SPACE DEBRIS ACTIVITIES IN EUROPE

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ABSTRACT

Space debris activities within Europe are predominantly performed by ESA, and by the national space agencies ASI (Italy), BSNC (UK), CNES (France), and DLR (Germany), with the support of European industry, research institutes, and academia. Since the year 2000 such activities are coordinated by a Space Debris Working Group, within a European Network of Centres, with representatives of the aforementioned agencies. The scope of debris activities covers research in the areas of ground-based and in-situ measurements, the development of debris and meteoroid environment models which are consistent with measurement data, the assessment of debris related risks on orbit and during re-entry, the development of effective shielding technologies, the improvement of techniques for hyper-velocity impact tests and computer simulations, the analysis of long-term effects of different debris mitigation measures, the implementation of such concepts in launcher and satellite designs, and the concerted work towards international agreements to arrive at common debris mitigation standards. The European partners ESA, ASI, BNSC, CNES, and DLR support the development of such international standards at the level of the UNCOPUOS Scientific and Technical Sub-Committee, and within the ISO Orbital Debris Coordination Working Group (TC20/SC14). These standardization efforts are supported by a European Code of Conduct on Space Debris Mitigation, and by the combined technical expertise provided by the Inter-Agency Space Debris Coordination Committee (IADC).

Key words: measurements; environment modeling; risk analysis; protection; mitigation; standardization.

1. INTRODUCTION

On Nov. 13, 1986, an Ariane-1 H-10 orbital stage exploded on a sun-synchronous orbit of 818 km mean altitude and 98.7° inclination, releasing a total of 488 trackable objects. This event intensified European activities on space debris, which were initiated earlier in 1986, by ESA's Director General, by forming a Space Debris Working Group, with the mandate to assess various aspects of the problem, and to recommend appropriate actions. In 1988 the working group issued their report (anon., 1988), which led to an ESA Council ”Resolution on the Agency's Policy vis-à-vis the Space Debris Issue” (approved as ESA/C(89)24 in 1989) where the main objectives of future activities were defined:

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

Although prior debris related research activities had been performed in Europe, for instance for the risk object re-entries of Skylab 1 and Cosmos 1402, and for the long-term collision risk in GEO, the end of the 1980s marked the beginning of systematic space debris research work, which was initially coordinated by a Space Debris Advisory Group (SDAG), and which was subsequently coordinated between ESA, ASI, BNSC, CNES, and DLR in the frame of a Network of Centres (NoC) Space Debris Working Group (SDWG).

The concerted European debris activities centered on the acquisition of ground-based and in-situ debris and meteoroid measurements, particularly in the low Earth orbit (LEO) and geostationary orbit regime (GEO), on the use of these data to develop consistent debris and meteoroid environment models, on risk assessment methods for on-orbit conjunctions and re-entries to ground, on the development on effective shielding techniques, on the implementation of supporting experimental facilities

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and simulation tools, on the definition of effective debris mitigation measures and their verification by long-term environment projections, on the technical aspects of the implementation of mitigation measures, and on legal issues.

To be effective, debris mitigation measures need to be applied by all space faring nations on an equal-terms basis. This can be best achieved, if a common understanding of the debris related problems and of recommended actions exist (anon., 1999a), (anon., 2001a). The Inter-Agency Space Debris Coordination Committee (IADC) was founded in 1991 to achieve this goal. The European partners ESA, ASI, BNSC, CNES, and DLR are members of IADC, which also includes CNSA (China), ISRO (India), JAXA (Japan), NASA (USA), NSAU (Ukraine), and ROSCOSMOS (Russia).

2. SPACE DEBRIS RESEARCH ACTIVITIES

In the following, different space debris research and development activities of European entities will be reviewed, particularly for the time span since the Third European Conference on Space Debris in 2001.

2.1. Space Surveillance

ESA started feasibility studies for a European Space Surveillance System (ESSS), which shall have a sensitivity similar to the US Space Surveillance Network (SSN), with the capability to produce a self-starting catalog of space objects. The proposed system consists of a set of phased array radar emitter antennas, operating in the UHF band, with a peak power of 9.6 MW, and a large array of dipole receiver antennas at a ground distance of 200 km.

The proposed electronic fence, if deployed at a latitude of about 37°N (e.g. in Spain), is predicted to cover up to 98% of all objects of the US SSN catalog in the LEO regime, and it will also be able to monitor intact objects up to 12 h MEO altitudes (i.e. including the GPS, GLONASS, and future Galileo constellations). Higher orbital regions in MEO and in the GEO vicinity will be surveyed by a globally distributed network of telescopes of 50 cm aperture, with CCD cameras. This optical part of the surveillance system could include dedicated telescopes in Australia, the Marquesas Islands, and Cyprus, plus the ESA space debris telescope at Tenerife (possibly augmented by data from the UK PIMS system).

The entire ESSS will be able to detect, track, and correlate between 95% and 98% of the SSN catalog, depending on the extent of the telescope network, and on orbit altitude. Following the completion of a feasibility study, the project is now in a system definition phase to study the feasibility of different implementation options. In parallel, an ESSS simulator tool is under development. It uses radar and optical system performance models adopted from ESA's PROOF tool (Program for Radar and Optical Observation Forecasting (Krag et al., 2002)) to predict the detection, tracking, correlation, and object characterization capabilities of the ESSS.

In France and Germany studies are in progress to identify the needs for an autonomous (European) space surveillance system. ESA has formed a board to address the same issue. In parallel, CNES is investigating possible civilian applications for the French GRAVES system (Grand Réseau Adapté à la Veille Spatial), a bi-static VHF radar, with an emitter near Dijon and a receiver near Apt. GRAVES is able to track and catalog objects larger than $1\,\mathrm{m}^2$ below 1,000 km altitude. The GRAVES concept is also planned to be used by the European Space Surveillance System.

2.2. Ground-Based Radar & Optical Measurements

ESA is making extensive use of their Zeiss telescope of 1 m aperture to survey about 120° of the GEO ring from Tenerife (Schildknecht et al., 2001). The telescope has entered its operational phase, following successful acceptance tests. It has a field of view of 0.7°, and is equipped with a liquid nitrogen cooled 2×2 CCD mosaic of $4,096 \times 4,096$ pixels. The demonstrated detection capability in GEO reaches down to magnitudes 19 to 20 (15 to 10 cm diameters). Processing of the observations revealed a large uncataloged population, mainly of sizes $d < 0.5$ m, probably indicating more than 10 unnoticed fragmentations near GEO. Another population on highly eccentric orbits was noted, which is probably associated with light-weight release objects, which are strongly perturbed by solar radiation pressure.

During the past few years, CNES has developed methods and software tools to track objects near GEO, using on-ground optical equipment with CCD detectors. Initial studies were performed by the Observatoire de la Côte d'Azur using their Schmidt telescope, which is located near Grasse. They could demonstrate the capability to detect GEO objects down to 20 cm diameter. The Tarot telescope at the same location, with a 25 cm aperture, a $2^\circ \times 2^\circ$ field of view, and a $2,048 \times 2,048$ pixel CCD camera, is expected to reach a limiting magnitude of 17 ($\sim$ 40 cm diameter). A new Tarot 2 telescope with 1.5 m aperture is currently under study. The Ministry of Defence of the UK is using their Passive Imaging Sensors (PIMS) of 40 cm aperture, with $1,024 \times 1,024$ pixel CCDs, to observe 165° of the GEO ring from Herstmonceux, Gibraltar, and Cyprus. Their detection threshold is about 0.5 m diameter.

ESA is continuing to perform beam-park experiments with the FGAN radar. Since 1993, 10 campaigns were performed (annually since 1999), most of them of 24 hours duration, with a range window from 300 to 2,000 km, and a detection threshold of about 2 cm diameters at 1,000 km range (Leushacke et al., 1997). When using the 34 m FGAN antenna as transmitter, and the 105 m Effelsberg antenna (of the Max Planck Institute of Radioastronomy, at $\sim$ 20 km distance) as receiver, the detection threshold can be reduced to 0.9 cm. The MPIfR antenna is currently upgraded to a 7 horn receiver, to allow the retrieval of directional information in addition to the standard range data. In the FGAN-only mode, more than 500 objects in 24 hours are typically detected, of which $\sim 80\%$ are not contained in the SSN Catalog. ESA is also exploiting backscatter data from the European Incoherent Scatter radars (EISCAT) in Norway, Finland, and Sweden to extract space debris information. Filter algorithms and dedicated hardware components have been developed to detect objects as small as 2 cm at 1,000 km range, as a by-product of the primary ionospheric research activities. An overview of European sensor capabilites is provided in (Klinkrad, 2002).

2.3. In-Situ Measurements

CNES is investigating in-situ optical techniques which could be deployed on micro-satellites to detect objects larger than 0.1 mm. ESA has performed industrial research activities with similar objectives, for a dedicated payload that could fly on the ISS.

ESA has been operating the DEBIE-1 impact detector on the PROBA satellite since 2001 (sensor area: $\sim 0.01\,\mathrm{m}^2$ per detector). The impact data are stored on board for downlink during station passes. First results are in line with MASTER-2001 impact predictions. A second unit, DEBIE-2, will be integrated into EuTEF, for launch in 2006 or 2007. The GORID plasma impact detector (sensor area: $\sim 0.1\,\mathrm{m}^2$) was operated on the Russian GEO satellite Ekspress-2 from 1997 to 2002. It collected valuable time-tagged impact data which seemed to indicate clouds of micro-particles, possibly from solid rocket motor firings.

Under UK and ESA funding, several institutes and laboratories are working on the characterization of impact features on retrieved surfaces from the Mir, the Japanese Space Flyer Unit (SFU), the solar arrays of the Hubble space telescope, and EURECA (Drolshagen, 1995). In collaboration with the USA, the UK is also sponsoring the development of in-situ capture devices based on aerogels, and of multi-layer polymer foil impact detectors. CNES is developing four prototype impact detectors based on MOS technology, to be flown on ISS, and on the Franco-Brazilian Micro-Satellite (FBM). Other techniques, know as PVDF, use thin plastic foils as detector surfaces. They are planned to fly on the French microsatellite PICARD.

In Germany the development of an Advanced Impact Detector Array (AIDA) is progressing. It will detect impacts either by means of calorimetry and impact ionization, or by a combination of PVDF and PZT technologies, with a total sensor area of $25\,\mathrm{cm} \times 25\,\mathrm{cm}$. A recent concept study by OHB and EMI suggests the on-orbit deployment of an impact detector, consisting of a detector plate of $\sim 0.1\,\mathrm{m}^2$, underlying PVDF sensors, and an autonomous power supply, data processing unit, and data transmission system. The ”piggy back” payload shall be mounted on orbital stages to collect impact data over long time spans.

For the coordination of in-situ detection activities within the European Network of Centres, a dedicated working group has been established.

2.4. Debris and Meteoroid Environment Modeling

In 2001 a significantly upgraded version of ESA's MASTER[1] and PROOF[2] programs was delivered to more than 200 users worldwide. MASTER allows to model the space debris and meteoroid environment from LEO to super-GEO altitudes, for particles larger than $1\,\mu$m, and to determine resulting collision fluxes for arbitrary target orbits, and for historic or future epochs (Bendisch et al., 2002). The PROOF tool simulates detailed system performance models for ground- or space-based radars or telescopes, and for a user-defined reference population (e.g. from MASTER), to predict corresponding detection rates (Krag et al., 2002). Both, MASTER and PROOF are currently undergoing further improvements, to account for recent environment data, and for new release events. Furthermore, a closed-loop iterative adjustment of the MASTER population to measurement data will be facilitated, and a new, more accurate way of spatial density and collision flux retrieval will be implemented, with a reduced sensitivity to sparse population data. The new MASTER and PROOF programs will be distributed in early 2006.

Special tools are necessary to study the long-term evolution of the space debris environment, as a function of traffic model assumptions and mitigation scenarios. Such models have been developed, and are maintained at ESA (DELTA and SDM), in the UK (DELTA and IDES), in Italy (SDM), and in Germany (LUCA). The DELTA model[3] is also used in MASTER to forecast a 100-year future, starting from a propagated population history at reference epoch. In the UK, the dedicated SCALP tool for GEO debris environment modeling was developed. It is, for instance, used in the UK licensing process for the launch of GEO satellites.

ESA is producing an upgraded Interplanetary Meteoroid Environment Model (IMEM), which will be based on the previous Divine-Staubach model (Grün et al., 2001), with new measurement data incorporated from Ulysses and Galileo sensors.

2.5. Hypervelocity Impact Testing and Shielding

In order to increase the survivability of a space system in the space debris environment, particularly in the densely populated LEO region, protective measures need to be taken. On-orbit shielding technologies have proven to be effective up to impactor sizes of about 1 cm. To improve the performance of such shields, ESA, ASI, BNSC, CNES, and DLR have been supporting generic studies in the areas of enhanced shield designs, material selection, damage prediction and characterization, hypervelocity accelerator technologies, and hydrocode developments.

In the past four years, ESA studies were completed or initiated to analyze pyrotechnic launcher capabilities, to

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[1] Meteoroid and Space Debris Terrestrial Environment Reference

[2] Program for Radar and Optical Observation Forecasts

[3] Debris Environment Long-Term Analysis

characterize impact damage on composite structures and MLI, to define material models for CFRP impact simulations, to optimize impact survivability by means of rearranged spacecraft components, to produce a database on impact test results, and to analyze the feasibility of expandable shield concepts. Shield designs for manned spacecraft were further scrutinized (Turner et al., 2002), with a recommended first bumper consisting of open cell Aluminium foam in a sandwich core, γ Titanium-Aluminide, and an MLI cover, a second bumper composed of Kevlar 2D, Kevlar 2.5D, and polyuretane foam, and a 4.8 mm backwall consisting of Al2219-T851. ESA also plans to perform test shots and assess resulting damage on functional batteries, heat pipes, electronic boxes, cables, and harnesses.

CNES, via the Centre d'Etudes de Gramat (CEG), performed HVI tests on different materials, including honeycomb sandwich structures. They also analyzed potential consequences (rupture or explosion) for pressurized, gas filled vessels due to HVI punctures. Another activity concentrated on spacecraft protection through architecture, by placing sensitive equipment on the lee side of the dominant impact flux direction. In the UK, similar studies are performed with the SHIELD tool. Further UK activities are concerned with HVI tests, also on tethers, and with extensions of the AUTODYN hydrocode capabilities. In Italy, CISAS has been working on the determination of ballistic limit equations, partly in cooperation with the Japanese space agency JAXA. Activities in Germany were mainly centered around the SDETES project (Space Debris End-to-End Study), and on related ballistic limit equations and damage predictions for user-defined shielding concepts.

ESA continues to use their ESABASE/Debris software to assess the consequences of hyper-velocity particle impacts (both debris and meteoroids) on user defined spacecraft structures (Bunte, 2004). The tool is presently undergoing major modifications towards a PC-based version, with increased user friendliness, combined with improved graphical presentations of damage results. ESABASE/Debris is routinely applied to all major ESA projects (e.g. Columbus, Envisat, ISO, XMM).

2.6. Databases

Hypervelocity impact tests are costly, and hence collaborative efforts for a coordinated execution of systematic tests, and for the installation of a common database of results will be of mutual benefit. The European Network of Centres is currently developing the necessary infrastructure via ESA. A Web-based access to impact results of retrieved surfaces is already existing at ESA's technology centre ESTEC (MADWEB database).

ESA's space operations centre ESOC installed the DISCOS database in 1991, in response to recommendations by the Space Debris Advisory Group (SDAG) in 1988 (Hernandez et al., 2001). Today, DISCOS maintains information on more than 28,500 cataloged space objects, of which nearly 9,000 are still on orbit. It is the most comprehensive single source of up-to-date space object information within Europe. DISCOS is, for instance, providing the launch data published by COSPAR, and annual GEO situation reports (Jehn et al., 2004) which are distributed to the UN, space agencies, and space operators. To improve user friendliness, DISCOS can now be accessed by registered users via a secure Web interface.

2.7. Debris Mitigation and Risk Reduction

Computer simulations of the long-term evolution of the space debris environment (e.g. by means of DELTA (Walker et al., 2000), IDES (Walker et al., 1999), SDM (Rossi et al., 1995), or LUCA) indicate that explosion prevention is the best near-term debris mitigation measure to stabilize the growth rate, while collision avoidance is the only effective means to inhibit the growth, and to maintain the debris population at a stable, acceptable level. Explosion prevention by passivation has, for instance been implemented on all Ariane orbital stages since flight V-59, in Sep. 1993 (Bonnal et al., 1997). Collision avoidance can be achieved by different means: active collision avoidance during the operational phase, re-orbiting (e.g. from GEO) to regions of low spatial density at the end of mission, or de-orbiting (mainly from LEO), via a controlled atmospheric entry, or via a reduced lifetime orbit with an uncontrolled re-entry within 25 years. ESA also analyzed the benefits of conductive tethers to allow a de-orbit from LEO altitudes above 1,000 km within 25 years.

ESA is performing routine conjunction predictions of their operational ERS-2 and Envisat satellites with objects from the US SSN Catalog, using their CRASS software (Alarcon, 2002), (Sanchez et al., 2004). Evasive manoeuvres may be performed, if the assessed collision probability exceeds 1 in 5,000 (1 in 10,000 prior to 2005). This led to 3 avoidance manoeuvres in 2004, for ERS-2 on Mar. 28 (Cosmos-3M stage passing at $\sim$ 160 m), Envisat on Sep. 02 (Cosmos 1269 spacecraft at 1.2 km), and Envisat on Oct. 22 (Zenith-2 explosion fragment at 80 m). CNES is also monitoring close fly-bys with their LEO spacecraft, using their ARC software, with a manoeuvre threshold for a collision probability of 1 in 1,000 (Alby, 1997). To dispose their satellite after mission completion, all European operators of GEO payloads apply the IADC GEO disposal guideline, which requests a re-orbit at EOL to a circular graveyard orbit which is $\sim$ 300 km above GEO. In compliance with this rule, ESA raised the ECS-4 orbit by $+414$ km on Dec.1, 2002 (as was done for 9 GEO mission since 1978). CNES successfully performed a de-orbit of their SPOT-1 satellite in Nov. 2003, reducing the remaining orbital lifetime to about 16.5 years, which is well below the 25 year lifetime limit recommended by IADC (Alby, 2003). After the final depletion burn the spacecraft was passivated to prevent a later explosion. A good example of a controlled re-entry is the de-orbit of the Astra-1K satellite which was performed by CNES (under contract to SES) on Dec. 10, 2002. Astra-1K previously failed to reach its GEO transfer orbit, due to a launcher failure. With no hope of a mission rescue it was decided to de-orbit the spacecraft into a steep, controlled re-entry over an uninhabited ocean area in the pacific.

In the case of uncontrolled re-entries (e.g. for a decay from a reduced lifetime orbit), it is necessary to assess the risk to the ground population due to surviving objects. In 1995 ESA initiated the development of the SCARAB[4] software to address this multi-disciplinary problem, which involves the definition of a spacecraft model, aerodynamic and aerothermodynamic analysis across all flow regimes, thermal analysis, structural analysis, and 6 degrees-of-freedom flight mechanics, applied to all fragments released in the course of the entry simulation. Meanwhile, the third generation of SCARAB is nearing completion. In the past years SCARAB was applied to ATV for nominal and contingency entries (for ESA and CNES), to the Ariane orbital and sub-orbital stages EPS/VEB and EPC (for ESA and CNES), to Beppo SAX (for ASI), and to ROSAT (for DLR). CNES is using internal tools to produce independent re-entry survival and risk analyzes, e.g. for Ariane and the ATV. ESA and CNES have developed tools which allow to translate results of re-entry survival predictions into casualty probabilities for the population inside the re-entry swath.

ESA has reached cooperative agreements with the German FGAN/TIRA radar, and with the French Monge/ARMOR radar to provide tracking data for collision or re-entry risk objects. ODIN[5], a dedicated orbit determination software, was developed to process such data, and to generate ephemerides and covariance information which is superior to TLE derived products, and which helps to control the risk on orbit and on ground.

2.8. Policies, Guidelines, and Handbooks

The European Network of Centres on Space Debris has drafted ”European Space Debris Mitigation Guidelines” (anon., 2001b), which were later modified into a policy document with the title ”European Code of Conduct for Space Debris Mitigation” (CoC). The CoC is in line with the IADC Space Debris Mitigation Guidelines, and it forms the basis for ESA's participation in standardization activities at ISO.

The European CoC and the IADC Mitigation Guidelines have annexes with technical information and implementation guidelines. Further in-depth background information is provided in the second issue of ESA's Space Debris Mitigation Handbook (Klinkrad, 2003). At present ESA is finalizing the development of DRAMA[6], which will assist debris analysts in assessing compliance with space debris mitigation guidelines for GEO re-orbiting, LEO de-orbiting (direct or delayed), on-orbit collision avoidance, and risk on ground due to re-entry. DLR sponsored the SDETES[7] project, with the objective to study application aspects of the full range of debris mitigation measures for specific satellite projects.

2.9. International Cooperation

Space debris activities within ESA, ASI, BNSC, CNES, and DLR are coordinated at the national level (via the agencies), at the European level (via the Network of Centres), and at the international level (e.g. via the IADC). The Inter-Agency Space Debris Coordination Committee, founded in 1994, consists of the 11 members, including CNSA (China), ISRO (India), JAXA (Japan), NASA (USA), NSAU (Ukraine), ROSCOSMOS (Russia), ESA, ASI, BNSC, CNES, and DLR. The 23rd IADC meeting will be held at ESOC on April 21–22, 2005. IADC's main objective is the exchange of technical information, and the identification of effective mitigation measures (anon., 2004), (anon., 2002). ESA maintains an IADC Common Database and Re-Entry Event Database to support international campaigns for re-entry predictions of risk objects. This service is routinely checked during annual IADC re-entry test campaigns, with participation also by European entities.

Since 1994 space debris has been an agenda item of the United Nations' Committee on the Peaceful Uses of Outer Space (UNCOPUOS). In the Scientific and Technical Sub-Committee (S&T SC) the IADC, national space agencies, and ESA are annually reporting on progress in their activities. In 2004 the S&T SC installed a space debris working group, with participation by IADC members, to draft a consensus document on the basis of the IADC Space Debris Mitigation Guidelines.

In 2003 the International Organization on Standardization (ISO) formed an Orbital Debris Coordination Working Group (ODCWG) under their Technical Committee TC20/SC14. Delegates from ASI, BNSC, CNES, DLR, and ESA are members of the ODCWG, which is tasked to initiate the production of ISO standards on space debris mitigation. The European Committee on Space Standardization (ECSS) is supporting this activity.

3. CONCLUSIONS

Over the past 20 years Europe has developed a recognized space debris expertise which is covering all major areas of importance: ground-based radar and optical observations, in-situ measurements, space debris and meteoroid environment modeling, statistical impact risk analysis, collision avoidance with respect to known space objects, re-entry forecast and risk analysis, hyper-velocity impact testing, shielding technologies and designs, the identification of effective mitigation measures, and the definition of guidelines and technical requirements for their implementation. Presently, ESA and the European partners are also investigating possibilities to deploy an autonomous European Space Surveillance System.

Space debris activities within Europe are recognized by the main space agencies ESA, ASI, BNSC, CNES, and DLR to be an essential part of their space programmes. Compliance with internationally accepted space debris mitigation measures is considered essential to maintain a stable space debris environment in the long term. If no

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[4] Spacecraft Atmospheric Re-Entry and Aerothermal Break-Up

[5] Orbit Determination with Improved Normal Equations

[6] Debris Risk Assessment and Mitigation Analysis

[7] Space Debris End-to-End Service

corrective actions are taken, then a ”business as usual” behavior of space operators will lead to collisions dominating the debris population within about 35 years from now. Cascading collisions in between collision fragments could then ultimately render valuable altitude and inclination bands unsafe for space activities.

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REFERENCES

Alarcón, J. Development of a Collision Risk Assessment Tool. Technical Report (final report) ESA contract 14801/00/D/HK, GMV S.A., Mar. 2002.

Alby, N. and Mesnard, R. Monitoring of On-Orbit Collision Risk. *48th IAC Congress*, IAC-97-IAA.6.4.05, Oct. 1997.

Alby, F. SPOT-1 End of Life Disposal Manoeuvres. *35th COSPAR Scientific Assembly*, PEDAS1/B1.6-0035-04, 2003.

anon. *Report of the ESA Space Debris Working Group*. ESA-SP 1109, 1988.

anon. *Technical Report on Space Debris*. United Nations Publications, New York, USA, 1999.

anon. *CNES Exigence de Securite – Débris Spatiaux: Méthode et Procedure*. CNES, MPM-51-00-12, issue 1, rev. 0, April 1999.

anon. *Position Paper on Orbital Debris*. International Academy of Astronautics, Paris, France, 2001.

anon. *European Space Debris Safety and Mitigation Standard – Draft*. issue 1, rev. 3, Nov. 2001.

anon. Protection Manual. Technical Report IADC-WD-00-03, rel. 3.0, Inter-Agency Space Debris Coordination Committee (IADC), 2002.

anon. *IADC Space Debris Mitigation Guidelines*. issue 1, rev. 1, Oct. 2004.

Bendisch, J., Bunte, K., Sdunnus, H., Wegener, P., Walker, R., and Wiedemann, C. Upgrade of ESA’s MASTER Model. Technical Report (final report) ESA contract 14710/00/D/HK, ILR/TUBS, Braunschweig, Sep. 2002.

Bonnal, C., Sanchez, M., and Naumann, W. Ariane Debris Mitigation Measures. In *Proceedings of the Second European Conference on Space Debris*, ESA SP-393, pages 681–688, March 1997.

Bunte, K.D., Langwost, A., and Drolshagen, G. Recent Upgrade and Future Perspectives of the ESABASE/Debris Tool. *Adv. Space Res.*, vol.34, no. 5:1130–1135, 2004.

Drolshagen, G. EURECA and HST Solar Array Post-Flight Impact Analysis. *Earth Space Review*, vol.4, no. 2:15–18, July 1995.

Grün, E., Gustafson, B., Dermott, S., and Fechtig, H. *Interplanetary Dust*. Springer Verlag, Berlin/Heidelberg/New York, 2001.

Hernández, C., Pina, F., Sánchez, N., Sdunnus, H., and Klinkrad, H. The DISCOS Database and Web Interface. In *Proceedings of the Third European Conference on Space Debris*, ESA SP-473, pages 803–807, March 2001.

Jehn, R., Hernandez, C., Klinkrad, H., Flury, W., and Agapov, V. Space Traffic Management in the Geostationary Ring. *55th IAF Congress*, IAA-04-IAA.5.12.4.05, 2004.

Klinkrad, H. (editor) *ESA Space Debris Mitigation Handbook*. ESA/ESOC, March 2003. Second Edition, Issue 1.0.

Klinkrad, H. Monitoring Space – Efforts Made by European Countries. In *Proc. of an International Colloquium on ”Europe and Space Debris”*, ANAE Proceedings, page 999 ff, Nov. 2002.

Krag, H., Bendisch, J., Rosebrock, J., Schildknecht, T., and Sdunnus, H. Sensor Simulation for Debris Detection. Technical Report (final report) ESA contract 14708/00/D/HK, ILR/TUBS, Braunschweig, Dec. 2002.

Leushacke, L., Mehrholz, D., and Jehn, R. First FGAN/MPIfR Cooperative Debris Observation Campaign: Experiment Outline and First Results. In *Proceedings of the Third European Conference on Space Debris*, ESA SP-393, pages 45–50, March 1997.

Rossi, A., Cordelli, A., Pardini, C., Anselmo, L., and Parinella, P. Modeling of the Space Debris Evolution: Two New Computer Models. *Advances in the Astronautical Sciences (Space Flight Mechanics)*, pp.1217–1231, 1995.

Sánchez-Ortiz, N., Belló-Mora, M., and Klinkrad, H. Collision Avoidance Maneuvers During Spacecraft Lifetime – Analysis of Operational Missions. *55th IAC Congress*, IAC-04-IAA.5.12.5.10, Oct. 2004.

Schildknecht, T., Ploner, M., and Hugentobler, U. The Search for Debris in GEO. *Advances in Space Research*, vol.28, no.9:1291–1299, 2001.

Turner, R., Taylor, E., McDonnell, J., Stokes, H., Marriot, P., Wilkinson, J., Catling, D., Vignjevic, R., Berthoud, L., and Lambert, M. Cost-Effective Debris Shields for Unmanned Spacecraft. In *Int. Journal of Impact Engineering*, pages 785–796, 2002.

Walker, R., Stokes, P., Wilkinson, J., and Swinerd, G. Enhancement and Validation of the IDES Orbital Debris Environment Model. *Space Debris Journal*, vol.1, issue 1:1–20, 1999.

Walker, R., Swinerd, G., Wilkinson, J., and Martin, C. Long Term Space Debris Environment Prediction. Technical Report (final report) ESA contract 12808/98/D/IM(SC), DERA, Farnborough/UK, May 2000.