INFLUENCE OF HIGH ECCENTRICITY OBJECTS ON THE EVOLUTION OF THE GEO ENVIRONMENT

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ABSTRACT

The long term influence of objects crossing or abandoned in GEO was evaluated, based on current practices, using the new Space Debris Mitigation model SDM 4.0. It was the latest version of a long term evolution code originally developed in the early 1990's, specifically designed to model with high accuracy the high Earth orbit regimes.

Starting from the MASTER-2005 debris population, the long term evolution of the GEO environment was simulated under a few realistic scenarios, based on increasingly aggressive mitigation strategies. Beyond the high eccentricity objects, also the influence of the rocket stages separated from GEO spacecraft and left in geosynchronous drift orbits was analyzed. The main mitigation measures considered included the re-orbiting of GEO spacecraft at the end-of-life in the super-GEO graveyard zone, the de-orbiting of GTO/HEO upper stages and the re-orbiting of the rocket stages usually abandoned in drift orbits.

These simulations allowed the quantitative estimation of the collision probability related to all the above mentioned classes of objects. The effectiveness of the current mitigation measures was assessed and the rationale of new mitigation guidelines devised to minimize the future collision risk in GEO was discussed.

1. INTRODUCTION

In order to guarantee the protection of the Geostationary Earth Orbit (GEO) region, the *Space Debris Mitigation Guidelines* [1] issued by the Inter-Agency Space Debris Coordination Committee (IADC) recommend the transfer to a super-GEO graveyard orbit of the stationary satellites at the end of their operational life. However, this recommendation does not take into account the effect of objects in high eccentricity orbits that can periodically cross the GEO protected region [1]. These bodies include upper stages in Geostationary Transfer Orbits (GTO) and (even if to a lesser extent) objects in high eccentricity orbits (HEO), having apogees at GEO altitudes and characterized by a precession of the line of apses when abandoned (as the uncontrolled spacecraft and rocket bodies in Molniya-like orbits, drifting out of the resonant regime at the critical inclination).

To evaluate the relative importance of such neglected bodies for the long term preservation of the GEO orbital regime, in April 2004, IADC approved a formal action item [2] to categorize the objects interfering with the GEO protected region (objects in GEO or crossing GEO), to propose corresponding mitigation measures (the same for all the objects or specific for each category), if needed, and to eventually propose a modification of the *Space Debris Mitigation Guidelines* [1].

The aim of this study was to address the IADC action item [2], following an approach proposed by the Italian delegation in July 2007 and successively endorsed by Working Group 4 [3]. To this purpose, the last version (4.0) of the Space Debris Mitigation (SDM) long-term analysis program, recently fully revised, redesigned and upgraded at ISTI/CNR under ESA contract [4], was employed.

Originally developed in the early 1990's, SDM 4.0 is now a full 3D simulation code, including advanced features that make it well-suited for long term studies of every orbital regime, from LEO to GEO, but with a new specific attention to the Medium Earth Orbit (MEO) and GEO regions [4][5]. In particular, a very fast and accurate analytical orbit propagator (LEGO), well suited for the GEO regime, was added together with an upgraded and optimized version of the semi-analytical Fast Orbit Propagator (FOP) [4]. The whole set of six Keplerian orbital elements can then be propagated, assuring a good accuracy even for resonant orbits, quite common both in MEO and GEO [4][5].

2. LONG TERM EVOLUTION STUDIES

In order to assess the long term evolution of the orbital debris environment in GEO, three scenarios were analyzed [4]:

1. Business As Usual (BAU), with upper stages in GEO, HEO and GTO left in orbit and no re-orbiting of satellites at the end-of-life;
2. Mitigation, with re-orbiting of satellites at the end-of life and upper stages left in their original orbits (MIT1);

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3. Mitigation, with re-orbiting of satellites and de-orbiting of upper stages at the end-of-life (MIT2).

The BAU scenario considered a launch rate based on the missions (number of satellites, upper stages, masses, orbits) and current practices (mission related objects, mission profile, propulsion systems) recorded over about 4.5 years (from 1 January 2004 to 31 May 2008) of worldwide space activity [4]. In addition, no end-of-life re-orbiting or de-orbiting of GEO spacecraft, apogee kick motors and GTO/HEO upper stages was performed all along the investigated time span of 200 years. Finally, in-orbit explosion suppression starting from 2025 was assumed, while from 2005 to 2024 the "energetic explosion" rate (4.6 per year) and type recorded in space over 5 years (from July 2003 to June 2008) were taken into account.

In the MIT1 scenario, all the GEO satellites were re-orbited at the end-of-life, considering an operational time span of 10 years, above the protected region, according to the IADC recommendation [1]. The upper stages, instead, were always left in their original orbits.

In the MIT2 scenario, on the other hand, in addition to the end-of-life re-orbiting of the GEO satellites following the IADC recommendation [1], all the upper stages potentially interfering with the GEO region and launched after 2010 were immediately de-orbited at the end of their mission.

The initial population adopted in all the scenarios was MASTER-2005 [6]. However, since the delivering of the model, the major Fengyun 1C breakup, in January 2007, appreciably modified the LEO environment, but not the GEO orbital regime considered in this paper. Anyway, the fragments produced by the Fengyun 1C anti-satellite test, as generated by simulating the event with the same breakup models adopted for the MASTER population, were added to the original MASTER-2005 environment, courtesy of Holger Krag (ESA/ESOC).

Concerning the breakups, the NASA's EVOLVE 4 explosion and collision models [7] were always used. The collision probability algorithm considered was always CUBE [8] and the orbits were propagated using FOP and LEGO [4], where applicable.

3. SIMULATION RESULTS

The three scenarios described in the previous section were simulated with SDM 4.0 over 200 years, starting in 2005. Each case was modeled with 40 independent Monte Carlo runs. Therefore, 120 SDM 4.0 runs over 200 years were carried out and their results were post-processed and analyzed. The lower limit for the size of the objects included in the simulations was 10 cm.

The long term evolution of the effective number of objects larger than 10 cm in the GEO region (i.e. in the altitude range between 30,000 and 40,000 km) is shown in Figs. 1 and 2. It can be noticed that the BAU and MIT1 cases are nearly equal, but this is not surprising, because the difference between the two scenarios lay in the re-orbiting (MIT1) or not (BAU) of old spacecraft in the super-GEO graveyard zone, included anyway in the plots. The upper stages were left in their original orbits in both cases. Therefore, no significant difference, in terms of number of objects, was expected. The MIT2 scenario, on the other hand, shows about 20% less objects at the final epoch of the runs, because the rocket bodies launched after 2010 were removed from space.

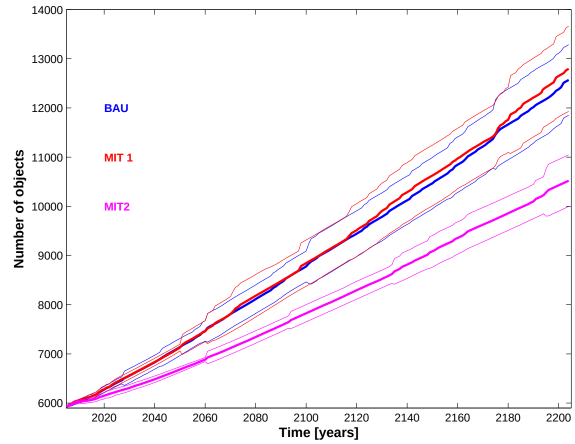

Figure 1. GEO region: effective number of objects larger than 10 cm in the BAU, MIT1 and MIT2 scenarios. The thin lines show, in each case, the $\pm 1\sigma$ boundaries of the 40 Monte Carlo runs.

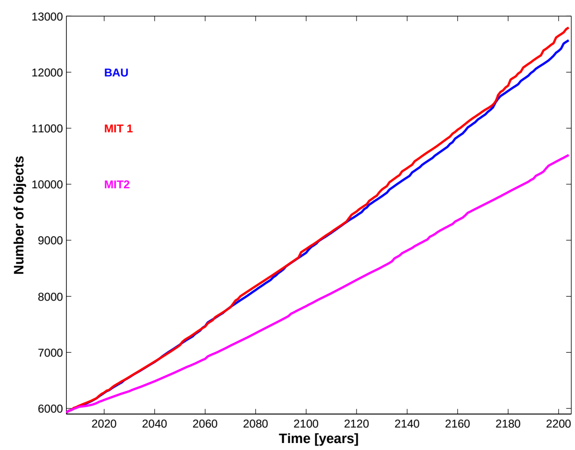

Figure 2. As in Fig.1, but showing only the average values of the 40 Monte Carlo runs.

The real difference between the three scenarios becomes apparent by looking at the spatial density of the objects, averaged over the Monte Carlo runs, after 200 years.

From Figs. 3 and 4 it can be seen how, in the BAU case, the objects larger than 10 cm cumulated around the nominal geostationary altitude, while in the mitigated cases (MIT1 and MIT2) the main peak of density moved to the super-GEO graveyard region, reducing the density in the operational ring. Moreover, note how, in the MIT2 scenario, the density below the geostationary altitude, due to objects in GTO and HEO, remained close to the initial values, due to the de-orbiting of the upper stages modeled after 2010.

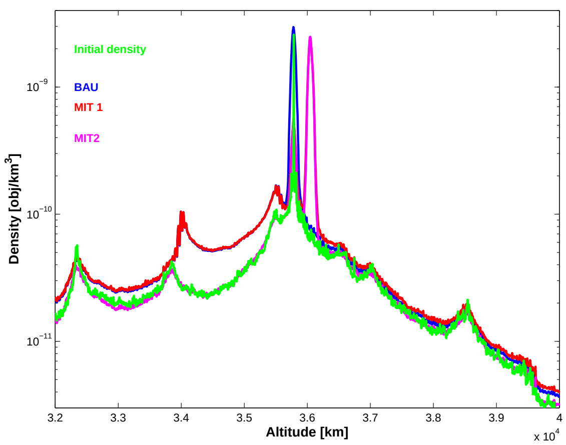

Figure 3. GEO region: initial (2005) and final (2205) spatial density of objects larger than 10 cm in the BAU, MIT1 and MIT2 scenarios.

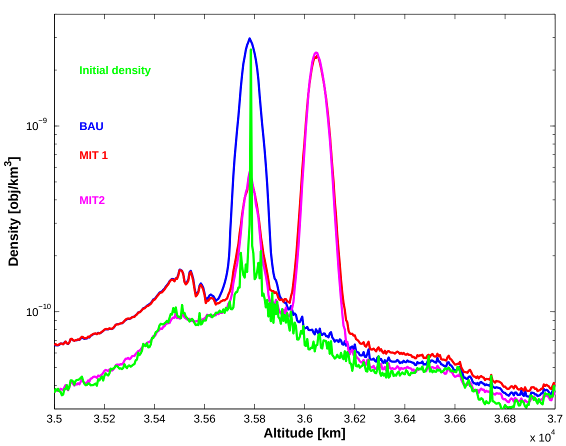

Figure 4. GEO region, around the geostationary altitude: initial (2005) and final (2205) spatial density of objects larger than 10 cm in the BAU, MIT1 and MIT2 scenarios.

Figs. 5 and 6 show the spatial density evolution of objects larger than 1 m (i.e. basically intact bodies). In these plots the influence of the GTO and HEO upper stages is further highlighted, but the same comments accompanying Figs. 3 and 4 apply.

Fig. 7 compares the spatial densities of the objects larger than 1 m and 10 cm in the MIT1 scenario. The main density peaks are nearly identical, but the density distribution of the fragments (typically the objects between 10 cm and 1 m), was spread over a larger altitude band, due to the eccentricity acquired by the debris orbits with the velocity impulses resulting from the fragmentations. Fig. 8 shows the time evolution of the spatial density of the objects larger than 10 cm around the geostationary altitude (between 35,700 and 35,900 km). The difference between the three scenarios analyzed appears clearly. In particular, it should be remarked that, by assuming the mitigation measures simulated with MIT1 and MIT2, the spatial density in the GEO operational zone remained practically constant throughout the investigated time span.

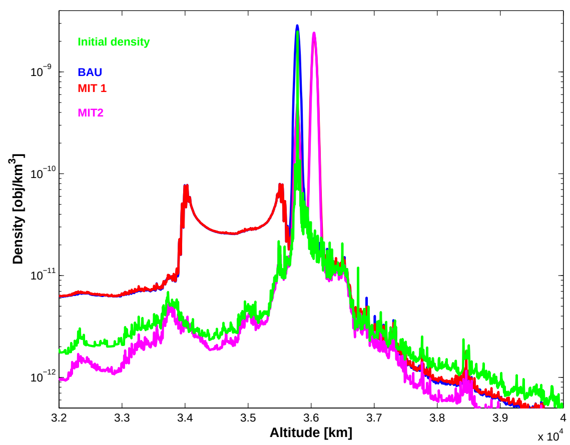

Figure 5. GEO region: initial (2005) and final (2205) spatial density of objects larger than 1 m in the BAU, MIT1 and MIT2 scenarios.

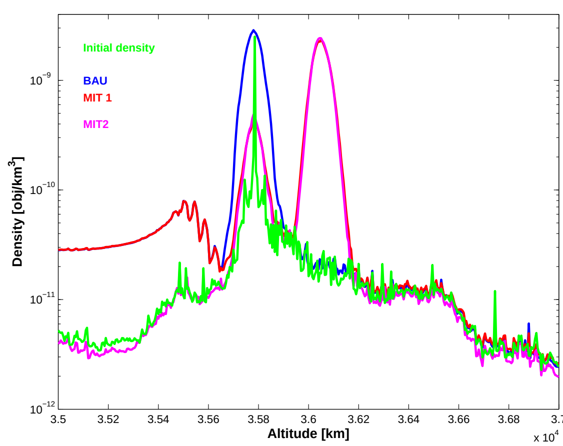

Figure 6. GEO region, around the geostationary altitude: initial (2005) and final (2205) spatial density of objects larger than 1 m in the BAU, MIT1 and MIT2 scenarios.

For the GEO region, Fig. 9 shows the cumulative number of stochastically generated fragmentations, averaged over the Monte Carlo runs, in the three investigated scenarios. The ± 1σ boundaries are plotted as well. It can be noted that, after 200 years, the average number of simulated fragmentations was the same in the BAU and MIT1 cases, while it was less than 40% in the MIT2 scenario.

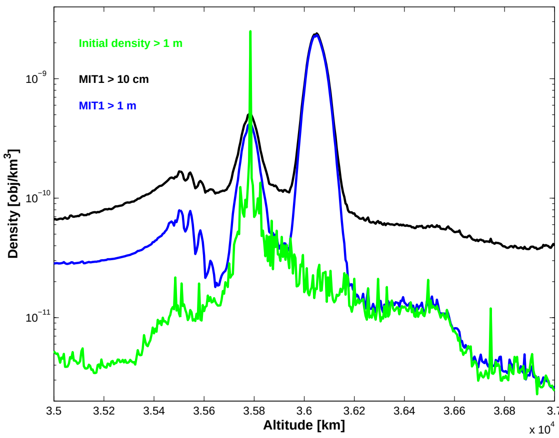

Figure 7. Comparison of the spatial density in GEO of objects larger than 10 cm and 1 m resulting from the MIT1 scenario after 200 years (2205). The initial density (2005) refers to objects larger than 1 m.

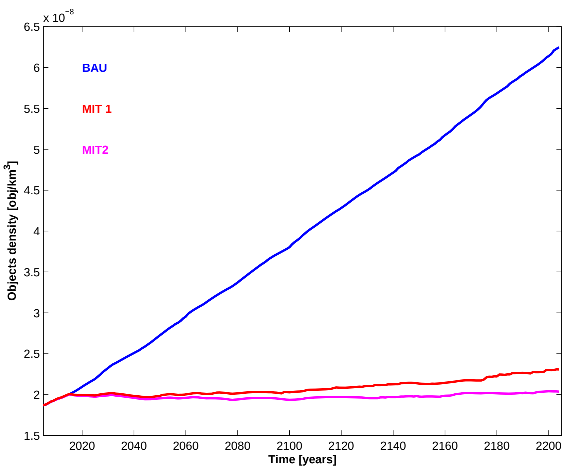

Figure 8. Evolution, over 200 years, of the spatial density of objects larger than 10 cm in the GEO altitude band between 35,700 and 35,900 km.

The situation appears different in Fig. 10, which presents the expected cumulative number of mutual collisions, averaged over the Monte Carlo runs, between the objects larger than 10 cm. However, it should be remarked that, in the GEO region, a collision between a 10 cm debris and a satellite, due to the lower impact velocities typical of such orbital regime, does not produce a catastrophic fragmentation. Therefore, Fig. 9, showing the actual simulated fragmentations, is not directly comparable with Fig. 10, which also includes the expected collisions not leading to catastrophic fragmentations. In this respect, the BAU scenario was slightly more risky, while MIT1 and MIT2 resulted, instead, comparable. This was probably due to the higher concentration of objects in the GEO ring of the BAU case, while in the mitigated scenarios there was a slightly larger dispersion of potential targets (i.e. intact spacecraft) in the super-GEO graveyard zone.

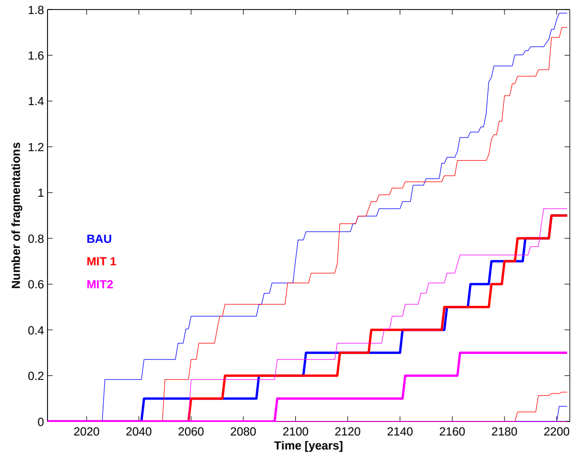

Figure 9. GEO region: time evolution of the average cumulative number of stochastically generated fragmentations in the BAU, MIT1 and MIT2 scenarios. The thin lines show, in each case, the ±1σ boundaries of the 40 Monte Carlo runs.

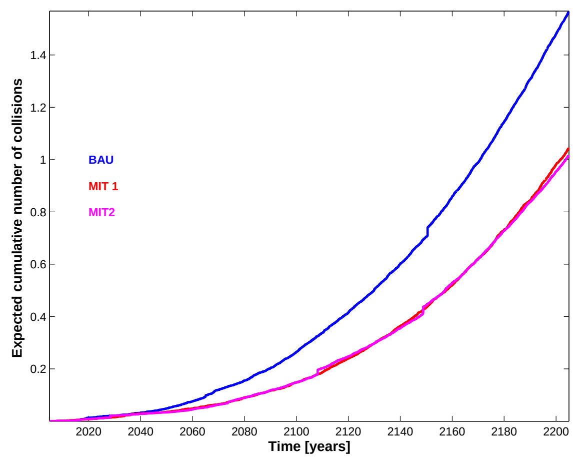

Figure 10. GEO region: time evolution of the expected cumulative number of mutual collisions, averaged over 40 Monte Carlo runs, between objects larger than 10 cm in the BAU, MIT1 and MIT2 scenarios.

Figs. 11, 12 and 13 show the altitude distribution of most of the fragmentations recorded over 200 years in all the 40 Monte Carlo runs carried out for each of the three scenarios. It should be noted that, in the BAU case, 36 out of 37 fragmentations occurred in the GEO protected region (geostationary altitude ± 200 km), as defined in [1], while in the MIT1 case all the collisional breakups (37) occurred outside the protected region (2 below and 35 above). Finally, in the MIT2 scenario, all the breakups (14) occurred in the super-GEO graveyard altitude belt.

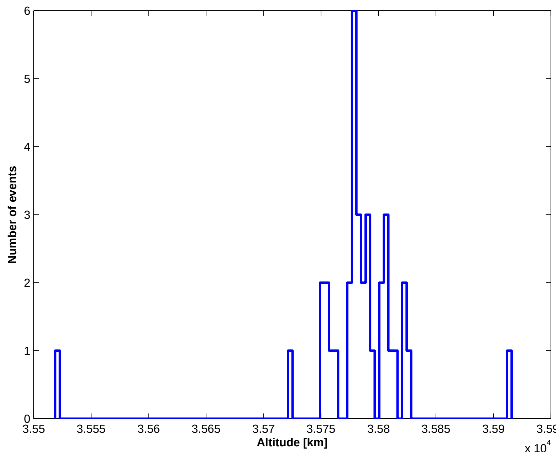

Figure 11. BAU scenario: altitude distribution of the 36 collisional breakups (out of 37) occurred in the GEO protected region, over 200 years, with 40 Monte Carlo runs.

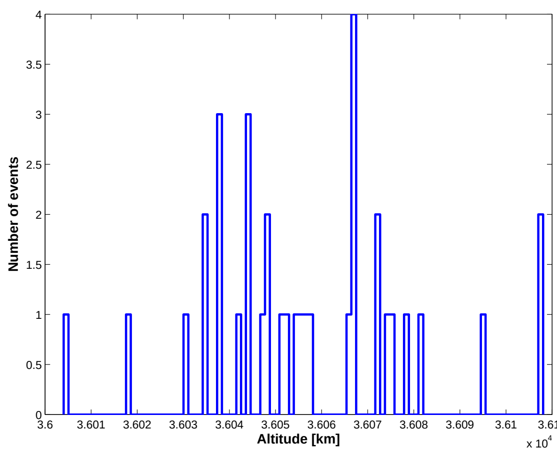

Figure 12. MIT1 scenario: altitude distribution of the 35 collisional breakups (out of 37) occurred in the super-GEO graveyard belt, over 200 years, with 40 Monte Carlo runs.

To further characterize the collision processes in the GEO region, Figs. 14 and 15 show the semimajor axis of the objects involved in all the fragmentations recorded over 200 years with the full set of Monte Carlo runs (40 for each scenario). The location, in an Earth centered reference system, of all the collision induced breakups is instead shown in Fig. 16.

In the BAU scenario there was one collisional breakup (corresponding to 2.7% of the total) involving two upper stages abandoned in nearly circular drift orbits, one just below and the other crossing the GEO protected region, two breakups (5.4%) involving operational GEO spacecraft vs. abandoned satellites and 34 fragmentations (91.9%) involving mutual collisions between uncontrolled GEO satellites left in the protected region (geostationary altitude ± 200 km). It should be also mentioned that in 12 events, corresponding to 32.4% of the total, old satellites, launched before the start of the simulations (2005) and abandoned in GEO, were involved.

In the MIT1 scenario there was one collision (2.7%) between a GTO upper stage and an uncontrolled GEO satellite in the super-GEO graveyard belt, one collision (2.7%) involving a GTO upper stage against a rocket body abandoned in nearly synchronous drift orbit below the protected region and one collision (2.7%) occurred at an altitude around 19,400 km, between a GTO upper stage and an old explosion debris in GTO as well, already present in the initial population. All the other 34 breakups (i.e. 91.9% of the total) were induced by collisions between uncontrolled satellites placed in super-GEO graveyard orbits during the time span of the simulations (i.e. 200 years).

No breakup involving rocket bodies, either in GTO or in nearly synchronous drift orbit, was instead recorded in the MIT2 scenario. All the 14 fragmentations (100%) found with the 40 Monte Carlo runs involved only uncontrolled satellites placed in super-GEO graveyard orbits during the time span of the simulations.

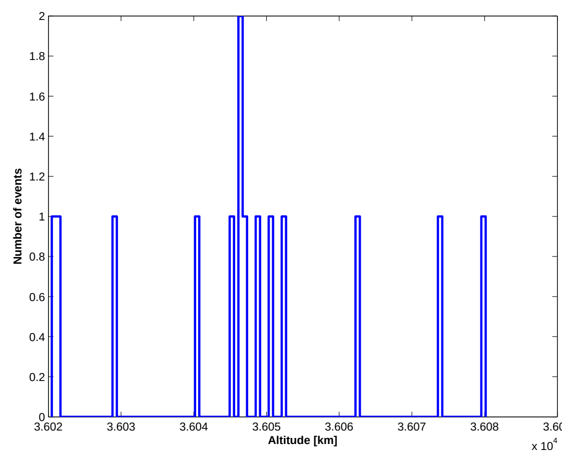

Figure 13. MIT2 scenario: altitude distribution of the 14 collisional breakups recorded over 200 years with 40 Monte Carlo runs. All the fragmentations occurred in the super-GEO graveyard belt (i.e. outside the GEO protected region).

4. CONCLUSIONS

In conclusion, it can be stated that the current mitigation measures recommended by the Inter-Agency Space Debris Coordination Committee [1], i.e. the end-of-life re-orbiting and passivation of synchronous spacecraft in super-GEO graveyard orbits [1], would be able to stabilize the population of intact objects and debris larger than 10 cm in the GEO protected region [1]. Assuming the current launch rates and operational lifetimes, the average number of collision induced fragmentations to be expected in the next 200 years is around one, but the end-of-life re-orbiting of satellites in the super-GEO graveyard belt would prevent, in all likelihood, any collisional breakup in the GEO protected region.

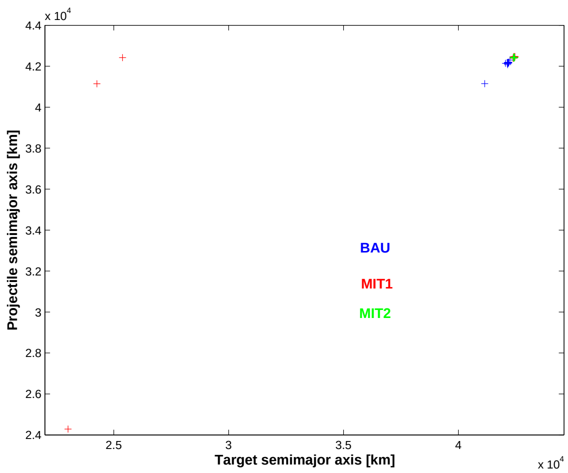

Figure 14. Semimajor axis of the objects involved in the collision induced breakups recorded in 40 Monte Carlo runs.

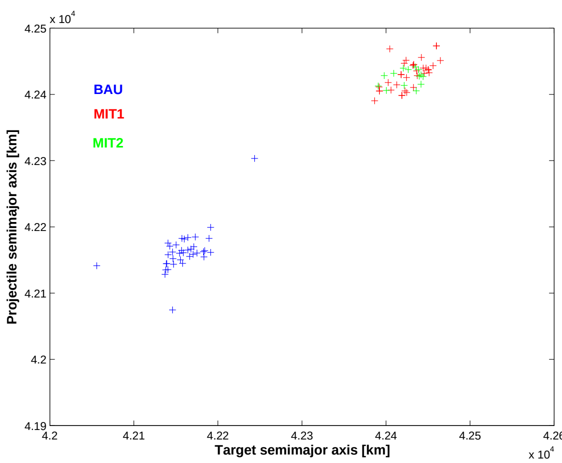

Figure 15. Semimajor axis of the objects involved in the collision induced breakup: detail of the region around GEO and the super-GEO graveyard belt.

In the 40 Monte Carlo runs carried out for each scenario, a few collision induced fragmentations involving GTO and GEO upper stages were recorded (but none involving other HEO intact objects, either spacecraft or rocket bodies). They amounted to approximately 5% of the total in the BAU and MIT1 scenarios, where no mitigation measure concerning the upper stages was considered, but all the collisions occurred outside the GEO protected region and only half of them involved rocket stages crossing it.

Though limited in number (and, of course, in terms of collision probability), these events might be, nevertheless, prevented, as shown by the MIT2 scenario results, through the de-orbiting the GTO upper stages after mission completion and the use of propulsion systems integrated into the satellites for the apogee injection in GEO. Alternatively, the apogee kick motors, when still in use, might be re-orbited in the super-GEO graveyard belt, as the spacecraft at the end-of-life.

However, the potential adoption of any mitigation measure specifically addressing the rocket bodies crossing the GEO protected region, or abandoned in it, should be weighed against the relatively small probability of catastrophic impacts (less than 3%) due to them and the current failure rate (about 58%, recorded between 1997 and 2008 [9][10]) to comply with the IADC re-orbiting recommendation for end-of-life satellites.

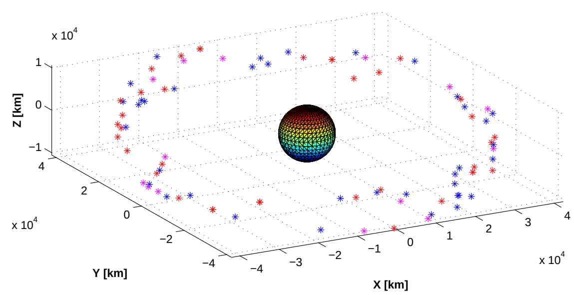

Figure 16. Location, in Earth centered Cartesian coordinates, of the collision induced breakups recorded in 40 Monte Carlo runs: BAU (blue asterisks), MIT1 (red asterisks) and MIT2 (magenta asterisks).

5. ACKNOWLEDGMENTS

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