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THE SPACE STATION WILL EAT ITSELF

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ABSTRACT. The collision hazard for the planned International Space Station *Freedom* is estimated for the present population of man-made space debris, and data for impact probabilities as functions of collision velocity and angle upon each orthogonal face are presented. Impact rates above certain threshold kinetic energies are also given. By considering the likely effect of the fragmentation of a nominal 10 tonne spacecraft on a rendezvous orbit with the Space Station it is shown that the collision hazard would be dominated by the debris thus produced, with the space debris previously in orbit being comparatively inconsequential. A cascade of disintegration and debris-production would be generated, so that the Space Station would 'eat itself'.

1. Introduction

Over the past decade there has been a heightened awareness of the threat posed to artificial satellites and spacecraft by the large amount of anthropomorphic material (space debris) left in geocentric orbit by our space-exploiting activities. An impact by quite a small piece of debris could lead to the dis-enablement of a functioning satellite, which in this era of increasing commercialization of space has significant economic consequences. However, there is also the problem of the danger to personnel, and this is especially the case when astronauts undertake missions of extended duration in large spacecraft; the most obvious example of this is the planned International Space Station *Freedom* (*ISSF*) which will be continuously manned over some decades, and is visualized to have a cross-sectional area of the order of thousands of square metres. Empirical determinations of the likely impact rates upon *ISSF*, along with investigations of the utility and durability in orbit of a variety of materials, was the major aim of many of the experiments on board the Long Duration Exposure Facility (*LDEF*) satellite (See *et al.*, 1990). Various detailed studies of the space debris environment at different altitudes have also been carried out, for use in the design of spacecraft (*e.g.* Kessler *et al.*, 1989).

In this paper I consider the hazard posed to the *ISSF* by the present population of space debris, as represented by the catalogue of tracked items larger than ~10 cm published in the *Satellite Situation Report* for 31 December 1988 (*SSR*, 1988). For the *ISSF* a zero-eccentricity geocentric orbit at altitude 650 km and inclination to the ecliptic of 28°.5 was used. For items in the *SSR* crossing 650 km the collision probability per square metre of each of the orthogonal faces of *ISSF* is calculated, and these probabilities accumulated in bins of both impact velocity and impact angle. The method used in this calculation is based upon a technique originated by Kessler (1981), and described (in terms of the velocity and angle binning) by Steel and McDonnell (1992). Since the *SSR* contains only the large, trackable, items of debris, whereas the multitude of fragments in the 1 mm - 10 cm (and maybe smaller) size range would in fact dominate the chance of a catastrophic impact upon *ISSF*, I then model the distribution of such smaller fragments upon the basis of the 20 space vehicles which are known to have fragmented in orbits crossing 650 km; information on these was derived from Johnson and Nauer (1990). With some knowledge of the cause of the fragmentation in each case, it was possible to allot size distributions to the debris clouds produced, and therefore the number of particles above any threshold mass. With the collision velocity being available in the computations, the probability of collisions above set threshold kinetic energies could then be calculated, and a measure of the hazard posed to the *ISSF* by these untracked debris then derived. It will be seen below that as aforesaid the hazard is dominated by these smaller untrackable (with present technology and economy) items.

In order to put the overall hazard from the present debris environment into some perspective I then calculate the hazard posed to the *ISSF* by a hypothetical 10 tonne spacecraft (say, some future shuttle or rendezvous craft) which fragments on an orbit which is very near the *ISSF* in (a, e, i)-space, as would be expected for a vehicle being used to construct or re-supply the *ISSF*. It will be seen that the hazard posed to the *ISSF* is then dominated by this single break-up event, and this would lead to a cascade of break-ups as the *ISSF* was repetitively struck: the Space Station would therefore eat itself.

2. The present debris environment

In this section I explore the repurcussions for the *ISSF* of the present day space debris environment in terms of a very simple model. No attempt has been made here to produce a model as sophisticated as many of those developed over the past few years (*e.g.* Kessler *et al.*, 1989), since the major aim of this paper is to point out that the present debris population is of little consequence compared to the hazard posed by the break-up of a spacecraft on a rendezvous orbit with the *ISSF*.

2.1 ITEMS IN THE *SSR* WHICH CROSS THE *ISSF* ALTITUDE

Although the number of items in the *SSR* varies from edition to edition due to the re-entry and launch rates altering, with the former being heavily dependent upon the solar cycle, as a rule ~7000 individual items are listed therein, with the lower size limit for low-Earth orbit being of the order of 10 cm. An impact by such a fragment at ~10 km/sec could hardly fail to cause the catastrophic failure of a spacecraft. In the edition of the *SSR* used there are 607 intact vehicles and 795 fragments of disintegrated spacecraft crossing 650 km.

For each of these the impact probability upon the *ISSF* was calculated, both on the basis of a spherical target (*i.e.* as a result of a calculation with Kessler's original algorithm), and also with the direction of the impact considered (*i.e.* as with the algorithm of Steel and McDonnell). I take the *ISSF* to have six orthogonal faces which are denoted as being East (the leading face, perpendicular to the motion vector), West (the trailing face, again perpendicular to the motion vector), North and South (in the satellite's orbital plane, one pointing north the other south), Space (outwards in the direction of the radius vector from the Earth's centre) and Earth (ditto, inwards). The results of these calculations are shown in Fig. 1.

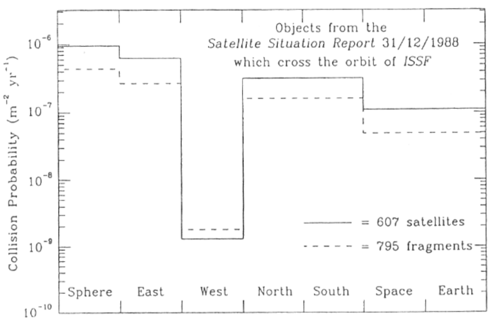


Figure 1: Collision probabilities upon each face of the International Space Station *Freedom* for the various tracked satellites and fragments which cross its nominal 650 km altitude.

As seen in Fig. 1, the majority of the impacts would occur upon the East face; about one-half the impacts on that face would occur on (each of) the North and South faces; and the flux to the Space and Earth faces would be reduced by about another factor of three from that on the North and South. Few impacts occur on the West face (about 1/200th–1/100th times the East face) since these would require the debris to be near-coplanar with a quite eccentric orbit, so that the debris catches the *ISSF* up from behind. The overall impact rate of about 1×10^{-6} m^{-2} yr^{-1} would mean that if the *ISSF* had a cross-sectional area of 10,000 m^2 then one impact per century would be expected on average.

If the *ISSF* is to be protected against debris impacts then some idea of both the velocity and direction of such impacts is needed. In Fig. 2a I show the velocity distributions of impacts for the different faces, and in Fig. 2b likewise the impact angle distributions. The distributions in each case are identical for the South and the North faces, and for the Earth and the Space faces. From Fig. 2a we note that most impacts on the West face are at low velocities (below 4 or 5 km/sec) whereas for the other faces the impact velocities are much higher, being in the range 6–13 km/sec, with some impacts as fast as 16 km/sec. Fig. 2b indicates that impacts upon the Space face are at quite shallow angles (above 65° from the face normal, or less than 25° in elevation) whereas for the East and North faces the impact angles peak at 25°–65°, whilst the distribution for the West face is largely flat. These figures clearly would have implications for the distribution of shielding on the different faces of the *ISSF*. Figs 2a and 2b are for only the 607 satellites selected; the plots (not shown) for the 795 fragments are similar, but distinct.

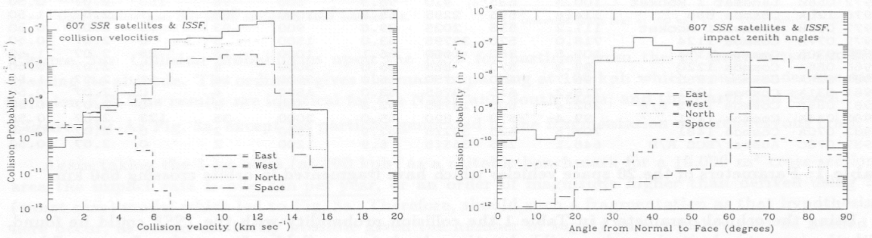


Figure 2a: Collision probabilities upon the *ISSF* for the 607 selected satellites binned in impact velocity. The lines for the South face would be the same as the North, and for the Earth face the same as the Space face in this plot.

Figure 2b: Collision probabilities upon the *ISSF* for those satellites binned in impact zenith angle (*i.e.* the angle from the normal to each face). On the Space face the impacts are at quite shallow angles, on the other faces steeper angles, this having implications for the shielding required and the threshold mass capable of causing perforations.

2.2 THE 20 FRAGMENTED SPACECRAFT WHICH CROSS THE *ISSF* ALTITUDE

From the tabulation presented by Johnson and Nauer (1990) I selected the 20 fragmented satellites whose orbits crossed the 650 km altitude; these are listed in Table 1. Apart from the designation, name and orbital data the original mass for each estimated by Johnson and Nauer is given, and also the number of tracked fragments still in orbit ('Frags up') and the number which were tracked by USSPACECOM radars but have since re-entered ('Frags Down'). For each object I estimate the fraction of the original mass remaining in orbit as being (Frags up) / (Frags up + Frags Down): this will tend to overestimate the mass still in orbit since the smaller (untracked) fragments generally have larger drag coefficients (larger cross sectional area per unit mass) and thus re-enter more swiftly. In addition I make the simplifying assumption that all debris produced is basically on the same orbit as the parent satellite/rocket body: this is invalid if a refined model were wanted, but in the context of this paper this assumption is acceptable. In the last two columns of Table 1 I list two mass distribution indices assumed for each object. MDI1 (= 2.07 in each case) is the mass distribution index for particles of mass m above 1/10,000th of the original mass tabulated (so that the cumulative number of particles varies as m^{-MDI}), whilst MDI2 is the index for particles below that mass. MDI2 must be below 2.0 to enable closure on the total mass left in orbit, and normalization is achieved by using a factor which renders that total mass in each case. The values of MDI2 are 0.50 where a low-intensity chemical explosion caused the fragmentation, or 1.50 where a high-intensity explosion or a collision caused the break-up; the number of small particles is higher for the latter.

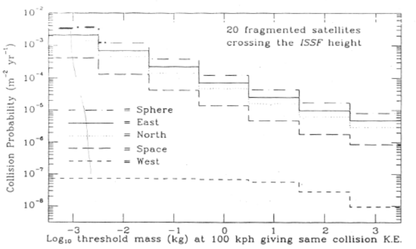
Design-ation	Name	Period Mins	Perigee ht km	Apogee ht km	Incl. deg	Mass kg	Frags Up	Frags Down	MDI1	MDI2
1963 047A	Atlas Centaur 2	107.9	475	1785	30.3	4600	14	5	2.07	0.50
1965 020D	Cosmos 61-63 R/B	106.0	260	1825	56.1	1500	23	124	2.07	0.50
1968 091A	Cosmos 249	112.2	490	2165	62.3	1000	62	47	2.07	1.50
1968 097A	Cosmos 252	112.4	535	2140	62.3	1000	62	77	2.07	1.50
1969 064B	Intelsat 3F-5 R/B	147.2	270	5445	30.4	70	2	24	2.07	0.50
1970 089A	Cosmos 374	112.3	530	2130	62.9	1000	47	56	2.07	1.50
1970 091A	Cosmos 375	111.8	525	2100	62.8	1000	31	16	2.07	1.50
1971 015A	Cosmos 397	113.5	575	2200	65.8	1000	81	34	2.07	1.50
1972 058B	Landsat 1 Rocket	100.3	635	910	98.3	800	76	150	2.07	0.50
1976 126A	Cosmos 886	114.8	595	2295	65.8	1000	68	7	2.07	1.50
1977 065B	Himawari Rocket	111.2	535	2025	29.0	900	93	75	2.07	0.50
1979 077A	Cosmos 1124	718.0	570	39795	63.0	1500	5	0	2.07	0.50
1980 030A	Cosmos 1174	105.5	380	1660	66.1	1000	18	28	2.07	1.50
1980 089A	Cosmos 1220	99.3	570	885	65.0	3000	5	73	2.07	0.50
1981 028A	Cosmos 1260	96.7	450	750	65.0	3000	16	52	2.07	1.50
1981 031A	Cosmos 1261	718.2	610	39765	63.0	1500	4	0	2.07	0.50
1981 088F	Cosmos 1305 R/B	262.4	605	13795	62.8	500	3	0	2.07	0.50
1983 044A	Cosmos 1461	99.4	570	890	65.0	3000	35	123	2.07	0.50
1983 070A	Cosmos 1481	707.5	625	39225	62.9	1500	2	0	2.07	0.50
1987 078C	Aussat/ECS R/B	646.1	245	36515	6.9	1200	2	0	2.07	0.50

Table 1: Parameters of the 20 space vehicles which have fragmented in orbits crossing 650 km.

Using the orbital parameters in Table 1 the collision probability with the *ISSF* could be found, with the impact velocity in each possible location also being available. It was therefore possible to derive the kinetic energy (KE) of impact for any stipulated mass, and from the above the number of particles more massive than that could also be estimated. An alternative, used here, is to calculate the number of impacts above some threshold KE. The KE's used here are those equivalent to masses of 1, 10 and 100 g, 1, 10 and 100 kg, and 1 tonne, all travelling at 100 kph (~60 mph). Whilst the KE does not necessarily reflect the scale of the damage done in a hypervelocity impact, it does provide a useful and tangible parameter in the present context: the reader is familiar with such speeds from personal experience, and the damage which may be caused by items with similar masses striking a fast-moving automobile. In Fig. 3a I present the collision probabilities for each of these seven masses (KE's) for the different faces of *ISSF*. For the sake of argument I will take the 1 kg mass (at 100 kph) as a suitable benchmark:we note that for a 10,000 m^2 cross-sectional area target the impact rate at such KE's would be about one per year.

3. The debris environment in the wake of a rendezvous craft fragmentation

I now move on to investigate the possible outcome, with regard to *ISSF* viability, of an explosion of a spacecraft (shuttle or other rendezvous craft) during the phase in which it is matching orbits with the Space Station. A low nominal mass of 10 tonnes will be assumed, with the debris attaining orbits of perigee 640 km, apogee 660 km, and inclination 28°5; in reality the disintegrating spacecraft may have a rather larger mass. A low-intensity fragmentation will be assumed (MDI2 = 0.50; *e.g.* a chemical fuel explosion). For such an event the outcome in terms of impacts upon the *ISSF* is as shown in Fig. 3b.



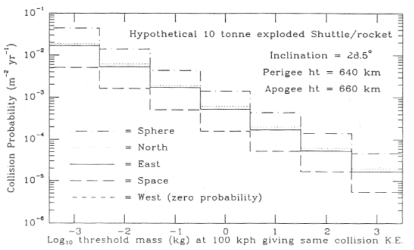


Figure 3a: Collision probabilities upon the *ISSF* for particles from the 20 fragmented satellites crossing its altitude. The ordinate gives the mass impacting at 100 kph which would render the same collision KE. The results are identical for the North and South faces, and the Earth and Space.

Figure 3b: As Fig. 3a, except for particles generated in the fragmentation of a rendezvous craft.

Again taking the 1 kg mass (at 100 kph) as a suitable benchmark for a 10,000 m^2 cross-sectional area the impact rate is over ten per year, or an order of magnitude higher than derived using the (worst case) model which led to Fig. 3a. Therefore, should such a fragmentation as that hypothesized here occur, as seems distinctly possible given the number of supply runs which would be needed to construct and maintain the *ISSF*, then the debris environment which had previously built up due to many other on-orbit fragmentations would be to first-order inconsequential with regard to the impact hazard faced by the Space Station: it is its own worst enemy.

There are a few other pertinent points to be noted from Figs 3a and 3b, especially with regard to the design of shielding for the *ISSF*. If one calculates for just one particle the raw collision probabilities with each face (*i.e.* no mass/KE consideration) then one finds the following values:

Sphere	: 8.2×10^{-9}	$m^{-2}\ yr^{-1}$
East	: 2.6×10^{-9}	$m^{-2}\ yr^{-1}$
North/South	: 3.6×10^{-9}	$m^{-2}\ yr^{-1}$
Space/Earth	: 1.2×10^{-9}	$m^{-2}\ yr^{-1}$
West	: 0.0	

These values would suggest that the North/South faces are expected to receive about 59% of the impacts between them, the East face about 21%, and the Space/Earth faces 20% between them. In fact, due to the impact velocity distributions for each face (not shown here) which indicate that the East face receives the majority of its impacts at 6–8 km sec^{-1} (the maximum value), whereas the other faces receive impacts more equably spread between 0–8 km sec^{-1}, that face does not underlie the North/South faces by a great deal in Fig. 3b, whereas the Space/Earth faces are considerably lower in that plot. The impact velocity distribution can greatly affect the number of impacts above the threshold levels, due to the steepness of the mass distribution. The actual balance is critically dependent upon the assumed eccentricity of the debris orbits.

For the present debris environment (Fig. 3a) the majority of impacts (above the KE thresholds) are found on the East (leading) face, followed by the North/South faces, then the Space/Earth faces, with very few anticipated on the West (trailing) face. As discussed above a rather different situation occurs for an exploded rendezvous craft due to the similarity of its orbit to that of the *ISSF*, and this contrast may be critical with regard to shielding design in view of the perceived source of the collision risk to *ISSF*.

4. Summary

The possible future collision hazard for the International Space Station *Freedom* has been investigated in terms of the present debris environment, and it has been shown that should (as seems regrettably likely) a rendezvous supply craft fragment whilst on a matching orbit, then the impact risk for the Space Station will be increased by over an order of magnitude. Under such circumstances the faces of the Space Station which are most at risk differ from those endangered by unrelated space debris. In addition, the frequency of impacts may well be sufficiently high that a knock-on effect will occur, with pieces dislodged from the Space Station returning to cause further damage, and thus a cascade leading to its eventual self-dismemberment.

5. References

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