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SPACE DEBRIS AND ORBITAL FLIGHT SAFETY

V.F.Utkin, S.V.Chekalin

Central Research Institute of Machine Building, Kaliningrad, Russia

ABSTRACT

A brief analysis of the current level of space man-made debris pollution and a forecast for the future are given. Evaluation of the probability of collision of orbital stations, GEO satellites and space objects with on-board nuclear power units with space debris is made. First - priority preventive measures for enhancing the survivability of orbiting assets are proposed.

Artificial pollution of the space environment poses serious hazards to the orbital flight safety. Despite a number of uncertainties in assessing the near-earth space debris population one may state the following:

The number of space fragmentations is consistently growing and accumulating on high orbits not subjected to self-cleaning due to atmosphere effects (H<600 km). For the 35 year period of spacecraft launches the ground tracking system cataloged over 22000 man-made space objects measuring more than 10-20 cm and 7000 of then remain orbiting the Earth. The highest concentration of fragmentations is observed at altitudes of 800, 1000 and 1500km. Spacecraft and rocket upper stage explosions are the major sources of orbital debris. They produce almost half of the cataloged objects and the bulk of untraceable but hazardous for spacecraft in flight small-size fragmentations (one to 10 cm in size).

By specialists' assessment the untraceable fragmentation population is an order of magnitude higher than that of the cataloged population. The number of still smaller fragmentations (less than 1 cm) runs into hundreds of thousands. The structural composition of the space debris population is shown in Fig.1a, Fig.1b.

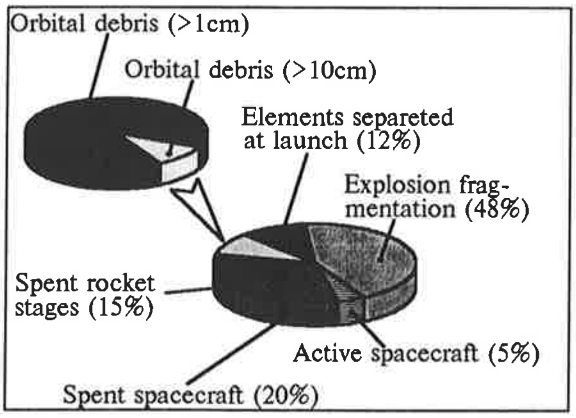


Figure 1a. Structural composition of orbital debris.

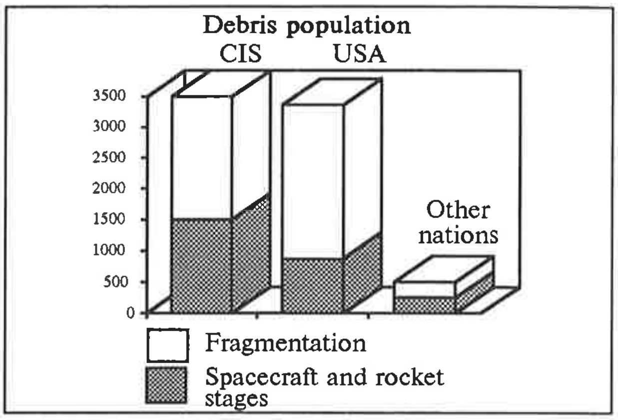


Figure 1b. Share of the nations in orbital debris generation

Debris produced by explosions are characterized by the fact that their orbit planes diverge with the passage of time. As a result fragmentation flight trajectories envelope thinly all the Earth leaving only both Poles uncovered.

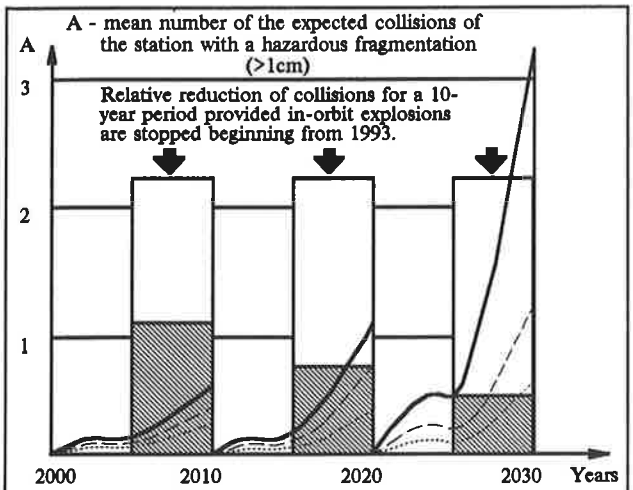
Bearing in mind that speeds of LEO objects on cross-courses are about 10 km/sec it is practically impossible to prevent destruction of an object colliding with debris sizing more than 1 cm. It is basically unreal to forecast and track trajectories of all hazardous directly untraceable debris (1 to several cm in size) with the purpose of making evasive anti-collision maneuvers. Therefore, if it is still possible to design an on-board protection technology for spacecraft against mm-sized debris then the only measure to oppose hazardous debris threat (≥1 cm) is to minimize their population or, at least, to check its potential growth.

For assessing and forecasting the probability of spacecraft collision with space debris a mathematical model was developed considering the current degree and expected growth rate of near-earth space pollution, spacecraft cross-section area, its orbit life time as well as the solar period effect on the orbital debris density.

An average number of expected spacecraft collisions with orbital debris during the spacecraft's active orbit lifetime is taken as a criterion for defining the space flight safety.

The developed model was used for assessing the impact space debris environment has on the survivability of a MIR-2-type orbital station (H_{orbit}=400 km, i=65°) with the body area of 1000 m^2. The annual increase of debris 1 cm and more in size was taken to be 10%, i.e. the same as during the previous 11 year solar period.

The research results are given in Fig.2 showing that if the station is put into operation in the year of 2000 the expected number of hazardous collisions during a 10 year period of its service will amount to 0.5 while a station put into operation in the years of 2010 and 2020 will run risk of more than one and three collisions accordingly.



——— without conduct of measures on reducing the space debris pollution growth rate.

- - - - provided that intentional explosions of spacecraft are stopped beginning from 1993.

·········· provided that intentional and accidental explosions of spacecraft and rocket stages are stopped begining from 1993.

Figure 2. Dependence of the mean number of the expected collisions of the orbital station with hazardous fragmentations (>1 cm) on its operation time.

Orbital debris poses no less threat to spacecraft with radioactive materials onboard. The probability of collisions of these spacecraft during their active orbital lifetime is low but it sharply grows when the spacecraft are transferred to "luminescence" orbits (H=800 - 1500 km) where they will stay for many hundreds of years. Now these orbits host 56 radioactive objects including spacecraft with radio-isotope thermoelectric generators, spacecraft with nuclear power units, separate nuclear reactor power plants with removal section and even fuel element assemblies thrown from reactors. If the debris environment in the year of 2000 is taken for predicting a collision risk one may anticipate up-to two collisions with hazardous space debris for the whole existing collection of used objects with radioactive materials onboard.

Risk of collision of GEO satellites with space debris is currently lower several orders of magnitude but provided that the existing rate of the GEO pollution persists (up-to 20-25 objects a year) this risk may pose a serious threat in the nearest future. The situation is aggravated by the fact that we don't have data on small fragmentations in this orbit since ground surveillance facilities are unable to track GEO objects measuring less than 1 m. But by analogy with low orbits GEO spacecraft and spent rocket stages may explode too. At least we know about two such explosions (the upper stage of a "Titan" rocket launcher in September, 1968 and an "Ekran" spacecraft in June, 1978). Judging by the statistics of accidental explosions in low orbits one can suppose that the number of explosions in GEO where there are about 450 traceable objects may come to 6-8.

To prevent spacecraft and launch vehicle stage explosions in space should be the first-priority preventive measure for enchancing the survivability of orbiting assets.

Such technology was implemented in the kick stage "D" of the "Proton" SLV which launches spacecraft in GEO. Remaining propellant components and fuel tank pressurization gases are vented after a spacecraft is cast off thus excluding the possibility of the kick stage destruction in its non-powered flight.

After analyzing the probable cause of the explosion of GEO spacecraft "Ekran" no. 1977-92-A (malfunctioning of the buffer chemical buttery charger) appropriate modifications were made and effectiveness of these modifications was proved by operation of the follow-on spacecraft. Works to analyze the causes of accidental explosions and measures to prevent low-orbit "Kosmos" - type spacecraft explosions as well as to minimize deliberate explosions of spacecraft are being carried out (see table I).

At present in order to minimize the GEO debris environment used spacecraft of the "Ekran", "Gorizont" - type are removed to outer relative to the GEO orbits using the remaining motive fuel of the spacecraft propulsion unit. Duration of the propulsion unit operation is defined provided that propellant components are fully utilized. Analysis of the statistical data on the national GEO spacecraft shows that such a removal makes it possible to elevate the altitudes of used spacecraft by 30 to 400 km depending on the quality of remaining motive fuel of the propulsion units. It is desirable to provide special motive fuel reserves onboard potential spacecraft allowing elevation of a spent spacecraft altitude by at least 200 km with guarantee (see Fig.3, region 4), for that purpose the required velocity increase will be only V_x=7.5 m/c.

Item №	Spacecraft Designation	Date of Destruction	Hypothetical Causes of Destruction	Measures to Eliminate Explosions
1	Ekran - 2		Explosion of the chemical battery during prolonged recharge.	Chemical battery modification.
2 3 4 5 6 7 8 9 10 11	Kosmos - 1094 Kosmos - 1220 Kosmos - 1260 Kosmos - 1355 Kosmos - 1405 Kosmos - 1461 Kosmos - 1588 Kosmos - 1646 Kosmos - 1682 Kosmos - 1769	17.9.1979 20.6.1982 8.5.1982 12.8.1983 20.12.1983 11.5.1985 11.8.1986 20.11.1987 18.12.1986 21.9.1987	Explosion of the liquid propulsion system due to availability of unused fuel. Explosion of the pressurized containers with buffer chemical batteries.	The propulsion and electric power supply system have been modified. Removal of spacecraft into the upper atmosphere after termination of their orbital lifetime is provided. No explosions have been registered onboard modified spacecraft since 1985.
12	Kosmos - 1275	24.7.1981	Explosion of the chemical battery due to failure of the current protection automatics.	The automatics has been modified
13	Kosmos - 1823	17.12.1987	Improper command to recharge the chemical battery, explosion due to the relay sparking.	The electric power supply system and control documentation have been updated.
14 15 16 17 18	Astron Kosmos - 1519-1521 Kosmos - 1603 Kosmos - 1656 Kosmos - 1710-1712	3.9.1984 4.2.1991 5.9.1992 5.6.1988 29.12.1991	Explosion of the propulsion unit of the starting system of the kick stage "DM".	Modification of the unused fuel component venting system of the starting system propulsion unit is being carried out.

Table 1. Hypothetical Causes of Spontaneous Explosions of a Number of Russian Spacecraft and Measures to Eliminate them.

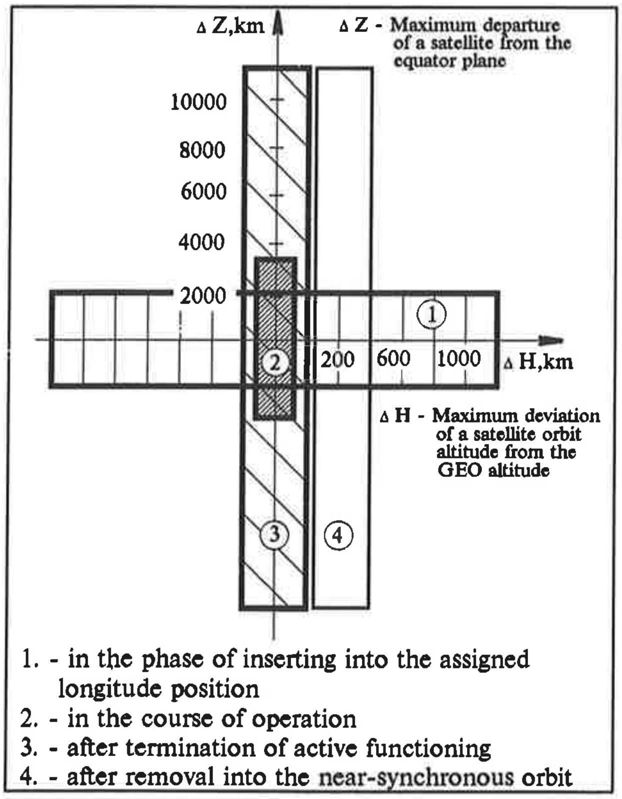


Figure 3. Regions of probable GEO satellite deviation in various flight phases.

Additional survivability of nuclear-powered spacecraft in case of their collision with debris and premature orbit departure is ensured by their testing on aerodynamic destruction down to fragmentations of non-hazardous sizes at their re-entry.

Efficiency of the measures to prevent in-orbit explosions is evidently demonstrated by the survivability of a MIR-2-type orbital station (see Fig.2). If explosions are stopped beginning from 1993 the probability of a collisions with a hazardous fragmentation for a ten-year period of the station operation would be lessened two, four and approximately seven times beginning from the years of 2000, 2010 and 2020 accordingly, i.e. the efficiency grows with the time passage and the earlier the measures to prevent explosions in space are undertaken, the higher the survivability of orbiting assets will be.

However, it should be noted that the exclusion of chemical explosions ensures minimization of the near-earth space debris pollution for a relatively short period of time (30-40 years). The accumulation of used objects in orbits collisions of these objects with debris will present the major source of contamination. Thus, later it would be necessary to prevent further contamination of near-earth orbits with used spacecraft and rocket stages.

Russian Design Offices began to investigate these problems. When updating the "Soyuz" launch vehicle the Central Specialized Design Office studied the technology of equipping the multi-purpose kick stage with a passive deceleration system representing a container with a large-diameter inflatable envelope. The ideology of using the passive deceleration system is as follows: when a spacecraft is put in an orbit of 500 km or less and if there is fuel remaining kick stage generates an impulse to sink itself in the Ocean or, in case there is no fuel left the passive deceleration system is activated. When a spacecraft is put in orbits of 1000-1500 km its kick stage (if there is fuel remaining) produces a deceleration impulse for an elliptic orbit transfer, then activates the passive deceleration system to speed up deceleration and upper-atmosphere re-entry.

No less important is the problem of cleaning near-earth orbits of already available debris. Reusable space vehicles of the "Buran" and "Shuttle" type may be used for removing singly large objects from the orbits. Currently such an operation is complicated and demands great expenditures. It would be worth expenses if it is aimed at cleaning the operating orbit for permanent orbital station or at preventing an uncontrolled drop of a large space object in populated areas of the Earth.

Specialists of the Scientific and Production Association "Energiya" intend to develop a special sweeper-spacecraft equipped with a nuclear power plant and an electric rocket engine for potential large-scale operations to clean the space environment of small and large debris. Such a sweeper-spacecraft can evaporate man-made fragmentations of up-to 1 cm in size at distances of up-to 30 km at altitudes of 800-2000 km using its 15 kW laser.

A similar sweeper-spacecraft fitted with grasping and towing facilities being inserted in a radiation-safe 800 km altitude by an "Energiya" launch vehicle is capable of picking up and removing used nuclear-powered assets from "luminescence" orbits to a space permanent disposal zone" (for example, into a heliocentric orbit) or being transferred into a GEO orbit can start cleaning it. Such a project may be fulfilled on the basis of international cooperation under supervision of the UNO and IAEA.

As for the international cooperation on the space debris mitigation it is currently expedient to:

- identify requirements to launch capabilities and space vehicles now under modification and development as regards minimization and prevention of space debris pollution and try to coordinate these requirements with the spacefaring nations with the aim of applying them when developing new technologies;

- specify the state of the space debris population and its potential growth forecast on the basis of tracking, experimental and simulation data for undertaking timely measures to ensure the orbiting asset surviv-ability;

- reach an agreement with all the nations engaged in space research on a regular exchange of space debris tracking and control data and of technologies for developing and utilizing "debris-clean" rocket and space hardware in the near-earth space environment.

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