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COMMITTEE ON THE PEACEFUL
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NATIONAL RESEARCH ON SPACE DEBRIS

SAFETY OF NUCLEAR-POWERED SATELLITES

PROBLEMS OF COLLISIONS OF NUCLEAR-POWERED SOURCES WITH SPACE DEBRIS

Note by the Secretariat

Addendum

1. The Secretary-General addressed a note verbale, dated 7 August 1997, to all Member States, inviting them to provide information on national research on space debris, safety of nuclear-powered satellites and problems of collisions of nuclear-powered sources with space debris.

2. The present document contains information provided in replies received from Member States between 1 December 1997 and 30 January 1998.

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REPLIES RECEIVED FROM MEMBER STATES

Germany

[Original: English]

Germany has continued its contribution to the work on space debris in the Committee on the Peaceful Uses of Outer Space through the preparation of its 1996 activities report, contained in document A/AC.105/659/Add.1 of 6 February 1997, and a presentation on debris observation at the 1997 session of the Scientific and Technical Subcommittee.

The German Space Agency (DARA) became a full member of the Inter-Agency Space Debris Coordination Committee (IADC) at its session held at Darmstadt in March 1997. That membership has been taken over by the German Aerospace Center (DLR), which was created on 1 October 1997 through the merger of DARA and the German Aerospace Research Establishment. The fourteenth meeting of IADC took place from 20 to 21 March 1997, together with the Second European Conference on Space Debris, which was organized by the European Space Operations Centre (ESOC) under the sponsorship, *inter alia*, of the German Space Agency.[1] A great number of German scientists and legal experts participated in that conference. The fifteenth meeting of IADC was held from 9 to 12 December 1997 at Houston, Texas, United States of America. A German delegation attended both IADC meetings and made contributions to the four working groups: on measurements, on environment and database, on protection and on mitigation.

As stated in its previous reports, German debris research activities are either conducted on a national footing or are funded under contracts with the European Space Technology Research Centre (ESTEC) and ESOC of the European Space Agency (ESA). The research activities are largely concentrated in (a) the Institute of Flight Mechanics and Space Flight Technology of the Technical University of Braunschweig (IFR/TUBS) and (b) the Research Establishment for Applied Science of Wachtberg-Werthhoven (FGAN). The main results of research of these institutions during 1997 are contained in sections A and B below; section C contains additional research activities in German institutes and industry.

A. Space debris modelling and mitigation

The research on space debris modelling was a central aspect of the work of IFR/TUBS in 1997 as in the past.

At DARA/DLR a study concerning the actual aspects of the space debris discussion is nearing completion, comprising, for example, additional space debris sources (RORSAT droplets, surface degradation particles, Al_2O_3 dust/slag from solid rocket motor firings) or the minimum spacing required between the graveyard orbit and the geosynchronous Earth orbit (GEO).

IFR/TUBS also carried out the development of the release version of the ESA space debris model MASTER, which now includes an option for the evaluation of natural meteoroid flux. The MASTER release is now available through ESA/ESOC in its May 1997 version. Since August 1997, IFR has also been conducting research on several upgrade features that will be integrated into MASTER before the next release, expected in 1999.

Apart from this work, IFR is preparing a European Space Debris Mitigation Handbook for ESA, covering both scientific and technical aspects of orbital debris evaluation and mitigation.

1. Additional source terms for orbital debris modelling

Since there are strong indications that other sources besides explosion and collision events contribute significantly to the debris flux on a target in an Earth orbit, multiple possible mechanisms for the orbital release of debris objects have been examined. The following are currently seen as the most likely sources:

(a) Liquid metal (NaK) coolant droplets from nuclear reactor cores dumped in a 950 km storage orbit;

(b) Aluminium oxide slag and micro particles from orbital solid rocket motor firings;

(c) Surface degradation particles due to atomic oxygen (AO) influences in combination with EUV radiation-related embrittlement and thermal cycling.

Of these sources, only the coolant droplets and the large-scale fraction of the aluminium oxide objects, called slag, are of some interest in terms of collision cascading. The micron-sized Al_2O_3 dust particles, as well as the surface degradation particles, only contribute to the micro debris flux that is responsible for those degradation effects.

Currently, IFR is developing modelling approaches for the generation of both of the relevant source terms in order to assess their impact on the global space debris environment and its evolution.

(a) Sodium-potassium droplets

The first (and apparently the most severe) of these two sources, the so-called RORSAT droplets, were found in the course of sample measurements with Haystack radar. It detected a large swarm of objects in near circular, 65° inclined orbits at an altitude of about 900 km (see figure 1). A more detailed examination of those objects, using the Millstone Hill and Goldstone radar sites as well as optical observations, showed that they were up to 5.6 cm in diameter, of spherical shape and exhibiting characteristics of specular metals. From decay measurements, a consistency of about 900 kg/m^3 could be derived. All these facts point in the direction of liquid sodium-potassium (NaK) droplets exhausted from the nuclear reactors of Russian RORSAT satellites that used NaK as a coolant.

Those satellites, which are not in use any more, are dumped in a 950 km storage orbit, where the later version of RORSATs release their fuel rods from the reactor core to ensure complete disintegration during later re-entry. Probably, in the course of this procedure, a large fraction of the NaK coolant is ejected into space. Effects like cavitational bursting within the outflowing stream may result in the generation of an appreciable number of even small droplets.[2] Due to very low evaporation rates, the thus generated droplets form metallic spheres that remain nearly unchanged in size for their orbital lifetime.

The problem here is similar to that posed for the modelling of orbital fragmentations: only the upper end of the diameter spectrum can be made subject to verification by direct measurement. Therefore, any mass or diameter distribution derived from a theoretical modelling of the outflow process suffers from a large margin of uncertainty—especially in this case, where nearly no data on the smaller end of the size spectrum are available.

Material data for NaK usually is only given for parameter intervals being of some interest for thermodynamic processes, and experiments to examine the effect of liquids spraying into a vacuum have so far only been conducted for water. However, some similarities between water and NaK, especially in terms of consistency, together with the general lack of data, seem to justify adopting at least the basic characteristics of the water droplet diameter distribution data for the NaK problem. This assumption is also supported by the fact that the vapour pressure of hot NaK (753 K) equals that of water at room temperature (293 K).

Figure 1. Total diameter distribution of NaK droplets as modelled for the group

of RORSATs above 800 km altitude

In this sense, a Weibull distribution has been chosen, which has been fit to the data points measured by radar and optical examination on the one hand and to the integral mass on the other hand. The advantage of this approach over models using a power law for the distribution lies within its more conservative assessment of the number of micro particles generated by such events. This seems to be a reasonable approach, particularly since the orbital vaporization is more effective for micro-droplets compared to larger drops, so that micro-droplets eventually will disappear.

In spite of these quite conservative assumptions, the total number of coolant-related objects accumulates to 115,000 for the 15 RORSAT events within the 950 km storage orbit range—excluding C1900, which only reached a 750 km storage orbit. The total mass accounts for 54 kg.

(b) Aluminium slag from solid rocket motors

The second source generating objects that have a considerable influence on the debris environment are orbital firings of solid rocket motors that are used for geostationary transfer orbit (GTO) or GEO insertion manoeuvres.

While the ejection of micron-sized Al_2O_3 particles in the course of solid rocket motor firings is a well-known fact that can easily be derived from the large amount of aluminium additives in the charge, the exhaust of relatively large slag objects in the burn-out phase was discovered only recently. Hence, the main problem in modelling the generation process of such aluminium oxide slag is the lack of reliable data. Until now, there were only a few measurements from solid rocket motor ground tests and radar observations of the solid booster plumes of ascending launchers. In addition, the data rendered from those measurements are quite inconsistent and subject to motor size scaling and extrapolation to orbital conditions.

A validation of model assumptions is mainly restricted to the small fraction of generated objects that exceeds the radar observation threshold of about 6 mm diameter in low Earth orbit (LEO). As a result, the current models only reflect a coarse impression of the generation and release mechanisms for aluminium slag, particularly in terms of mass or diameter distribution.

But independent from any model assumptions in the smaller diameter range, the measurement data prove the exhaust of a significant number of large objects in every single solid rocket motor burn. These objects, in contrast to the dust particles, contribute to the background flux in a diameter range that has the potential of severely damaging a target and they also may contribute to a future collisional cascading process. Hence, aluminium slag from orbital solid rocket motor firings must be regarded as a relevant space debris source. Future analyses will have to show the level up to which the slag population may accumulate, taking into account the influence of sink mechanisms like atmospheric drag or solar radiation pressure.

2. The spacing between GEO and the graveyard orbit

Currently, spacecraft in the geosynchronous orbit are not deorbited at the end of their operational lifetime, primarily because of the large amount of additional fuel needed for such a manoeuvre. Instead, they are lifted to a graveyard orbit slightly above GEO, in order to at least reduce the object density and, thus, the collision risk within the highly frequented geostationary ring itself.

In the context of an increasing need for international consensus on this procedure, also called re-orbiting, the question arose as to what amount of minimum spacing between this graveyard orbit and GEO should be demanded to preclude a later drift of the discarded spacecraft back into the sensitive geostationary region. Recently, the discussion seems to settle on the value of 300 km, which had already been adopted by some international institutions like ESA or the International Telecommunication Union (ITU) and is also recommended by the National Aeronautics and Space Administration (NASA) space debris mitigation handbook.

Simulations of the long-term orbit evolution performed at IFR have shown that the variation of the perigee altitude due to perturbation influences generally remains small for objects larger than 1 cm (see figure 2, top). For particles in the sub-millimetre diameter range the solar radiation pressure effects a considerable drift of the perigee altitude, but such particles can only result from a collision event in the graveyard orbit itself. In this case, however, the kinetic energy set free would throw the fragments into a variety of different orbits that, especially for very small particles, can be highly eccentric (see figure 2, bottom). Since there is no gap at all that would protect GEO against interference with such small fragmentation debris, the problem cannot be solved in any event in connection with graveyard orbit spacing.

Although the graveyard orbit itself seems to be relatively stable, one has to take into account not only orbit perturbations. Apart from GEO itself, an operational space above it has to be kept clear of debris for the purpose of shifting manoeuvres during the satellite positioning phase. Furthermore, as for all technical considerations, one has to apply a reasonable safety margin to the minimum spacing that results from the above-mentioned basic demands.

Figure 2. Orbit variations owing to perturbations (top) and fragment orbits resulting from a low-intensity collision in GEO graveyard orbit (bottom)

In this context, the proposed spacing of 300 km, at least for intact satellites, appears to be a good compromise between safety and economy requirements.

3. Large constellations and their impact on collision risk

In connection with the introduction of large commercial satellite constellations in LEO, the impact of such a huge number of satellites on the space and space debris environment has been discussed. Mainly, interest has been focused on the internal collision risk in case of a fragmentation within the constellation, on the one hand, and its contribution to the global debris evolution, on the other.

Studies carried out at IFR indicate that the first of these two problems seems to be negligible. Of course, the members of a constellation operate at the same altitude band, often in multiple nearly polar orbit planes that are phased in right ascension and intersect at high declinations. Nevertheless, a collision of constellation members among one another is seen as extremely unlikely owing to active satellite controlling by the ground stations during operational life and intended de-orbiting strategies afterwards. Even in case of the fragmentation of one member as a result of a collision with an object of the background debris population, the additional flux imposed by this fragmentation cloud to the remaining satellites of the constellation is several orders of magnitude below the background flux.[3]

The second problem, the impact of constellations on the overall debris evolution, is much more severe. The constellations planned for the future comprise up to several hundreds of satellites and, thus, will contribute significantly to the cumulated in-orbit area within their altitude regime. In addition, most of these constellations will operate at an altitude of 700-1,400 km, which is even now the area of highest object density. Hence, the risk of a collision followed by complete disintegration of the target is increased to a comparatively high level.

A way to keep the number of actual collision events low in an environment with a significant risk of such an event is to reduce the overall area-time product. In the case of new satellite launches, as in connection with the planned LEO constellations, the area is increased, leaving only the orbital dwell time as a parameter to adjust. Most of the companies projecting such constellations have agreed to include an end-of-life de-orbiting procedure into their system concept. But even in the idealistic case that every satellite launched can be removed after its operational life, the collision risk is enlarged significantly owing to the steady large number of operational satellites added to the background population. Simulations performed using long-term projection software underline these results by predicting a faster increase in the density of small objects when considering constellations.

4. New features of the MASTER 1997 space debris model

The most obvious change as compared with the pre-release version is the implementation of one of the most sophisticated meteoroid models currently available into the MASTER software environment by making use of the theory of Divine and Staubach. The scope of applications offered by the MASTER package now not only comprises the evaluation of man-made debris fluxes of objects down to 0.1 mm on any target satellite as it did before, but also comprises the determination of the natural meteoroid background flux.[4]

Because of the generally lower masses of natural meteoroids, the internal mass threshold for this source was lowered to 10^{-13} kg ($d = 4.243.10^{-6}$ m). Only the core, asteroidal and A sources out of the five Staubach meteoroid classes have been included in the MASTER implementation, since the contributions of the B and C population are negligible within a mass regime above 10^{-13} kg.

Furthermore, the reference population of the MASTER debris branch has been updated to 31 March 1996.

5. The ESA Space Debris Mitigation Handbook

The purpose of the Handbook is to provide technical information on the space debris situation and guidance on how to avoid space debris in future spacecraft design and mission planning. It is the intention that the Handbook can be used for these purposes within ESA and in European industry as well as in space research planning.[5]

Figure 3. Main chapters of the Handbook

Outline of Debris Mitigation Handbook—revised 18 September 1997

1. Definition of terms, abbreviations
2. Definition of the scope of the ESA debris mitigation guidelines
3. The current space debris and meteoroid environment
4. Impact risk assessment and collision fluxes
5. The future space debris environment
6. Mitigation measures
7. Spacecraft and launcher passivation at end-of-life
8. De-orbit and re-entry of spacecraft and upper stages
9. On-orbit collision avoidance (for LEO)
10. On-orbit shielding technology
11. Conclusion

In itself, the Handbook has no regulatory character. However, if regulations were to be introduced in Europe by other documents, reference could be made to suitable paragraphs of the Handbook. An approach of this kind, which has already started, is the drafting of the European Cooperation for Space Standardization (ECSS), in which initial paragraphs on space debris are contained and can later include reference to the Handbook.

The Handbook is printed out as the product of an underlying software. The software controls the text as well as all graphical material, such as diagrams, sketches and tables. By making changes to the parameters of the underlying software, the Handbook can easily be updated according to technology and environment changes. The underlying software calls upon a set of computer codes, such as MASTER and CHAINEE, and produces the graphs in the Handbook (or updates thereof) in an automatic editing manner. A loose-leaf book edition is envisaged in order to update the copies of all users.

B. Radar observation and analyses of space debris and meteoroids

The Tracking and Imaging Radar (TIRA) system of FGAN Research Institute for High-Frequency Physics (FHP) is primarily used to investigate methods and techniques for classification and identification of spacecraft and aircraft. To a certain extent, TIRA is additionally used to gain radar data of space debris and meteoroids.[6,7,8] For that purpose, mainly three modes of operations were developed: first a tracking mode of operation to measure selected objects in low Earth orbit, in geosynchronous orbit and in geostationary transfer orbit. Secondly, a beam-park mode of operation to collect data on the population density of man-made space objects in defined space volumes. Thirdly, a beam-park mode of operation with compensation for Earth’s rotation to get information on the meteoroid influx during major meteor stream activities.

The TIRA system consists of narrow-band tracking radar and high-resolution imaging radar. Both are supported from a 34-m parabolic antenna. Methods and algorithms have been developed to analyse narrow-band radar signatures, to compute radar images from high-resolution radar data and to estimate physical properties of space debris such as size, shape, dimensions, intrinsic motion, mass, orbit and orbital lifetime. These methods and techniques are continuously being improved and refined to cope with mid-size space debris (size 1-50 cm) and meteoroids.

In 1997, space debris and meteoroid activities at FGAN-FHP were mainly conducted within the framework of three ESA/ESOC study contracts:

(a) Advanced radar techniques for space debris observation (February 1995-September 1998);

(b) Cooperative debris tracking (April 1997-July 1998);

(c) Development of algorithms for mid-size debris detection with radar (April 1997-July 1999).

The main goals of these activities are as follows:

(a) The investigation of improved debris observation and data-collection techniques;

(b) The development and implementation of efficient, highly automated techniques and algorithms for data processing, and debris and meteoroid detection and analysis;

(c) Support for establishing a unique, clearly defined interface between measurement results and modelling predictions.

1. Radar observations and data analysis

Careful sensitivity assessment reveals that the TIRA L-band radar is currently capable of detecting 2 cm spheres at a 1,000 km range, using optimum detection strategies and taking into account all hardware and signal-processing modifications and improvements proposed and implemented within the framework of ESA study contracts. In 1996, a considerably increased detection performance could be achieved in a bistatic radar experiment, in which the world's largest steerable radio telescope (100 m aperture in diameter) at Bad-Münstereifel-Effelsberg, operated by the Max-Planck Institute for Radio Astronomy, has been used as a secondary receiver with very high sensitivity.[9]

COBEAM-1/96 was successfully carried out on 25/26 November 1996, resulting in about 150 GB of raw radar data for the 24 hours of continuous observation. The threshold at the telescope was determined as 9 mm at a 1,000 km range. Analysis of the COBEAM data was finished in September 1997.[10] The results are, in most aspects, in reasonable agreement with those from other sensors (e.g. the Haystack radar) and with model predictions. Special interest was devoted to those subpopulations of the debris environment that are currently not properly taken into account by environment models: the NaK droplets (assumed coolant leaking from RORSAT nuclear power reactors) and the family of debris from the PEGASUS/HAPS break-up in June 1996.

A major meteor stream activity of the Leonids in November 1999, for which NASA predicts an increase in the background flux by a factor of 10,000-30,000, can cause hazards to operational satellites. Based on the experience gained from the Leonid observations in 1996, a four-day radar campaign was planned and performed for the predicted yearly maximum around 17 November 1997. The collected data will be used to improve the experimental setup and to assist in the development of algorithms for the estimation of the meteoroid influx.

2. Comparison of radar measurements with model predictions

In order for debris measurement data to be useful for the validation of ESA’s MASTER model, discussions have been started for the definition and implementation of a unique interface between models and measurements. During a joint working meeting between ESA/ESOC, the Technical University of Braunschweig, eta_max space GmbH and FGAN, it was concluded that a suitable extension of MASTER to deal with this problem has to be developed in cooperation with model and sensor experts.

3. Radar observation and analysis of malfunctioning satellites

In cases of unexpected events, e.g. debris collision of an operational satellite or other malfunctions, TIRA has been used to assist in the analysis of the problem. In the framework of study contracts, observations were performed with the L-band and Ku-band imaging radar, and analysis results were used to support the examination of the causes and amount of damage. Examples in 1997 include the observation and analysis of CERISE (damaged as a result of a collision with Ariane upper-stage debris), ADEOS (solar panel destroyed due to mechanical stress) and SPOT-3 (loss of power due to uncontrollable rotation).

4. Re-entry predictions of high-risk space objects

The objective of this activity is to provide the Federal Minister of the Interior during re-entry of high-risk space objects with reliable predictions of re-entry windows (time and ground track), estimations of the object’s attitude, and risk assessments. Within cooperation agreements, FGAN-FHP provides ESA/ESOC with tracking radar data of high-risk space objects to support European re-entry predictions. In order to test the existing procedures and algorithms, the re-entry of the LEWIS satellite (United States of America) was monitored with TIRA in September 1997.

C. Other research activities

Some further work has been done in the field of meteoroid and debris protection. The investigations of the preceding years at the Ernst-Mach Institute (EMI) are continuing. Under ESA contract, EMI investigates the hypervelocity impact effects on pressurized vessels, especially for application in satellites. Other investigations by EMI are being conducted under subcontracts to ESA programmes: for the Cassini/Huygens mission, the effects of debris impacts on the thermal protection system (TPS) have been simulated by tests; and for the European ISS-Element COF, hypervelocity impact tests on samples for the reinforcement of the impact shielding of very high exposed locations have been performed.

In the past months a nationally funded study has started at EMI to simulate the degradation effects on optical surfaces of optical terminals for communication satellites.

Notes

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[2] C. Wiedemann and P. Wegener, “Internal report on new space debris sources; RORSAT droplet generation” (IFR/TUBS, 1997), unpublished.

[3] S. Theil, “Vergleich der Ausfallwahrscheinlichkeit unterschiedlicher Satellitenkonstellationen zu Navigationszwecken durch deterministische Untersuchung des Kollisionsrisikos”, diploma thesis (IFR/TUBS, 1996), unpublished, German only.

[4] “MASTER Software User Manual”, postscript documentation distributed with the MASTER software, available through ESOC, Darmstadt, Germany.

[5] D. Rex, H. Klinkrad and J. Bendisch,“The ESA Space Debris Mitigation Handbook”, *Proceedings of the Second European Conference on Space Debris, Darmstadt, Germany, 17-19 March 1997* (ESA SP-393).

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[7] L. Leushacke and others, “Radar detection of mid-size space debris”, final report No. 6-94, ESA/ESOC contract No. 10182/92/D/IM (Wachtberg-Werthhoven, FGAN-FHP, November 1994).

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[9] L. Leushacke, “First FGAN/MPIfR Cooperative Debris Observation Campaign: experiment outline and first results”, *Proceedings of the Second European Conference on Space Debris, Darmstadt, Germany, 17-19 March 1997* (ESA SP-393).

[10] L. Leushacke, “Mid-size space debris measurement with the TIRA system”, *Proceedings of the Forty-eighth International Astronautical Congress, Turin, 1997.*