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Draft technical report on space debris of the Scientific and Technical Subcommittee

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Introduction

1. The item on space debris was included on the agenda of the Scientific and Technical Subcommittee at its thirty-first session, in February 1994, in accordance with General Assembly resolution 48/39 of 10 December 1993. The Subcommittee, at its thirty-first session, expressed its satisfaction at having the subject of space debris as a separate agenda item after many years of discussion in various international forums, including the Subcommittee and the Committee on the Peaceful Uses of Outer Space. The Subcommittee agreed that consideration of space debris was important and that international cooperation was needed to evolve appropriate and affordable strategies to minimize the potential impact of space debris on future space missions (A/AC.105/571, para. 64). At its subsequent sessions, the Subcommittee continued its consideration of that agenda item on a priority basis.

2. The Subcommittee agreed that it was important to have a firm scientific and technical basis for future action on the complex attributes of space debris and that it should, *inter alia*, focus on understanding aspects of research related to space debris, including: debris measurement techniques; mathematical modelling of the debris environment, characterizing the space debris environment; and measures to mitigate the risks of space debris, including spacecraft design measures to protect against space debris (A/AC.105/605, para. 79). In order to advance in its consideration of space debris, the following work plan was adopted by the Subcommittee at its thirty-second session (A/AC.105/605, para. 83):

> <u>1996: Measurements of space debris, understanding of data and effects of this environment on space systems</u>. Measurements of space debris comprise all processes by which information on the near-Earth particulate environment is gained through ground- and space-based sensors. The effect (impact of particles and resulting damage) of this environment on space systems should be described;
>
> <u>1997: Modelling of space debris environment and risk assessment.</u> A space debris model is a mathematical description of the current and future distribution in space of debris as a function of its size and other physical parameters. Aspects to be addressed are: an analysis of fragmentation models; short- and long-term evolution of the space debris population; and comparison of models. The various methods for collision risk assessment should be critically reviewed;
>
> <u>1998: Space debris mitigation measures.</u> Mitigation comprises reduction of the space debris population growth and protection against particulate impact. Measures for the reduction of space debris growth include methods for debris prevention and removal. Protection against space debris includes physical protection with shielding and protection through collision avoidance.

3. Each session was to review the current operational debris mitigation practices and consider future mitigation methods with regard to cost-efficiency. The Subcommittee agreed that the work plan should be implemented with flexibility and that notwithstanding the selection of a specific topic for the next session, delegations wishing to address the Subcommittee at that time on other aspects of scientific research related to space debris should be free to do so (A/AC.105/605, paras. 83-84).

4. The Subcommittee noted that a certain amount of research on space debris had already been undertaken in some countries, which had allowed for a better understanding of the sources of debris, the areas in near-Earth orbit that were reaching high levels of space debris density, the probabilities and effects of collisions and the necessity to minimize the creation of space debris (A/AC.105/605, para. 88). The Subcommittee agreed that Member States should pay more attention to the problem of collision of space objects, including those with nuclear power sources on board, with space debris and to other aspects of space debris. It also agreed that national research on space debris should continue and that Member States should make available to all interested parties the results of that research (A/AC.105/605, para. 85).[1]

5. The Subcommittee encouraged Member States and relevant international organizations to provide information on practices that they had adopted and that had proven effective in minimizing the creation of space debris (A/AC.105/605, para. 88). The information was compiled by the Secretariat and made available as United Nations documents. A list of the documents relevant to the subject "Space debris" is provided in the annex.

6. In order to have a common understanding of the term "space debris", the Subcommittee at its thirty-second session proposed a definition of the term that it modified at its subsequent sessions to read as follows: "Space debris are all man-made objects, including their fragments and parts, whether their owners can be identified or not, in Earth orbit

or re-entering the dense layers of the atmosphere that are non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorized” (A/AC.105/672, para. 112). However, there is still no consensus agreement on the definition.

7. At its thirty-third session, the Subcommittee initiated the development of its technical report on space debris in order to establish a common understanding that could serve as the basis for further deliberations of the Committee on that important matter. The technical report was structured according to the specific topics addressed by the work plan during the period 1996-1998 and carried forward and updated each year. The text was drafted during the sessions of the Subcommittee by an unofficial group of experts provided by Member States. In drafting the technical report, working papers prepared for the sessions and scientific and technical presentations made by leading space debris experts were evaluated.

8. Especially valuable contributions to all parts of the technical report, in particular graphical and numerical data, were made by the Inter-Agency Space Debris Coordination Committee (IADC), which had been formally founded in 1993 to enable space agencies to exchange information on space debris research activities, to review the progress of ongoing cooperative activities, to facilitate opportunities for cooperation in space debris research and to identify debris mitigation options. The founding members of IADC were the European Space Agency (ESA), Japan, the National Aeronautics and Space Administration (NASA) of the United States of America and the Russian Space Agency (RSA). China joined in 1995; it was followed by the British National Space Centre, the Centre nationale d’études spatiales (CNES) of France and the Indian Space Research Organization (ISRO) in 1996 and by the German Aerospace Research Establishment (DLR) in 1997. Recently, the Italian Space Agency (ASI) applied for membership.

9. At its thirty-first session, the Subcommittee agreed that the final technical report of the Subcommittee on space debris should be adopted at its thirty-sixth session, in 1999, after final editing during the inter-sessional period and consideration by relevant organizations (such as IADC and the International Academy of Astronautics (IAA)).

1. Measurements of space debris

1.1 Ground-based measurements

10. Remote sensing of space debris from ground-based measurements generally falls into two categories: radar measurements and optical measurements. Typically, radar measurements have been used for space debris in low Earth orbit (LEO), while optical measurements have been used for high Earth orbit (HEO). For passive optical measurements, the signal intensity return is inversely proportional to the square of the distance or altitude of the object since the incident illumination from the Sun is essentially independent of altitude. For radar measurements, the signal intensity return is inversely proportional to the fourth power of distance since radars must provide their own illumination. The result is that an optical telescope of modest size can outperform most radars for detection of debris at high altitudes. Some optical measurements of small debris in LEO have been done, but in general radars outperform telescopes for measurements in LEO.

1.1.1 Radar measurements

11. Ground-based radars are well suited to observe space objects because of their all-weather and day-and-night performance. The radar power budget and operating wavelength are limiting factors for detection of small objects at long ranges.

12. Basically two types of radars are used for space object measurements:

(a) Radars with mechanically controlled beam direction using parabolic reflector antennas. Only objects in the actual field of view—given by the mechanical direction of the parabolic reflector antenna—can be detected and measured;

(b) Radars with electronically controlled beam direction using phased array antennas. Multiple objects at different directions can be detected and measured simultaneously.

13. The first type of radar is used mainly for tracking and/or imaging satellites, and the second type is used mainly for both tracking and search tasks.

14. The following radar modes are used for observation of space debris: tracking mode; beam-park mode; and mixed mode (sometimes called stare-and-chase).

15. In the tracking mode the radar follows an object for a few minutes, gaining data on angular direction, range, range rate, amplitude and phase of the radar echoes. From the evaluation of direction and velocity (angular rate and range rate) as a function of time, orbital elements can be derived.

16. In the beam-park mode, the antenna is kept fixed in a given direction and echoes are received from objects passing within its field of view. This gives statistical information on the number and size of the detected objects but less precise data on their orbit.

17. In the mixed mode, the radar would start in the beam-park mode and change to the tracking mode when an object passes the beam, thereby gaining more precise orbital data. Once the data are collected, the radar might return to the beam-park mode.

18. Radars have been used in both a monostatic (a single antenna for both transmitter and receiver) and bistatic (transmitting from one antenna and receiving from a second antenna) configuration. In the bistatic mode, an additional receiver antenna, separate from the emitting antenna, is used. This allows a greater sensitivity, which enables the detection of smaller objects and flexibility for networking different kinds of antennas.

19. From radar measurements principally, the following space object characteristics can be derived (all of the following parameters will have some degree of uncertainty):

(a) Orbital elements, describing the motion of the object's centre of mass around Earth;

(b) Attitude, describing the motion of the object around its centre of mass;

(c) Size and shape of the object;

(d) Orbital lifetime;

(e) Ballistic coefficient, as defined in paragraph 47 (g) below, specifying the rate at which the orbital semi-major axis decays;

(f) Object mass;

(g) Material properties.

20. The deterministic data can go into a catalogue of space objects, as well as the statistical information on numbers of detected objects of a given size in a given region at a certain time.

21. Both the Russian Federation and the United States (United States Space Command) operate networks of radars (and optical telescopes) for detecting, tracking and cataloguing orbiting space objects. These catalogues date from the first artificial satellite launch in 1957 and include space debris as small as 10-30 cm in diameter.

22. Radar measurements of orbital debris population statistics at sizes smaller than 30 cm (the nominal limit for the Russian and United States catalogues) have been conducted by the United States using Haystack, Haystack Auxiliary (HAX) and Goldstone radars, by the Russian Federation using some Russian radars and by Germany using the Research Establishment for Applied Science of Wachtberg-Werthhoven (FGAN) radar and the Effelsberg Radio Telescope. Haystack, HAX and Goldstone radars have provided a statistical picture of LEO debris environment at sizes down to 0.5 cm (with some data down to 0.2 cm). FGAN radar measurements have not extended to quite such small sizes but in general agree with the NASA results. The picture that emerges from these and other measurements is that the debris population exceeds the natural meteoroid population for all sizes (except between 30 and 500 µm).

23. The MU radar of Kyoto University of Japan has observed the radar cross-section variation of unknown objects for a period of 20 seconds. A bistatic radar system of the Institute of Space and Astronautical Sciences (ISAS) of Japan has the capability to detect objects as small as 2 cm at an altitude of 500 km.

24. The existing and planned radar capabilities for observation of debris for sizes smaller than 10-30 cm in diameter are given in table 1.

1.1.2 Optical measurements

25. Debris can be detected by a telescope when the debris object is sunlit while the sky background is dark. For objects in LEO, this period is limited to an hour or two just after sunset or before sunrise. However, for objects in HEO, such as those in geosynchronous orbit, observations can often be continued during the entire night. The requirement of clear, dark skies is another limitation on optical measurements.

Table 1
Radar facilities for debris observation

Country	*Organization*	*Facility*	*Type*	*Primary operation mode*	*Configuration*	*Field of view*	*Wave-length (m)*	*Sensitivity (diameter) (m)*	*Status*
Germany	FGAN	TIRA	Dish	Mixed	Monostatic	0.5	0.23	0.02 at 1,000 km	Operational
Germany	MPIfR	Effelsberg	Dish	Stare	Bistatic with TIRA	0.16	0.23	0.009 at 1,000 km	Experimental
Japan	Kyoto University	MU radar	Phased array	Stare	Monostatic	3.7	6.4	0.02 at 500 km	Operational
Japan	ISAS	Uchinoura	Dish	Mixed	Bistatic	0.4	0.13	0.02 at 500 km	Experimental
Japan	ISAS	Usuda	Dish	Mixed	Bistatic	0.13	0.13	0.02 at 500 km	Experimental
Ukraine/ Russian Federation	..	Evpatoria	Dish	Stare	Bistatic	0.1	0.056	0.003 at 1,000 km	Developmental
United States	NASA/ NSF	Arecibo	Dish	Stare	Bistatic	0	0.13	0.004 at 575 km	One-time experiment
United States	NASA/ DoD	Haystack	Dish	Stare	Monostatic	0.1	0.03	0.006 at 1,000 km	Operational
United States	NASA/ DoD	HAX	Dish	Stare	Monostatic	0.1	0.02	0.05 at 1,000 km	Operational
United States	NASA	Goldstone	Dish	Stare	Bistatic	0	0.035	0.002 at 500 km	Operational
United States	DoD	TRADEX	Dish	Mixed	Monostatic	0.61/ 0.30	0.23/ 0.10	0.03 at 500 km	Operational

26. The United States Space Command employs aperture telescopes of 1 m fitted with intensified vidicon detectors to track HEO objects. These measurements are used to maintain the HEO part of the Space Command catalogue. The capability of these telescopes is limited to detection of objects of 1 m at geosynchronous altitudes, corresponding to a limiting stellar magnitude of 16. Charge-coupled device (CCD) detectors are planned for these telescopes, which will improve their performance. RSA has a similar telescope capability used to maintain the orbits of HEO objects in its catalogue.

27. In general, the United States Space Command and the Russian geostationary orbit (GEO) catalogues are concerned with intact spacecraft and rocket bodies. However, there are reasons to believe that small orbital debris resulting from explosions also exist in the GEO region. A Russian Ekran satellite in GEO was observed to explode in 1978. Many uncatalogued objects have been seen in high elliptical orbits at an inclination of 7 degrees, possibly the result of Ariane geotransfer stage break-ups. The United States Space Command telescope on Maui, in Hawaii, accidentally observed the break-up of a Titan transtage (1968-081E) in February 1992. There are other stages near GEO that may still have the potential to explode. Some of these stages appear to be lost and may have exploded.

28. An exceptional combination of sensitivity and field of view is required to survey the GEO region for the small orbital debris that are suspected to exist there. A limiting stellar magnitude of 17 or greater is needed to detect debris smaller than 1 m near geosynchronous altitude, and as wide

a field of view as possible is needed to allow the rapid surveying of large areas. Most astronomical telescopes that have sufficient sensitivity have a small field of view. This is useful for accurate determination of satellite positions (once their approximate locations are known), but not for surveying large areas of the sky.

29. Some preliminary measurements have been done to survey the region near GEO for debris objects smaller than 1 m. NASA used a small telescope capable of detecting objects as faint as 17.1 stellar magnitude (equivalent to an object about 0.6 m in diameter at geosynchronous altitude), with a field of view of about 1.5 degrees. The results showed that there does exist an appreciable population of debris near those altitudes. Further debris surveys are justified. IADC is currently conducting an exploratory GEO orbital debris campaign.

30. The existing and planned optical capabilities for optical observation of debris are summarized in table 2.

Table 2

Optical facilities for debris observation

Country	*Organization*	*Telescope aperture (m)*	*Field of view (degrees)*	*Detection type*	*Limiting magnitude*	*Status*
	ESA	1	1	CCD	19	In development
France	French National Centre for Scientific Research	0.9	0.5	CCD	19	In development
Japan	SUNDAI	0.75	0.04	CCD	17	Operational
Japan	CRL	1.5	0.28	CCD	18.7	Operational
Russian Federation	RAS[a] RAS[a]	1 0.6	0.2 0.2	CCD CCD	19 18	Operational Operational
Russian Federation	RSA[b]	0.6	0.2	TV	19	Operational
Switzerland	University of Berne	1	0.5	CCD	19.5	Operational
United Kingdom of Great Britain and Northern Ireland	Royal Greenwich Observatory/MOD	0.4	0.6	CCD	18	Two telescopes operational, United Kingdom and overseas
United States	NASA	0.3	1.5	CCD	17.1	Operational
United States	NASA	3	0.3	CCD	21.5	Operational

[a] Russian Academy of Sciences.

[b] Russian Space Agency.

1.2 Space-based measurements

1.2.1 Retrieved surfaces and impact detectors

31. Information on submillimetre-sized particles can be gained with the analysis, after return to Earth, of surfaces or spacecraft exposed to the space environment. Similar information can also be obtained through dedicated debris and dust detectors. Most of them contain, as a key element, a detection surface. Some of them are designed to catch an impact particle for further analysis. For cost reasons, surfaces are retrieved for later analysis only from LEO.

32. Examples of retrieved spacecraft and surfaces are given in table 3.

Table 3
Examples of retrieved spacecraft and surfaces

Name	*Orbit*	*In orbit*	*Stabilization*	*Exposed area*
Salyut 4 and 6	350 km 51.6 degrees	1974-1979	Various	~7 m² of sensors and cassettes
STS-7 Window (NASA)	295-320 km 28.5 degrees	June 1983	Various	~2.5 m²
Solar Maximum Mission (NASA)	500-570 km 28.5 degrees	Feb. 1980-Apr. 1984	Sun-pointing	2.3 m²
STS-52 (Canada/NASA)	350 km 28.4 degrees	Oct. 1992	Various	1 m²
LDEF (NASA)	340-470 km 28.5 degrees	Apr. 1984-Jan. 1990	Gravity-gradient	151 m²
EURECA (ESA)	520 km 28.5 degrees	July 1992-June 1993	Sun-pointing	35 m² of spacecraft plus 96 m² of solar arrays
HST Solar Array (NASA/ESA)	610 km 28.5 degrees	May 1990-Dec. 1993	Sun-pointing	62 m²
Mir/EUROMIR 95 (RSA/ESA)	390 km 51.6 degrees	Oct. 1995-Feb. 1996	Gravity-gradient	20 x 30 cm (cassette)
Mir	390 km 51.6 degrees	1986-1998	Various	~15 m² of cassettes and other elements
Mir (Canada/Ukraine)	390 km 51.6 degrees	Nov. 1997-Feb. 1999	Various	1 m²
SFU (Japan)	480 km 28.5 degrees	Mar. 1995-Jan. 1996	Sun-pointing (except 1 month IR telescope operation)	50 m²
Space Shuttle Orbiter (NASA)	300-600 km 28.5-51.6 degrees	1992-present	Various	100 m²

33. After exposure to the space environment, spacecraft surfaces are covered with a large number of impact craters caused by meteoroids and debris. The size of individual impact craters and holes ranges from micrometres to several millimetres. A basic problem is to distinguish between impacts of meteoroids and man-made debris. A proven method to determine their origin is chemical analysis. However, there are some difficulties associated with this method. Because of the high impact speed, little of the impacting material survives unaltered. The particle vaporizes and then recondenses on the surrounding surfaces. In many cases, therefore, the origin of an impacting particle cannot be uniquely determined. In order to relate the size of the impact feature with the size of the particle, ground-calibration tests (hypervelocity impact tests) have been performed for different materials.

34. From impact statistics and calibration experiments, the flux for meteoroids and debris can be determined as a function of particle size. An important issue to be considered is that of secondary impacts. If these are not properly treated, the derived flux figures will be overestimated.

35. The Long-Duration Exposure Facility (LDEF) was covered by more than 30,000 craters visible to the naked eye, of which 5,000 had a diameter larger than 0.5 mm. The largest crater, 5 mm in diameter, was probably caused by a particle of 1 mm. LDEF showed that some impacts were clustered in time, and it also pointed to the existence of a submillimetre population in elliptical orbits.

36. On the European Retrievable Carrier (EURECA), the largest impact crater diameter was 6.4 mm. Among the retrieved surfaces, the returned solar array of the Hubble Space Telescope (HST) had been the one with the highest orbit altitude. An interesting finding was that the impact flux for HST was considerably higher (factor of 2-8) than for EURECA for crater pit sizes larger than 200-300 µm.

37. The Space Flyer Unit (SFU) launched by an H-II rocket in March 1995 was retrieved by the Space Shuttle in January 1996. A post-flight analysis (PFA) is under way.

38. The cases discussed above give evidence of the effect of the particulate environment on spacecraft in orbit. In all cases, no functional degradation of the spacecraft was observed. Available information on the submillimetre population is limited to altitudes below 600 km. In particular, no information is available in the regions of highest density of space debris in LEO (at an altitude of about 800-1,000 km) as well as in geostationary orbit. In 1996, an ESA debris and dust detector was placed in geostationary orbit on the Russian spacecraft Express-2. CNES will place active and passive detectors on Mir in 1999. CNES plans to use the same detectors on the French satellite STENTOR in geostationary orbit (1999) and in heliosynchronous orbit on an Israeli satellite (1999).

39. Since 1971, regular measurements of submillimetre-sized meteoroid and debris particles have been carried out on the Russian space stations Salyut 1, 2, 3, 4, 6 and 7 and Mir. The measurements have been carried out by capacitive sensors with an overall exposed area of about 3 m^2, as well as by changeable returned cassettes with an exposed area of about 0.1 m^2 each. In January 1998, during the Space Shuttle mission, eight sections of solar panels from the space station Mir, with an overall area of about 10 m^2 and an exposure time of about 10 years, were returned to Earth for further investigation.

1.2.2 Space-based debris measurements

40. Space-based measurements in general have the advantage of higher resolution because of the smaller distance between the observer and the object. Also, there is no disturbing effect of the atmosphere (extinction and absorption of electromagnetic signals). The costs of space-based systems are in general higher than the costs of ground-based systems, and careful cost-performance trade-offs are needed.

41. The infra-red astronomical satellite (IRAS), launched in 1983 to perform a sky survey at wavelengths ranging from 8 to 120 µm, was operational during the 10 months in a Sun-synchronous orbit near an altitude of 900 km. The satellite was pointing radially away from Earth and scanning the celestial sphere. The complete set of unprocessed IRAS data has been analysed by the Space Research Organization of the Netherlands (SRON), in Groningen, in order to characterize the infra-red emission of debris objects and to extract a comprehensive set of debris sightings. The method of identifying space debris signatures is based on the recognition of their track over the IRAS focal plane. The 200,000 potential debris sightings are stored in a database. About 10,000 sightings are attributed to real objects. From the debris sightings, it is not possible to compute the orbital elements of a debris object in a unique manner.

42. In 1996, the United States launched the MSX spacecraft into a 900 km orbit. Its visible and infra-red sensors are being used to observe nearby small debris.

43. In September 1996, the impact ionization detector Geostationary Orbit Impact Detector (GORID) was placed into GEO on board the Russian telecommunication satellite

Express 12. It is stationed at 80 degrees east longitude and measures the submillimetre-sized meteoroid and space debris population.

44. To measure the small-sized solid particle population in different orbits and on a more regular basis, a low resource standard *in situ* detector called DEBIE is under development. The first flight of DEBIE is planned on the small ESA technology satellite PROBA in polar orbit.

1.3 Summary of measurements

45. Figure I presents a compilation of the results of many of the measurement systems described in previous sections. It shows the cross-sectional flux (number of objects per year per square metre) for objects of a given size and larger. The figure summarizes measurements in LEO near 500 km altitude.

1.4 Cataloguing and databases

46. A catalogue is a record of the characteristics of the orbital population that have been derived from measurements or records. (For the purposes of the present report, the term catalogue includes the collection of orbital elements.) The purposes of a catalogue are to provide current orbital elements, which can be used to predict orbital motion, and to provide correlation with observations of orbiting objects; to act as a historical record of orbital activity for the purposes of environment monitoring; to serve as an input to modelling the behaviour of orbiting objects; and to provide a basis for predicting future launch and operational activity.

47. The following characteristics of orbiting objects may be recorded:

(a) Regularly updated state vectors: the characteristics of the orbit of an object derived at a particular instant in time and used for orbit propagation;

(b) Mass: the launch mass, beginning of life mass and dry mass (end of life);

(c) Radar cross-section: the returned signature of an orbiting object, from which shape, orientation and size can be derived; (the radar cross-section is dependent on the wavelength of the radar; therefore, the wavelength of the measurement must also be recorded);

(d) Albedo: a measure of the reflectivity of an object that characterizes the optical visibility of an object;

(e) Dimensions;

(f) Orientations;

(g) Ballistic coefficient: a measure of the aerodynamic and area-to-mass characteristics of the object that will influence the orbital lifetime of an object until its entry into the upper atmosphere;

(h) Material composition: although not currently of importance, to effectively represent shedding of micro-debris would require the definition of surface characteristics;

(i) Launch characteristics: this will include the launch vehicle, launch date and launch site.

48. There are two catalogues of space objects that are frequently updated by observations: the United States Space Command catalogue and the space object catalogue of the Russian Federation. Data are also archived in the Database and Information System Characterizing Objects in Space (DISCOS) of ESA based on those two catalogues. Figure II shows the growth of the number of objects in the United States catalogue with time (limited to sizes larger than 10-30 cm).

49. The National Space Development Agency (NASDA) of Japan is studying a debris database that can provide data to the international common debris database currently being discussed in IADC. NASDA is also studying a trajectory prediction analysis for re-entering objects and collision avoidance analysis for new launches.

50. NASDA currently depends on the United States Space Command orbital element data as the source of its debris database. NASDA will add the orbital data of its own spacecraft acquired through observations conducted by the National Astronomy Observatory.

51. A catalogue record can be stored on a number of media. A hard-copy (paper) format is not well suited to the dynamic nature of the orbital population. An electronic format is well suited to the recording of such information, modification and updating of characteristics, manipulation of data for the purposes of comparison and input to models, and access via networks by users for the purposes of interrogation and contribution.

Figure I
Approximate measured debris flux in low Earth orbit, by object size

Figure II
Number of objects in the United States catalogue, by type, 1959-1996

52. Current catalogues contain information on satellites and debris as small as 10-30 cm in diameter. Some recent activities in the United States are aimed at improving the sensitivity of the United States catalogue to provide detection of 5 cm objects at altitudes below 600 km. Some studies have looked at improvements to provide detection of objects as small as 1 cm. However, improvements of catalogues beyond 5 cm are not likely in the near future. Therefore, modellers must continue to use statistical measurements for smaller sizes (see figures III and IV).

1.5 Effects of the space debris environment on the operation of space systems

53. Four factors determine how the space debris environment affects space systems operations. These are time in orbit, projected area, orbital altitude and orbital inclination. Of these, time in orbit, projected area and orbital altitude are the dominant factors.

Figure III

Coverage of ranges of debris diameter and period of exposure: space-based data, 1980-1998

Figure IV
Coverage of ranges of debris diameter and period of exposure: ground-based data, 1980-1998

1.5.1 Effects of large debris objects on the operation of space systems

54. Large debris objects are typically defined as objects larger than 10 cm in size. Such objects are capable of being tracked, and orbital elements are maintained. During the course of shuttle missions, orbiters have executed collision avoidance manoeuvres in order to avoid catastrophic collisions with these large debris objects. Two unmanned satellites have also performed collision-avoidance manoeuvres to avoid large debris: The European remote sensing satellite (ERS-1) in June 1997 and Satellite pour l'observation de la Terre (SPOT-2) in July 1997. In 1996, the first recorded natural collision occurred between two catalogued objects, the operational Cerise satellite and a fragment from an exploded Ariane upper stage.

1.5.2 Effects of small debris objects on the operation of space systems

55. To date, small debris objects (smaller than a few millimetres in diameter) have caused damage to operational space systems. These impacts have had no known effect on mission success. This damage can be divided into two categories. The first category is damage to surfaces or subsystems. The second category is the effect on operations.

1.5.2.1 Damage to surface or subsystems

56. Examples of damage that affect the surface of operational systems are:

(a) Damage to shuttle windows;

(b) Damage to HST high gain antenna;

(c) Severing of the Small Expendable Deployer System-2 (SEDS-2) tether;

(d) Damage to other exposed shuttle surfaces.

In the damage described in subparagraphs (a), (b) and (d) above, there is clear evidence of damage due to orbital debris. In subparagraph (c), it is unclear whether the damage is caused by man-made debris or a micrometeoroid.

1.5.2.2 Effects of space debris on human space operations

57. In order to protect crews from debris during flight, operational procedures have been adopted. In the case of the Space Shuttle, the orbiter is often oriented during flight, with the tail pointed in the direction of the velocity vector. This flight orientation was adopted to protect the crew and sensitive orbiter systems from damage caused by collisions with small debris.

58. Operational restrictions have also been adopted for extravehicular activities (EVAs). Whenever possible, EVAs are conducted in such a way as to ensure that the EVA crew is shielded from debris by the orbiter.

1.6 Other effects of space debris

59. Astronomers are observing during wide field imaging an increasing number of trails per plate caused by orbital debris. These trails degrade the quality of the observation. Orbital debris trailing will entirely negate a photometric observation when debris cross the narrow photometric field.

2. Modelling of the space debris environment and risk assessment

2.1 Modelling of the space debris environment

2.1.1 Introduction and methodology

60. Space debris models provide a mathematical description of the distribution of objects in space, the movement and flux of objects and the physical characteristics of objects (e.g. size, mass, density, reflection properties and intrinsic motion). These models can be deterministic in nature (i.e. each object is described individually by its orbital parameters and physical characteristics), statistical in type (i.e. characterization of an ensemble by a sample number of objects) or a combination (i.e. hybrid). These models can be applied to risk and damage assessments, prediction of debris detection rates for ground-based sensors, prediction of avoidance manoeuvres of operational spacecraft and long-term analysis of the effectiveness of debris mitigation measures.

61. Space debris models must consider the contribution to the population of orbiting objects of the following source mechanisms:

(a) Launches (including launch vehicle upper stages, payloads and mission-related objects);

(b) Manoeuvres (to account for solid rocket motor firings);

(c) Break-ups (produced by explosions and collisions);

(d) Material separation from surfaces (ageing effects, e.g. paint flakes);

(e) Material due to leakage (e.g. nuclear power source (NPS) coolant).

62. The following sink mechanisms must also be considered:

(a) Orbital decay due to atmospheric drag or other perturbations;

(b) Retrievals from orbit;

(c) Deorbiting;

(d) Fragmentation (leading to a loss of large objects).

A debris environment model must contain all or some of these elements.

63. Space debris models make use of available data sources. These include:

(a) Deterministic data on decimetre-sized and larger objects within the United States Space Command Satellite catalogue and the Russian Space Surveillance catalogue (see figure V for the related spatial density distribution);

Figure V
Spatial density of catalogued objects (as at 21 August 1997)

(b) Statistical data on centimetre-sized objects derived from dedicated radar campaigns in LEO;

(c) Statistical data on encountered submillimetre debris populations inferred from analysis of retrieved surfaces and from *in situ* impact sensors;

(d) Statistical data on decimetre and larger objects in LEO using ground-based telescopes;

(e) Ground-based simulations of hypervelocity collisions with satellite and rocket bodies;

(f) Ground-based simulations of explosive fragmentations.

64. These models are limited by the sparse amount of data available to validate the derived relationships. The models must rely upon historical records of satellite characteristics, launch activity and in-orbit break-ups; in addition, there are only limited data on spacecraft material response to impact and exposure to the orbital environment. Furthermore, major assumptions must be made in applying these models to predict the future environment. In particular, future traffic scenarios and the application of mitigation measures will have a major influence on the outcome of model predictions. Space debris models must be continually updated and validated to reflect improvements in the detail and size of observational and experimental data sets.

65. Environment models may take two forms: as discrete models, which represent the debris population in a detailed format, or as an engineering approximation. Furthermore, these models can be short term in nature (considering time-frames of up to 10 years) or long term (considering time-frames of over 10 years). In the preparation of all these models, the initial debris population is represented at a particular starting epoch and propagated forward in time in a stepwise manner, taking account of source and sink mechanisms and relevant orbit perturbations. Neither the short-term nor the long-term models account for the periodic concentrations of debris that exist hours to months following a break-up; such “very short-term” models are occasionally used to assess the hazard to specific space systems but are not discussed below.

66. The pertinent characteristics of the models are compared in table 4.

Table 4
Debris environment models

Model name	*Source*	*Evolutionary period*	*Engineering model available*	*Minimum size*	*Orbital regime*
CHAIN	NASA	Long term	No	1 cm	LEO
CHAINEE	ESA	Long term	No	1 cm	LEO
EVOLVE	NASA	Short and long term	No	1 mm	LEO
IDES	DERA	Short and long term	No	0.01 mm	LEO
LUCA	TUBS	Long term	No	1 mm	LEO/ MEO
MASTER	ESA	Short term	Yes	0.1 mm	LEO/ GEO
Nazarenko	RSA	Short and long term	No	0.6 mm	LEO
ORDEM96	NASA	Short term	Yes	1 µm	LEO
SDM/STAT	ESA/ CNUCE	Short and long term	No		LEO/ GEO

2.1.2 Short-term models

67. The following short-term models are available in the scientific and engineering community:

(a) *EVOLVE* was developed by the NASA Johnson Space Center to provide both short-term and long-term forecasts of the LEO environment with excessive source terms and detailed traffic models, based on quasi-deterministic population propagation techniques that are suitable for both LEO and GEO modelling;

(b) *ORDEM96* is a semi-empirical engineering model developed by NASA Johnson Space Center. It is based upon extensive remote and *in situ* observations and is used to support United States Space Shuttle and International Space Station design and operations;

(c) *MASTER* is an ESA semi-deterministic environment model based on 3-D discretization of spatial densities and transient velocities. The model is applicable to altitudes from LEO to GEO, providing environment estimates in the short term. A less detailed version of MASTER is available as an engineering format. Both models were developed by the Technical University of Braunschweig under ESA contract;

(d) *IDES* is a semi-deterministic model of the environment using detailed historical and future traffic models to provide short-term and long-term predictions of the orbital debris environment and the collision flux it presents to specific satellites. The model was developed by the Defence Evaluation and Research Agency (DERA), Farnborough, United Kingdom;

(e) *Nazarenko*, a model developed by the Centre for Programme Studies (CPS) of RSA, is a semi-analytic, stochastic model for both short-term and long-term prediction of the LEO debris environment, providing spatial density, velocity distributions and particle fluxes. The model takes account, in average form, of debris sources (except for the cascading effect) and of atmospheric drag; it has been adjusted on the basis of Russian and American catalogue data and published measurements of somewhat smaller fragments (more than 1 mm), while also taking account of a priori information;

(f) *SDM* is a semi-deterministic model to provide both short-term and long-term predictions of the orbital debris environment. The code, developed at CNUCE, makes use of a detailed traffic model, including satellite constellations, and considers several source model options for explosions, collisions and RORSAT leaks. SDM has been developed under ESA and ASI contracts.

68. These models can be used to “predict” the current environment. Several different models have been used to develop “envelopes of solution” for the current environment, as shown in figure VI.

Figure VI
Model values for current spatial density

2.1.3 Long-term models

69. The scope of the long-term modelling of the orbital debris environment is the long-term (up to 100-year) prediction of the number of objects as a function of time, of altitude, of inclination and of object size. These projections are important for assessing the necessity and the effectiveness of debris mitigation techniques and the impact of new space activity.

70. In addition to the sources of space debris that are considered in the modelling of the current debris population, it is necessary to take into account collisions among larger objects (>10 cm). Currently, collisions among larger objects do not play a significant role in the increase of the number of objects, since their probabilities are low. However, in the future, the interactive risk for so-called destructive collisions, i.e. collisions that generate larger fragments, may increase. This so-called interactive collision risk among all objects of the population is proportional to the square of the number of objects. Hence, in the future, long-term mitigation should consist of the removal of mass and cross-section from orbit.

71. In order to assess the consequences of collisions among larger objects, it is necessary to have reliable break-up models for collisions of this type. However, it is very difficult to simulate on-orbit collisions without having test data for validation purposes available. Hence, a certain degree of uncertainty is introduced into the models by the collision simulation.

72. Other than the modelling of the present debris population, the long-term modelling requires assumptions describing the future space flight activities, including the debris generation mechanisms, in terms of, for example:

(a) Future number of launches and related orbits;

(b) Future number and size of payloads per launch;

(c) Future number of mission-related objects (fairing, bolts etc.);

(d) Future number of explosions of spacecraft and upper stages;

(e) New uses of space (e.g. commercial LEO communications satellite constellations).

73. All of these parameters are subject to variations with time due to technical/scientific, financial and political aspects. Hence, some uncertainties are added to those uncertainties that are due to the mathematical model itself (break-up models etc.).

74. A number of models have been developed for the purpose of long-term modelling of the debris environment. They can be characterized briefly as follows:

(a) *CHAIN* and *CHAINEE:* CHAIN was developed by the Technical University of Braunschweig under contract. Since 1993, this model has been maintained and improved by NASA. CHAINEE, the European extension of CHAlN, is used by ESA. The model, an analytical “particle-in-a-box” model, describes the population and the collision fragments up to an altitude of 2,000 km using four altitude bins in LEO and five mass classes. CHAIN and CHAINEE are extremely fast computer codes. It enables the identification of relative trends associated with specific mitigation policies. The resolution of CHAIN is limited due to the binning used;

(b) *EVOLVE*: The EVOLVE model has been developed by NASA. It is a semi-deterministic model (SDM), i.e. debris objects are described individually by a set of parameters. In addition to being capable of modelling the present debris environment, it can be used to investigate future evolutionary characteristics under various mitigation practices using Monte Carlo techniques. For this purpose mission model data are used;

(c) *IDES*: The IDES model was developed at the Space Department of DERA. Historical sources such as launches, break-ups and paint flakes are simulated and evolved to generate the current debris environment. This is used as the initial conditions, together with a detailed mission model, to simulate the future evolution of the debris environment. IDES can be used to study the collision interactions of multiple LEO satellite constellations and the effectiveness of debris mitigation measures;

(d) *LUCA*: For the detailed analysis of future scenarios, especially if a high resolution concerning the orbital altitude and the declination is required, the semi-deterministic computer code LUCA has been developed at the Technical University of Braunschweig. This code combines the advantages of a high spatial resolution and of a tolerable computer time need. In order to calculate the time-depart collision risk, a special tool has been implemented. This tool reflects the increased collision risks at higher declinations (e.g. close to the polar regions);

(e) *SDM/STAT*: The semi-deterministic model (SDM) and the stochastic approach (STAT) use the same initial population, as provided by a computer model, and the same source and sink assumptions, including collisions. In SDM, orbits of a representative subset of the population are used to map the population forward in time; by means of parametric studies, effects of launch policies and mitigation measures can be analysed. STAT is a computer time-efficient "particle-in-a-box" alternative to SDM. It is based on a system of coupled differential equations for the populations of 80,000 bins in mass, semi-major axis and eccentricity. The two codes can be compared and given similar results;

(f) *Dual-size particle-in-a-box*: these are two models with the ability to handle LEO constellations;

(g) *Nazarenko*: the Nazarenko model, developed by CPS (Russian Federation), is a semi-analytic, stochastic model for both short-term and long-term predictions of the LEO environment, providing spatial density, velocity distributions and collision risk assessment. The model is based on Russian and United States catalogue data and on published data on small space debris (>1 mm). The model uses the same initial population, based on the satellite catalogues and an averaged space debris source. Source characteristics are based on the historical analysis of space debris contamination. Forecasting is performed by integrating the partial differential equations for the space debris distribution as a function of altitude. Atmospheric drag, distribution of ballistic coefficients and orbit eccentricity are taken into account in the orbit propagation.

75. The major findings of the above-mentioned long-term debris models can be summarized as follows:

(a) The debris population may grow in an accelerated manner in the future if space flight is performed as in the past. This is because of the increasing number of collisions that will occur among larger objects;

(b) Currently, depending on size, fragments from explosions are the main source of space debris. Beyond a certain point in time, collision fragments may dominate the population;

(c) Should the second stage of this evolution occur, the so-called collisional cascading effect may set in. This means that collisional fragments will contribute to the number of subsequent collisions. At that point in time, the population will grow exponentially;

(d) Suppressing explosions can reduce the number of objects in orbit, but cannot prevent collisional cascading, which is driven by the total mass in orbit and the number of large objects;

(e) Only by limiting the accumulation of mass in LEO can collisional cascading be prevented;

(f) At some point in the future, collisional fragments may dominate the environment. Without some technology development there will be no practical capability to halt growth of the environment; therefore, mitigation measures should be implemented before this point is reached.

76. The results of the long-term debris models do not agree quantitatively because of differences in assumptions and initial conditions. However, the basic trends and tendencies obtained by the models agree qualitatively. The number of major collisions predicted by several models (EVOLVE, CHAIN, CHAINEE and IDES) are presented as envelopes of predictions in figure VII. The number of fragments generated by future sources is less consistently predicted for small fragments.

77. The collision probabilities among the larger objects are initially low. Hence, it is essential to analyse a number of single Monte Carlo runs or to use mean value approaches in order to obtain reliable trends and tendencies. The above models take care of that effect.

2.2 Space debris risk assessments

2.2.1 Introduction

78. Risk assessments include the probability of an event, as well as its subsequent consequences. With the assistance of models of the orbital debris environment, the risk of collision among operational spacecraft and orbital debris can be evaluated. Spacecraft in LEO are routinely bombarded by very small particles (<100 µm) because of the large number of such debris, but the effects are normally slight due to the small masses and energies involved. Because of the smaller population of large debris objects, the likelihood of collision decreases rapidly as the size of the debris increases. However, the severity of collisions between large objects increases.

79. The principal risk factors are the spatial density and average relative collisional velocity along the orbit (altitude and inclination) of the space object of interest, the cross-sectional area of the space object and the duration of the flight. The consequences of a collision will depend upon the respective masses and compositions of the objects involved. Whereas the collision risk between an orbiting object and a meteoroid is essentially independent of altitude, the probability of collision between orbital objects is strongly related to altitude, in general being an order of magnitude higher in LEO than in GEO.

2.2.2 Collision risk assessments in low Earth orbit

2.2.2.1 Methodology

80. Risk assessments have been routinely performed on LEO spacecraft since the 1960s. The Poisson model is used in cases where there is a large number of independent events and each event has a small probability of occurring. Man-made debris and micrometeoroids meet these criteria for independence, except in cases of a recent break-up or a meteor storm.

81. To compute the probability of an impact from space debris requires a meteoroid/orbital debris (M/OD) environment model, a spacecraft configuration and a mission profile. To compute the probability of a penetration and/or a failure due to space debris requires detailed knowledge of the spacecraft configuration, including:

(a) The geometry of critical subsystems;

(b) The penetration resistance or ballistic limit equation of each subsystem;

(c) Data on the ability of each subsystem to tolerate damage.

Figure VII
Typical ranges for number of major collisions for three scenarios, 1995-2095

82. Based on this information, computer codes can calculate:

(a) The probability of space debris impacts for a particle of a given size;

(b) The probability of impact damage to any given subsystem;

(c) The split between damage from man-made debris and micrometeoroids.

2.2.2.2 Results of risk assessments

83. Risk assessments in LEO are routinely utilized to enhance the safety of space operation. In cases involving human space flight, risk assessments have proved invaluable in ensuring the safety of shuttle operations. Shuttle missions are operationally reconfigured whenever a pre-flight risk assessment indicates that the risks of space debris are at an unacceptable level.

84. Risk assessments are being utilized to design the location and type of space debris shielding that will protect the crew as well as the crucial subsystems on the International Space Station.

85. Risk assessments are also utilized in the design of unmanned spacecraft. They aid in the placement and protective shielding design of critical subsystems and components, as well as in the system design of large communication satellite constellations. An example of risk assessment at LEO is given in table 5.

2.2.3 Collision risk assessments in geostationary orbit

86. Currently, the population of space objects in and near the GEO regime (see figure VIII) is well known for only spacecraft and upper stages. The limited number of these objects, their wide spatial distribution and the lower average relative velocities (500 m/sec) combine to produce a substantially lower probability of collision in GEO. Moreover, as more spacecraft and upper stages are left in orbits above or below GEO, the number of uncontrolled intact objects intersecting the GEO regime is increasing at a very slow rate. Special collision possibilities exist in GEO because of the close proximity of operational spacecraft at selected longitudes, but these collision hazards can be eliminated by spacecraft control procedures. The limited number of large objects near GEO also permits the prediction of close approaches between operational spacecraft and tracked orbital debris in sufficient time to conduct an evasive manoeuvre.

87. The number of orbital debris of less than 1 m in diameter near GEO is not well known. Two break-ups (one a spacecraft and one an upper stage) have been identified, and some evidence suggests that additional break-ups may have occurred. Such debris would be perturbed into new orbits, possibly reducing the residence time in GEO but increasing the relative collision velocity, making the flux contribution nearly constant with inclination change. In many cases debris fragments would be widely dispersed in both altitude and inclination. Additional orbital debris measurements in GEO are needed before more accurate risk assessments can be performed. Also, new techniques to predict collision probability may need to be developed to take into account the non-random nature of close approaches in GEO.

Table 5
Mean time between impacts on a satellite with a cross-section area of 10 square metres

	Objects 0.1-1.0 cm	*Objects 1-10 cm*	*Objects >10 cm*
	Likely result of impact		
Height of circular orbit	*Possible loss of satellite*	*Probable loss of satellite*	*Fragmentation of satellite*
500 km	10-100 years	3,500-7,000 years	150,000 years
1,000 km	3-30 years	700-1,400 years	20,000 years
1,500 km	7-70 years	1,000-2,000 years	30,000 years

Figure VIII
Payloads and upper stages launched into geostationary orbit, 1963-1996

88. There is no natural removal mechanism for satellites in GEO. Therefore, operational spacecraft are at risk of being damaged by uncontrolled spacecraft. This annual collision risk for an operational satellite is currently estimated at 10^{-5}.

2.2.4 Risk assessments for re-entering space debris

89. The risk assessment discussed here is limited to uncontrolled re-entry from Earth orbit.

90. There have been more than 16,000 known re-entries of catalogued space objects in almost 40 years. No significant damage or injury has been reported. In large measure this can be attributed to the large expanse of ocean surface and the sparse population density in many land regions. In the past five years, approximately once each week, an object with a cross-section of 1 m^2 or more has re-entered Earth’s atmosphere and some fragments have been known to survive.

91. The risk of re-entry is not only from mechanical impact, but also from chemical or radiological contamination to the environment. Mechanical damage will be caused by objects surviving aerodynamic heating. This risk will depend on the characteristics of the final orbit, the shape of the object and its material properties.

92. An assessment of re-entry risk must include the modelling of objects, analysis of the break-up altitude, identification of components that can survive re-entry and the calculation of total casualty area.

93. There is no international consensus on human casualties caused by re-entry. A casualty expectation of 10^{-4} per re-entry event is presented in NASA safety standard 1740.14, entitled “Guidelines and assessment procedures for limiting orbital debris”.

3. Space debris mitigation measures

3.1 Reduction of the debris increase in time

3.1.1 Avoidance of debris generated under normal operation

3.1.1.1 Mission-related objects

94. Approximately 12 per cent of the present catalogued orbital debris population consists of objects discarded during normal satellite deployment and operations. Typical objects in this category are fasteners, yaw and yo-yo weights, nozzle covers, lens caps, multiple payload mechanisms and so forth. It is normally relatively easy, both technically and economically, to take mitigation measures against these objects. Many agencies are reported to have taken such action. For example, clamp bands and sensor covers should be retained by parent bodies, and all fragments of explosive bolts should be captured. However, there may be some parts that will be released for unavoidable reasons, such as a structural element left in geostationary transfer orbit (GTO) during a multiple payload mission. Every agency is encouraged to minimize these kinds of debris whenever possible using state-of-the-art equipment or techniques.

3.1.1.2 Tethers

95. Tethers may become orbital debris if they are discarded after use or if they are severed by an impacting object (man-made debris or meteoroid). Tethers several thousand metres in length and a few millimetres in diameter might not survive for extended periods. New multi-strand tether designs can reduce the risk of being severed. At the end of missions, tethers may be retracted to reduce the possibility of collision with other objects or both end masses may be released to accelerate the orbital decay of the tether.

3.1.1.3 Solid rocket motor effluents, paint and other exterior materials

96. Other mission-related particles may be generated unintentionally, as in the release of slag (up to several centimetres in diameter) during and after the burn of solid rocket motors. The precise nature of the amount and distribution of these slag ejecta are unclear, and the improvement of solid propellant and motor insulation to minimize the released solids is difficult. Attempts should be made to inhibit the generation of very small debris caused by the effects of the space environment, for example, atomic oxygen erosion, solar radiation effects and the bombardment of small meteoroids. The application of more long-lasting paint and protective covering could be an effective remedial measure.

3.1.2 Prevention of on-orbit break-ups

97. The consequences of fragmentations of upper stages and spacecraft constitute approximately 43 per cent of the current identified satellite population and may account for as much as 85 per cent of all orbital debris larger than 5 cm in diameter. At least 153 space objects, with a total dry mass of more than 385,000 kg, are known to have broken up in Earth orbit as at 1 September 1998. Fortunately, 60 per cent of the catalogued debris generated in those events have fallen back to Earth. Such fragmentations are caused primarily by either explosions or collisions.

3.1.2.1 On-orbit explosions

98. Thirty-six per cent of all resident space objects break-ups are upper stages or their components that operated successfully but were abandoned after the spacecraft delivery mission was completed. Such incidents have affected a wide range of launch vehicles operated by the United States, the Russian Federation, China and ESA. Accidental explosions can also be caused by malfunctioning propulsion systems, overcharged batteries or explosive charges. Intentional break-ups have also been conducted.

99. ecraft and upper stages have shown that vehicle deorbiting or passivation, i.e. the removal of all forms of stored energy, would eliminate most such events. Effective

measures include the expulsion of residual propellants by burning or venting, the discharge of electrical storage devices, the release of pressurized fluids, thermal control and safing of unused destruct devices and the unloading (despinning) of momentum wheels and similar attitude control apparatus. These measures should be performed soon after the vehicle has completed its mission.

3.1.2.2 On-orbit collisions

100. The probability of an accidental collision in Earth orbit is currently slight, but it is becoming greater as the number and size of satellites are increasing. In 1996, the French CERISE spacecraft was struck and partially disabled by the impact of a fragment which, according to the United States Space Command monitoring network, came from an exploded Ariane upper stage. In addition, the possibility of other break-ups being caused by collision cannot be denied because the causes of many break-up events remain unknown. Effective measures to mitigate the consequences of break-ups caused by collision include the spacecraft design, selection of an orbit where the probability of collision is low, and collision avoidance manoeuvres (see paragraphs 112-118 below).

3.1.3 Deorbiting and reorbiting of space objects

3.1.3.1 Mission termination of space systems

101. For space objects in LEO reaching end of mission, each vehicle should be deorbited or placed in a reduced lifetime orbit to reduce the possibility of an accidental collision. Studies have shown that the growth of orbital debris can be mitigated by limiting orbital lifetimes. This may be done with a controlled re-entry manoeuvre or by transferring the vehicle to a lower altitude.

102. For space objects at higher altitudes, moving vehicles into disposal orbits can also be effective for the foreseeable future. For example, the transfer of geostationary orbit spacecraft to orbits above GEO not only protects operational spacecraft but also reduces the probability of derelict objects colliding with one another and creating debris that might threaten the GEO regime. A standardized minimum reorbit distance value should be determined by taking into consideration factors such as perturbation effects by the gravitational force of the Sun and the Moon and solar radiation pressure. The upper stages or components of launch vehicles left in GTO may be manoeuvred to prevent interference with systems in GEO. The perigee altitude of the upper stage could be selected to ensure a limited orbital lifetime.

3.1.3.2 In case of failure

103. Space systems on orbit should be continuously monitored especially for critical malfunctions that could lead to the generation of large amounts of fragments or to loss of the ability to conduct mitigation measures. The propulsion system, batteries and the attitude and orbit control subsystem should be monitored in that context. If a malfunction occurs and the mission cannot be maintained, procedures should be implemented to preclude accidental explosion and to prevent as much as possible interference with useful orbits.

3.2 Protection strategies

104. Given the current orbital debris population, spacecraft designers should consider incorporating implicit and explicit protection concepts into their space vehicles. A hazard for space objects and orbital stations is posed by hypervelocity impact with meteoroids and space debris particles 1-2 mm or larger. High-velocity impacts by particles as small as 1 mm in diameter can lead to loss of functions and potentially mission failure. Even small impacts on pressure vessels may result in container ruptures. Such damage may also prevent planned passivation measures or post-mission disposal options. In many cases, the relocation of vulnerable components can greatly increase spacecraft survivability. Prudent selection of the orbital regime and collision avoidance are other potential protection strategies.

3.2.1 Shielding

105. Orbital debris shields for both manned and unmanned spacecraft can be quite effective against small particles. Protection against particles 0.1-1 cm in size can be achieved by shielding spacecraft structures. All objects 1-10 cm in size cannot currently be dealt with by on-orbit shielding technology, nor can they be routinely tracked by operational surveillance networks. However, protection against particles 1-10 cm in size can be achieved through special features in the design of space systems (redundant subsystems, frangible structures, pressure vessel isolation capabilities, maximum physical separation of redundant components and paths of electrical and fluid lines etc.). Physical protection against particles larger than 10 cm is not yet technically feasible.

106. Shielding designs may vary from simple single sheet Whipple bumpers, located in front of the spacecraft wall, to

complex layers of metal and ceramic/polymer fabrics that are designed first to break up the impacting particle and then to absorb the energy of the resulting ejecta. Bumper shields should be positioned at sufficient distance from the shielded object to ensure a wide dispersion of the fragment cloud, created as a result of the impact of the debris particles on the shield. Thus, the impact loads should be distributed over a considerable area of the protected object’s body. Successful shield designs may take advantage of the structure of the vehicle and the directionality of orbital debris to protect critical components. In addition, spacecraft can be designed to place critical components in the geometric shadow of the prevailing direction of debris flux. The application of lightweight, multilayer insulation may provide protection against small debris, and the placement of sensitive equipment behind existing vehicle structures may also improve survivability.

107. The penetration depth, or damage potential, of an impacting object depends on its mass, density, velocity and shape and on the material properties of the shield. Different modelling and simulation tools are available to predict the damage resulting from impacts on various shield designs (e.g. the NASA BUMPER model, the ESA ESABASE model, the Russian BUFFER model and several hydrocodes to perform simulations under conditions not possible using ground-based test facilities). Ground-based tests of spacecraft shields are limited, as testing for the entire range of possible impact velocities is not possible. Ground-based accelerators are currently limited to velocities of the order of 13 km/s (e.g. using shaped charge devices), but most existing data are for 7 km/s. New methods are being developed and further refined for calculating the processes involved in hypervelocity collisions between space debris particles and shields at impact velocities of 5-15 km/s.

3.2.1.1 Human space flight

108. Manned spacecraft, particularly space stations, are normally larger than most unmanned vehicles and must demonstrate higher safety standards. Protection strategies for manned missions may incorporate both shielding measures and on-orbit repair of damage caused by penetrations. Current shield designs offer protection against objects smaller than 1 cm. The probability of no penetration (PNP) is the main criterion for shield design. PNP calculations are based on meteoroid and debris environment models and on the ballistic limit curves obtained in hydrocode simulations and hypervelocity impact experiments. The reliability of the PNP calculations is strongly linked to the accuracy of the debris and meteoroid environment model. The degree of shielding required is highly dependent upon the nature (material, thickness etc.), location and orientation of the surface to be protected. Consequently, the International Space Station will employ over 200 different types of orbital debris and micrometeoroid shields.

109. On manned spacecraft it is possible to install automatic detection systems to locate damage. In case of a puncture of a pressurized module, isolation of the module or reaction time in sealing the puncture is of primary importance. The amount of time available depends on the size of the puncture, and the time required for repair is a function of the means employed and the strategy adopted.

110. Crew members engaged in extravehicular activities (EVA) need protection from natural and man-made debris. Current spacesuits have many features with inherent shielding qualities to offer protection from objects of sizes up to 0.1 mm. By properly orienting their spacecraft, astronauts may be able to use their vehicles as shields against the majority of orbital debris or direct meteoroid streams.

3.2.1.2 Unmanned spacecraft

111. For unmanned spacecraft, lower PNPs are tolerable. An acceptable level of protection against small debris and meteoroid objects (smaller than 1 mm) may be attained through the use of reinforced multilayer insulation materials and via design modifications, such as internal installation of fuel lines, cables and other sensitive components (for example, as implemented by RADARSAT of Canada). Solar array designs can minimize the effects of damage from collisions with small particles by using designs that have multiple electrical paths and that minimize structural mass, i.e. frangible configurations.

3.2.2 Collision avoidance

112. Current space surveillance systems do not reliably track objects in LEO with a radar cross-section of less than 10 cm in equivalent diameter. In addition, it is difficult to maintain orbital parameters on small catalogue objects due to factors such as a high area-to-mass ratio and, consequently, a higher susceptibility to atmospheric density variations. For space objects large enough to be tracked by ground-based space surveillance systems, collision avoidance during orbital insertion and on-orbit operations is technically possible.

113. Collision avoidance manoeuvres impact satellite operations in several ways (e.g. propellant consumption,

payload data and service interruptions, and temporary reduction in tracking and orbit determination accuracy), and they should be minimized, consistent with spacecraft safety and mission objectives. Collision avoidance strategies are most effective when the uncertainty in the close approach distance is kept small, preferably less than 1 km. Collision avoidance is always probabilistic. NASA uses an acceptable risk criterion of 1 in 100,000 to consider a collision avoidance manoeuvre for the United States Space Shuttle missions.

3.2.2.1 On orbit

114. The United States Space Surveillance Network (SSN) and the Russian Space Surveillance System (SSS) monitor the LEO environment to warn crewed spacecraft if an object is projected to come within a few kilometres. For example, if an object is predicted to pass through a box measuring 5 km x 25 km x 5 km oriented along the flight path of the United States Space Shuttle, the SSN sensor network intensifies its tracking of the potential risk object. If the improved fly-by prediction indicates a conjunction within a box measuring 2 km x 5 km x 2 km, an avoidance manoeuvre may be performed. During the period 1986-1997, the United States Space Shuttle executed four such evasive manoeuvres. The Russian SSS performs similar collision avoidance assessments for the Mir space station.

115. Russian specialists have compiled a catalogue of dangerous approaches to space objects (several million approaches) and an algorithm for deciding whether to proceed with an avoidance manoeuvre. It is proposed to identify hazardous situations involving the predicted approach of space debris and to intensify data coverage of such events and flight control of the spacecraft requiring protection. Work is under way to establish a special telecommunication system linking RSA management with the mission control centre in Korolev.

116. ESA and CNES are using orbit determinations of their LEO spacecraft to forecast conjunction events and to initiate evasive manoeuvres if certain fly-by range limits or estimated collision risk levels are violated. For an accepted collision risk of 1 in 10,000, the ERS-1 and ERS-2 spacecraft of ESA would need to perform 1 or 2 manoeuvres each year. Collision avoidance manoeuvres were performed by the ESA satellite ERS-1 in June 1997 and by the CNES satellite SPOT-2 in July 1997.

117. As more spacecraft are launched into the GEO region, coordinated station-keeping is becoming increasingly beneficial. Inclination and eccentricity vector separation strategies can be efficiently employed to keep co-located GEO spacecraft at safe distances. Eccentricity vector control may also be employed to reduce the risk of collision between members of a given LEO satellite constellation.

3.2.2.2 Launch

118. Calculations made prior to the launch of United States spacecraft permit the establishment of safe launch windows, ensuring that the spacecraft will not pass near resident manned spacecraft (i.e. Space Shuttle, Mir or the International Space Station). For the Space Shuttle, similar alert procedures are used as for the on-orbit conjunction analysis. In the case of a predicted conjunction, the launch is delayed; to date two Space Shuttle launches have been delayed to avoid potential collisions.

3.3 Effectiveness of debris mitigation measures

119. Probably one of the most important mitigation measures has been the increased awareness of the threats posed by the orbital debris environment and of the many sources of orbital debris. Incorporation of debris mitigation measures early in the vehicle design phase could be cost-effective. Educational efforts among the aerospace industries and national space agencies have reaped the rewards of voluntary action, guided by the principles of good stewardship of near-Earth space.

120. Since the early 1980s, the adoption of mitigation measures has had an effect on the growth of the orbital debris environment. The frequency of significant satellite fragmentations, both accidental and intentional, has dropped, moderating the rate of growth of orbital debris. For long-lived mission-related debris even a decrease is noticeable. New debris shield technologies and designs have substantially reduced the weight of protection while increasing its effectiveness.

121. The aerospace community is working to illustrate the effectiveness and cost of typical mitigation scenarios. Long-term environment simulation models are useful in such work. The models cannot provide accurate predictions of the space environment several decades into the future, but they can evaluate the relative influences of different operational practices.

3.3.1 Scenarios of mitigation measures

122. Mission-related objects, satellite fragmentations and end-of-mission disposal practices are important factors in the potential growth of the orbital debris population. The five typical mitigation scenarios for all space missions presented below show the potential effectiveness of mitigation measures; they are not intended to be prescriptive in nature and should be used only for simulation purposes. The scenarios are the following:

(a) Reference scenario with current mitigation measures;

(b) Elimination of mission-related objects;

(c) Universal passivation at end of mission;

(d) Universal disposal at end of mission for GEO;

(e) Deorbiting at end of LEO and GTO mission: this includes both lowering the orbit to reduce the satellite lifetime (e.g. to less than 25 years) and immediate re-entry.

123. Initial studies have shown that the greatest near-term benefit can be gained by the elimination of accidental explosions of spacecraft and upper stages. Such break-ups are best controlled by the passivation of the vehicles at the end of mission, as demonstrated by many spacecraft and launch vehicle operators.

124. In the long term, the accumulation of objects in orbit may pose a significant increase of the threat to space operations in both low and high altitude regimes. Without

Figure IX

Total population of debris particles larger than 1 centimetre in low Earth orbit for different scenarios, 2000-2200

remediation of the debris environment or operational changes, the growing number and total cross-section of resident space objects would increase the likelihood of collisions, which in turn could generate new debris. Placing LEO and GTO spacecraft into disposal orbits with limited orbital lifetime (e.g. 25 years or less) has a pronounced effect on curbing the growth of the debris population. Figure IX illustrates the total population of debris particles larger than 1 cm in LEO for a number of scenarios.

3.3.2 Cost or other impact of mitigation measures

125. Debris mitigation measures can affect the design and cost of spacecraft and launch vehicles as well as their operations.

3.3.2.1 System development cost

126. Modifying the designs of spacecraft and launch vehicles to implement mitigation measures generally adds to the system development cost. However, allowing for mitigation measures early in the design process is more cost-effective than modifying a design later. Although increased vehicle complexity may arise, some mitigation measures may lead to simpler designs as well as weight savings.

3.3.2.2 Launch performance and mass penalty

127. Providing for the upper stages of launch vehicles to re-enter the atmosphere directly or to have a short orbital lifetime may influence launch trajectory and performance. Likewise, any weight added to the launch vehicle or the spacecraft to meet mitigation objectives lowers the useful payload capacity. Additional propellant or electrical power resources may be needed. The magnitude of these consequences will vary depending upon the mitigation measure selected and the vehicle.

3.3.2.3 Mission lifetime

128. For a given design, implementing disposal or deorbiting strategies may reduce the active mission lifetime. Many GEO spacecraft operators have accepted this penalty in order to preserve their orbital regimes. If the penalty is considered during the design process, full mission lifetime requirements can still be achieved, although at the potential expense of increased weight or cost.

3.3.2.4 Reliability

129. Incorporating debris mitigation measures into spacecraft and upper stages may increase or decrease overall reliability. For example, shielding measures offer protection against small debris and radiation and may improve spacecraft reliability. The addition of relief valves to deplete residual propellants might decrease system reliability, but these effects are often quite small.

4. Summary

130. During its multi-year investigation of the space debris topic, the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space has examined: (a) the state of knowledge of the near-Earth debris population from both *in situ* and terrestrial-based sensors; (b) the capabilities of computer models to assess debris risks and to forecast the growth of space debris; and (c) a variety of space debris mitigation measures.

131. With the use of ground-based optical and radar surveillance systems around the world, space objects with diameters larger than 10 cm in LEO and larger than 1 m in GEO can be observed and tracked. More than 8,500 catalogued objects are in Earth orbit. The number of in-orbit catalogued objects has been increasing at a relatively linear rate for the past several decades.

132. Some nations have developed computer models of orbital debris based upon the large, catalogued population and upon statistical observations obtained by a wide variety of sensors. Despite the differences in the techniques applied in the models, the trends and tendencies predicted for the future orbital debris environment are qualitatively in agreement.

133. Of the debris mitigation measures identified, the limitation of mission-related debris and the prevention of accidental explosions have been found effective and have already been introduced to some extent. Also, the transfer of GEO spacecraft into disposal orbits at the end of their active life is already customary practice, followed as an intermediate measure to prevent future problems in GEO. IADC has suggested an algorithm for the determination of the minimum altitude of the disposal orbit above GEO. For some satellites on long lifetime LEO orbits, a transfer to shorter lifetime orbits is planned at the end of their active

life. Such procedures, in general, would be most effective in limiting the density of objects in those altitude bands that are most highly populated at present. Since most of the mitigation measures introduce some cost burden to missions, it is essential that the same debris avoidance procedures are applied globally.

134. Many organizations involved in space operations have become aware of the potential threats of space debris, and some of those organizations have initiated efforts to mitigate debris generation and to share the results of those efforts with the international community. The activities of international organizations such as IADC and IAA have made positive contributions to space debris research and education. IADC members represent essentially all of the nations with launching capabilities and those that design and build the majority of space systems.

135. In most cases, man-made space debris today poses little risk to the successful operations of approximately 600 active spacecraft now in Earth orbit. However, the known and assessed population of debris is growing, and the probabilities of potentially damaging collisions will consequently increase. Because of the difficulty of improving the space environment with existing technologies, the implementation of some debris mitigation measures today is a prudent step towards preserving space for future generations. In some cases, technical work remains to be done to determine the most effective and cost-efficient solutions.

Notes

[1] The Subcommittee at its thirty-sixth session will have before it the latest document containing such information (A/AC.105/708).

Annex

List of documents relevant to the subject “Space debris”

Reports on sessions of the Scientific and Technical Subcommittee

Report of the Scientific and Technical Subcommittee on the work of its thirty-first session (A/AC.105/571, 10 March 1994)

Report of the Scientific and Technical Subcommittee on the work of its thirty-second session (A/AC.105/605, 24 February 1995)

Report of the Scientific and Technical Subcommittee on the work of its thirty-third session (A/AC.105/637 and Corr. 1, 4 March 1996)

Report of the Scientific and Technical Subcommittee on the work of its thirty-fourth session (A/AC.105/672, 10 March 1997)

Report of the Scientific and Technical Subcommittee on the work of its thirty-fifth session (A/AC.105/697 and Corr.1, 25 February 1998)

Reports on national research on space debris

Use of nuclear power sources in outer space (A/AC.105/C.1/WG.5/L.24, 15 January 1990)

Use of nuclear power sources in outer space (A/AC.105/C.1/WG.5/L.24/Add.1, 14 February 1990)

Use of nuclear power sources in outer space (A/AC.105/C.1/WG.5/L.24/Add.2, 26 February 1990)

Use of nuclear power sources in outer space (A/AC.105/C.1/WG.5/L.24/Add.3, 28 February 1990)

Space debris; status of work in Germany: working paper by Germany (A/AC.105/C.1/L.170, 12 February 1991)

National research on the question of space debris (A/AC.105/510, 20 February 1992)

National research on the question of space debris (A/AC.105/510/Add.1, 21 February 1992)

National research on the question of space debris (A/AC.105/510/Add.2, 26 February 1992)

National research on the question of space debris (A/AC.105/510/Add.3, 26 February 1992)

National research on space debris; safety of nuclear-power satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/542, 8 February 1993)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/542/Add.1, 17 February 1993)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/542/Add.2, 19 February 1993)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/565 and Corr.1, 16 December 1993)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/565/Add.1, 21 February 1994)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/565/Add.2, 23 February 1994)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593, 1 December 1994)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593/Add.1, 24 January 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593/Add.2, 6 February 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593/Add.3, 7 February 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear power sources with space debris (A/AC.105/593/Add.4, 24 February 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/619, 21 November 1995)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/619/Add.1, 1 February 1996)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/659, 13 December February 1996)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/659/Add.1, 6 February 1997)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/659/Add.2, 14 February 1997)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/680 1 December 1997)

National research on space debris; safety of nuclear-powered satellites; and problems of collisions of nuclear-powered sources with space debris (A/AC.105/680/Add.1, 2 February 1998)

Documents on mitigation steps taken by space agencies

Steps taken by space agencies for reducing the growth or damage potential of space debris (A/AC.105/620, 21 November 1995)

Steps taken by space agencies for reducing the growth or damage potential of space debris (A/AC.105/663, 13 December 1996)

Steps taken by space agencies for reducing the growth or damage potential of space debris (A/AC.105/681, 17 December 1997)

Scientific and technical presentations

Scientific and technical presentations to the Scientific and Technical Subcommittee (A/AC.105/487, 9 May 1991)

Scientific and technical presentations to the Scientific and Technical Subcommittee (A/AC.105/516, 29 May 1992)

Scientific and technical presentations to the Scientific and Technical Subcommittee (A/AC.105/546, 18 May 1993)

Scientific and technical presentations to the Scientific and Technical Subcommittee at its thirty-first session (A/AC.105/574, 12 May 1994)

Scientific and technical presentations to the scientific and technical subcommittee at its thirty-second session (A/AC.105/606, 27 April 1995)

Scientific and technical presentations to the scientific and technical subcommittee at its thirty-third session (A/AC.105/638, 7 May 1996)

Scientific and technical presentations to the scientific and technical subcommittee at its thirty-fourth session (A/AC.105/673, 7 May 1997)

Scientific and technical presentations to the scientific and technical subcommittee at its thirty-fifth session (A/AC.105/699, 20 April 1998)

Working papers and reports

Space debris: a status report submitted by the Committee on Space Research (A/AC.105/403, 6 January 1988)

Environmental Effects of Space Activities: report submitted by the Committee on Space Research and the International Astronautical Federation (A/AC.105/420, 15 December 1988)

The problem of space debris: working paper submitted by Australia, Belgium, Canada, the Federal Republic of Germany, the Netherlands, Nigeria and Sweden (A/AC.105/L.179, 1 June 1989)

Use of nuclear power sources in outer space; space debris: working document submitted by the Russian Federation (A/AC.105/C.1/L.193, 21 February 1994)

Space debris: report of the International Astronautical Federation (A/AC.105/570, 25 February 1994)

Collisions between nuclear power sources and space debris: working paper submitted by the Russian Federation (A/AC.105/C.1/L.204, 13 February 1996)

Brief review of the work done by Russian scientists on the problem of the technogenic pollution of near space: working paper submitted by the Russian Federation (A/AC.105/C.1/L.205, 13 February 1996)

Space debris: working paper submitted by the International Academy of Astronautics (A/AC.105/C.1/ L.217, 12 January 1998)

Space debris: working paper submitted by the Russian Federation (A/AC.105/C.1/L.219, 10 February 1998)

Revisions to the technical report

Revisions to the technical report on space debris of the Scientific and Technical Subcommittee (A/AC.105/C.1/ L.214, 26 February 1997)

Revisions to the technical report on space debris of the Scientific and Technical Subcommittee (A/AC.105/C.1/ L.224, 19 February 1998)