more at some altitudes. The highest order of difference found is 18,600 at 300 km. Again, this high value can be explained by the fact that ORDEM does not consider the air drag involving the Earth's atmosphere. As the air drag decreases at higher altitudes, the difference between both models decreases to reach an order of difference of approximately 600 at 1900 km (Figure 2 (h)). Hence, the order of difference between the two debris environment models is very high. This observation is important when choosing a debris environment model during the design phase, as it may greatly affect the resources needed for a project.

The solution to reducing the differences between both debris environment models is to obtain more data through the use of in-situ measurements conducted aboard spacecraft, and thereby evaluate the number of debris in real time.

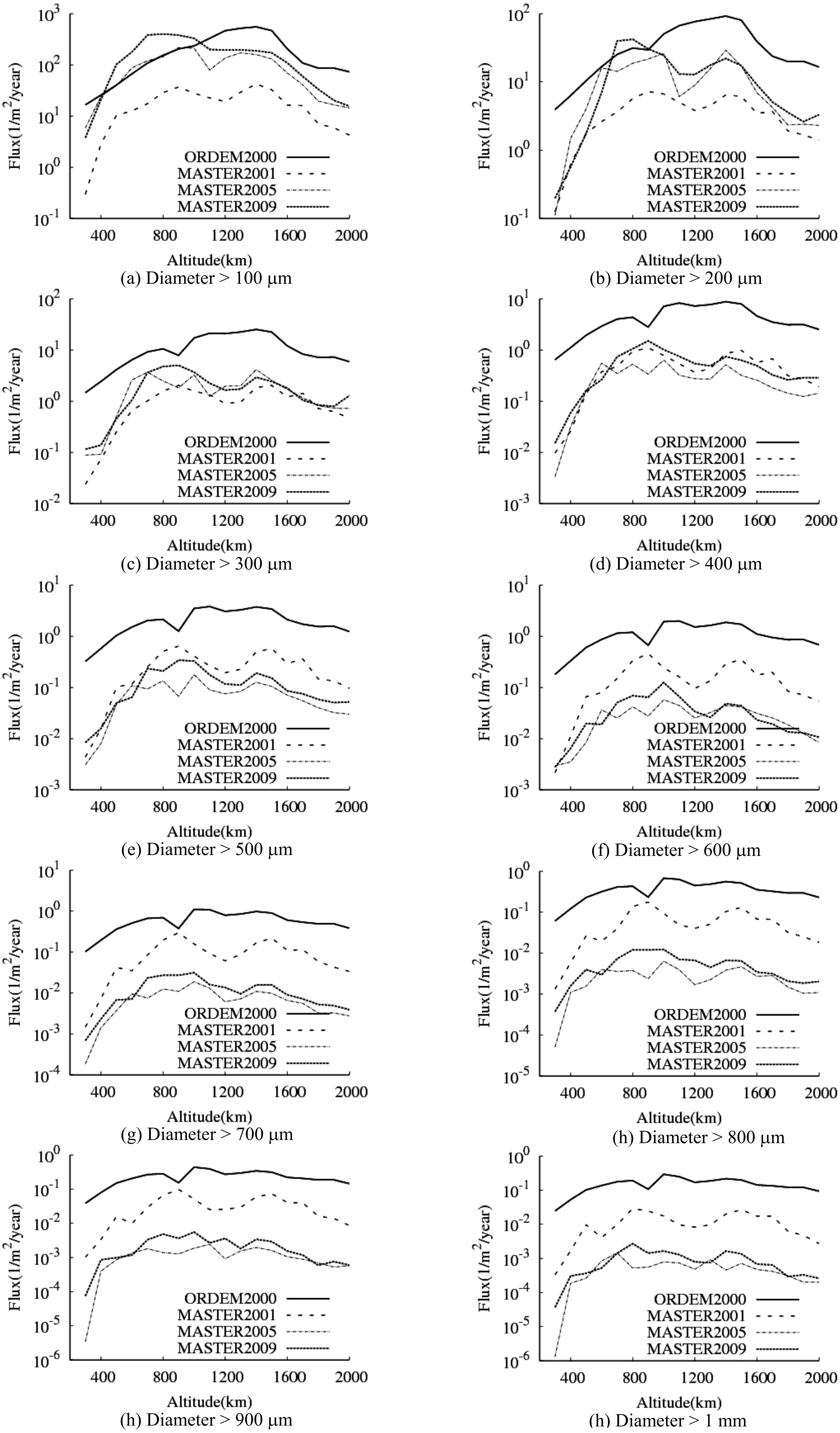


Figure 2. Debris flux against altitude at inclination of 100 degrees for debris 100 μm to 1 mm in diameter.

3-4. Comparison of impact flux calculated by debris environment models for the Shizuku (GCOM-W1) satellite's orbit

The authors compared the four debris environment models' results for the Japanese satellite Shizuku, also known as Global Change Observation Mission (GCOM). GCOM aims to conduct global observations of the Earth's environmental changes from space. Table 3 lists the specifications of the Shizuku satellite.

Horyu II is a small satellite under development at the Kyushu Institute of Technology (KIT). It will operate for one year in sun-synchronous orbit. Horyu II's main mission is to generate 300 V, and it may undertake eight other missions.

The Japan Aerospace Exploration Agency (JAXA) will launch GCOM-W1 and Horyu II together on a HII-A rocket in 2012.

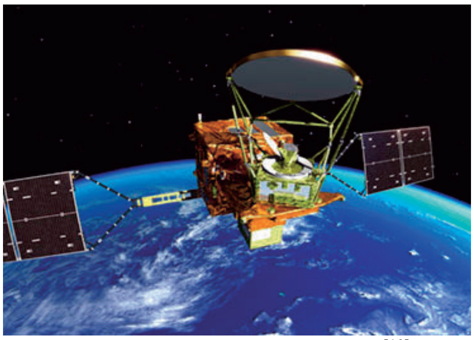


Figure 3. Shizuku (GCOM-W1)[10].

Table 3 lists the GCOM-W1's parameters chosen for calculations with the different debris environment models.

Table 3. GCOM-W1 satellite's parameters used for calculations with each model's threshold year.

Item	ORDEM2000	MASTER-2001	MASTER-2005	MASTER-2009
Calculation epoch	2000/1/1	2001/5/1	2005/5/1	2009/5/1
Altitude [km]	700			
Inclination [degree]	98.2			
Size range [m]	10^{-5} - 1			
Resulting data	Cumulative flux			
Debris	Yes			
Meteoroids	None			

Note: After the release of the ORDEM2000, MASTER-2001 and MASTER-2005 models, many new events occurred, such as the breakups of upper stages, ASAT, and collision between Cosmos-2251 and Iridium-33, thereby increasing the population of space debris. Moreover, MASTER-2005 cannot calculate the impact flux for debris smaller than 1 mm after May 1, 2005.[8] MASTER-2009 can calculate the impact flux of debris smaller than 1 mm for periods after May 1, 2009, but without considering information on the MLI population.[9] Thus, in order to compare the models, the authors decided to perform the calculations by considering the threshold year of each model as the epoch.

Figure 4 shows the debris impact flux against the debris diameter as calculated by each model for the GCOM-W1 satellite's orbit. Large differences between the impact fluxes can be observed for each model. In the previous sections, assumptions were made to explain these differences, and the differences observed are believed to result from the same assumptions.

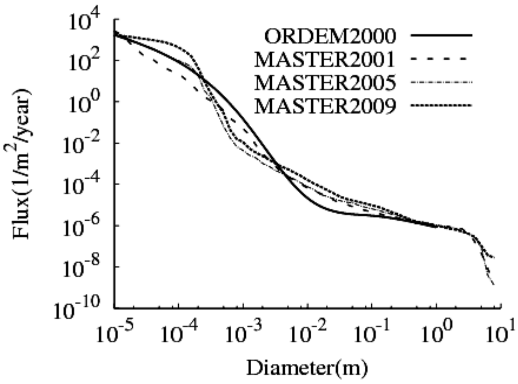


Figure 4. Debris impact flux against the debris diameter for GCOM-W1 as calculated for each model's threshold year.

Table 4 lists the GCOM-W1's parameters chosen to calculate the impact flux with the different environment models. Here, for all models, the year 2012 was chosen as the epoch.

Table 4. GCOM-W1 satellite's parameters used for calculations with each model for the year 2012.

Item	ORDEM2000	MASTER-2001	MASTER-2009
Calculation epoch	2012/1/1	2012/1/1	2012/1/1
Altitude [km]	700		
Inclination [degree]	98.2		
Size range [m]	10^{-5} - 1		
Resulting data	Cumulative flux		
Debris	Yes		
Meteoroids	None		

Note: Since the GCOM-W1 satellite will be launched in 2012, the authors decided to perform the calculations with each model for the year 2012. However, MASTER-2005 cannot calculate the impact flux for debris smaller than 1 mm after May 1, 2005;[8] thus, the calculations made with MASTER-2005 do not appear in this table.

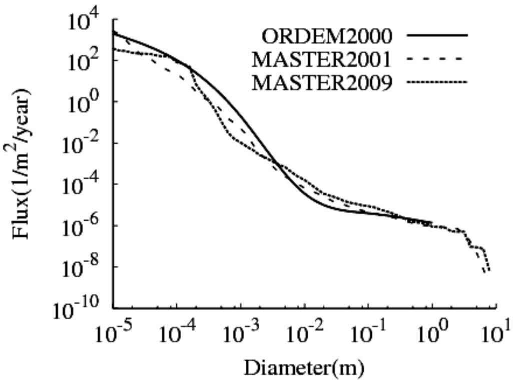


Figure 5. Debris impact flux against the debris diameter for GCOM-W1 as calculated with each model for the year 2012.

Figure 5 shows the debris impact flux against the debris diameter as calculated by each model for the GCOM-W1 satellite's orbit. Figures 4 and 5 present similar profiles; thus, the assumptions previously stated are valid. However, compared to Figure 4, the decrease in impact flux calculated with the MASTER-2009 model is noticeable for particles smaller than 10^{-4} m. Since these particles are very small, they probably re-enter the Earth's atmosphere due to the air drag. Moreover, the MASTER-2009 model does not consider the MLI population after May 1, 2009, and the graph represents the cumulative impact flux. The impact flux calculated for the year 2012 is consequently smaller than the flux calculated for the year 2009.

4. Conclusions

The results of comparing the ORDEM2000, MASTER-2001, MASTER-2005 and MASTER-2009 debris environment models revealed particularly large differences in the impact flux estimation for debris larger than 100 μm and 1 mm in diameter. A debris population ranging from hundreds of micrometers to several millimeters in size is particularly critical for reliable spacecraft design. Therefore, spacecraft designers must improve their evaluation of space debris impact risk through improved protection, observation, experimentation and simulation techniques.

One solution currently being explored is to reduce the differences between the environment models by obtaining more data on debris ranging from 100 μm to 1 mm from in-situ measurements taken by systems located onboard a spacecraft that can give a ground station real-time data on the number of debris for a given orbit.

5. References

[1] <http://celestrak.com/satcat/boxscore.asp>, (accessed 2011-12-6).

[2] "JAXA Space Debris Protection Design Manual Appendix 2," *JAXA*, JERG-2-144-HB001, 2008.

[3] Sdunnus H., Beltrami P., Klinkrad H., Mantney M., Nazarenko A., and Wegener W., "Comparison of debris flux models," *Advances in Space Research*, Vol. 40, 2004, pp.1000-05.

[4] Fukushige S., Akahoshi Y., Kiyazawa Y., and Goka T., "Comparison of Debris Environment Models; ORDEM2000, MASTER2001 and MASTER2005," *IHI Engineering Review*, Vol. 40, No. 1, February 2007.

[5] Drolshagen G., Dikarev V., Landgraf M., Krag H., and Kuiper W., "Comparison of meteoroid flux models for near Earth space," *Proc. of the Earth, Moon, and Planets*, 11-15 June 2007, DOI: 10.1007/s11038-007-9199-6 (Springer: Barcelona, Spain).

[6] Liou J.C., Matney M., Anz-Meador P.D., Kessler D., Jansen M., and Theall J.R., "The New NASA Orbital Debris Engineering Model ORDEM2000," *NASA*, NASA/TP-2002-210780, 2002.

[7] Bendisch J., Bunte K.D., Krag H., Sdunnus H., Wegener P., Walker R., and Wiedemann C., "MASTER-2001 Final Report," *Institute of Aerospace Systems,* December 2002.

[8] Oswald M., Stabroth S., Wiedemann C., Wegener P., and Martin C., "MASTER-2005 Final Report," *Institute of Aerospace Systems*, April 2006.

[9] Flegel, S. *et al.*, "MASTER-2009 Final Report," *Institute of Aerospace Systems*, June 2011

[10] <http://www.jaxa.jp/pr/brochure/pdf/04/sat25.pdf>, (accessed 2011-11-28).