JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 48, No. 1, January–February 2011

Microsatellite Impact Tests to Investigate the Outcome of Satellite Fragmentations

Junko Murakami* and Toshiya Hanada†
Kyushu University, Fukuoka 819-0395, Japan
and
J.-C. Liou‡
NASA Johnson Space Center, Houston, Texas 77058

DOI: 10.2514/1.49204

To predict the future orbital environments, it is necessary to know outcome of the satellite fragmentation. The NASA standard breakup model is designed to describe the outcome of typical satellite fragmentation. This model is an empirical model and the major data sources are the 1980s on-orbit satellite breakup events and the ground-based Satellite Orbit Debris Characterization Impact Test series conducted in early 1990s. The target cubic satellites ranged from 15 to 20 cm in size and about 1000 g in mass. Results from all seven impact tests carried out in 2008 are shown in this paper and compared with the NASA standard breakup model to demonstrate potential improvements of the model in the future.

Nomenclature

A/M	=	area-to-mass ratio, m^2/kg
D	=	area-to-mass ratio distribution function
E_{imp}	=	impact energy, J
L_c	=	characteristic length, m
M_t	=	target mass, g
M_p	=	projectile mass, g
N	=	normal distribution function
N_{cum}	=	cumulative number of fragments equal to or greater than a given value
N_{frag}	=	fragments number
V_{imp}	=	impact velocity, km/s
x, y, z	=	NASA orthogonal projection dimensions, m
λ_c	=	$\log_{10}(L_c)$
μ	=	mean
σ	=	standard deviation
χ	=	$\log_{10}(A/M)$

I. Introduction

THE human space activities in the last 50 years have created an orbital debris problem in the near-Earth environment. To better understand the future environments, it is necessary to know the outcome of the satellite fragmentation. To describe the satellite fragmentation, the NASA standard breakup model was developed based on well-observed on-orbit breakup events and ground-based hypervelocity impact tests. To continue to improve the understanding of the satellite fragmentation, Kyushu University and the NASA Orbital Debris Program Office (ODPO) have collaborated on microsatellite impact tests since 2005. First, 15-cm cubic microsatellites were prepared as targets to investigate the outcome of hypervelocity and low-velocity impacts. Then 20-cm cubic microsatellites were prepared as targets to investigate the effects of different impact directions. Finally, multilayer insulation (MLI) and a solar panel were added to the 20-cm cubic microsatellite to investigate MLI and solar panel pieces. Conducting satellite impact tests contributes to increase the test data and to expand the versatility of the breakup model. This paper summarizes the impact tests and the analysis of the outcome.

Received 4 February 2010; revision received 28 June 2010; accepted for publication 3 August 2010.

*Master Course Student, Aeronautics and Astronautics, 744 Motooka, Nishi-ku; junko_m@aero.kyushu-u.ac.jp.

†Associate Professor, Aeronautics and Astronautics, 744 Motooka, Nishi-ku; toshi@aero.kyushu-u.ac.jp. Senior Member AIAA.

‡Space Scientist, NASA Orbital Debris Program Office, Mail Code KX; jer-chyi.liou-1@nasa.gov.

II. NASA Standard Breakup Model

The NASA ODPO released a new standard breakup model in 2001. It is quite different from other fragmentation models (see [1]). Previously, mass and diameter (or size) was used interchangeably as independent variables. However, with the incorporation of area-to-mass ratio distributions, this interchangeability is lost. The characteristic length Lc is chosen as an independent variable. The characteristic length of an object is defined as the average of the three orthogonal dimensions, x, y and z, where x is the longest dimension, y is the longest dimension in the plane perpendicular to x, and z is the longest dimension perpendicular to both x and y. Thus

$$L_c = \frac{1}{3}(x + y + z) \tag{1}$$

The following subsections will describe the hypervelocity collision model adopted in the NASA standard breakup model 2001 revision.

A. Size Distribution

Collisions between two satellites may be noncatastrophic, characterized primarily by fragmentation of the smaller object and by cratering of the larger object, or catastrophic, wherein both objects are totally fragmented. The difference between a catastrophic and a noncatastrophic collision is determined by the ratio of kinetic energy at impact to target mass. If the ratio is equal to or greater than 40 J/g, then the collision is catastrophic. Based on several laboratory hypervelocity impact experiments, including the highly instrumented Satellite Orbital Debris Characterization Impact Test (SOCIT) [2,3] series as well as the on-orbit collision of the Solwind spacecraft, the number of fragments of a given size and larger can be described by

$$N_{cum} = 0.1(M_{tot})^{0.75}(L_c)^{-1.71} \tag{2}$$

B. Area-to-Mass Ratio

For objects with Lc smaller than 8 cm, a single area-to-mass ratio, A/M, distribution function has derived from hypervelocity impact experiments as follows:

$$D_{A/m}^{\mathrm{SOC}}(\lambda_c, \chi) = N[\chi; \mu^{\mathrm{SOC}}(\lambda_c), \sigma^{\mathrm{SOC}}(\lambda_c)] \tag{3}$$

where

$$\lambda_c = \log_{10} L_c, \qquad \chi = \log_{10} A/m \tag{4}$$

and N is a normal distribution in χ about the mean value of

$$\mu^{\mathrm{SOC}}(\lambda_c) = \begin{cases} -0.3 & \lambda_c \leq -1.75 \\ -0.3 - 1.4(\lambda_c + 1.75) & -1.75 \leq \lambda_c < -1.25 \\ -1.0 & \lambda_c \geq -1.25 \end{cases} \tag{5}$$

with a standard deviation of

$$\sigma^{\mathrm{SOC}}(\lambda_c) = \begin{cases} 0.2 & \lambda_c \leq -3.5 \\ 0.2 + 0.1333(\lambda_c + 3.5) & \lambda_c > -3.5 \end{cases} \tag{6}$$

Note that the A/M distribution function given by Eq. (3) is assumed to describe adequately the A/M characteristic of small debris produced in the collision and explosive breakup of either spacecraft or rocket booster.

III. Microsatellite Impact Tests Series

A. History

Satellite impact testing at Kyushu University was initiated in 1994 [4]. Simulated spacecraft walls were selected as targets while solid stainless steel spheres were used as projectiles. The impact velocities were up to about 300 m/s, and the outcomes were all noncatastrophic (only a small amount of fragments were generated from impact craters or holes on the target walls). Many international orbital debris research groups have adopted results from this initial study for geosynchronous Earth orbit (GEO) modeling [5].

As discussed previously, NASA standard break up model is an empirical model derived from on-orbit data and ground-based experiments. The authors have two motivations to conduct additional testing. First, the NASA model derived from hypervelocity impact and it is uncertain that this model could be applied to the low-velocity impact. It is necessary to extend tests to different velocity regimes to cover potential low-velocity collisions in the GEO region. Second, the previous test targets were made with technology developed in 1960 s and the materials were dominated by metals. Mass distribution and A/M distribution of the fragments are directly influenced by the materials of the parent satellites. As more lightweight composite materials are used for modern satellites, there is a need for impact tests on targets made of the new materials to better characterize the outcome of future on-orbit breakups.

In 2004, a can-sized satellite named CANSAT, which is a microsatellite popular among universities teaching space engineering, was prepared as a target to investigate the applicability of the NASA standard breakup model to a low-velocity catastrophic impact. The result showed the NASA model, which is defined by hypervelocity impacts, could be applied to low-velocity catastrophic collisions. This CANSAT impact test started the collaboration between Kyushu University and the NASA ODPO for additional microsatellite impact tests.

For the first collaborated impact tests, two 15-cm cubic satellites, using modern materials, carbon fiber reinforced plastic (CFRP) and glass fiber reinforced plastic (GFRP), were fabricated. These tests in 2005 consisted of hypervelocity and low-velocity impact tests, denoted as HVI and LVI, respectively. After those tests, two 20-cm cubic satellites were prepared to investigate the effects of impact directions and impact energy in 2007 (shot 1, 2, and 3) [6]. Finally in 2008, two 20-cm cubic microsatellites covered with multilayer insulation (MLI) and equipped with a solar panel were built for the experiments [7,8]. The inclusion of MLI and solar panels was primarily motivated by the recent discovery of high A/M objects in GEO and the Fengyun-1C antisatellite test [9]. Hundreds of high A/M objects have been observed to have orbital periods close to 1 day near GEO. They are likely to be MLI pieces (see [10]). In addition, many of the fragments generated after the Fengyun-1C antisatellite test also have high A/M values consistent with MLI, solar panel, or lightweight plastic materials. These types of materials were not part of the targets used in the development of the current NASA standard breakup model. Therefore, data from the Kyushu University-NASA impact experiments may provide knowledge that will be needed to better describe the current and future on-orbit MLI, solar panel, and composite material fragments.

B. Target Satellite and Tests Conditions

The microsatellite impact test conducted in 2005, 2007 and 2008 as shown in Fig. 1. Three different types of microsatellites were designed and fabricated for the test series. The first targets (in 2005) were 15 by 15 by 15 cm in size and 740 g in mass. The second (2007) and third (2008) sets of targets were 20 by 20 by 20 cm in size, slightly larger than the first ones. As will be described later, a solar panel and MLI were added to the third sets of targets so that their masses were different; the second set of targets was 1300 g in mass and the third ones were 1500 g in mass. When considering based on the target satellites used in second tests (2007), the difference between the ones used in first tests (2005) is the size and because of the difference, weight is also of course different. On the other hand, the difference between the ones used in the third tests (2008) is whether these have MLI and solar panel or not, the target satellite used in the third experiments new materials were added, i.e., MLI and a solar panel to the second target. Regarding the third tests, the four side panels and the bottom layer were covered with MLI sheets and the remaining side was equipped with a solar panel. The MLI sheets had six layers and consist of two sections, A and B, as shown in Fig. 2. Section III.A was attached to the bottom layer while Sec III.B was wrapped around the four side panels. They were attached to the satellite surfaces with velcro. A single solar panel consisted of six solar cells and an aluminum honeycomb sandwich panel with CFRP face sheet. As shown in Fig. 3, main structure of each microsatellite was composed of five layers (top and bottom layers and three internal layers parallel to the top and bottom layers) and four side panels.

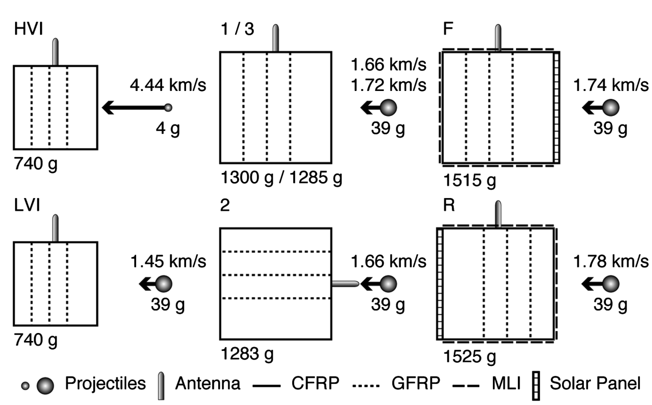

Fig. 1 Microsatellite impact parameter.

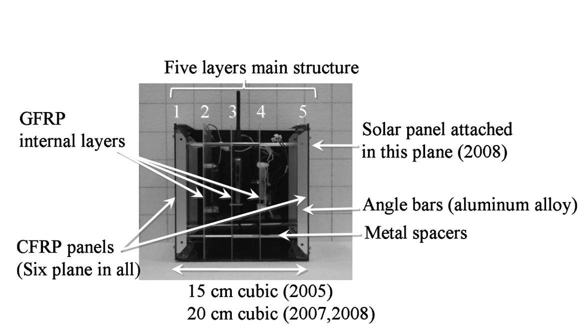

Fig. 2 Target microsatellite structure.

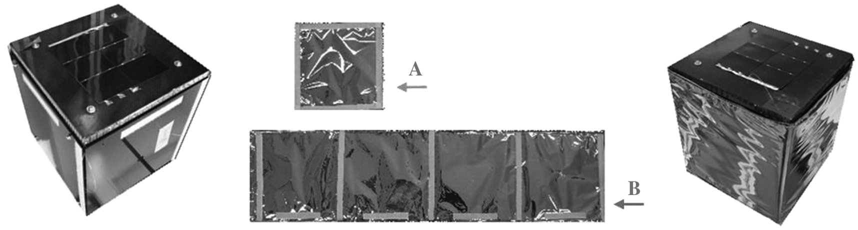

Fig. 3 Target microsatellites and MLIs: target microsatellite not covered with MLI (left), MLIs (center), and target microsatellite covered with MLI (right).

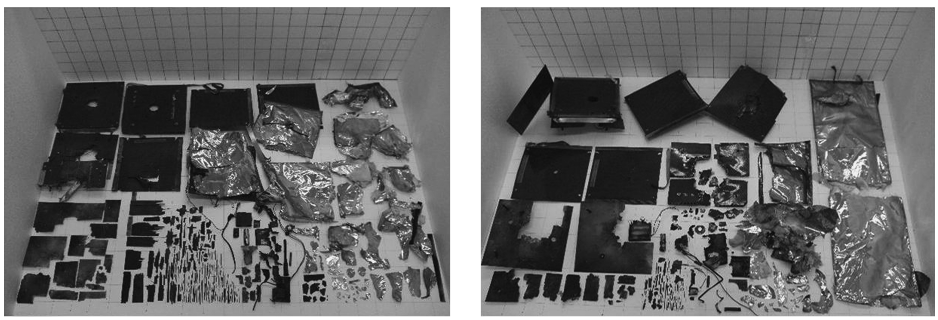

Fig. 4 Overview of the fragments from shot F (left) and from shot R (right).

They were assembled with angle bars made of aluminum alloy and metal spacers. The top and bottom layers and side panels were made of CFRP, while the three internal layers were made of GFRP. The interior of each microsatellite was equipped with fully functional electronic devices, such as a wireless radio, lithium-ion batteries, and communication, electric power supply, and command and data handling circuits. Figure 4 shows the overview of the fragments collected from the tests.

C. Two-Stage Light Gas Gun

All microsatellite impact testing summarized in Table 1 and Fig. 1 was conducted using a two-stage light gas gun (LGG) at the Kyushu Institute of Technology in Kitakyushu, Japan. The LGG is driven by gunpowder to perform impact tests. The combustion gas of the gunpowder pushes a piston to compress helium in the first stage. Then the highly compressed light gas accelerates a projectile in the second stage right after the light gas ruptures a diaphragm between the stages. The LGG can shoot projectiles large enough to fragment prepared microsatellites catastrophically. Details of the LGG can be found in [11].

IV. Analysis and Discussions

A. Size Distribution

Figure 5 shows the cumulative distributions as functions of characteristic lengths. There is a measurement level-off below 10^{-3} m in characteristic length. Overall the tests results show reasonable agreements with the NASA standard breakup model. The minor differences could be due to the materials used to construct the target satellites. Since the 1990s, lightweight CFRP and other composite materials have been extensively used for satellite structure instead of the metals. Fragments made of the new materials could have properties different from metallic debris. For example, hundreds of needlelike fragments were collected from several microsatellite experiments. The abundance of these fragments contributes to the discrepancy between the actual data and the NASA model.

B. Area-to-Mass Ratio (A/M)

A/M is an important parameter for debris. Perturbations, including orbit decay, due to atmospheric drag and solar radiation pressure are related to an object's A/M. For fragments with perigee altitudes below 1000 km, the A/M's determine their orbital lifetimes. The A/M distribution is one of the key elements of any breakup model.

The largest disagreement between the NASA model and the microsatellite impact experiments is the A/M distribution, as shown in Fig. 6. As mentioned above, the lightweight composite materials used to build the microsatellites have a direct influence on the fragments' A/M distribution. Composite materials are obviously lighter than metals and have higher A/M values.

Two groups with distinct peaks are observed in the 2005 and the 2007 data. The higher A/M group (the one to the right) comes from the CFRP fragments. Its peak A/M value is about a factor of 10 higher than the peak A/M value of the distribution predicted by the NASA model. The lower A/M group (the one to the left) consists of other materials, including metal components, of the target microsatellites. This group, although similar in shape to the distribution predicted by the NASA model, has a peak value about a factor of 3 higher than that of the distribution predicted by the NASA model.

Table 1 Impact parameter

Year	Shot	M_t, g	M_p, g	V_{imp}, km/s	E_{imp}, J/g	Impact direction (with respect to layers)	N_{frag}
2005	HVI	740	4.03	4.44	53.7	Normal	1500
	LVI	740	39.2	1.45	55.7	Normal	1500
2007	1	1300	39.2	1.66	41.5	Normal	1300
	2	1283	39.2	1.66	42.0	Parallel	1000
	3	1285	39.2	1.72	45.1	Normal	1500
2008	F	1515	39.2	1.74	40.7	Normal	2400
	R	1525	39.3	1.78	39.3	Normal	1250

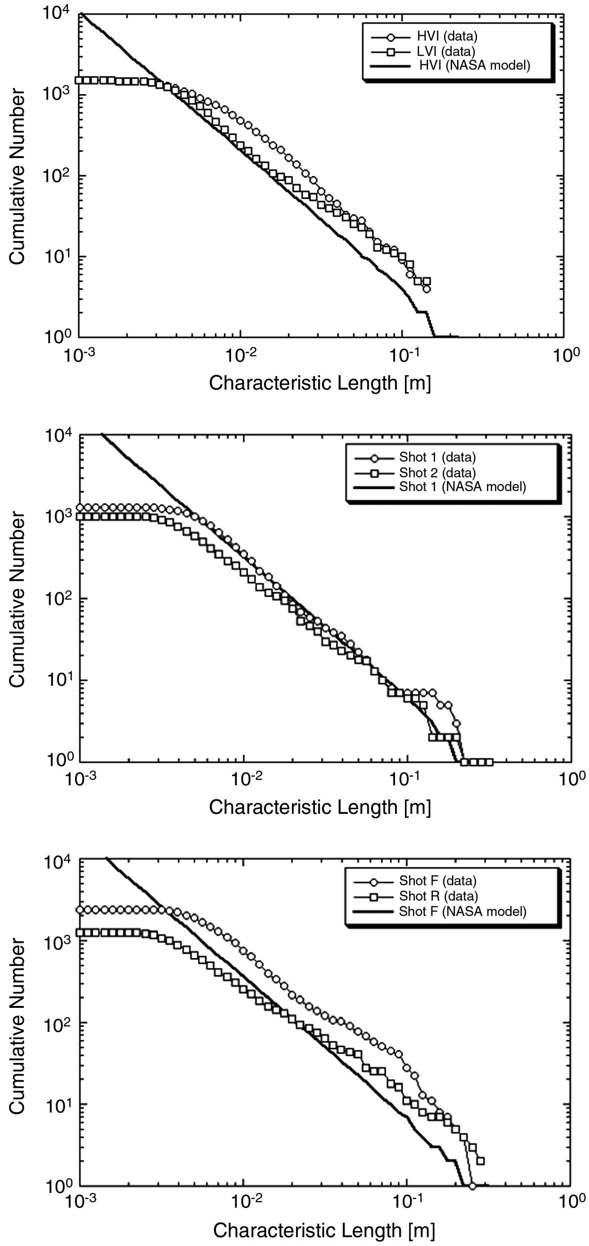

Fig. 5 Size distributions.

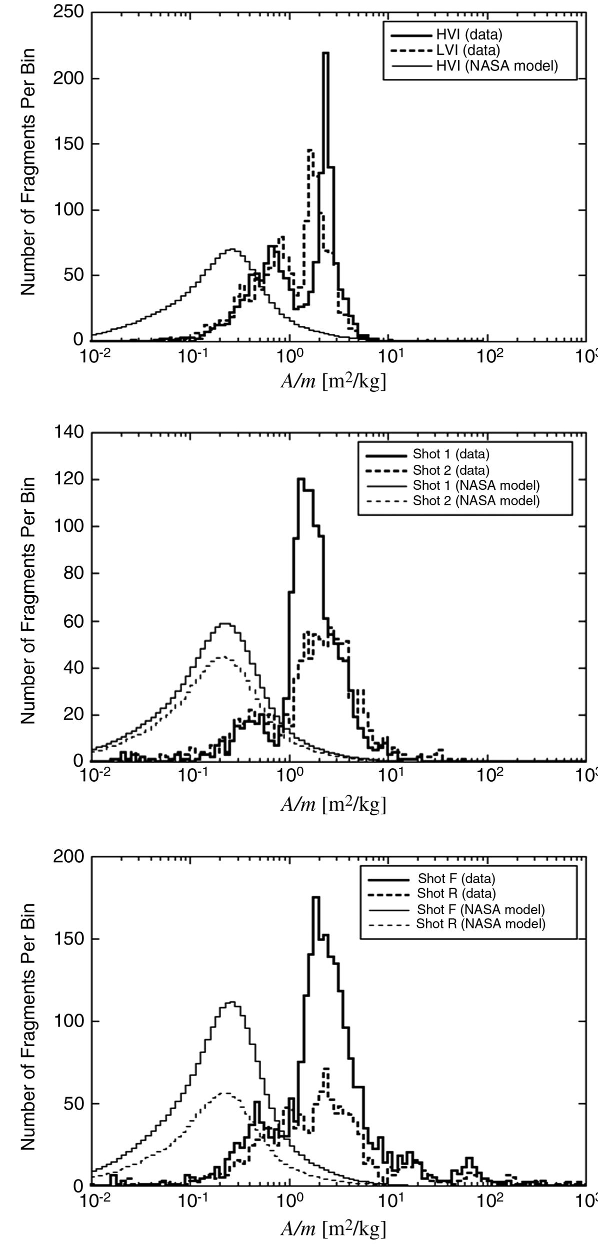

Fig. 6 ***A/M*** **distributions.**

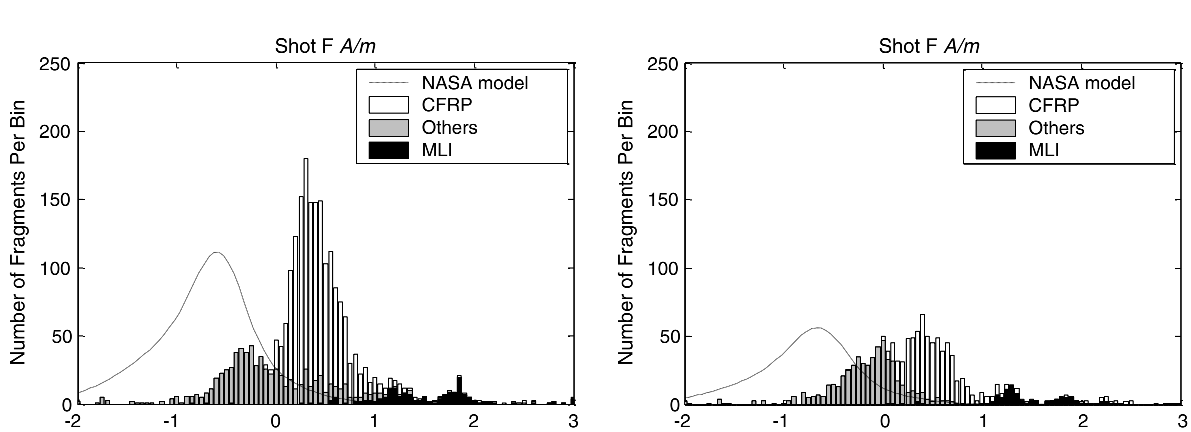

Fig. 7 ***A/M*** **distributions classified into three groups in shot F (left) and R (right).**

Fragments from the 2008 tests form three groups in the A/M distribution. The first two are similar to those observed from the 2005 and 2007 data. The third group includes fragments with A/M values ranging from about 10 to 100 m^2/kg or higher. These are MLI pieces. Those consist of multiple layers have lower A/M values while those consist of just a single layer of MLI tend to have higher A/M values (see also Fig. 7). Therefore, to provide a more complete description of the various components of the microsatellite fragments, it is beneficial to develop three separate functions to characterize the different components.

V. Conclusions

This paper provides a summary of the seven microsatellite impact tests conducted since 2005. Fragments were collected and individually measured after each test. Fragment size and area-to-mass ratio distributions were derived and compared with the NASA standard breakup model predictions.

In terms of the size distribution, the NASA standard breakup model and test results seem to have a similar trend. Some minor discrepancy was observed. It is caused by the modern, lightweight materials, such as carbon fiber reinforced plastic, used in the target microsatellite. The difference in material property also leads to an area-to-mass ratio distribution that is very different from the NASA model prediction. The inclusion of the multilayer insulation in the last two tests also shows a new multilayer insulation fragment area-to-mass ratio distribution that is much higher than other fragments collected from the impact tests. As more and more lightweight composite materials are used in satellite construction, a new area-to-mass ratio distribution may be needed to better account for the satellite fragments in the future environment. An area-to-mass ratio distribution for the multilayer insulation pieces needs to be considered as well to complete the description of the debris populations in the environment.

For future works, the authors have to consider the size factor. Actual satellites in orbit are much larger and more massive than the microsatellites used in the experiments. Whether or not our test results are applicable to fragments generated from large/massive satellites will need to be investigated in the future. However, the lessons learned and the processes established from these seven impact tests are very valuable. For example, the test results clearly demonstrate the need for different distributions for modern materials and multilayer insulation fragments. The authors will also look into the possibility of using larger target satellite in our future impact tests.

Acknowledgment

The authors wish to acknowledge Yasuhiro Akahoshi of Kyushu Institute of Technology and his students for their dedicated assistance in the microsatellite impact experiments.

References

[1] Johnson, N. L., Krisko, P. H., Liou, J.-C., and Anz-Meador, P. D., "NASA's New Breakup Model of EVOLVE 4.0," *Advances in Space Research*, Vol. 28, No. 9, 2001, pp. 1377–1384. doi:10.1016/S0273-1177(01)00423-9

[2] McKnight, D. S., Johnson, N. L., Fudge, M. L., and Maclay, T. D., "Satellite Orbital Debris Characterization Impact Test (SOCIT) Series Data Collection Report," Kaman Sciences Corp., Rept. NAS9-19215, Alexandria, VA, 1995.

[3] McKnight, D. S., Johnson, N. L., Fudge, M. L., and Maclay, T. D., "Analysis of SOCIT Debris Data and Correlation to NASA's Breakup Models," Kaman Sciences Corp., Rept. NAS9-19215, Alexandria, VA, 1995.

[4] Yasaka, T., Hanada, T., and Hirayama, T., "Low-Velocity Projectile Impact on Spacecraft," *Acta Astronautica*, Vol. 47, No. 10, 2000, pp. 763–770. doi:10.1016/S0094-5765(00)00127-2

[5] Lewis, H. G., Swinerd, G. G., Williams, N., and Gittins, G., "DAMAGE: A Dedicated GEO Debris Model Framework," *Proceedings of the Third European Conference on Space Debris*, ESA Publications Division, Darmstadt, Germany, 2001.

[6] Hanada, T., Sakuraba, K., and Liou, J.-C., "Three New Satellite Impact Tests," *Orbital Debris Quarterly News*, Vol. 11, No. 4, 2007, pp. 4–6.

[7] Murakami, J., Hanada, T., Liou, J.-C., and Stansbery, E., "Two New Microsatellite Impact Tests in 2008," *NASA Orbital Debris Quarterly News*, Vol. 13, No. 1, 2009, pp. 4–7.

[8] Hanada, T., Ariyoshi, Y., Miyazaki, K., Maniwa, K., Murakami, J., and Kawamoto, S., "Orbital Debris Modeling at Kyushu University," *Journal of Space Technology and Science*, Vol. 24, No. 2, 2009, pp. 23–35.

[9] Liou, J.-C., and Johnson, N. L., "Physical Properties of the Large Fengyun-1C Breakup Fragments," *Orbital Debris Quarterly News*, Vol. 12, No. 2, 2008, pp. 4–5.

[10] Liou, J.-C., and Weaver, J. K., "Orbital Evolution of GEO Debris with Very High Area-to-Mass Ratios," *Orbital Debris Quarterly News*, Vol. 8, No. 3, 2004, pp. 6–7.

[11] Akahoshi, Y., Furukawa, K., Matsuda, E., and Hata, H., "New Test Range for Two-Stage Light Gas Gun in Kyushu Institute of Technology," *Proceedings of the 10th International Conference of Pacific Basin Societies (ISCOPS, Formerly PISSTA)*, AAS Paper 03-452, 2003, pp. 919–926.

A. Ketsdever
Associate Editor