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COLLISION RISK MITIGATION IN GEOSTATIONARY ORBIT

L. Anselmo• & C. Pardini•

The short and long-term effects of spacecraft explosions, as a function of the end-of-life re-orbit altitude above the geostationary orbit (GEO), were analyzed in terms of the additional contribution to the debris flux in the GEO ring. The simulated debris clouds were propagated for 72 years, taking into account all the relevant orbital perturbations.
The results obtained show that 6-7 additional explosions in GEO would be sufficient, in the long-term, to double the current collision risk with sizable objects in geostationary orbit. Unfortunately, even spacecraft re-orbit in between 300 and 500 km above GEO would not improve significantly the situation and an altitude increase of at least 2000 km should be adopted to reduce by one order of magnitude the long-term risk of collision among geostationary satellites and explosion fragments.
The optimal debris mitigation strategy should be a compromise between the reliability and effectiveness of spacecraft end-of-life passivation, the re-orbit altitude and the acceptable debris background in the GEO ring. However, until the re-orbit altitudes currently used will be less than 500 km above GEO, new spacecraft explosions will have to be absolutely avoided for the long-term preservation of the geostationary environment.

INTRODUCTION

Due to the rapid increase in the number of spacecraft and apogee kick motors in the geo-synchronous region, a growing concern mounted in the 1980s, regarding the possible overcrowding of the geostationary orbit (GEO) and the consequent menace to its long-term utilization and exploitation[1, 2]. The risk of collision between space objects in GEO was estimated, in particular to devise affordable and effective end-of-life disposal measures, such as satellite re-orbiting[3]. In the following decade it became clear that also spacecraft and upper stage breakups contribute to the GEO debris environment and, recently, an international campaign of optical observations has confirmed the presence of a large population (~ 1600) of decimeter sized objects, probably generated by several undetected explosions[4, 5].

• Research Staff of CNUCE/CNR, Spaceflight Dynamics Section, Via Moruzzi 1, 56124 Pisa, Italy

A few years ago, in order to preserve the geostationary orbit for future use, the Inter-Agency Space Debris Coordination Committee (IADC) proposed a re-orbiting strategy for the geostationary spacecraft at the end-of-life[6]. They should be disposed to a region above the geostationary altitude and passivated, in order to reduce the risk of inadvertent explosions. The recommended perigee of the disposal orbit should be higher of the geostationary altitude by an amount ΔH (km) given by

$$\Delta H = 235 + C_r \times 1000 \times A/m \tag{1}$$

where A is the satellite average cross-sectional area (m^2), m is the satellite mass (kg) and C_r is a radiation pressure coefficient, typically between 1 and 2, specifying the amount of solar radiation transmitted, absorbed and reflected by the spacecraft.

In a series of previous papers, the long-term effects of spacecraft and upper stage explosions, in terms of the additional debris density in the geostationary ring, were analyzed in detail with a new modeling approach, in particular to evaluate the effectiveness of end-of-life re-orbiting for debris mitigation[7-11]. This work, and the associated modeling, has now been extended to include the debris flux, making easier the evaluation of the long-term risk associated with explosions in, or near, GEO.

EXPLOSIONS SIMULATION

In the present study, a 2000 kg spacecraft was supposed to suffer a low intensity explosion[12, 13] at five different heights, between 0 and 2000 km above the geostationary altitude (Tables 1 and 2). The breakups were simulated using the CLDSIM software developed at CNUCE[14], while the fragments – 1733 with a diameter greater than 1 mm – were propagated for 72 years with a modified, multi-object version of the ASAP trajectory predictor, developed at the Jet Propulsion Laboratory (JPL)[15]. The perturbations taken into account were the harmonics (8 × 8) of the geopotential, the luni-solar third body gravitational attraction and the direct solar radiation pressure with eclipses.

Snapshots of the debris clouds evolution were obtained and saved at specific explosion elapsed times (0, 1, 6, 12, 18, 24, 30, 36, 42, 48, 54, 60, 66 and 72 years), during the 72 years interval considered in the simulations. Each of these snapshots represented a population of objects that could be analyzed to extract the information sought for, in particular regarding its interaction with the GEO ring, defined as the volume of space centered on the geostationary orbit (mean altitude of 35,786 km, zero inclination), ± 75 km in altitude and ± 0.1° in declination.

In order to numerically identify, if any, its intersection(s) with the GEO ring, any object of a cloud snapshot was propagated for one full orbit, obtaining its state vector at fixed mean anomaly steps $\Delta M = 0.75°$. In total, $360°/\Delta M = 480$ state vectors were obtained for each object, but only those corresponding to positions inside the GEO ring were retained (i.e. between ~ 500 and ~ 15,000 state vectors for every cloud, soon after the explosion, depending on the breakup altitude above GEO). All these state vectors were therefore used to build, for any debris cloud snapshot, a new representative population of fictitious space objects, each weighted by a fractional sampling factor $\Delta M/360° = 1/480$. The reason for that was to obtain a set of debris populations which could be processed and analyzed by using the Space Debris Impact Risk Analysis Tool (SDIRAT)[16, 17].

Table 1

EXPLOSION ALTITUDES ABOVE GEO

Simulation Number	Altitude above GEO (km)
1	0
2	300
3	500
4	1,000
5	2,000

Table 2

CHARACTERISTICS OF THE SIMULATED FRAGMENTATION EVENTS

Explosion epoch	11 May 1999
Explosion right ascension	298°
Explosion declination	0°
Fragments ≥ 1 mm	1733
Fragments ≥ 1 cm	1630
Fragments ≥ 10 cm	705
Maximum debris ΔV	1.94 km/s

SDIRAT is a software code developed at CNUCE to assess the orbital debris impact risk on a specified target in earth orbit, in terms of flux, relative and impact velocity, direction of the incoming particles, debris mass and diameter. Based on a new deterministic approach, it can use in input any debris population, provided that each representative particle is identified by its mass, size, weighting sampling factor and state vector at a reference epoch[16, 17]. All this information was available, at any snapshot time, for the debris clouds simulated as described above and the application of SDIRAT was, therefore, straightforward to assess the impact risk on the GEO ring, both short and long-term, due to the explosion fragments.

For the study presented in this paper, the target orbit with respect to assess the collision risk was the geostationary one. The radial ($\Delta R = \pm$ 75 km) and latitudinal ($\Delta\delta = \pm$ 0.1°) amplitudes of the control cells used by SDIRAT around the target orbit were chosen coincident with the GEO ring, as defined at the beginning of this section, while one degree of right ascension was adopted for the longitudinal amplitude ($\Delta\alpha = \pm$ 0.5°).

First of all, in order to obtain a benchmark with respect to compare the effects of the simulated explosions, SDIRAT was used to estimate the collision risk for a geostationary spacecraft due to the existing debris population. For this purpose, the 1999.0 CNUCE Orbital Debris Reference Model (CODRM-99)[18, 19] was employed, with the same control cells sizes previously described. Moreover, only the uncontrolled spacecraft crossing the GEO ring, plus spent upper stages and debris, were taken into account, for obvious reasons.

This analysis was separately repeated for all the explosion events (5) and debris clouds snapshots (14) considered in the study, for a total of $5 \times 14 = 70$ runs of SDIRAT (plus one for the background population). The results obtained were then analyzed and compared with the impact risk due to the existing environment, in order to assess the long-term consequences of satellite explosions in, or near, the GEO region and to evaluate the effectiveness of the possible mitigation measures that could be adopted to preserve the geostationary ring, such as the IADC recommendations[6].

THE BACKGROUND POPULATION OF UNCONTROLLED OBJECTS

Abandoned spacecraft, upper stages, mission-related objects and breakup fragments contribute to the orbital debris collision risk in geostationary orbit, although the typical relative and collision velocities are significantly smaller than at low altitude. The results obtained with SDIRAT using the CODRM-99 population are summarized in Table 3, while Figures 1-3 show the debris cross-sectional area flux as a function, respectively, of the azimuth, elevation and relative velocity, for the objects larger than 10 cm. The azimuth and elevation angles are referred with respect to the local horizontal plane in geostationary orbit.

Table 3

DEBRIS IMPACT RISK IN GEO DUE TO THE BACKGROUND POPULATION

Objects Diameter	Average Relative Velocity [m/s]	Average Collision Velocity [m/s]	Cross-Sectional Area Flux [m^{-2} yr^{-1}]
≥ 10 cm	136	807	6.649×10^{-9}
≥ 1 cm	235	1234	1.267×10^{-8}
≥ 1 mm	1120	2150	1.334×10^{-7}

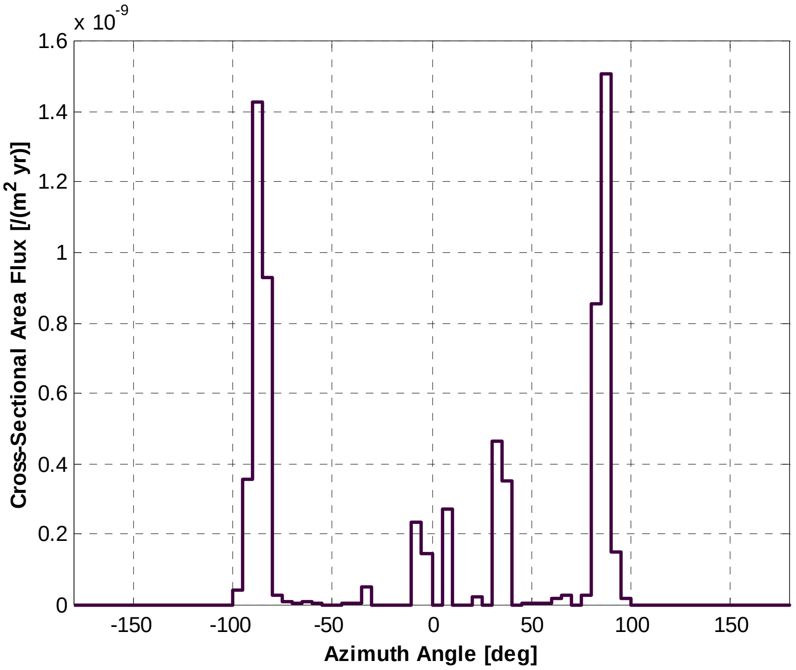

Figure 1. Background flux in GEO, as a function of azimuth, of debris ≥ 10 cm

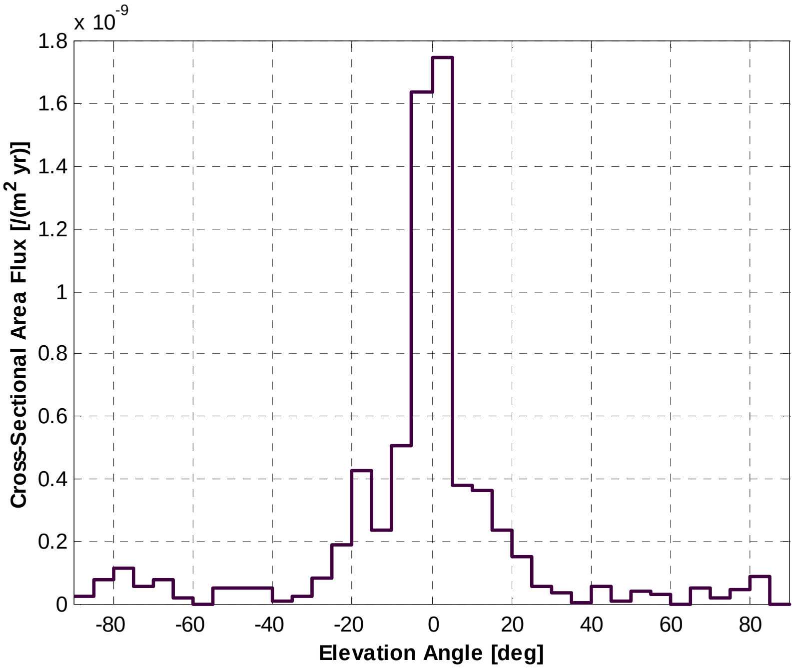

Figure 2. Background flux in GEO, as a function of elevation, of debris ≥ 10 cm

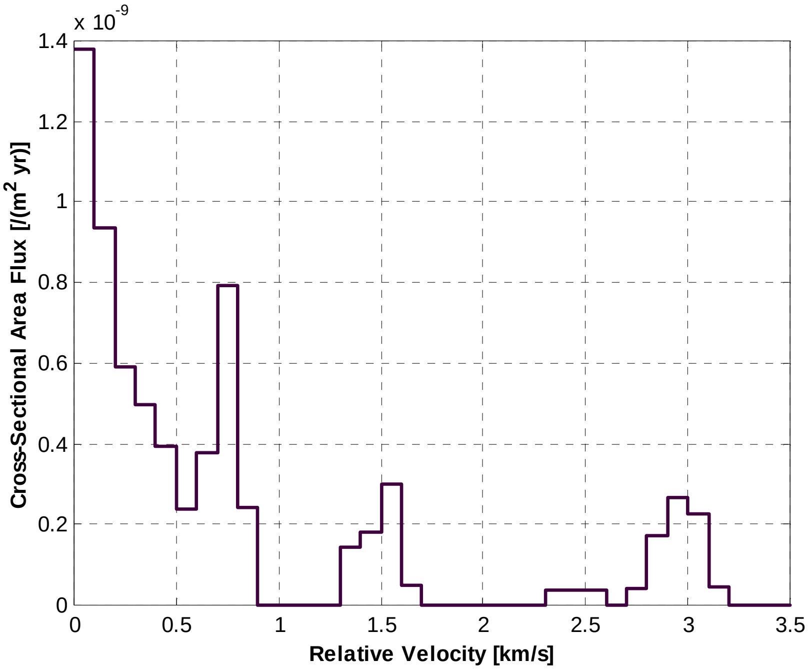

Figure 3. Background flux in GEO, as a function of relative velocity, of debris ≥ 10 cm

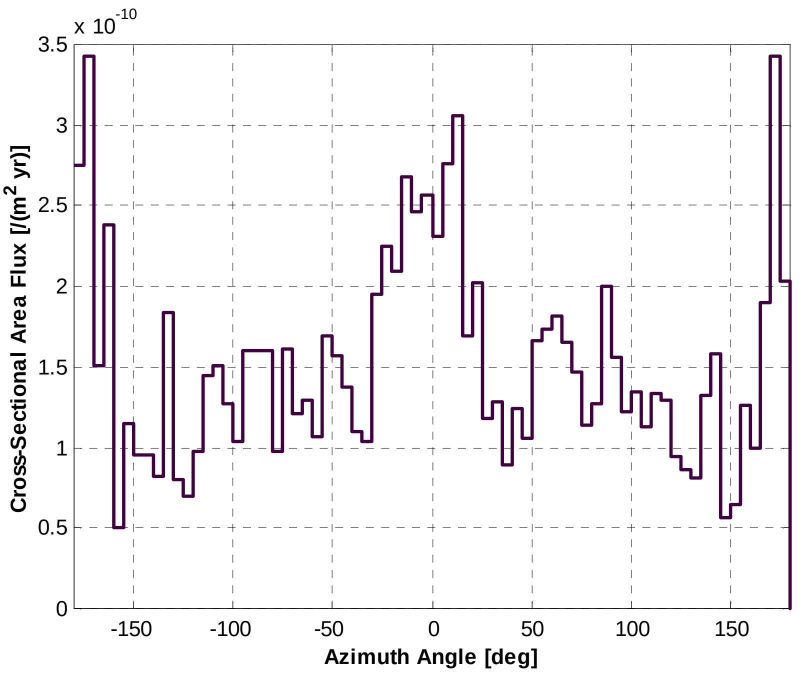

Figure 4. Flux of debris ≥ 10 cm in geostationary orbit, as a function of azimuth, due to an explosion in GEO (explosion elapsed time = 0 years)

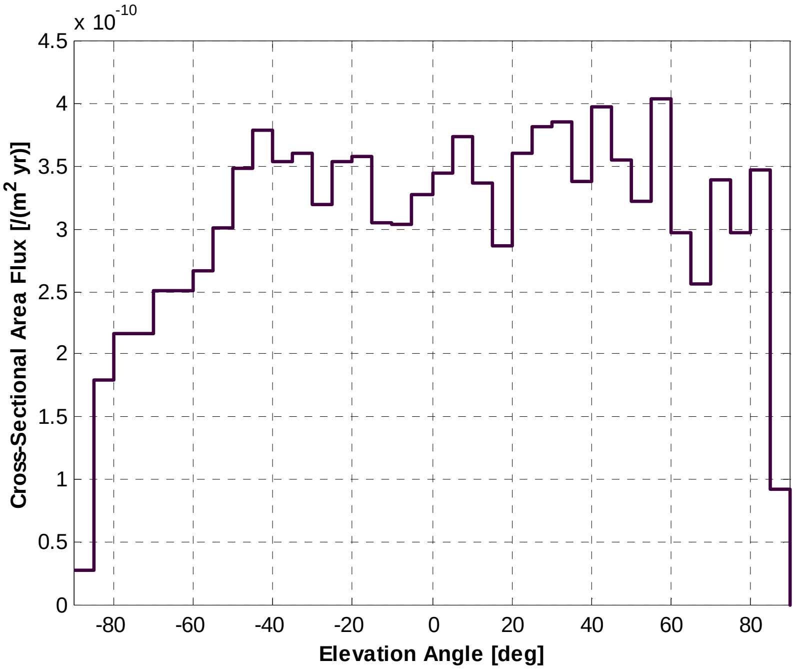

Figure 5. Flux of debris ≥ 10 cm in geostationary orbit, as a function of elevation, due to an explosion in GEO (explosion elapsed time = 0 years)

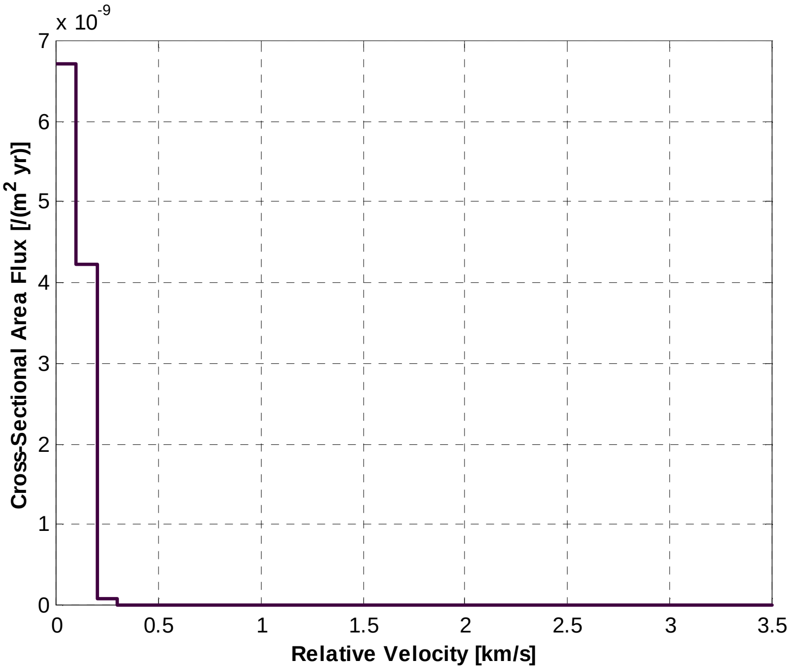

Figure 6. Flux of debris ≥ 10 cm in geostationary orbit, as a function of relative velocity, due to an explosion in GEO (explosion elapsed time = 0 years)

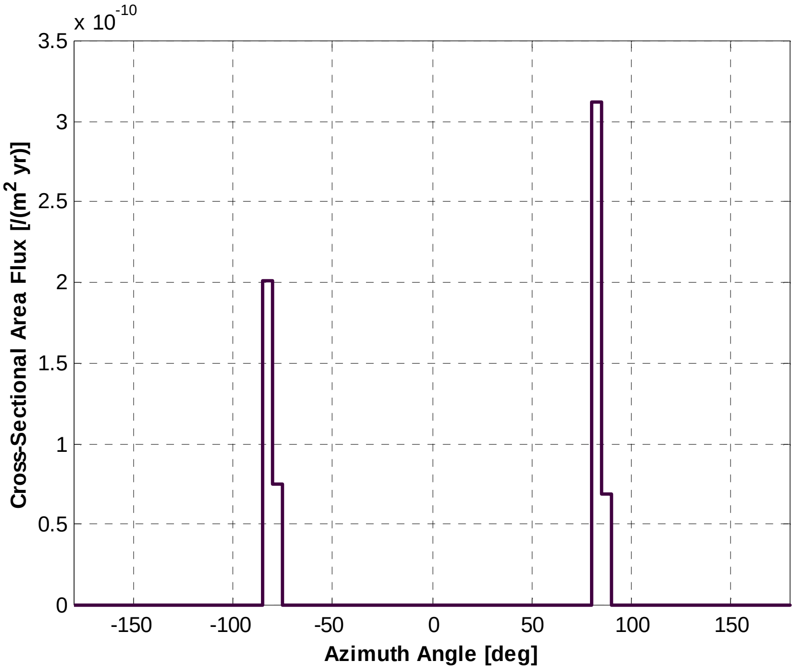

Figure 7. Flux of debris ≥ 10 cm in geostationary orbit, as a function of azimuth, due to an explosion in GEO (explosion elapsed time = 24 years)

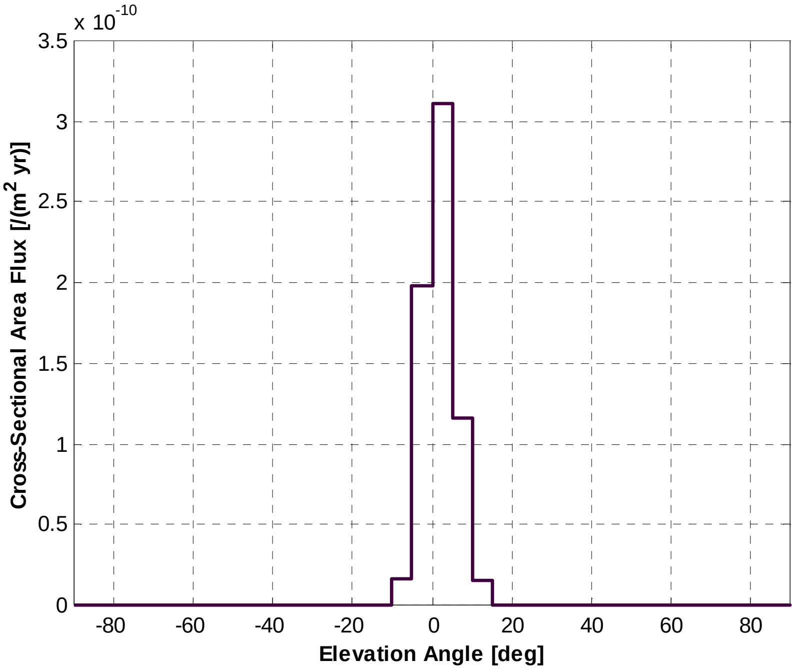

Figure 8. Flux of debris ≥ 10 cm in geostationary orbit, as a function of elevation, due to an explosion in GEO (explosion elapsed time = 24 years)

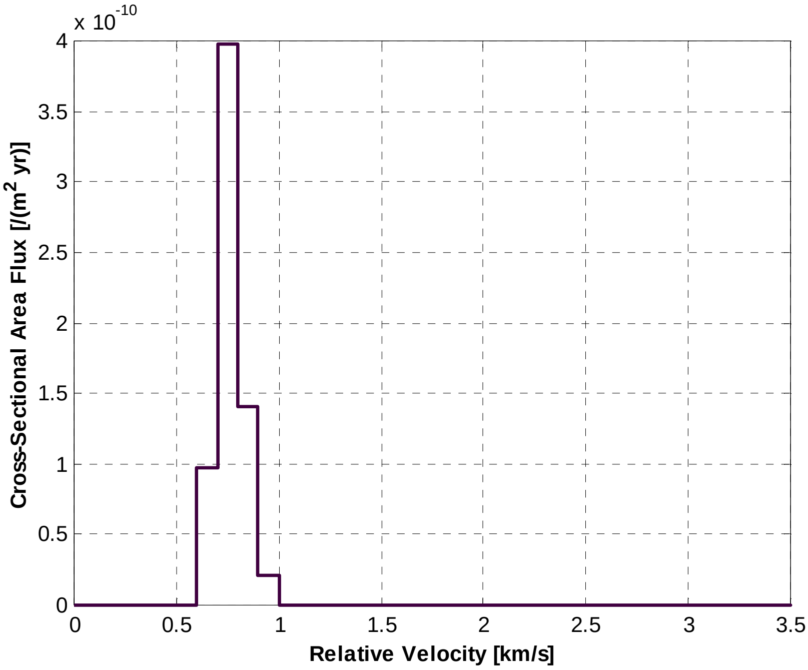

Figure 9. Flux of debris ≥ 10 cm in geostationary orbit, as a function of relative velocity, due to an explosion in GEO (explosion elapsed time = 24 years)

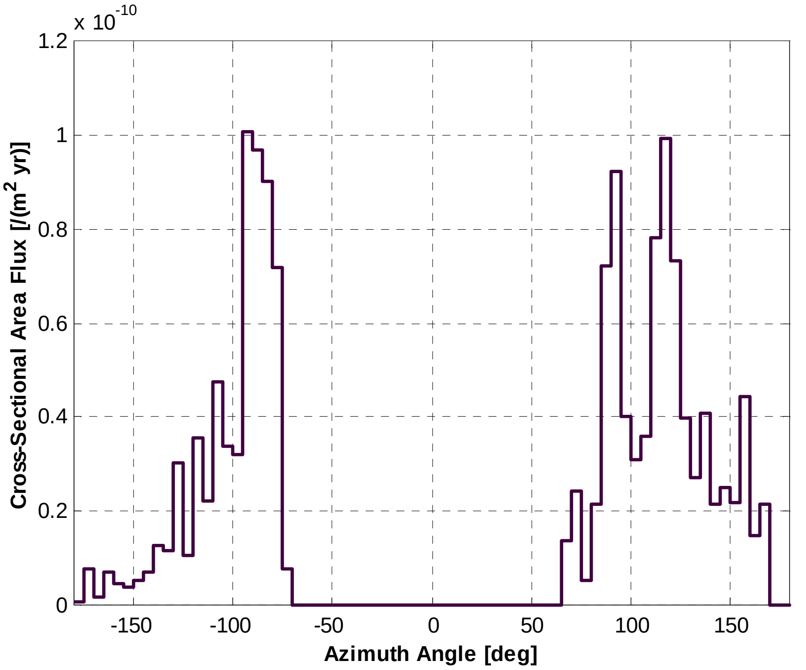

Figure 10. Flux of debris ≥ 10 cm in geostationary orbit, as a function of azimuth, due to an explosion in GEO (explosion elapsed time = 54 years)

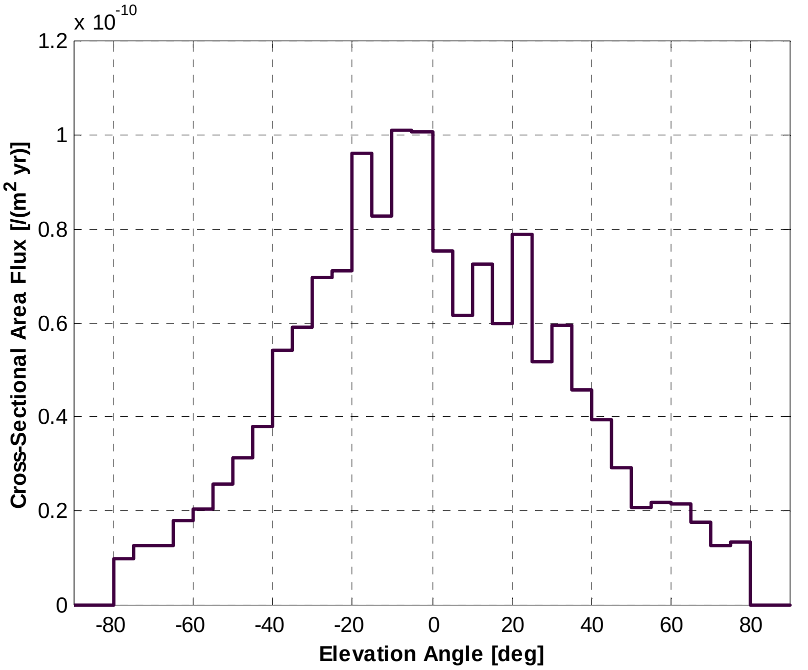

Figure 11. Flux of debris ≥ 10 cm in geostationary orbit, as a function of elevation, due to an explosion in GEO (explosion elapsed time = 54 years)

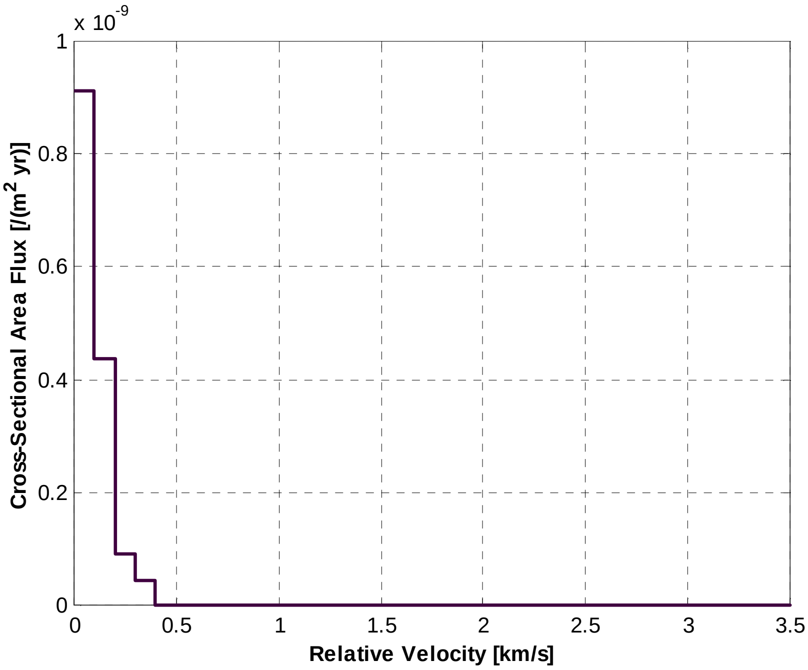

Figure 12. Flux of debris ≥ 10 cm in geostationary orbit, as a function of relative velocity, due to an explosion in GEO (explosion elapsed time = 54 years)

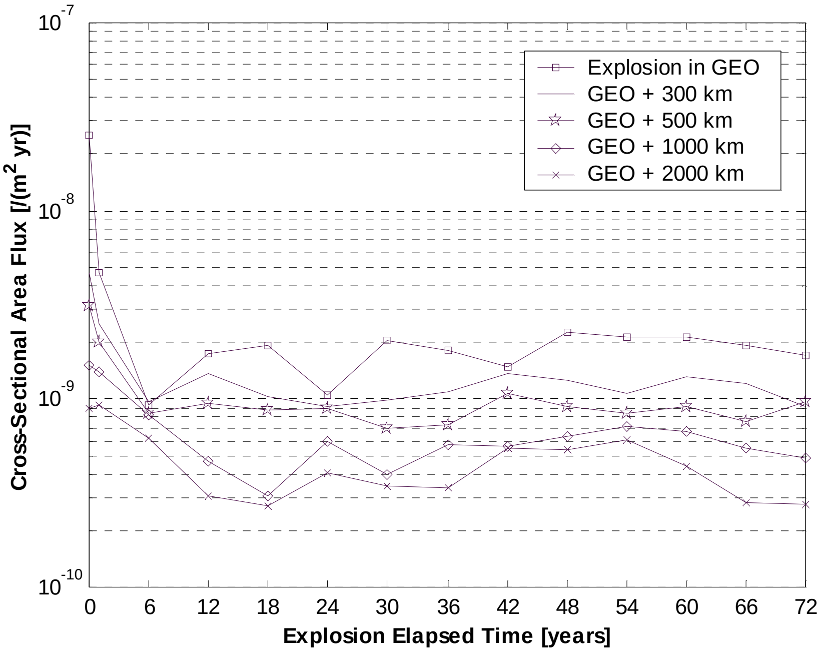

Figure 13. Flux of explosion fragments ≥ 1 mm in geostationary orbit, as a function of the breakup altitude and elapsed time

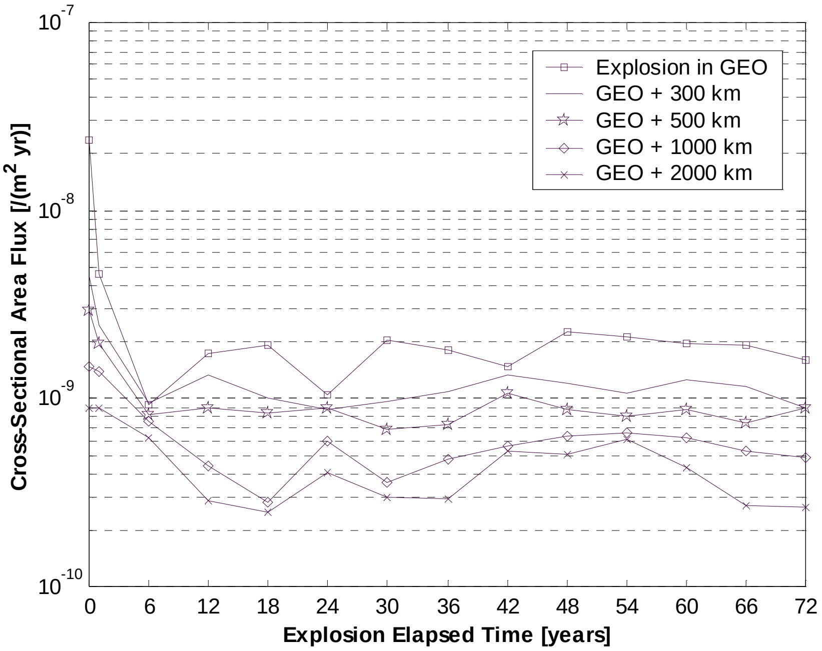

Figure 14. Flux of explosion fragments ≥ 1 cm in geostationary orbit, as a function of the breakup altitude and elapsed time

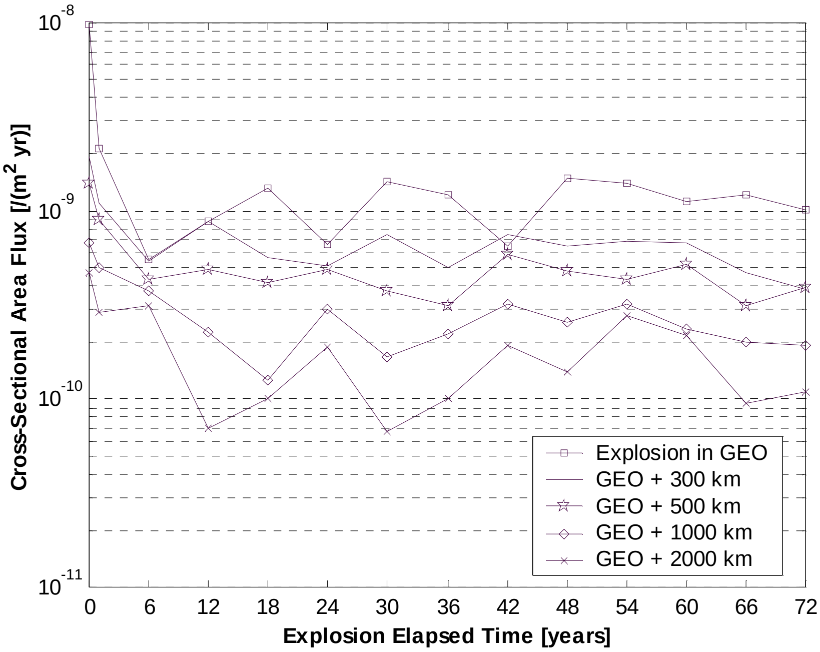

Figure 15. Flux of explosion fragments ≥ 10 cm in geostationary orbit, as a function of the breakup altitude and elapsed time

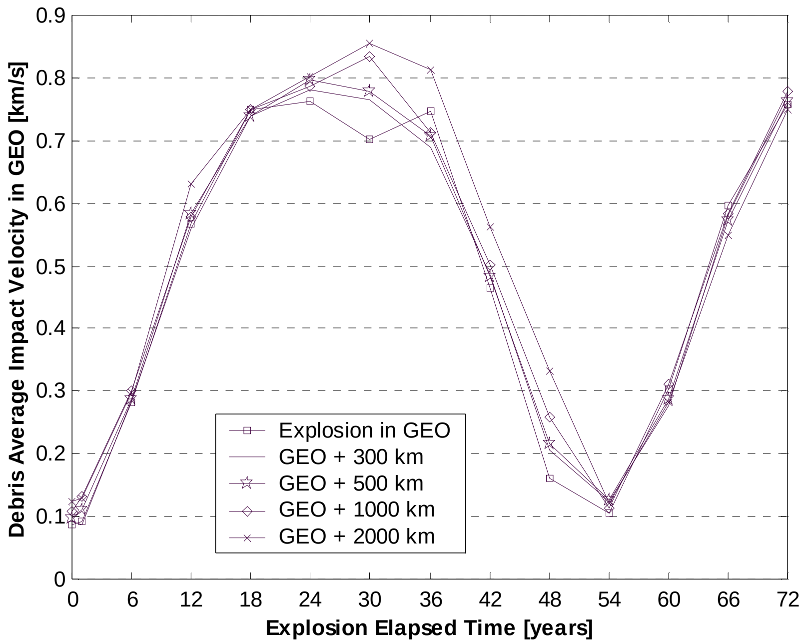

Figure 16. Time evolution of the debris average impact velocity in geostationary orbit as a function of the explosion altitude

The vector characteristics of the flux, evident in Figures 1-3, basically depend on four populations of objects:

1. Objects in near-synchronous orbit, with inclinations $\leq 15°$;
2. Objects in low inclination (< 30°) geostationary transfer orbits;
3. Objects in high inclination (> 40°) geostationary transfer orbits;
4. Objects in drifting (uncontrolled) Molniya orbits.

These four groups of satellites can be easily identified in Figure 3, which presents the cross-sectional area flux in GEO as a function of the relative velocity. The objects in near-synchronous orbit are grouped below 900 m/s, those in low inclination geostationary transfer orbits are found around 1.5 km/s, those in high inclinations geostationary transfer orbits, coming from Baikonur launches, are found around 2.5 km/s and those in drifting Molniya orbits account for the peak around 3 km/s. A similar correspondence can be drawn from the peaks appearing in Figures 1 and 2, taking into proper account the relative orbit geometry.

THE EFFECT OF A SATELLITE EXPLOSION IN GEOSTATIONARY ORBIT

The simulated low intensity explosion in geostationary orbit produced a sizable amount of fragments affecting the GEO ring. Immediately after the event, the average debris cross-sectional area flux on a geostationary spacecraft was 2.53×10^{-8}, 2.37×10^{-8} and 9.85×10^{-9} $m^{-2} \cdot yr^{-1}$, respectively, for particles larger than 1 mm, 1 cm and 10 cm. These values were approximately 1/5 of the debris background for particles greater than one millimeter, while the flux due to centimeter and decimeter sized fragments was higher, respectively, by 90% and 50% with respect to the background population.

Figures 4-6 show the cross-sectional area flux in GEO due to the fragments larger than 10 cm generated by the simulated explosion, as a function, respectively, of the azimuth, elevation and relative velocity. To be remarked are the average collision velocity smaller than 100 m/s (Figure 6) and the almost omnidirectional debris flux (Figures 4 and 5).

In less than one year also the flux of fragments greater than 1 and 10 cm resulted to decrease below that of the background environment, due mainly to the luni-solar attraction. However, in the long-term it stabilized around 1.7×10^{-9} $m^{-2} \cdot yr^{-1}$, for centimeter sized particles, and around 10^{-9} $m^{-2} \cdot yr^{-1}$, for decimeter sized debris, with a residual modulation by 30-50% due to the orbital perturbations. These results mean that 6-7 additional low intensity explosions in geostationary orbit would be sufficient, in the long-term, to double the current collision risk in the GEO ring with objects larger than 1 and 10 cm.

Even though the average flux resulted approximately stabilized five years after the simulated explosion, the effect (mainly) of the luni-solar perturbations induced dramatic changes on the debris cloud orbital geometry, modifying the "quality" of its interaction with the GEO ring, as summarized, for the fragments larger than 10 cm, by Figures 7-9 (24 years after the explosion) and Figures 10-12 (54 years after the explosion).

EFFECTS OF EXPLOSIONS ABOVE THE GEOSTATIONARY RING

The time evolution of the average cross-sectional area flux on the GEO ring due to spacecraft explosions at and above the geostationary altitude is shown in Figures 13, 14 and 15 for, respectively, debris larger than 1 mm, 1 cm and 10 cm. Figure 16 presents the time evolution of the average impact velocity only for the decimeter sized fragments, but the results obtained for smaller particles were very similar.

The variation of the average impact velocity (Figure 16), as well as that of the directional properties of the flux (see Figures 4-12 for the explosion in GEO), is a direct consequence of the debris orbital plane evolution, with a period of about 54 years, due to the luni-solar perturbations. Smaller debris density oscillations in GEO, with periods in between 27 years and one month, are induced by the luni-solar attraction and the low degree and order tesseral harmonics of the geopotential, while the solar radiation pressure plays a not negligible role only on the trajectory of the smaller particles.

Even for the explosions above the geostationary altitude, the same general patterns found for the fragmentation in GEO were observed (Figures 13-15), but with a reduction of the debris flux in the GEO ring for increasing breakup altitudes. The explosion simulated 300 km above GEO, an altitude close to that obtained by applying Eq. (1) to typical communication satellites, produced on the GEO ring, immediately after the event, an average debris cross-sectional area flux of 4.69×10^{-9}, 4.46×10^{-9} and 1.94×10^{-9} $m^{-2} \cdot yr^{-1}$, respectively, for particles larger than 1 mm, 1 cm and 10 cm. These values were approximately 1/30 of the debris background for particles greater than 1 mm and about 1/3 of the background for centimeter and decimeter sized fragments.

In a few years the flux dropped to a long-term equilibrium value close to 10^{-9} $m^{-2} \cdot yr^{-1}$, for particles larger than 1 cm, and to 6×10^{-10} $m^{2} \cdot yr^{-1}$, for fragments greater than 10 cm, with the above mentioned oscillations, characterized by a maximum total amplitude of 20-40%, superimposed. These results demonstrate that about ten explosions of typical spacecraft, at the end-of-life re-orbit altitude recommended by IADC, would be sufficient to double the average flux, in the GEO ring, of debris larger than 1 and 10 cm, matching the effect of the existing background. An increase of the re-orbit altitude to 500 km would not significantly improve the situation (the long-term equilibrium flux obtained was smaller by just 20-30%), as shown in Figures 13-15.

To reduce by one order of magnitude the long-term average flux of explosion fragments larger than 10 cm with respect to the breakup in geostationary orbit, a re-orbiting altitude at least 2000 km above GEO should be used. In that case, about one hundred spacecraft catastrophic explosions would be necessary for producing an additional debris flux on the GEO ring comparable to the existing background. However, for centimeter sized particles, the same threshold would be reached with approximately 1/3 of the breakups.

CONCLUSIONS

The short and long-term effects of spacecraft explosions, as a function of the end-of-life re-orbiting altitude (0 – 2000 km) above the geostationary orbit, were analyzed in terms of the additional contribution to the debris flux in the GEO ring. The simulated clouds of fragments were propagated with a high precision trajectory integration code, taking into account all the relevant orbital perturbations.

In the altitude range considered, the fragments produced by the different explosions display a similar evolution of the average relative and impact velocity (Figure 16) with respect to a satellite in geostationary orbit. Their relative contribution to the collision risk in the GEO ring is, therefore, mainly a function of the average fragment density there and, as expected, the explosion in geostationary orbit resulted to be the most detrimental for the GEO environment[10, 11].

The debris density and relative velocity in the GEO ring are both affected by a large periodic variation, due mainly to the luni-solar perturbations, with a period T of about 54 years. However, the density and relative velocity changes are out of phase by π (i.e. 27 years), and the overall resulting effect is the approximate long-term stabilization of the debris flux F in the GEO ring, occurring less than six years after the simulated fragmentation, irrespective of the explosion altitude, according to the relationship

$$F \approx K_0 + K_1 \cos\left(\frac{2\pi}{T} t\right) + K_2 \cos\left(\frac{4\pi}{T} t\right) \tag{2}$$

where t is the explosion elapsed time and K_0, K_1 and K_2 are three constants, functions of the breakup characteristics and altitude. Relatively small oscillations, due to the lunar nodal regression ($T \approx 18.6$ years), the advance of the lunar line of apsides ($T \approx 8.9$ years), the tesseral harmonics of the geopotential ($T \approx 3$ years) and so forth, were superimposed to the general trend of the long-term debris flux approximated by Eq. (2).

The results obtained show that 6-7 additional low intensity explosions in geostationary orbit would be sufficient, in the long-term, to double the current collision risk in the GEO ring with objects larger than 1 and 10 cm. Unfortunately, even the adoption of the end-of-life re-orbiting recommended by IADC, resulting, for typical satellites, in an altitude increase in between 300 and 500 km, would not improve much the situation, because a dozen of explosions would be sufficient to double the average flux of debris larger than 1 and 10 cm, matching the effect of the existing background. To significantly reduce the long-term average flux of explosion fragments larger than 10 cm, a re-orbiting altitude at least 2000 km above GEO should be used. In that case, about 100 breakups would be necessary for producing an additional debris flux on the GEO ring comparable to the existing background.

In conclusion, the optimal debris mitigation strategy in geostationary orbit should be a compromise between spacecraft end-of-life passivation effectiveness, spacecraft end-of-life re-orbiting altitude and the acceptable debris background in the GEO ring. If the preservation of the existing background is assumed as goal by the international community of space agencies and operators, the recommended end-of-life re-orbiting altitude would depend critically on the level of application, reliability and effectiveness of satellite passivation and long-term explosion avoidance. Therefore, the re-orbiting strategy recommended by IADC would only be adequate if satellite passivation was extensively and successfully carried out. However, if this was not the case, higher re-orbiting altitudes should be considered.

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