ACTIVITIES ON SPACE DEBRIS IN EUROPE

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ABSTRACT

Activities on space debris in Europe are carried out by ESA, by national space agencies such as ASI (Italy), BNSC (United Kingdom), CNES (France) and DLR (Germany) and by various research groups.

The objectives of ESA's activities in the field of space debris have been defined by the Council of ESA in 1989, and were updated in 2000 with the adoption of the Resolution for a European policy on the protection of the space environment from debris. ESA's debris-related activities comprise research, application of debris mitigation measures and international cooperation. The research activities address the knowledge of the terrestrial particulate environment, risk assessment, hypervelocity impacts and protection, and preventative measures. In all these areas substantial progress has been achieved. Examples are the MASTER 99 model, the DISCOS database, beam-park experiments with the FGAN radar, the discovery of a small-size debris population in GEO with the Space Debris telescope at the Teide observatory, and the GORID dust detector in the geostationary orbit. The ESA Space Debris Mitigation Handbook was issued, and in a joint effort of ESA and the national agencies ASI, BNSC, CNES and DLR the European Space Debris Safety and Mitigation Standard (draft) was established. This standard will be harmonized with standards of other agencies through the deliberations in the Inter-Agency Space Debris Coordination Committee (IADC).

In order to strengthen the European cooperation, the pilot network of centers – Working Group on Space Debris was created in 2000. The members are ESA, ASI, BNSC, CNES and DLR. An integrated work plan has been established for the period 2001-2003.

Global cooperation among the space-faring nations is achieved through the IADC.

ESA and its Member States strongly support the deliberations on space debris within the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS).

1. INTRODUCTION

Already in the seventies ESA has addressed space debris issues, e.g. the collision risk in the geostationary orbit and the re-entry of risk objects. Following the issue of the *ESA Report on Space Debris* [1], in 1989 the Council of ESA adopted the resolution on Space Debris (ESA/C/LXXXVII /Res. 3 (final) "Resolution on the Agency's policy vis-à-vis the Space Debris issue") and approved ESA/C(89)24, rev. 1 "ESA Activities for Space Debris", where the Agency's objectives in the field of space debris are formulated:

- to minimise the creation of space debris to ensure free access to space and reduce the risk for manned and unmanned space flight;
- to reduce the risk on ground due to re-entry of space objects;
- to reduce the risk for geostationary satellites;
- to acquire through its own facilities and in cooperation with other space agencies the data on space debris which are necessary to assess the extent of the problem and its consequences;
- to study the legal aspects of space debris.

The importance, urgency and gravity that ESA and its Member States attach to the space debris problem is underlined by the "Resolution for a European Policy on the Protection of the Space Environment from Debris", approved by ESA's Council in December 2000 (ESA/C(2000)93).

The activities on space debris in Europe comprise space debris research, application of mitigation measures and international cooperation.

2. SPACE DEBRIS RESEARCH AND APPLICATION OF MITIGATION MEASURES

The space research activities cover the full spectrum of measurements, modelling and mitigation.

2.1 The Terrestrial Meteoroid and Debris Environment

The objectives are to gain a comprehensive knowledge of the space debris population in terms of size and spatial distribution and to upgrade the European capabilities for obtaining the necessary observations. Main areas for research are the Low Earth Orbit (LEO) region (altitude below 2000 km), the geotransfer space at low inclination, and the geostationary ring.

Due to a lack of an own space surveillance system, Europe is largely dependent on external information. Europe has some limited capabilities to carry out spot checks of selected objects, gather information on reentering risk

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objects, and collect information on micro-debris and meteoroids.

The Agency has established the DISCOS space debris database at ESOC for its own use and entities in the Member States [4,5]. It supplies information on the currently catalogued objects and is a basis for risk assessments and understanding of the evolution of the debris environment. Among other data DISCOS contains the RAE Table of Earth Satellites [6] and some 4'000'000 records of the NASA Two-Line Elements (TLE) which are orbital element sets of all known (about 8'700) catalogued space objects[1]. Upgrading of the DISCOS debris database is ongoing.

The first comprehensive ESA meteoroid and debris reference model (MASTER[2]) was issued 1997 [8]. The upgraded model MASTER'99, which is available for general distribution on a CD-ROM, describes the debris and meteoroid environment from LEO to the geostationary orbit (GEO) for a minimum object size of 0.001 mm. The model is based on the catalogued population and on the known breakups of spacecraft and rocket upper stages in orbit [9,10]. It constitutes a common basis in Europe for debris-related analyses in industry, research institutes and space agencies. Validation and upgrading of ESA's MASTER model for space debris are ongoing. The meteoroid model has been upgraded by the Max-Planck-Institute for Nuclear Physics, Heidelberg [11-13]. Recent dust measurements of interplanetary probes (Galileo and Ulysses) have been taken into account. Methods for the calculation of the long-term evolution of Earth orbiting debris (up to 100 years) have been developed [42-45].

Current space debris models in LEO suffer from significant uncertainties for objects smaller than about 30 cm. This is of particular concern for spacecraft which require protection, as shielding against objects larger than 1-2 cm is technically not feasible. For the validation of the MASTER model, five 24-hours beam-park experiments have been carried out with the radar facilities of FGAN (Forschungsgesellschaft für Angewandte Naturwissenschaften), located at Wachtberg (Germany). FGAN operates a high power radar system TIRA (tracking and imaging radar) which is able to track and image aircraft, functioning satellites and space debris [14-17]. It is composed of three main sub-systems: a 34-meter parabolic dish antenna, an L-band tracking radar (1.333 GHz, wavelength 22.5 cm), and a Ku-band imaging radar (16.7 GHz, wavelength 1.8 cm).

The purpose of these campaigns was to detect in a specific volume in LEO all objects above a minimum size, and compare the detections with those predicted by a space debris model. The pointing direction of the radar remained unchanged (beam park experiment). The minimum size of detectable objects with the FGAN radar at 1000 km altitude is near 2 cm. Such measurement campaigns are excellent methods for the validation of the MASTER model in the centimeter size range. In order to ease the comparison with MASTER, the analysis tool PROOF was developed which predicts the number of detections based on the MASTER model [18].

FGAN conducted 24-hours beam park experiments on February 4-5 and April 11-12, 1999, with an altitude window from 330 km to 1140 km. The number of detections was 362 in Feb. 1999. It includes 69 catalogued objects. From the 336 detections in April 1999 83 were catalogued objects. A comparison of the spatial density derived from the measurements with the spatial density extracted from the MASTER model shows good agreement.

The fifth beam park experiment BPE 1/2000 was carried out on 27/28.10.2000 with a range window of 300 – 2000 km [19]. Through the involvement of NASA, five US radar facilities participated in this campaign, which was conducted under the auspices of IADC.

Powerful radars for the tracking of space objects are located on the French vessel Monge. First measurement campaigns with the Armor radar (10 meter dish) jointly with FGAN were initiated in 2000.

The EISCAT incoherent scatter radar system in Northern Scandinavia and Svalbard offers interesting prospects for the detection and characterization of small-size space debris. In spring 2000 a feasibility study was started for the detection of space debris [20]. The goal is to be able to conduct space debris measurements in parallel with normal EISCAT ionospheric work.

A 1-meter aperture Zeiss telescope has been installed at the Teide Observatory in Tenerife, and final acceptance tests are in progress [21,22]. The telescope will serve primarily as check-out facility for the optical data link between ARTEMIS and SPOT-4 (SILEX experiment). The space debris optical system has a field of view of 0.7 degrees and the telescope is equipped with a nitrogen cooled 4096x4096 pixel CCD camera. The minimum size of detectable objects is 10-15 cm in GEO. Test observations [22] with this telescope in GEO have led to the discovery of an unexpectedly large population of uncatalogued objects as small as 10-15 cm, which in all likelihood are fragments. The only plausible source for this population are breakups of spacecraft and rocket upper stages.

Another research area is space-based optical detection. Studies have shown that with small aperture (10 cm)

[1] The minimum size of the catalogued (or trackable) objects is about 10-50 cm in LEO and about 1 m in the geostationary orbit (GEO). They are tracked by radar and optical sensors of the United States' Space Command.

[2] Meteoroid And Space Debris Terrestrial Environment Reference Model

optical instruments valuable information can be gained on the mid-size debris population (1 to 50 cm).

Significant contributions have been made to the knowledge of small-size (micron to millimeter) particles with EURECA and the returned solar array of the Hubble space telescope (HST) [23,24]. All outer surfaces were systematically surveyed for impacts. Observed impact features range in size from about 3 microns to a maximum of 7 mm of shattered cover glass. Thousands of craters were visible with the naked eye. About 150 impacts have completely penetrated the solar array of the HST. The observed number of impacts agrees largely with the models for craters smaller than about 1 mm and exceeds the predictions for the larger craters. In several European institutes samples from EURECA and the HST solar array have been analyzed for impact residues and hypervelocity calibration tests have been performed. The EURECA and HST impact data are available in an electronic database.

Experiments on micro-debris and cosmic dust have also been carried out on the MIR space station [25], e.g. ESEF on EUROMIR, a flight instrument attached to the exterior of MIR. The instrument was designed to measure the impacts and trajectory of micro-debris and meteoroids. Part of a solar array has been removed from the core module in Nov. 1997 and returned to Earth in Jan. 1998.

The spare cosmic dust detector of the Ulysses mission has been placed on the Russian geostationary EXPRESS-2 spacecraft (launch 26 September 1996). This allows monitoring the micro-debris particles in the geostationary orbit (GORID experiment [26,27]). The interpretation of the measurements is, however, not a straightforward process due to the interaction with charged particles in the Earth's environment. Efforts are made to improve the capabilities of small-size particle detectors in order to gain more accurate information on relevant parameters (e.g. impact velocity and mass). The standard in-situ detector DEBIE for small-size particles has been developed. Its first application will be on the PROBA spacecraft which will be placed in a near-polar circular orbit near 1000 km altitude in 2001.

2.2 Risk Analysis and Collision Avoidance

Despite reduced launch activities and application of debris control measures, the space debris population in orbit is steadily growing with a corresponding increase of the hazard. The first accidental collision between an operational spacecraft and a catalogued debris objects occurred on July 24, 1996, when a fragment from the third stage H10 of the 16-th Ariane launch (V16, 1986) collided with the French microsatellite Cerise [28].

Collision Avoidance. An example of the growing hazard in space is the situation of ESA's Earth observation satellites ERS-1 and ERS-2, which are in sun-synchronous orbits at 780 km altitude. During a five-years period the chance of an ERS satellite to collide with a 1 cm size particle – which could lead to severe damage or destruction – amounts to 1 to 2 %. A proximity analysis with current data from the DISCOS database has shown, that during a period of a few days several near-misses (typical minimum distance 0.3 to 2 km) between ERS and other catalogued space objects (satellites, rocket, stages, large fragments) occur. A collision with a large object would very likely be fatal for ERS because of the large impact velocity (on average near 13 km/s). Since ERS-1 has completed its operational life, proximity predictions are being carried out routinely for ERS-2 only. The same approach will be adopted for ENVISAT, which will be placed into an orbit similar as the ERS spacecraft.

ESABASE/DEBRIS. ESABASE/DEBRIS is ESTEC's 3D software tool for the impact risk analysis (number of impacts and damage assessment) of manned and unmanned spacecraft due to debris and meteoroids. For potential damage assessment and post-flight analysis ESABASE/ DEBRIS has been applied to various projects, e.g. EURECA, HST, Columbus COF, ENVISAT, ISO and XMM. ESABASE/DEBRIS will be further upgraded for application to the Agency's programmes. This includes implementing new damage laws, new results in material response under impact, and advanced methods for risk assessment.

Meteoroid streams. In general, meteoroids pose a minor hazard to operational spacecraft. However, meteoroid streams with high Earth approach velocity (60-70 km/s) combined with a strongly enhanced particle flux could inflict damage on spacecraft. Because of the enhanced activities of the Leonids, precautionary measures were taken and observations were made [29].

The International Space Station. As space debris may endanger the function or the survival of large space vehicles, detailed risk assessments have been conducted for the Columbus Orbiting Facility. The overall protection requirement of the International Space Station (ISS) against meteoroids and debris asks for a probability of at least 81% over 10 years of operation of no penetration by particles smaller than 1-2 cm size of critical items such as propellant tanks and manned modules. Collisions with catalogued objects will be avoided through orbit changes of the ISS.

2.3 Hypervelocity Impacts and Protection

The flux of space debris in LEO has reached such a level that shielding of manned vehicles is needed. The growing amount of man-made objects in LEO may, however, also require the protection of sensitive parts of unmanned spacecraft, e.g. the electronic boxes of Earth observation spacecraft. In order to understand how to protect against space debris, first the effect of debris on spacecraft structures must be investigated. Generic work on hypervelocity impact tests and protective measures for manned vehicles (shield design) have been carried out at several facilities within the Member States [30-33].

Upgrading of impact test facilities and numerical methods is necessary for realistic simulations of the space environment and its effect on space systems. Experimental tests and numerical simulations should be extended with regard to impact direction and velocity, pressure regime, and type of materials.

The ESA technological activities in the field of shielding against space debris are divided into four domains:

- characterization of material
- development of advanced test techniques
- validation of computer codes for hypervelocity impact simulation
- design of optimized shields.

Characterization of materials covers the determination of impact damage laws for insufficiently documented materials or configurations. Carbon fiber reinforced plastics (cfrp), multi-layer insulations and sandwich panels with cfrp facing and aluminium honeycomb cores have been tested. New materials for re-entry vehicles are studied: ablative materials such as AQ60 developed by Aerospatiale, carbon-carbon, carbon-sic and flexible external insulations which are made of silica felt and Nextel.

Experimental work is being performed to study hypervelocity impacts on pressurized vessels. Boundaries between simple impact holes and catastrophic bursts are being determined for gas filled pressure vessels made of aluminum and titanium.

The experimental simulation of impact conditions expected in LEO requires test techniques able to accelerate projectiles at least up to velocities around 15 km/s. Unfortunately, with the currently available technology maximum velocities of about 11 km/s can be reached. Two techniques have been developed in order to reach high impact velocities. Shaped charges are used to generate cylindrical projectiles, while multi-stage active disk launchers accelerate flat disks up to the required velocity. These advanced techniques are mostly used to obtain experimental impact data on state of the art shields. These data are compared with computer code impact simulations in order to validate selected codes.

In the shielding area research activities have focused on the selection of optimum materials and the design of shields with minimum mass for a given safety and damage tolerance. The objective is to reach cost-effective protection of unmanned spacecraft in LEO and to design shield and protection of manned vehicles, e.g. the planned ESA module of the International Space Station, in compliance with the safety requirements of the Agency.

The Columbus shielding performances have been quantified experimentally on limited size unpressurized flat samples in the velocity range between 3 and 7 km/s. The baseline configuration (double bumper) limits efficiently the damage of the pressurized module for particles below 0.5 – 1.2 cm size [34,35].

2.4 Debris Mitigation Measures

Mitigation measures for Ariane. The debris preventative measure of venting the Ariane upper stage has been carried out routinely from flight 59 (V59, Sept. 1993) onwards, regardless of the type of the target orbit. Debris mitigation measures for Ariane V (passivation of upper stage) have been implemented [36,37].

Reduction of mission-related debris. First steps for the reduction of mission-related objects are being applied by projects. During the operational lifetime of ENVISAT the creation of mission-related objects will be precluded. At end-of-life controlled venting of pressure vessels and residual fuel, discharge of batteries, and shutdown of the power system are foreseen.

Reorbiting of geostationary satellites. Several geostationary satellites have been reorbited into a graveyard orbit above the geostationary orbit (the figures in bracket indicate the achieved altitude increase and the year of reorbiting, [7,39,40]): GEOS-2 (260 km, 1984), OTS-2 (318 km, 1991), METEOSAT 2 (334 km, 1991), ECS-2 (335 km, 1993), OLYMPUS (-213 km, 1993), METEOSAT 3 (940, 1995), METEOSAT 4 (833 km, 1995), MARECS-A (1536 km, 1996), ECS-1(377 km, 1996) and ECS-5 (602 km, 1999). Due to a spacecraft failure OLYMPUS could not be inserted into a graveyard orbit above the geostationary ring. ESA's earlier policy was to reorbit into a graveyard orbit with a perigee located at least 300 km above the geostationary orbit, which corresponds to the ITU recommendation ITU-R S.1003 on the environmental protection of the geostationary orbit. Since 1998 the IADC recommendation is adopted, which defines the minimum altitude increase as 235 km plus a spacecraft-dependent term. The geostationary orbit is the single most used orbit – currently about 300 spacecraft are operational in GEO [38].

Debris Preventative Measures and End-of-Life Disposition. Currently, the growth of the space debris population is determined by launch operations and in-orbit breakups (explosions). Accidental collisions are not yet a growth factor. However, current practices could lead to a self-sustaining proliferation process as a consequence of collisions among large objects. More efficient mitigation measures have to be considered, which may include removal from space of rocket bodies and spacecraft after completion of their mission [41-45]. Therefore, strategies for de-orbiting of spacecraft and rocket upper stages in LEO have to be elaborated. Such measures will have far-reaching implications with regard to design and cost of space system. Thorough cost-benefit trade-offs will be needed to identify the suitable disposal of decommissioned spacecraft and rocket stages. The issue of disposal orbits must be carefully examined. Reorbiting should only be considered as an interim measure, since potentially useful space will be occupied. Ultimately, removal from orbit will be required.

2.5 Reentry of Space Objects

Uncontrolled reentry of derelict space objects occurs frequently (one large object about once per week). In most cases nearly complete disintegration occurs and there is little hazard on ground. However, objects with a mass of several tons or compact spacecraft elements made of heat-resisting material will not burn up completely and may pose a hazard on ground. The SCARAB tool has been developed for the analysis of the disintegration process of reentering spacecraft and rocket stages [46,47]. Its capabilities will be extended and upgraded.

Reentry of Risk Objects. In case of the uncontrolled reentry of massive objects where hazardous fragments are expected to reach the ground, ESOC provides forecasts to ESA's Member States on time and location of the re-entry based on data from European facilities, US Space Command, and Russia. Important tracking and imaging data are contributed by the radar facility of FGAN at Wachtberg-Werthhoven (Germany). Another capable radar facility is located on the French vessel Monge. Examples from the reentry of risk objects in past years are Salyut-7/Kosmos-1686 (1991) [48,49], the Chinese re-entry module 1993-063A which reentered in March 1996 in the South Atlantic Ocean, and Kosmos 398 in December 1995. Kosmos 398, a spacecraft with a mass of several tons, has been launched in 1971 as part of the Soviet Lunar Programme. Of significant interest was the controlled deorbiting of the MIR space station. The Russian control center TSUP succeeded in the controlled disposal of the 140 ton space station in the southern Pacific Ocean on March 23, 2001 [50].

The experience gained and cooperation established during this campaign will be helpful to cope with similar events in the future. Within the framework of the IADC activities a central server was installed at ESOC to support the fast exchange of orbit data, status and general information on the reentering risk object.

2.6 Handbook and Standards

ESA's Space Debris Mitigation Handbook [51,52], issued in 1999, introduces the space debris problem to designers and operators and advises on debris mitigation concepts. It allows to assess the hazards to spacecraft caused by space debris and meteoroids. The Handbook has no regulative character.

ESA has defined in 1988, as part of the safety policy, a specific requirement in PSS-01-40 for prevention of debris creation. The PSS documents, which represent formal standards for space system design, are in the process of being replaced by the European Cooperation for Space Standardisation (ECSS). Suitable standards addressing the space debris issue have to be introduced in ECSS for design and operation of space systems.

The draft "European Space Debris Safety and Mitigation Standard" [53] was prepared by the European Debris Mitigation Standard Working Group which includes members from ESA, ASI, BNSC, CNES and DLR. The main inputs were the CNES standard [54] and the ESA Space Debris Mitigation Handbook [51]. In September 2000 the draft standard was distributed in Europe for comments to space organisations, industry and other interested groups. An important step will be the harmonization with the IADC. This future standard will be proposed to ECSS in due time.

3. HARMONIZATION IN EUROPE AND INTERNATIONAL COOPERATION

As space debris is a global problem which only can be solved by a joint effort, discussions and cooperation with Member States, other space agencies and relevant organizations are of great importance.

Harmonization has proceeded at European level between Member States and worldwide cooperation between ESA and other space agencies within the framework of the Inter-Agency Space Debris Coordination Committee (IADC).

The coordination meetings earlier held between ESA and the national space agencies ASI (Italy), BNSC (United Kingdom), CNES (France) and DLR (Germany) are superseded since 2000 by the activities of the Network of Centers – Working Group on Space Debris. Main issues are the harmonization of European space debris research activities and the coordinated use of national facilities for space debris observation (radar, optical), hypervelocity impact tests, analysis of material returned from space and the identification of methods and approaches for debris reduction. The research programmes are closely coordinated between the national Space Agencies and ESA such as to avoid duplication and reduce overlapping of activities. An important joint project is the development of a European safety and mitigation standard for space debris.

The Inter-Agency Space Debris Coordination Committee. The Inter-Agency Space Debris Coordination Committee (IADC) with its current members ESA, Japan, NASA, Rosaviakosmos (Russia), ASI (Italy), BNSC (United Kingdom), CNES (France), CNSA (China), DLR (Germany), ISRO (India) and NSAU (Ukraine), offers a forum for discussion and coordination of technical space debris issues. The primary purpose of the IADC is to exchange information on space debris research activities, to facilitate opportunities for cooperation in space debris research, to review the progress of on-going cooperative activities and to identify debris mitigation options. IADC comprises a Steering Group and four technical Working

Groups dedicated to specific areas: i) measurements of the environment, ii) database and environment, iii) protection, iv) mitigation. Current activities focus on

- joint measurement campaigns,
- reentry of risk objects,
- improved meteoroid and debris models,
- optical observations and debris detection in the geostationary ring,
- debris mitigation guidelines.

The 19-th IADC meeting took place at DLR/Cologne on March 22-23, 2001. The 20-th IADC meeting is scheduled for April 9-12, 2002, at SSTL/Surrey.

Space Debris at the United Nations. Since 1994, the topic *space debris* has been on the agenda of the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS). The S&T Subcommittee adopted in 1995 a multi-year work plan:

- 1996: Measurements of space debris and effects of the environment on space systems
- 1997: Modeling of the space debris environment and risk assessment
- 1998: Space Debris mitigation measures (protection, prevention, removal)
- 1999: Consolidation and completion of the UN Report on Space Debris.

The "Technical Report on Space Debris" (Rex Report) [55] summarizes the technical findings of the space debris deliberations 1996-1999. Later sessions dealt with the geostationary orbit (2000), and the costs and benefits of various mitigation measures (2001).

An important decision was taken, when at the 38th session of the Scientific and Technical Subcommittee of UNCOPUOS the IADC was requested to prepare guidelines for space debris mitigation.

ESA and its Member States are supporting the technical discussions at the Scientific and Technical Subcommittee of UNCOPUOS. In order to ensure that the hazards to space operations caused by space debris will remain within acceptable limits, ultimately a code of conduct or a legal instrument established through the United Nations will be needed.

4. CONCLUSIONS

European capabilities to gain information on the space debris environment are rather limited. They are restricted to spot checks of selected objects, some capabilities to gather information on reentering risk objects, and collection of data of micro-debris.

Current risk levels due to space debris are low but are increasing.

Despite the application of debris reduction measures number and mass of debris objects are increasing. Expendable space transportation systems are a major debris source. Reusable launch systems would largely eliminate this source.

Ultimately more efficient debris control measures will be needed, such as selective removal from orbit of used upper stages and decommissioned spacecraft. A critical issue is the use of graveyard orbits, since they occupy potentially useful space.

ESA and its Member States have recognized the serious nature of the space debris problem since many years. A systematic approach towards the problem has been adopted, which is based on research, application of mitigation measures, and international cooperation. The efforts have been strengthened with the creation of the Network of Centers – Working Group on Space Debris.

In order to deal with the space debris problem in an effective manner, cooperation among all space-faring nations is required. The IADC is of paramount importance for the identification of cost-efficient debris mitigation measures. An important role of IADC is the provision of technical consultancy to the UNCOPUOS Scientific and Technical Subcommittee.

Several debris preventative measures are currently applied on a voluntary basis. However, the degree of application is rather mixed. While passivation of rocket upper stages is widely carried out, the reorbiting of geostationary spacecraft according to the recommendations of the IADC and ITU is only applied by about one third of the operators. In order to improve the situation, there is a clear need for a code of conduct or a legal instrument established through the United Nations.

5. REFERENCES

1. ESA Space Debris Working Group, *Space Debris – The Report of the ESA Space Debris Working Group*, ESA SP-1109, Nov. 1988.

2. Flury W. (ed.), *Proc. of the First European Conference on Space Debris*, ESA SD-01, July 1993.

3. Kaldeich B. and Harris B. (eds.), *Proc. of the Second European Conference on Space Debris*, ESA SP-393, May 1997.

4. Pina Caballero F., Sdunnus H., Database and Information System Characterising Objects in Space, Final Report ESOC Contract No. 12327, GMV, Madrid, 2000.

5. Hernandez C. et al., DISCOS database and web interface, Third European Conference on Space Debris, ESA SP-473, 2001.

6. King-Hele D.G., Walker D.M.C. , Winterbottom A. N. , Pilkington J.A., Hiller A., Perry G.A., The RAE Table of Earth Satellites 1957-1989, RAE, Farnborough, England, 1990.

7. Janin G., ESA Bulletin of Space Objects, Issue 21, ESOC, Darmstadt, 2001.

8. Klinkrad H., Bendisch J., Sdunnus H., Wegener P., Westerkamp R., An Introduction to the 1997 ESA MASTER Model, Second European Conference on Space Debris, ESA SP-393, 1997.

9. Sdunnus H., Bendisch J., Klinkrad H., The ESA MASTER'99 space debris and meteoroid reference model, Third European Conference on Space Debris, ESA SP-473, 2001.

10. Wegener P. et al., The Orbital Distribution and Dynamics of Solid Rocket Motor Particle Clouds for an Implementation into the MASTER Debris Model, *Adv.in Space Res.*, Vol. 23, No. 1, 161-164, 1999.

11. Grün E., Zook H. A., Fechtig H., Giese R.H., Collisional Balance of the Meteoritic Complex, *Icarus*, Vol. 62, 244-272, 1985.

12. Staubach P., Grün E., Upgrade of the DISCOS meteoroid model, ESOC Contract No. 10463, Max-Planck-Institute for Nuclear Physics, Heidelberg, 1996.

13. Landgraf M., Jehn R., Dikarev V., Altobelli N., Interstellar dust module for the ESA Meteoroid Model, Third European Conference on Space Debris, ESA SP-473, 2001.

14. Mehrholz D., Radar Detection of Mid-Size Debris, *Adv. of Space Res.*, Vol. 16, No. 11, 17-27, 1995.

15. Mehrholz D., Leushacke L., Jehn R., The COBEAM-1/96 Experiment, *Adv. of Space Res.*, Vol. 23, No. 1, 23-32, 1999.

16. Rosebrock J., Leushacke L., Mehrholz D., Cooperative Debris Tracking and Development of Algorithms for Mid-Size Debris Detection with Radar, Final Report ESOC Contract No. 12247, FGAN, Wachtberg, 1999.

17. Leushacke L., Mehrholz D., Jehn R., First FGAN/MPIfR cooperative debris observation campaign: experiment outline and first results, Second European Conference on Space Debris, ESA SP-393, 1997.

18. Bendisch J. et al., Extension of ESA's MASTER Model to Predict Debris Detections (PROOF), Final Report ESOC Contract No. 12569, TU Braunschweig, Braunschweig, 2000.

19. Banka D., Jehn R., Leushacke L., Rosebrock J., Beam-park experiment 1/2000: results and comparison with MASTER/PROOF'99, Third European Conference on Space Debris, ESA SP-473, 2001.

20. Lehtinen M., Markkanen J., Huuskonen A., Using EISCAT radars for space debris detection, Third European Conference on Space Debris, ESA SP-473, 2001.

21. Flury W., Massart A., Schildknecht T., Hugentobler U., Kuusela J., Sodnik Z., Searching for Small Debris in the Geostationary Ring, ESA Bulletin 104, 92-100, Nov. 2000.

22. Schildknecht T., Musci R., Ploner M., Optical observations of space debris in the geostationary ring, Third European Conference on Space Debris, ESA SP-473, 2001.

23. Drolshagen G., McDonnell J.A.M., Stevenson T., Deshpande S., Kay L., Tanner W., Mandeville J.C., Carey W., Maag C., Griffiths A., Shrine N., Aceti R., Optical survey of micrometeoroid and space debris impact features on EURECA, *Planet. and Space Sci.*, Vol. 44, No. 4, 317-340, 1996.

24. McDonnell J.A.M., Griffiths A., Drolshagen G., Mandeville J.C., Carey W., Meteoroid and debris impact environment of the Hubble Space Telescope solar arrays – first results, Proc. of the Hubble Space Telescope Solar Array Workshop, ESTEC, WPP-77, 501-509, 1995.

25. Mandeville J.C., Bariteau M., Cosmic Dust and Micro-Debris Measurements on the MIR Space Station, 33rd COSPAR Scientific Assembly, Warsaw, 16-23 July 2000.

26. Drolshagen G., Svedhem H., Grün E., Grafodatsky O., Prokopiev U., Microparticles in the geostationary orbit (GORID experiment), *Adv. of Space Res.*, Vol. 23, No. 1, 123-133, 1999.

27. Drolshagen G., Svedhem H., Grün E., Measurements of cosmic dust and micro-debris with the GORID impact detector in GEO, Third European Conference on Space Debris, ESA SP-473, 2001.

28. Alby F., Lansard E., Michal T., Collision of Cerise with space debris, Second European Conference on Space Debris, ESA SP-393, 1997.

29. Brown P., Leonid Shower Analysis: Radar and Electro-Optical Results, Final Report ESOC

Contract No. 13808, Crestech and University of Western Ontario, Canada, 2001.

30. Lambert M., Shielding against natural and man-made debris, a growing challenge, ESA. J., Vol. 17, No. 1, pp. 31-42, 1993.

31. Stilp A., Hypervelocity impact research, Second European Conference on Space Debris, ESA SP-393, 1997.

32. Thoma K., Hypervelocity impacts and protection, Third European Conference on Space Debris, ESA SP-473, 2001.

33. Turner R., Taylor E., Cost Effective Debris Shields for Unmanned Spacecraft, Final Report ESTEC Contract No. 12378, Matra Marconi Space, Stevenage, 2000.

34. Beruto E., Destefanis R., Faroud M., Buchwald P., High resistance debris shielding development for the Columbus Orbital Facility, Second European Conference on Space Debris, ESA SP-393, 509-517, 1997.

35. Palmieri D., Simulation of Hypervelocity Normal Impacts on the Columbus Double Bumper Shields, EWP-2141, ESTEC, Noordwijk, 2001.

36. Sanchez M., Bonnal C., Naumann W., Ariane debris mitigation measures, Second European Conference on Space Debris, ESA SP-393, 1997.

37. Bonnal C., Dartigalongue A., Mitigation measures for Ariane, Third European Conference on Space Debris, ESA SP-473, 2001.

38. Hernandez C. and Jehn R., Classification of Geostationary Objects, Issue 3, ESOC, Darmstadt, Jan. 2001.

39. Herman J., Fischer H.-J., The Long-Term Evolution of Uncontrolled Objects in Geostationary and Near-Geostationary Orbits, Final Report ESOC Contract No. 14127, Alcatel, Gilching, 2000.

40. Flury W., Space Debris Issues in the Geostationary Ring, AIAA 2000-1120, 18th AIAA Int. Communications Satellite System Conf. and Exhibit, Oakland, CA, April 2000.

41. Flury W., Heusmann H., Naumann W., Cost Effectiveness of Debris Mitigation Measures, 46th IAF Congress, Oslo, 1995.

42. Bendisch J., Rex D., Analysis of Debris Mitigation Measures, Final Report ESOC Contract No. 11263, TU Braunschweig, Braunschweig, 1996.

43. Anselmo L., Cordelli A., Farinella P., Pardini C., Rossi A., Long-Term Evolution of Earth Orbiting Debris, Final Report ESOC Contract No. 10034, Consorzio Pisa Ricerche, Pisa, 1996.

44. Anselmo L., Cordelli A., Pardini C., Rossi A., Space Debris Mitigation. Extension of the SDM Tool, Final Report ESOC Contract No. 13037, Consorzio Pisa Ricerche, Pisa, 2000.

45. Walker R., Swinerd G., Wilkinson J., Martin C., Long Term Space Debris Environment Prediction, Final Report ESOC Contract No. 12808, DERA, Farnborough, 2000.

46. Fritsche B., Koppenwallner G., Ivanov M., Kashkovsky A., Grinberg E., Boriskin O., Advanced Model for Spacecraft Disintegration During Atmospheric Reentry, Final Report ESOC Contract No. 12804, HTG, Göttingen, 2000.

47. Klinkrad H., Fritsche B., Kashkovsky A., Prediction of Spacecraft Destruction During Uncontrolled Reentry, Proceedings of the European Conference on Spacecraft Structures, Materials and Mechanical Testing, Nov. 29 – Dec. 1, 2000, 485-490, ESA SP-468, 2001.

48. Flury W., Longdon N. (Eds.), Reentry of Space Debris, Proceedings of ESOC Workshop, ESA SP-246, 1985.

49. Battrick B., Flury W. (Eds.), The Reentry of Salyut-7/Kosmos-1686, Proceedings of ESOC Workshop, ESA SP-345, 1991.

50. Sawaya H., Flury W. (Eds.), The Controlled Deorbiting of the MIR Space Station, Proceedings of ESOC Workshop, ESA SP-498, 2001.

51. Klinkrad H. (Ed.), The ESA Space Debris Mitigation Handbook, Rel. 1.0, ESOC, Darmstadt, Feb. 1999.

52. Walker R., Sdunnus H., Klinkrad H., Stokes H., Update of the ESA Space Debris Mitigation Handbook, Third European Conference on Space Debris, ESA SP-473, 2001.

53. European Space Debris Safety and Mitigation Standard, Issue 1, Rev. 0, Sept. 27, 2000.

54. Exigences de sécurité – Débris spatiaux, Méthode et Procédure, Référentiel Normatif CNES, Ed. 1, Rev. 0, April 19, 1999, CNES, Toulouse.

55. The Technical Report on Space Debris, A/AC.105/720, United Nations, New York, 1999.