UNITED
NATIONS

A

General Assembly

Distr.
GENERAL

A/AC.105/619*
21 November 1995

ENGLISH
ORIGINAL: ENGLISH/SPANISH

COMMITTEE ON THE PEACEFUL
USES OF OUTER SPACE

NATIONAL RESEARCH ON SPACE DEBRIS

SAFETY OF NUCLEAR-POWERED SATELLITES

PROBLEMS OF COLLISIONS OF NUCLEAR-POWERED SOURCES WITH SPACE DEBRIS

Note by the Secretariat

CONTENTS

*This document has not been formally edited.

V.95-59611T

INTRODUCTION

1. In its resolution 49/34, paragraph 32, of 9 December 1994, the General Assembly considered it essential that Member States pay more attention to the problem of collisions of space objects, including nuclear power sources, with space debris, and other aspects of space debris, and 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. To the extent possible, the Assembly noted, information thereon should be provided to the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space.

2. The General Assembly, in paragraph 17 of the same resolution, invited Member States to report to the Secretary-General on a regular basis with regard to national and international research concerning the safety of nuclear-powered satellites.

3. The Secretary-General addressed a note verbale dated 4 August 1995 to all Member States, inviting them to communicate to the Secretariat, by 31 October 1995, the information requested above so that the Secretariat could prepare a report containing that information for submission to the Subcommittee at its thirty-third session.

4. The present document was prepared by the Secretariat on the basis of information received from Member States as of 31 October 1995. Information received subsequent to this date will be included in addenda to the present document.

REPLIES RECEIVED FROM MEMBER STATES

Canada

[Original: English]

The Canadian Space Agency is pleased to report the following with respect to the acquisition and understanding of data on the characteristics of the space debris environment and mitigation techniques:

- MELEO: The Materials Exposure in Low Earth Orbit (MELEO) was an active experiment flown on Shuttle mission STS-52 in October 1992. The experiment was primarily designed to measure the effect of the environment on material specimens (313 in total) which were mounted on the CANADARM (Canadian robotic arm on the U.S. Shuttle) and exposed in the "ram" direction during the mission for a total of approximately 30 hours. The experiment also included two active quartz crystal microbalances which were designed to operate in reverse fashion to measure the atomic oxygen fluence during exposure. The experiment was developed by a number of co-investigators several of whom included materials designed to capture small orbital debris particles and micrometeorites. During the mission, a solid rocket motor was used to raise a satellite payload to a high orbit after deployment from the Shuttle. It was this event that provided the majority of data on orbital debris during the mission. Although the material specimens were protected during the firing itself, many of the specimens which were returned to Earth for evaluation had been impacted by many small particles. The estimated particle size was consistent with the expected effluent from the solid rocket although the duration of persistence of the debris cloud was not expected. As a result, this experiment provided data on the orbital debris caused by the burning of a solid rocket motor.

- ACOMEX: The Advanced Composite Material Exposure Experiment (ACOMEX) was also a Shuttle-based experiment flown on STS-41G in October 1994. The purpose of this experiment was to gather data on the degradation of composite materials in low Earth orbit. The experiment consisted of a number of material specimens mounted on the CANADARM which was positioned in the "ram" direction for approximately 40 hours during the mission. This experiment was not designed to measure orbital debris but examination of the material specimens which were returned to Earth after the mission provided some observations which were identified as likely a result of impacts in space. Although no detailed data resulted, this experiment did contribute to the design of the MELEO experiment noted above.

- LDEF: One of the experiments aboard the Long Duration Exposure Facility was provided by Canadian Investigators from the University of Toronto. Much has been published to date on the results from the LDEF spacecraft, which includes the results obtained from this Canadian experiment. After return to Earth this experiment was thoroughly examined to identify impact sites. Over 70 impact sites were clearly identified. In addition, the data from the entire spacecraft as reported through the Orbital Debris Special Investigation Group was analysed and presented in the form of an Engineering Monogram that could be used for design of spacecraft. Furthermore, ground testing has been used to correlate the size and type of damage experimented in the specimens with probable particle size and velocity.

- The Institute for Space and Terrestrial Science (ISTS) and the University of Western Ontario are studying the space debris monitoring potential for large diameter, non-steerable, ground-based telescopes based on the liquid mirror concept developed at Université de Laval.

- MBP Technologies of Pointe-Claire, Quebec, is conducting a study of possible electro-optical and infrared sensors for space surveillance, particularly space-based sensors and systems; the interest is in application of millimetre-wave radar technology to observation, tracking and identification of debris.

- Based on impact data recorded from LDEF, the University of Toronto Institute for Aerospace Studies (UTIAS) develops design monograms for predicting the number of impacts on a spacecraft as a function of altitude, inclination, time in orbit and orientation.

- The University of Toronto Institute for Aerospace Studies (UTIAS) is developing protective technologies to mitigate damage caused by orbital debris. Furthermore, it is working on flight test experiments to be performed on the exterior of space stations.

- The Physics Department of the University of British Columbia is performing research on the fundamental behaviour of matter at high energy density; research has contributed to the understanding of impact phenomena occurring at hypervelocities; the two-stage light-gas gun has operated at 4 km/sec, could be operated at up to 6 km/sec, and with modifications has a potential velocity of 8 km/sec; no further large-scale testing is planned in the near future due to budgetary constraints.

Chile

[Original: Spanish]

Chile reports that at present it is not conducting any research relating to space debris and that it does not have satellites that operate with nuclear energy. Consequently, studies are not being conducted on possible collisions of nuclear-power sources with space debris.

Japan

[Original: English]

RECENT SPACE DEBRIS ACTIVITIES IN JAPAN

Space debris is intrinsically a global problem that all space-faring nations must solve in cooperation in order to preserve a safe environment for future space activities. One of the world's earliest warnings on this issue was made in Japan in 1971 by M. Nagatomo and his colleagues of the Institute of Space and Astronautical Science (ISAS).[1] Since that time, independent research on this topic has been carried out by various organizations in Japan. However, any systematic or organized activities were not performed until 1990 when the Japan Society for Aeronautical and Space Sciences (JSASS) founded the Space debris Study Group. The study group consisted of over 30 members from space-related organizations and industries and issued an interim report in January 1992 and a final report in March 1993.[2] Some of the recommendations presented in the report have been followed up by the two newly formed JSASS Study Groups. As a result of the continuing efforts by the JSASS Study Groups, Japanese space related agencies and organizations have now recognized that the space debris hazard is no longer an abstract problem, but rather a real and serious threat to manned and unmanned activities in space. The Japanese Government Space Activities Commission (SAC) has expressed Japan's policy on space debris in the report on Japan's Space Long Term Vision which was published in July 1994:[3] "Japan will aim to develop such systems that will leave as little space debris as possible. With regard to existing space debris, we will cooperate with other countries in considering ways of reducing it." The National Space Development Agency of Japan (NASDA), which is responsible for implementing practical applications of space developments in Japan, founded its own working group in August 1993 to study space debris problems and to establish the NASDA policy and debris mitigation and protection standards.

In this article, the recent and planned activities in the space debris field in Japan are briefly reviewed.

I. SPACE DEBRIS MEASUREMENT

A. Optical observation

Optical observations of geo-stationary objects have been made by the Communication Research Laboratory (CRL) utilizing an optical observation system in Koganei, Tokyo (35.42°N, 139.29°E). It consists of a 1.5 m aperture telescope, a peltier cooled CCD camera with a chip size of 1242 x 1152 pixels, an image processing computer and other scientific and communication equipment. The system was originally built as a fixed ground station for space communication experiments using a geostationary satellite. With this CRL optical observation system, objects as small as 20 cm at geostationary altitude are theoretically observable. Therefore, it is expected to contribute to an international cooperative project to measure the debris population in and around Geostationary Orbit (GEO).

As a collaborative study with NASDA, the National Astronomical Observatory in Japan (NAO) has been conducting observations of the GEO satellites since 1992, using the Schmit telescopes of the Kagoshima Space Center (KSC) of ISAS (31.13°N, 131.04°E) and the Kiso Observatory of the University of Tokyo (35.48°N, 137.38°E). The use of other telescopes in Japan has also been found to be promising. For more detailed and long-lasting observations, however, a dedicated debris observation system will be required. JSASS and NASDA will start the preliminary joint studies on a GEO satellite to detect space debris in GEO in July 1995.

B. Radar observation

Space debris monitoring by a bistatic radar system has been studied by T. Takano and his group at ISAS. They have successfully demonstrated the applicability of this system in the observation experiment of "Yokoh" which is a scientific satellite with a mass of 420 kg in a circular orbit of 600 km altitude and at an inclination of 31.3°. In the experiment, they used the 20 m diameter antenna at KSC as a transmission station and the 64 m diameter antenna at the Usuda Deep Space Center (UDSC) of ISAS (36.13°N, 138.37°E) as a reception station. The distance between the two stations is about 1,000 km. By means of modern communication technology, objects as small as 2 cm at 500 km altitude are detected.

The laser radar system for detecting space debris has been investigated by an ISAS group led by T. Yokota. The system is composed of a Nd:Yag laser, a light beam expander, a telescope, a CCD camera, a photo multiplier and a computer. It is estimated to have the capability to detect a particle 1 mm in diameter at a distance of 1 km. Therefore, it can be used as an on-board space debris observation system for detecting small-size debris and for collision avoidance manoeuvres. They have developed an engineering model of the system and are testing its basic performance.

Radar has been the most effective means of observing LEO (low Earth orbit) debris of "threatening size," which is debris pieces larger than about 1 cm. All existing databases and statistics of such space debris, including the famous USSPACECOM catalogue, depend largely on observations with various radars. They usually contain an important item "size," which is determined from the strength of the received echo. In evaluating the impact of a collision of debris with a shielding wall, for example, it is common to interpret it as the diameter of a sphere.

However, statistical studies showed that it is an overestimate by comparing the size estimated by radars with that calculated from the physical projected area determined from the orbital decay due to atmospheric drag. [4]

The size of the target is computed from the radar cross section (RCS), which is defined as the area of an isotropic scatterer whose echo power is the same as the given target. It indeed agrees with the physical cross section for large metallic spheres, but often differs largely for objects with irregular shapes, especially when observed at a high frequency band. For example, a piece of thin wire may be misinterpreted as a cannon-ball.

For objects smaller than the radar wavelength, RCS is inversely proportional to the 4th power of the wavelength (or to the 4th power of the frequency). Most radars used for space debris monitoring thus employ a frequency of 5-10 GHz, or even higher, in order to obtain a high sensitivity for small debris. At such a high frequency, the RCS varies drastically as the orientation of the target relative to the radar changes. It is then hard to estimate the real cross section from the observed RCS.

At a lower frequency, on the other hand, the relation between the physical cross section and the RCS becomes much simpler, although we have to pay an expensive cost in the sensitivity reduction for small targets.

The MU (Middle and Upper atmosphere) radar of Kyoto University, Japan, is a powerful VHF radar operating at 46.5 MHz; its 1 MW output power and the 100 m antenna compensate for the reduced sensitivity at this frequency. It has roughly equal sensitivity to the radars used for USSPACECOM catalogue maintenance. [5]

The main target of this radar is Earth's atmosphere, or more precisely, weak backscattering from irregularities in the refractive index of the air caused by the atmospheric turbulence. Since this atmospheric echo is so weak, scientists have been bothered by contamination of strong "undesired" echoes from various objects such as space debris. We decided to make use of these previously discarded echoes and started a statistical study of space debris in 1988.

The antenna of the MU radar consists of 475 Yagi antennas constituting an active phased array. The advantage of this type of antenna is that it can observe different directions almost simultaneously by electronically switching multiple antenna beams. Figure 1 shows an example of debris observation using eight antenna beams switched sequentially from pulse to pulse around the zenith.[6] The target, which turned out to be the Kosmos 1023 rocket booster, passed through these beams, and the variation of RCS was tracked for about 20 sec. It is also possible to roughly determine the orbit of the target from a single observation. Conventional radars with a large parabola antenna cannot continuously observe an orbital object for more than a fraction of a second unless its orbit is given beforehand.

The large and smooth variation of RCS versus time (shown in the lower-right panel of figure 1) indicates the rotation of the rocket booster. The maximum value roughly agrees with its maximum physical cross section.

The most direct way to "see" the shape of a target using radar is to make the antenna beam sharp enough so that it can resolve the target. It is, however, impractical to get a resolution of 1 m at a distance of 100 km because the necessary diameter of the antenna is in the order of 10 km. A more sensible technique is to make use of the rotation of the target. The idea is to resolve a different part of a target moving at a different velocity relative to the radar by measuring the Doppler velocity spectra. This method is called ISAR (Inverse Synthetic Aperture Radar), or RDI (Range-Doppler Interferometry), and has been widely used in military radars and in radar astronomy. It was already applied to space debris by using German FGAN radar, which revealed a clear image of a Salyut-Kosmos complex.[7] At the moment, the resolution is limited to about 1 m so it cannot be used to identify the shape of small targets 1-10 cm in size, which is of the greatest concern.

Figure 1. The angular motion (left), the height variation (upper right), and the RCS variation (lower right) of Kosmos-0123 rocket booster as observed by the MU radar. The circles in the upper left panel show the coverage of the antenna beams.

Some statistical information on the shape of space debris is obtained by comparing the physical cross section estimated from the atmospheric drug with RCS, as shown above. The major limitation of this technique is that the same object has to be monitored for a long duration in order to detect orbital decay.

The results of our MU radar observations also provide similar information. Numerical simulations showed that the magnitude of RCS variation can be interpreted in terms of the prolateness of the object. Since a single observation gives the variation seen from one direction, we need to interpret many observations in a statistical manner. The result of such analysis indicates that the volume of relatively small debris observed with the MU radar is less than half of the sphere which has the same RCS.

In order to evaluate the actual size of space debris, shape information must be obtained. Although the first priority in designing a future debris radar is that it should have a sensitivity to detect objects of 1-10 cm, it also should have the capability to track an unknown object continuously for at least 10 sec, which is necessary to carry out both ISAR (RDI) analysis and/or the statistical analysis shown above. The phased array antenna is the essential element in realizing this capability.

C. Impact measurements

Based on the one-year intensive study, the JSASS Study Group on Space Debris and Micrometeoroid Impact Detection has proposed the post flight analysis (PFA) of the Space Flyer Unit (SFU) to the Institute for Unmanned Space Experiment Free Flyer (USEF).

SFU is a Sun-pointing, 3-axis stabilized, unmanned platform facility. It was launched on 15 March 1995 by the H-II third flight and is scheduled to be retrieved by the Shuttle STS-72 in January 1996. It will stay in a circular orbit at an altitude of 300-500 km and at an inclination of 28.5° and will become the first Japanese space structure to be returned to Earth. The total area of the exposed surfaces of SFU is about 150 m² and the four main large surfaces are the planned targets for PFA:

- Payload Unit Multi-Layer Insulation (MLI), which is an octagonal structure 4.46 m in diameter and 1.40 m in height;
- Exposed Facility Flyer Unit (EFFU), which is a box-like structure with a top surface that measures 1.48 m x 1.48 m and is covered with silver-coated Teflon for a radiator and with four side plates 1.05 m in height that are covered with aluminized Kapton MLI;
- Solar Array Paddle with a length of 24.4 m and a width of 2.36 m; and
- Two-Dimensional Deployable High Voltage Solar Array, which is a triangle sail with a height of 3.84 m and a base length of 3.62 m in the full deployed configuration.

It is expected that much information will be obtained through comparison with LDEF, EURECA and HST solar array PFA data.

The Japanese Experimental Module Flight Demonstration (JFD) is planned on board the Space Shuttle as a verification test of the manipulator system for the Japanese Experimental Module (JEM) of the International Space Station Alpha (ISSA). Utilizing this opportunity, the Parts and Material Laboratory of NASDA is planning to perform the Experiment of Space Environment with Materials (ESEM). The ESEM system consists of Dust of Space debris collectors (DC) and material sample holders (MSH) for evaluation of the atomic oxygen effect in space. They will be mounted on the top of the JFD experiment apparatus in the Shuttle payload bay and will be exposed to the Shuttle flight direction for 40 hours. This program is slated for April 1997.

II. SPACE DEBRIS MITIGATION

Among the different types of orbital objects, the largest number is that of fragment debris created by explosions. These are the result of rocket upper stage explosions, intentional distractions and other unknown factors. The nature of the latter is not quite clear, but is believed to include explosions caused by hypervelocity impacts. In order to avoid significant accidental debris creation, NASDA has implemented draining of residual propellants (LOX, LH_2, N_2H_4) and the residual helium gas of the H-I/H-II second stage. The release of mechanical devices at satellite separation and solar paddle deployment has been avoided except in some particular missions, such as the separation of spent apogee motor for the geostationary meteorological satellite. For the purpose of the prevention of unintended destruction of the H-II second stage in space, the command destruct system is disabled immediately after injection into orbit and its pyrotechnics are thermally insulated to preclude spontaneous initiation.

The objects on the geostationary transfer orbits (GTO) are increasing and are considered to be hazardous to future space activities because of their long orbital life. An effort is currently being made to decrease the orbital life of the second stage of the H-II.[8] The second stage (1994-056B) of the H-II second flight of 28 August 1994, for instance, was deorbited from the ETS-VI GTO with an apogee of 36,346 km and a perigee of 251 km to GTO with an apogee of 32,298 km and a perigee of 150 km by performing idle mode burn and the depletion of residual propellants. It was observed that the second stage had fragmented into at least six new objects by 31 March 1995 and they have already decayed.[9] NASDA has also implemented reorbiting GEO satellites after the end of life (EOL) at least 150 km upward, aiming at 300 km since 1985.

JSASS formed the committee on space debris prevention design standards in September 1993 at the request of NASDA. The main objective is to discuss the technical backgrounds and to make a draft document for the "NASDA Orbital Debris Mitigation Design Standards," which is to be established around 1997. The committee consists of members from the National Aerospace Laboratory (NAL), ISAS, NASDA, universities and major space-related companies. An extensive study on the technical and economical feasibility of space debris mitigation measures has been conducted placing emphasis on:

- Spacecraft and rocket upper stage passivation;
- GTO upper stage deorbit;
- GEO satellite deorbit after EOL; and
- Other feasible and important measures, such as prevention of operational debris.

The report of fiscal year 1994 was published in March 1995.[10]

III. SPACE DEBRIS PROTECTION

Space debris protection systems have been studied by NASDA for JEM. More than a hundred impact test data have been obtained in the impact velocity range of up to 5 km/s using a two-stage hydrogen light gas gun. Hypervelocity impact experiments are important, not only for the design of space station protection systems, but also for the development of basic hypervelocity impact science and for understanding debris creation and dispersion phenomena. A basic hypervelocity impact study has been conducted at NAL in collaboration with various organizations. Impact experiments have been performed in various velocity ranges, that is, at around 2 km/s velocity with a one-stage powder gun at Kyoto University, at 4 km/s velocity with a two-stage helium gas gun at Tohoku University and at around 7 km/s with a rail gun at ISAS. The target specimen was made of three aluminum alloy plates 3.5 mm thick which were set up with about 60 mm of space between each plate. After the experiment it was noted that all three plates were perforated like a petal and that the petalled hole of the back plate was bigger than that of the front plate. This illustrates that the two bumper plates before the main plate provided no protection against the debris impact with 14 g in mass and 2 km/s in collision velocity. In order to investigate hypervelocity impact phenomena at velocities of up to 15 km/s, NAL has been conducting a collaborative study with Mitsubishi Heavy Industries Limited on a shaped charge explosive launching system which is able to accelerate gram order mass aluminum projectiles to velocities of over 10 km/s. A series of explosion experiments for modelling the breakup of a rocket upper stage is also planned.

IV. CONCLUSIONS

The preservation of the space environment is indispensable for insuring long-lasting and expanding space activities. Various scientific and technical proposals have been made so far, and they would necessitate, more or less, additional costs and the reduction of space system capabilities. What is needed is to identify acceptable technically effective and cost-efficient measures. The most critical uncertainties in space debris problems are due to our ignorance of the exact space debris environment. The cooperative efforts of Japan with other space-faring nations and organizations are required to examine the debris population, to accumulate hard data for verifying various theories and proposals, and to evaluate various measures and the associated penalties.

Notes

[1]M. Nagatomo, H. Matsuo and K. Uesugi, "Some considerations on utilization control of the near Earth space in future", Proc. 9th ISTS, Tokyo, pp. 257-263 (1971).

[2]S. Toda and T. Yasakka, "Space debris studies in Japan", *Adv. Space Res.*, 13, 8, pp. 289-298 (1993).

[3]*Toward Creation of Space Age in the New Century* (Report on Japan's Space Long-Term Vision) by Special Committee on Long-Term Vision, Space Activities Commission (July 1994).

[4]G. D. Badhwar and P. D. Anz-Meador, "Determination of the area and mass distribution of orbital debri s fragments", *Earth, Moon, and Planets*, 45, 29-51 (1989).

[5]T. Sato, H. Kayama, A. Furusawa and I. Kimura, "MU radar measurements of orbital debris", *J. Spacecraft*, 28, 677-682 (1991).

[6]T. Sato, T. Wakayama, T. Tanaka, K. Ikeda and I. Kimura, "Shape of space debris as estimated from RCS variations", *J. Spacecraft*, 31, 665-670 (1994).

[7]D. Mehrholz, "Radar tracking and observation of noncooperative space obje cts by reentry of Salyut-7/Kosmos-1686", *Proc. Internat. Workshop on Salyut-7/Kosmos-1686 Reentry*, No. ESA SP-345, pp. 1-8 (1991).

[8]T. Ujino, I. Yamazaki, T. Nakagawa and K. Mori, "Debris prevention plans of the H-II rocket", Proc. 44th IAF, IAF-93-V.5.633, Graz, Austria (Oct. 1993).

[9]N. Johnson, private communication (April 1995).

[10]Report on the Study for Establ ishment of the Orbital Debris Mitigation Design Standards, Japan Society for Aeronautical and Space Sciences (May 1995).

United Kingdom of Great Britain and Northern Ireland

[Original: English]

In March 1995 and November 1995 the British National Space Centre (BNSC) continued its discussions with the national space agencies of France (CNES), Germany (DARA), and Italy (ASI) and the European Space Agency (ESA) on harmonisation of debris activities. The topics covered were technical objectives, operational requirements, the results of completed and ongoing research studies, identification of future studies, coordination of activities and the search for a common policy on space debris mitigation. BNSC coordinated the collection and processing of data relating to the activities and capabilities (software tools and facilities) of United Kingdom industry, academic institutions and government research centres. The information was passed on to ESA for collation with descriptions from other member States. A report summarizing this information will be published by ESA and made available to both member States and non-member States. These international coordination meetings also provided an opportunity for ESA, which currently represents the member States on the Inter-Agency Debris Co-ordination Group (IADC), to disseminate information exchanged at IADC meetings, the 1995 IADC meeting was held at Houston, Texas, during March 1995.

The third United Kingdom Orbital Debris/Co-ordination Group Meeting was held at the University of Southampton in Hampshire, England, on Friday, 7 April 1995. This brought together speakers from BNSC, the University of Southampton, the University of London, the University of Kent, SIRA, the Defence Research Agency and Advanced System Architectures. Amongst the topics discussed were short-term and long-term debris hazard modelling, ground-based optical and radar detection of debris objects, measurement of the micro-debris through the analysis of retrieved surfaces, and international initiatives relating to space debris. The meeting was again well attended and provided the opportunity for a further dissemination of information on international programmes at the ESA and IADC levels.

A number of technical papers have been produced by United Kingdom research groups during 1995. The reference section of this report lists some of the published papers.

UNISPACE, the Unit for Space Sciences at the University of Kent, continues to lead the European community in the analysis of spacecraft surfaces retrieved from orbit. The return of both the European Retrievable Carrier (EURECA) and one of the solar arrays from the Hubble Space Telescope (HST) [1] provided a large surface area of exposed surface which could be examined for impact sites. Through the application of empirical impact formulae relating the material characteristics of both impactors and spacecraft surfaces and the impactor speed and incidence to these surfaces to impact features, it was possible to infer the encountered micro-debris environment by counting, measuring and chemically analysing the residue observed in impact sites [2]. This will enable engineers to evaluate current models of the meteoroid and space debris populations and to validate damage predictions of different subsystem elements. Such analyses also require some impact calibration tests to study the response of unique array materials to hypervelocity impact. The solar arrays of Eureca [3] were at 99 m^2 the largest exposed area on the retrieved satellite. High and low resolution images of impact sites on the array were recorded totalling more than 3,000 impact sites (>50 micron size). There were over 1,000 impacts visible to the naked eye on each array. The HST analysis concentrated on impact sites with features greater than 1.2 mm on the 20 m^2 array area. A total of 704 large impact features were recorded. In each case the location, size parameters, morphological features and direction of impact were measured. All such images were digitized and stored on compact discs that are available through ESA for further analysis. The micro-debris flux encountered by HST [4] was between 2 and 8 times greater than that encountered by EURECA.[5] It has been argued that this demonstrates the strong influence of atmospheric density, which reduces exponentially with altitude, and which determines the orbital lifetime of the debris particulates. Such effects[6] have also been investigated by UNISPACE and they concluded that there must be a larger population of high orbital eccentricity particulates close to HST and EURECA altitudes than models predict in order to justify the high fluxes encountered. It is interesting that many of these models rely upon the observable large debris population for the basis of their definition. UNISPACE have also identified discrete differences in size and direction of impact of particulate populations,[7] which permits identification of man-made debris from natural meteoroids. The Timeband

Capture Cell Experiment (TICCE)[8] flown on the Eureca platform offered the capability to capture intact micro-debris particulates in materials such as aerogel.[9] The flux encountered by the experiment[10] could then be analysed chemically and direction of impact permitted discrete populations of debris and meteoroids to be identified. Comparison of encountered fluxes with design environment models such as the ESABASE continues.

Two further university departments are actively engaged in collaborative research with industry to assess the short-term and long-term collision hazard to spacecraft posed by debris.

The first group at the University of Southampton in Hampshire are building upon their reputation as a centre of excellence for astrodynamics studies to find novel and efficient methods for characterizing the collision hazard that a breakup could pose for satellite systems. A number of studies have looked at the threat to a payload from the breakup of a launch vehicle,[11] the threat to a satellite constellation from the breakup of one of the satellite elements,[12] and a comparison of modelling techniques both in Europe and the United States of America.[13]

The second group is at the University of London, Queen Mary and Westfield College. The focus of their work is on the long-term prediction of the debris population through application of direct simulation Monte Carlo techniques to represent the environment evolution. Applying techniques developed for collision dynamics in rarefied gas systems, the group have been able to model collision-induced breakups within the population. The model will be used to investigate fully the phenomenon of collisional cascading.[14]

Two groups are involved in the detection and observation of debris objects from the ground using optical telescopes. SIRA are building on experience gained supporting ESA in previous feasibility studies to contribute to the commissioning of a 1 m ESA telescope. Under ESA contract 10623/93/D, SIRA have provided advice and guidance to the prime contractor, the Astronomical Institute at the University of Berne, Switzerland, on algorithms for detecting and analysing debris using CCD arrays. The second group, the Royal Greenwich Observatory, have contributed to papers considering the feasibility and accuracy of detecting objects in orbit using optical telescopes.[15] These studies have demonstrated that there are significant selection effects where objects in eccentric orbits are less likely to be detected than those in circular orbits.

The Defence Research Agency at Farnborough provides a technical focus for all the groups within the United Kingdom and supports BNSC at UNCOPUOS. It was the first group to highlight the potential problems associated with distributed space architectures such as satellite constellations at discrete altitude. A joint paper[16] with the University of Southampton identified that for the large constellation sizes predicted for the end of the century, there were significant risks to both the constellation systems and the neighbouring missions in close proximity due to debris impacts. This study is being extended to take account of second order (cascade) effects in a software package called Integrated Debris Evolution Suite (IDES). This can also be used to carry out mitigation effectiveness studies.

These studies demonstrate that the United Kingdom is involved in, and in many cases has a unique capability in, a broad range of activities aimed at defining the orbital environment, assessing the hazard to space missions, and formulating policies to alleviate the growing space debris problem.

Technical objective	Activity	Organization(s)
Define environment	Retrieved surface analysis	University of Kent
Define environment	Optical detection	SIRA, Royal Greenwich Observatory
Define environment	Population modelling	Defence Research Agency, University of London
Assess hazard	Short-term modelling	University of Southampton
Assess hazard	Long-term modelling	Defence Research Agency
Mitigation/policy	Evaluation	Defence Research Agency

Notes

[1]G. Drolshagen, J.A.M. McDonnell, T. Stevenson, R. Aceti and L. Gerlach, "Post-flight measurements of meteoroid/debris impact features on Eureca and the Hubble Solar Array", *Adv. Space Res.*, Vol. 16, No. 11, pp. 85-89, 1995.

[2]W. G. Tanner Jr., J.A.M. McDonnell, H. Yano, H. J. Fitzgerald and D. J. Gardner, "Meteoroids and space debris hypervelocity impact penetrations in LDEF MAP foils compared with hydrocode simulations", submitted to *Adv. Space Res*. 95.

[3]J.A.M. McDonnell, G. Drolshagen, D. J. Gardner, R. Aceti and I. Collier, "EuReCa's exposure in the near-Earth space environment: hypervelocity impact cratering at a time of space debris growth", *Adv. Space Res.*, Vol. 16, No. 11, pp. 73-83, 1995.

[4]G. Drolshagen, W. C. Carey, J.A.M. McDonnell, T. Stevenson and J-C. Mandeville, "Impact damage to a solar array caused by debris and meteoroids", *Preparing for the Future*, Vol. 5, No. 2, ESA publication, June 1995.

[5]R. Aceti, G. Drolshagen and J.A.M. McDonnell, "Micrometeoroids and space debris: the EuReCa post-flight analysis", *ESA Bulletin*, No. 80, pp. 21-26, November 1994.

[6]J.A.M. McDonnell, P. R. Ratcliff and I. Collier, "Atmospheric drag modelling for orbital micro-debris at LEO altitudes", *Adv. Space Res.*, Vol. 17, No. 12, pp. 183-188, 1996.

[7]J.A.M. McDonnell, "Eureca's hypervelocity impact score: microcrater flux decreases but the large crater flux increases in specific directions", Lunar and Planetary Science Conference, 1994, Abstracts Volume, p. 867.

[8]H. Yano, I. Collier, N. Shrine and J.A.M. McDonnell, "Microscopic and chemical analyses of major impact sites on timeband capture cell experiment of the Eureca spacecraft", submitted to *Adv. Space Res. 95*.

[9]M. J. Burchell and R. Thomson, "Intact hypervelocity particle capture in aerogel in the laboratory", presented at American Physical Society Topical Conference on Shock Compression of Condensed Matter, Seattle, August 1995.

[10]D. J. Gardner, I. Collier, N.R.G. Shrine, A. D. Griffiths and J.A.M. McDonnell, "Micro-particle impact flux on the timeband capture cell experiment of the EuReCa spacecraft", *Adv. Space Res.*, Vol. 17, No. 12, pp. 193-199,

1996.

[11]S. P. Barrows, G. G. Swinerd and R. Crowther, "Debris-cloud collision risk analysis: polar platform case study", *Journal of Spacecraft and Rockets*, Vol. 33, No. 5, 1996.

[12]S. P. Barrows, G. G. Swinerd and R. Crowther, "The cascade fragmentation of a satellite constellation". *Adv. Space Res*., Vol. 16, No. 11, pp. 119-122.

[13]S. P. Barrows, G. G. Swinerd and R. Crowther, "Cloud debris-collision risk analysis", *Journal of Spacecraft and Rockets*, Vol. 32, No. 5, 1995.

[14]L. Wang, J.P.W. Stark and R. Crowther, "Direct Monte-Carlo simulation of collision frequency of orbital debris", IAA paper, IAA-95-IAA.6.4.02, 46th Astronautical Congress, Oslo.

[15]R. Crowther, R. Walker, J.S.B. Dick, S. F. Green and J. Marchant, "Detectability of satellite fragmentations in highly eccentric orbits", *Adv. Space Res*., Vol. 16, No. 11, pp. 123-126.

[16]R. Crowther, P. H. Stokes, R. Walker, S. P. Barrows and G. G. Swinerd, "Characterisation of the potential impact of space systems on the orbital debris environment: satellite constellations", paper presented at Aerosense, Florida, April 1995.