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**Committee on the Peaceful Uses of Outer Space**

## National research on space debris, safety of space objects with nuclear power sources on board and problems relating to their collision with space debris

### Note by the Secretariat

## Contents



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# I. Introduction

1. In its resolution 63/90 of 5 December 2008, the General Assembly considered that it was essential that Member States pay more attention to the problem of collisions of space objects, including those with nuclear power sources, with space debris, and other aspects of space debris, called for the continuation of national research on that question, for the development of improved technology for the monitoring of space debris and for the compilation and dissemination of data on space debris, also considered that, to the extent possible, information thereon should be provided to the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space and agreed that international cooperation was needed to expand appropriate and affordable strategies to minimize the impact of space debris on future space missions.

2. At its forty-fifth session, the Subcommittee agreed that research on space debris should continue and that Member States should make available to all interested parties the results of that research, including information on practices that had proved effective in minimizing the creation of space debris (A/AC.105/911, para. 91). In a note verbale dated 5 August 2008, the Secretary-General invited Governments to submit information on the matter by 31 October 2008, so that that information could be submitted to the Scientific and Technical Subcommittee at its forty-sixth session.

3. The present document has been prepared by the Secretariat on the basis of information received from Germany and Japan.

# II. Replies received from Member States

## Germany

[Original: English]

1. In Germany, research activities related to space debris issues in general cover various aspects, including space debris observation technology, space debris environmental modelling, investigation of impact physics in order to improve understanding of hypervelocity impact phenomena and technologies to protect space systems from space debris and limit the future generation of space debris.

2. Financing is ensured either directly via the national space budget of Germany or via the European Space Agency (ESA). German activities executed under ESA contracts are presented in the corresponding report of ESA.

3. Information on nationally funded research activities that were initiated and carried out in Germany in 2008 is provided below.

### Re-entry wind-tunnel tests and comparisons of ORSAT and SCARAB

4. Hyperschall Technologie Göttingen (HTG) of Germany and the National Aeronautics and Space Administration (NASA) of the United States of America have continued to cooperate in the framework of a project aimed at comparing two atmospheric re-entry simulation programmes: the Spacecraft Atmospheric Re-entry

and Aerothermal Break-up (SCARAB) of HTG and the Object Re-entry Survival Analysis Tool (ORSAT) of NASA. That cooperation started in 1998. Studies have confirmed that both tools provide almost identical results for the re-entry of objects with a simple shape (i.e. sphere, box or cylinder). However, analyses involving a complex satellite have shown large differences between the predicted ground risks.

5. The objective of the project is to improve knowledge of the behaviour of material during spacecraft re-entry, thus enabling more accurate predictions to be made with regard to the fragmentation processes.

6. The project has focused on the following activities, which were identified as the most important sources of uncertainty:

(a) Development of a more realistic modelling approach and improved analysis of the aerothermal destruction of carbon-fibre-reinforced plastic (CFRP) elements during re-entry. Tests have been executed at the arc-heated wind tunnel facility of the German Space Agency (DLR) in Cologne to investigate material destruction under re-entry conditions;

(b) Improvement of the aerothermodynamism of aerodynamically misshapen construction elements (hollow or box-shaped objects moving in arbitrary flow directions). Tests have been executed at the DLR hypersonic vacuum wind tunnel facility in Göttingen, Germany, to investigate aerothermal heating under re-entry conditions;

(c) Comparison of the fragmentation processes of a simplified generic test satellite in the framework of ORSAT and SCARAB, as a result of which ORSAT and SCARAB have been compared again.

*Wind-tunnel tests for assessing material destruction*

7. The necessity for carrying out experimental tests on materials arose out of previous SCARAB re-entry analyses, which were carried out at a time when the aerothermal destruction mechanism and the corresponding material data for refractory materials, including alloys like invar and copper, glass-ceramic material and bulk CFRP, were unknown. Therefore, the arc-heated wind-tunnel facility in Cologne was used to conduct material destruction tests under re-entry conditions.

8. Those tests revealed that CFRP burns up very slowly due to a chemical reaction with the atomic oxygen of the flow, but that it is destroyed at very high surface temperatures (over 2,000 Kelvin), thus ensuring an effective radiative cooling. Thus, CFRP acts as quite a resistant ablative heat protection for space craft components. The results were used in SCARAB, but only preliminarily based on the standard material destruction mechanism for metals. Chemical destruction mechanisms, e.g. oxidation, were not implemented.

9. The space industry is increasingly using honeycomb structures made of CFRP in satellite missions. Typical examples are the ESA scientific satellite mission Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) and the German radar satellite mission TerraSAR-X, but CFRP is also used in large components of the Ariane 5 upper stages. In order to improve the destructive re-entry prediction for such construction elements, more material tests are necessary. Only on the basis of the results of such tests can new destruction mechanisms be implemented in SCARAB to reduce major uncertainties for re-entry ground risk prediction.

10. Material destruction tests have been conducted in the arc-heated wind-tunnel facility in Cologne. Fourteen material samples and one heat flux probe have been tested under re-entry conditions. Comparisons with SCARAB have shown that the wind-tunnel conditions used are similar to real conditions at an altitude of 53.6 km and a velocity of 3.6 km/s. The corresponding coldwall flux was about 1.4 megawatts/m$^2$.

11. Seven samples were of the aluminium-honeycomb sandwich with CFRP face sheets, which were representative samples of the Ariane 5 payload adapter SYLDA provided by ESA.

12. Another three samples were from the GOCE project. One sample was again an aluminium-honeycomb sandwich with CFRP face sheets used for the GOCE solar panel. The other two samples were special carbon-carbon materials used within the gradiometer instrument of GOCE, provided by Alenia Spazio of Italy.

13. The remaining four material samples included an aluminium-honeycomb core with glass fibre/epoxy resin face sheets, a plain titanium alloy and the same alloy coated with CFRP to represent CFRP overwrapped titanium high-pressure tanks used in Ariane 5 upper stages, and a two-part copper model, one half of which was coated with a nickel-chromium alloy for surface catalycity investigations.

14. The destruction behaviour of all aluminium-honeycomb models with CFRP or glass fibre face sheets was similar. The characteristic destruction event was the failure of the first face sheet. A wide range of failure was observed. The carbon-carbon material proved to be very resistant. The plain titanium model was not destroyed; after testing, the model was only covered by a porous oxide layer. However, the same titanium alloy was destroyed when it had been coated by CFRP. The nickel-chromium coating of the copper model did not show any damage.

15. In order to compare the measurement results with numerical simulations, SCARAB has been used in a new, experimental wind-tunnel mode. The primary objective of the SCARAB simulations was to reproduce the wind-tunnel conditions, especially the heat flux that was used for the tests at the arc-heated wind-tunnel facility in Cologne.

16. The following general conclusions were drawn from the comparative tests:

(a) The SCARAB results and the measurements taken at the arc-heated wind-tunnel facility in Cologne show a good agreement for the general destruction prediction (i.e. no destruction for titanium, a similar ablation rate of CFRP and a similar destruction sequence of CFRP-aluminium-honeycomb sandwich structures), and some similarities with respect to temperature evolutions;

(b) There were large differences in the details of the temperature evolution resulting from SCARAB analysis deficits. For example, there were no chemical destruction processes (such as surface oxidation and ablation) and the radiative surface for layered models was incorrect;

(c) Heat loss due to thermal conduction into the model holder should be quantified.

*Wind-tunnel tests for aerothermal heating*

17. Satellites and most spacecraft parts do not usually have an aerodynamic shape. During re-entry, any flight attitude is possible, in principle. In most cases, satellite components are shaped like hollow cylinders (pipes), boxes, struts with various cross-sections or thin-walled plates and shells.

18. For such non-aerodynamically shaped bodies, only a limited amount of experimental data is available that could be used to verify numerical analysis methods, which is why experimental testing from all angles of attack is necessary.

19. Since most of those objects are blunt, aerodynamic force coefficients can be calculated with sufficient accuracy based on a modified Newtonian theory. However, calculating the heat flux distribution and the corresponding integral heat flux on the whole of the object still causes significant problems. In addition, although tumbling and open, hollow objects can allow internal flow at certain altitudes, it is very difficult to analyse that flow numerically. Nonetheless, such objects are very commonly used as components in spacecrafts.

20. The heat transfer tests carried out on 22 objects with different shapes provided a valuable set of data on the relationship between the integral heating rate on body shape and the angle of attack.

21. For the tests, the objects were placed in one of two groups: group A and group R. Group A objects were used to test angles of attack between minus 90 and plus 90 degrees and group R objects were used to test rotating models. Both groups included solid and hollow objects.

22. The test results for solid and hollow objects, which also allow internal flow and internal heating, were compared. Compared with a solid object with a similar frontal area, a hollow object whose hollow part was pointing in the direction of the flow experienced a large internal heating flow and the heating rate increased greatly. With an increase in the angle of attack, the internal flow and heating decreases whereas the external heating increases due to a larger external area exposed to the flow. The combination of the two contrasting effects resulted in a smoothing out of the heating rate change with angle of attack.

23. Selected heating flux results on solid objects were compared with the SCARAB analysis method. The heating rate, which is dependent on the normalized angle of attack, are reasonably predicted with SCARAB methods. A more detailed comparison with the SCARAB analysis method is foreseen within the verification procedure of the new 3.1L version of SCARAB, which is currently under development.

*Comparisons of ORSAT and SCARAB*

24. In order to achieve better coordination and adaptation of the software systems of ORSAT and SCARAB under real spacecraft re-entry conditions, a simplified generic test satellite was used to compare the results of the numerical simulation of the fragmentation processes and predictions. In the past, such comparisons proved to be very difficult, at least for complex satellites.

25. The test satellite was developed jointly by the NASA and HTG teams. It weighed about 400 kg and was not necessarily a realistic model as its main purpose

was to help in the identification of different destruction processes occurring during re-entry that led to different results on the ground.

26. The main difference between ORSAT and SCARAB is in the treatment of fragmentation. In ORSAT, a break-up altitude of 78 km was assumed. At that altitude, all modelled objects were released to the flow and then analysed separately. In SCARAB, the connectivity (touching) between the modelled objects was analysed in order to identify fragments that were no longer connected because they had melted to other parts of the spacecraft. Loose fragments were analysed separately. The approach adopted in the framework of ORSAT led to a single, instantaneous fragmentation event at an altitude of 78 km, whereas the SCARAB approach caused a more continuous fragmentation regime that reached a peak at an altitude of 60-80 km.

27. The results of the ORSAT and SCARAB analyses for the test satellite showed good agreement in terms of the trajectory. The ground impact footprints had similar shapes and only shifted by about 70 km along the track direction.

28. Survivability comparisons also showed a fairly good degree of agreement. Surprisingly, however, ORSAT predicted slightly more surviving fragments than SCARAB and a casualty area that was larger than the one predicted by SCARAB.

29. A detailed comparison of the surviving fragments revealed that the main differences in terms of the ground risk were due to the different fragmentations of the battery box. In the case of ORSAT, where fragmentation took place at an altitude of 78 km, all internal components were released as separate fragments and survived re-entry. This resulted in a larger number of impactors. In the case of SCARAB, the internal battery components remained attached to each another and survived as one fragment. The larger number of ground impact fragments in the ORSAT case strongly increased the ground risk. In general, both scenarios were possible and neither appeared to be more likely than the other.

30. It is not possible yet to determine whether ORSAT or SCARAB results better reflected the real process of spacecraft fragmentation during re-entry. Further research is necessary, especially with respect to the validation or better verification of the re-entry simulation programmes through the observation of real re-entry events.

**Improvement of hypervelocity impact testing**

*Development of an accelerator for simulating, in a laboratory, the impact of space debris particles in the millimetre regime at a velocity of 10 kilometres per second*

31. The objective of the project is to assess and improve the performance of the test facilities at the Ernst-Mach-Institut (EMI) in Germany for simulating space debris hypervelocity impacts on spacecraft structures and components in the millimetre regime at a velocity of about 10 km/s. In order to simulate hypervelocity impacts, EMI is using the light-gas gun technique, which makes it possible to shoot multiple particles without changing their physical properties. Another objective of the project is to reduce the cost of carrying out such tests by decreasing the loads of the light-gas gun.

32. At the beginning of the project, assessments were made of the limitations of the gun's performance by using analytical theories, and the possible improvement in

performance that could be achieved by making geometrical changes was identified by numerical simulations. It was found that, in order to improve performance, more light-gas pressure was required. Tests on the geometrical modifications made to a 4-mm calibre, two-stage light-gas gun (the so-called "Baby LGG") showed that it was possible to improve the acceleration cycle. Most importantly, a redesign of the high-pressure section resulted in a longer section with a concave shape.

33. During the first six months of the reporting period, the preparatory work on the launch tube was finalized. The procurement of the needed materials had been initiated. A new high-pressure section was being produced. The sealing between the high-pressure section and the launch tube had been modified. The function was demonstrated by numerical simulation of its installation.

*The twin gun: a new accelerator concept*

34. At the start of 2008, a new project started between DLR and EMI on the development of a new accelerator concept for the experimental simulation of the hypervelocity impact of space debris. In the above-mentioned project, the feasibility of a new accelerator concept, known as the "twin-gun concept" was tested. The objective of the concept was to make millimetre-sized particles move faster than with the current light-gas gun, but in a reproducible and wear-reduced way. The concept was based on the light-gas gun technique, but the aim of the twin gun was to increase the speed of the particles by using two pistons in two parallel guided tubes, connected to the same explosive powder chamber and leading to one launch tube.

35. By appropriately combining operational parameters, the pressure pulse at the entrance of the launch tube becomes wider than that of a conventional light-gas gun. Through this "pressure pulse shaping" and because of a more effective acceleration section, a projectile can reach higher velocities. Also, critical pressure limits will not be exceeded.

36. Research on the performance and the design of the twin-gun concept is under way.

*The position of Germany with regard to space debris mitigation measures in relation to the economy and sustainability*

37. Analysing the position of Germany with regard to space debris mitigation measures in relation to the economy and sustainability aims to support the national position on such measures in the context of scientific and technical discussions affecting the economy and sustainability. It also aims to support the position of the delegation of Germany in ESA and international committees such as the Inter-Agency Space Debris Coordination Committee (IADC) and the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space.

38. Although based on cost-benefit analyses already carried out in the framework of the project entitled "Space Debris End-to-End Service", the analysis presented below is more detailed. Aspects such as the consideration of experience gained from space debris mitigation measures already included in spacecraft design and operation, as well as the judgement of proposals to remove debris from space, deepen the analysis.

39. The relevant literature gives detailed information on the basics of cost models and on the applicability of space debris environmental models for determining the risk of losing spacecraft. Available cost models have been studied, on the basis of which a modified model has been used to estimate the cost of damages caused by hypervelocity impact for all past satellite missions.

40. Based on the particle flux data provided by the 2005 version of the Meteoroid and Space Debris Terrestrial Environment Reference software (also known as "MASTER-2005"), the influence of the space debris environment and the temporal development of the risk can be quantified by the combination of satellite cost estimations with risk analyses. The purpose of systematically analysing the influence of hypervelocity impacts on past satellite missions is to estimate the temporal evolution of the threat posed by space debris to space missions and the resulting risk costs for satellite operators. Altogether, the results of analyses conducted on 3,893 satellites have been examined. The determined service life for all satellites was set at seven years. The respective orbits and the different dimensions of the satellites were considered. Other parameters, such as the design and dimensions of the satellite wall and the number and types of payloads, were assumed to be identical for all satellites. For every satellite, the costs were estimated depending on its "beginning of life" mass. Using the MASTER-2005 software, a large database of the particle flux environment for each satellite was generated. Based on damage equations for wall structures, an analysis was carried out on which of the impacting particles would be able to penetrate the satellite wall. The probability of failure was determined for every satellite. Finally, the risk costs were calculated given the satellite costs and the probability of failure.

41. Those costs indicate the probable loss to the investor by the premature failure of the satellite resulting from damage caused by particle impacts. The amortization loss indicates the risk costs due to particle impacts on a satellite. By summing up those costs, it is possible to determine the total economic loss due to damages at a particular point in time. The simulation is very complex, because it requires a risk analysis to be carried out for about 4,000 satellites that includes the determination of subsystem distribution, failure probability and cost estimates. The overall damage costs vary between 200 million and 700 million United States dollars, depending on which vulnerability model is selected. That corresponds to the value of losing between 2 and 5 satellites. Because the definition of the vulnerability of satellites had to be greatly simplified, the numbers should only be understood as an estimate of orders of magnitude. The work shows that a risk and cost analysis concerning the interaction of space debris with a high number of satellites is possible.

42. As part of the project, a study was carried out of the relevant texts in which various methods to remove debris from space were proposed. Essentially, such methods were based on the reorbiting or deorbiting of objects with laser or tether technologies or by robotics. A list of known proposals is available but not all them have been evaluated.

**Application of national space debris mitigation guidelines to German space missions**

*Environmental Monitoring and Analysis Program**

43. The Environmental Monitoring and Analysis Program (EnMAP) is a German mission that uses a hyperspectral satellite with more than 200 channels within the broad spectral range of 420-2,450 nanometres and with a ground resolution of 30 m. EnMAP will be carried out by a small satellite built with state-of-the art bus technology and will be sent into orbit approximately 650 km above the surface of the Earth. The main tasks of the EnMAP mission are related to the global determination of ecosystem parameters as well as biophysical, biochemical and geochemical variables. EnMAP will also make it possible to perform analyses of natural disasters and land and water pollution. The mission data will be used for the preparation of future commercialization and operational services.

44. The possibility of applying the national space debris mitigation guidelines, adapted from the European Code of Conduct for Space Debris Mitigation to the needs of EnMAP is being assessed. The work includes analysing end-of-life measures (in particular, analysis of the passivation process and the implementation of disposal manoeuvres) and re-entry safety measures (in particular, assessing the possibility that debris stemming from spacecraft may reach the Earth's surface, investigating the related risk to the population and property on the ground and assessing the potential risk of harmful contamination of the Earth's environment) (A/AC.105/918, paras. 4-7).

*Technologie Erprobungs Träger (Technology Test Carriers)*

45. The goal of the Technologie Erprobungs Träger (TET) programme is to find new technologies that can be applied to space projects. It focuses on carrying out in-flight demonstrations and testing components and spacecraft subsystems for use in power generation, guidance, navigation and control, among others.

46. DLR provides in-flight opportunities for testing new technologies on various platforms and satellites. The programme is based on the use of the TET, which is a German-built satellite that weighs about 120 kg and has a payload capacity of about 50 kg.

47. A TET satellite will be launched into low-Earth orbit. The planned mission duration is one year. DLR provides the TET satellite with the mission operations and transfers data to the user, in addition to ensuring the assembly, integration and testing of the system.

48. The possibility of applying the national space debris mitigation guidelines, adapted from the European Code of Conduct for Space Debris Mitigation, to the needs of the project will be investigated within the framework of TET. Special focus will be placed on prevention measures (e.g. mission-related objects and fragmentation), end-of-life measures (e.g. passivation, de-orbiting and disposal) and re-entry safety (A/AC.105/918, paras. 8-11).

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* The original document submitted by Germany in English can be found on the website of the Office for Outer Space Affairs of the Secretariat (http://www.unoosa.org/oosa/natact/sdnps/2008/index.html).

## Japan

[Original: English]

1. Activities related to studies of space debris, mainly conducted by the Japan Aerospace Exploration Agency (JAXA) and Kyushu University, have focused on the areas described below.

**Ground-based space debris observation**

2. Optical telescopes are routinely used to observe objects in geosynchronous orbit and to determine those objects' orbital characteristics. Research is under way to develop software that can automatically detect smaller objects in geosynchronous orbit. Objects in low-Earth orbit (LEO) are observed using radar telescopes. Research to better observe objects in LEO is being carried out using high-speed tracking optical telescopes. Furthermore, the light curves of some spacecraft have been observed and their tumbling motion characteristics have been analysed (see information submitted by Japan in A/AC.105/918, para. 2).

**Modelling and analysis tools**

3. The LEO debris environment evolutionary model developed by Kyushu University and JAXA and the Debris Mitigation Standard Support Tools (DEMIST) are being upgraded. A debris collision risk analysis tool is also under development. To date, it has only been possible to analyse debris impact probability, but damage risk assessments are also being conducted using ballistic limit equations.

**Orbital debris evolutionary models**

4. Kyushu University plans to contribute, on behalf of JAXA, to the "benefits of active debris removal on the LEO debris population," an "action item" being explored by Working Group 2 of the Inter-Agency Space Debris Coordination Committee (IADC). Through the action item, Working Group 2 aims to reach a consensus with regard to the stability and instability of current orbital debris population in LEO. A parametric study on the effects of active debris removal and a comparison of results from different tools will be conducted. The National Aeronautics and Space Administration (NASA) of the United States of America will lead study participants from the Italian Space Agency (ASI), the British National Space Centre, the Indian Space Research Organisation and JAXA and provide the first results by the next IADC meeting, to be held in April 2009.

5. The international space communities have recommended placing aged geosynchronous spacecraft in drift orbits at higher altitudes so that they do not interfere with operational spacecraft. Over the past eight years, over 80 per cent of aged geosynchronous spacecraft were re-orbited above the nominal geosynchronous altitude. However, some of those spacecraft were not able to reach the altitude recommended by IADC.

6. Kyushu University has predicted what the size of the orbital debris population in the geosynchronous regime will be for the next 100 years by projecting current disposal practices to the future. Such projections have indicated that, in order to preserve geosynchronous orbit, efforts should be: to ensure post-mission disposal, in

line with the recommendations of the international space communities, and to adopt procedures for the safe keeping of all rocket bodies and spacecraft after their missions have ended. Projections have also helped identify the technical issues involved in placing aged (end-of-life) spacecraft in drift orbits at higher altitudes: the difficulty in evaluating fuel consumption (residual fuel) and the lack of system reliability for end-of-life spacecraft (malfunctions).

7. Kyushu University and JAXA plan to develop a full-scale LEO-to-geosynchronous orbit model with the aim of accounting for all Earth-orbiting objects. Based on that plan, Kyushu University has started to upgrade its geosynchronous orbit model so that it is based on modelling techniques that are more realistic than those adopted in the LEO model.

**Hypervelocity impact testing**

8. Hypervelocity impact tests were carried out for aluminium plates and carbon-fibre-reinforced plastic (CFRP) plates by using the two-stage gas guns developed by Tohoku University, in Japan, and Padova University, in Italy. During the tests, the fracture behaviour of the target was observed by a high-speed camera. There were differences in the size of the damage and debris clouds caused by aluminium alloys and epoxy-based CFRPs. A two-stage gas gun was introduced by JAXA to promote the acquisition of additional test data.

9. The shaped charge impact device was also used for hypervelocity impact tests, which involve the use of projectiles weighing more than 1 g and travelling at over 10 km/s. A jet removal system was developed solely to obtain results for a main jet collision.

**Micro-satellite impact testing**

10. Kyushu University and the Orbital Debris Program Office of NASA have collaborated on a series of impact tests on microsatellites. Two microsatellites covered with multilayer insulation and equipped with a solar panel were used as targets. The microsatellites measured 20 cm x 20 cm x 20 cm and had a mass of approximately 1,500 g. The impact tests were carried out to investigate solar panel parts and parts with multilayered insulation. The outcome of the impact tests were then compared with the NASA standard break-up model. The impact speed was about 1.7 km/s and the ratio of impact kinetic energy to satellite mass for the two tests was about 40 J/g. Impact phenomena were captured using an ultra-high-speed camera of the Japan Broadcasting Corporation. The results will be utilized to improve understanding of high area-to-mass ratio objects and to improve break-up models for better orbital debris environment modelling.

11. Knowing more about fragment shapes is important for improving the estimation of the area-to-mass ratio of each fragment. However, it is also important for conducting a reliable assessment of the probability of non-penetration of spacecraft such as the International Space Station. All fragments collected from previous impact tests (A/AC.105/918) were analysed based on their 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 in the plane perpendicular to both x and y. Two groups can be observed in the x/y versus y/z distribution of fragments: fragments with larger x/y values were represented by

a needle and fragments with smaller x/y values were represented by a plate. The fragments with smaller x/y values can have a wide variety of y/z values and can be box-like (when they have smaller y/z values), needle-shaped (when they have larger y/z values) and plate-like (when they have intermediate values of y/z).

**Electrodynamic tether to hasten orbital decay for unused spacecraft**

12. To mitigate debris generation alone is insufficient for preserving the orbital environment because the chain reaction of collisions among existing debris has already been observed in specific orbital regions. The best way to improve the environment would be to remove large objects completely from densely populated orbital regions. One technical solution for ensuring that such removal missions are conducted in a cost-effective manner would be to utilize the electrodynamic tether system, which slows unused space objects and reduces their orbital lifetime. Research and development activities related to electrodynamic tether systems have been conducted by JAXA. Current efforts are directed at developing a small electrodynamic tether system aimed at in-orbit demonstration using a small satellite.

**Mission success rate of electro-dynamic tether for active debris removal**

13. IADC has identified the "potential benefits and risks of using electro-dynamic tethers for the end-of-life de-orbiting of LEO spacecraft" as one of its action items. Although a tether strand is thin, it is long enough to have a large area, making it vulnerable to smaller particles. That vulnerability might be the weakest point of a tether system against orbital debris. In order to overcome this weakest point, a promising system in which two tether strands are tied together at regular intervals to form equally spaced loops has been suggested. In order to contribute to the action item, Kyushu University developed a mathematical model aimed at evaluating the survival probability of that double-tether system.

14. Kyushu University then extended the mathematical model it had developed once work on the action item had been completed. The resulting model can provide the maximum mission success rate that a double-tether system with a finite clearance can attain regardless of the number of loops. Kyushu University is using the new model to evaluate the mission success rate of an electro-dynamic tether system proposed by JAXA. More information on the topic will be published in the journal *Advances in Space Research*.