LONG TERM EFFECTS AND ΔV ANALYSIS OF THE DE-ORBIT MITIGATION MEASURES

A. Rossi[1] and G.B. Valsecchi[2]

[1]CNUCE–CNR, Area della Ricerca del CNR, Via Moruzzi, 1, 56100 Pisa, Italy
[2]IAS–CNR, Area della Ricerca di Roma Tor Vergata, Via Fosso del Cavaliere, 00133 Roma, Italy

ABSTRACT

The effect, on the growth of the space debris population, of the mitigation measures proposed at the international level, is investigated. We consider scenarios involving only the de-orbiting of satellites at the end-of-life and mixed scenarios involving both the de-orbiting and the re-orbiting in different super-LEO graveyard zones (above 1700, 2000 or 2500 km). Then the mitigation measures are analyzed in terms of the ΔV required to accomplish the de-orbiting or re-orbiting maneuvers, in a realistic traffic scenario. The use of delayed reentry disposal orbits, e.g. with 25-years residual lifetime, allows, on average, a saving of $\sim$ 30 % on the amount of propellant. The use of the graveyard regions further reduces the propellant needs, while introducing possible problems due to the accumulation of a large number of objects in restricted regions of space. In particular, a collision risk analysis shows that the use of the lowest proposed graveyard zone, above 1700 km, gives way to a dramatic increase in the number of catastrophic collisions in the graveyard region, in the next decades. On the other hand, it has been shown that the de-orbiting of old spacecraft on elliptical disposal orbits with residual lifetime around 25 – 50 years significantly increase the collision risk for the International Space Station.
A mixed strategy, involving de-orbiting to 25-year residual lifetime disposal orbits and re-orbiting to a storage zone above 2000 km, appears to be the best compromise between the debris mitigation problem and the practical operational issues (i.e. in terms of ΔV required to accomplish the maneuvers).

1. MITIGATION MEASURES

From previous studies [5], [1], [6] it has been shown that the most important action to be taken to limit the growth of the space debris population is the suppression of the in-orbit explosions, responsible for the majority of the centimetric and larger debris tion of all the spacecraft after they completed their operative mission, either by venting the upper stages of the residual fuel or by discharging the batteries on board the satellites, should further reduce the occurrence of the most common type of explosions.

On the other hand the stopping of the explosions alone, while able to sensibly reduce the growth of the population, does not appear enough to actually stabilize, or even reduce, it. To achieve this goal, the old spacecraft have to be removed from the crowded regions of the LEO space at the end of their operative lifetime [6]. The most obvious and effective measure would be to send the spacecraft directly into the atmosphere. Nonetheless this would require in many cases a large propellant expenditure, incompatible with the mission requirements. An intermediate solution has been proposed: to move the spacecraft to lower orbits having a given residual lifetime under the effect of the air drag. The value of this residual lifetime has to be chosen within a few options ranging from the immediate de-orbiting into the atmosphere (0 years residual lifetime) to 50 years residual lifetime. NASA, NASDA and CNES proposed in their Space Debris Mitigation Standards the value of 25 years. These disposal orbits could be, in principle, circular or elliptic. The two options have both advantages and disadvantages: a circular disposal orbit avoids the possible periodic crossing of the orbit of important assets in LEO, such as the ISS, but, on the other hand it requires two maneuvers to reach the final disposal orbit starting from a generic higher one. In [6] it has been shown that the energetic cost of the de-orbiting into circular disposal orbits is too high to be of practical use; therefore in the present paper the analysis will be limited to elliptic disposal orbits, requiring a single maneuver to lower the perigee.On the other hand, an elliptic disposal orbit might cross continuously the Low Earth operational orbits increasing the risk of collision in those regions (see Sec. 5).

Since for LEO objects with high perigee, the de-orbiting into a disposal reentry orbit could be too costly, in terms of ΔV, it has been proposed to move the spacecraft at end-of-life into a storage orbit above

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proposed actually different regions with NASA suggesting 2500 km, CNES 2000 km and NASDA 1700 km [3]; the effect of these different altitudes will be investigated and commented in the next Sessions. It is worth stressing that the adoption of this latter possibility is more debated due to the uncertain long term effects of the accumulation of objects in a LEO region.

For the geostationary ring, the re-orbiting of spacecraft in the super-GEO disposal zone (approximately 300 km above the ring, with the exact altitude depending from the actual cross-sectional area of the spacecraft) is widely accepted [3].

To study the effectiveness of these mitigation measures, the SDM 2.1 software package was used. SDM is a highly detailed software for the study of the long term evolution of the space debris population [5], [1]. It allows the simulation of complex scenarios involving detailed models of the future launch traffic, explosions and collisions, along with many options to simulate suitable mitigation measures. In particular the possibility to de-orbit or re-orbit the satellites, at the end of a given operative life, estimating the ΔV of the optimal maneuver (in the energetic sense) is foreseen [6]. Presently, an impulsive maneuver is always simulated and it is always assumed to perform a minimum energy transfer between coplanar orbits (i.e. Hohmann like transfers and no changes of inclination).

2. SIMULATION SCENARIOS

The efficiency of the different mitigation measures, have been investigated by simulating several different scenarios.

The reference one (code-named REF) assumes a constant rate of *routine* launches (i.e. objects not related to constellations or large structures, such as the International Space Station) of 80 launches per year, with an orbital distribution of the payloads and (optional) upper stages that mimics the one of the past years. The upper stages are supposed to be left in orbit until the year 2010; after that date they are immediately de-orbited after the end of their mission. This might be not a completely realistic assumption, but the issue of the disposal of upper stages is still open. For them, anyway, it appears more reasonable to assume, for the time being, always an immediate de-orbiting instead of a delayed one, due to the different design and mission requirements of upper stages with respect to satellites. In addition to this constant rate, the building of 12 large constellations of satellites in LEO, including some already operational (e.g. IRIDIUM and GLOBALSTAR), other in the advanced planning phase (e.g. TELEDESIC) and other purely hypothetical, introduced in order to have a constellation-related traffic covering the whole 100-year time span, is simulated. The explosion rate, threshold of 40 000 J/kg for satellites and of 60 000 J/kg for upper stages has been assumed.

A few mitigation measures have been included already in the REF case, since, as stated above, there is a general agreement on their efficiency: the explosions are supposed to stop in the year 2010 and the GEO satellites are re-orbited in the super-GEO graveyard orbit at an altitude above the GEO ring, following the IADC guidelines [3].

Building on the REF case, we simulated the following mitigated scenarios:

- DEO_0: the same as REF, but, starting in the year 2010, the LEO satellites are immediately de-orbited into the atmosphere, at the end-of-life (set to 10 years on average);
- DEO_25: the same as REF, but, starting in the year 2010, the LEO satellites are de-orbited into an elliptical disposal orbit with a residual lifetime of 25 years, at the end-of-life;
- DEO_50: the same as DEO_25 but now the residual lifetime is set to 50 years;
- DEO_25_1700: the same as DEO_25, but now, for each satellite at the end-of-life, the code looks for the best maneuver, in terms of ΔV, between the de-orbiting to a 25-year residual lifetime disposal orbit and re-orbiting in a LEO graveyard zone above 1700 km;
- DEO_25_2000: the same as DEO_25_1700 but now the LEO graveyard zone is above 2000 km;
- DEO_25_2500: the same as DEO_25_1700 but now the LEO graveyard zone is above 2500 km.

In all the last three scenarios the width of the storage zone is 100 km, with the actual semimajor of the satellite being extracted from an asymmetric triangular distribution centered on the storage zone lowest limit [1].

In all the scenarios the initial population was composed by the objects larger than 1 mm included in the ESA MASTER 99 model [4].

3. EFFICIENCY OF THE MITIGATION MEASURES

First we are going to analyze the effect of the simulated mitigation measures on the growth of the debris population. All the Figures in this section are obtained averaging the results of 20 Montecarlo runs of SDM and refer, if not otherwise specified, to the altitude band from 0 to 3000 km, in order to com-

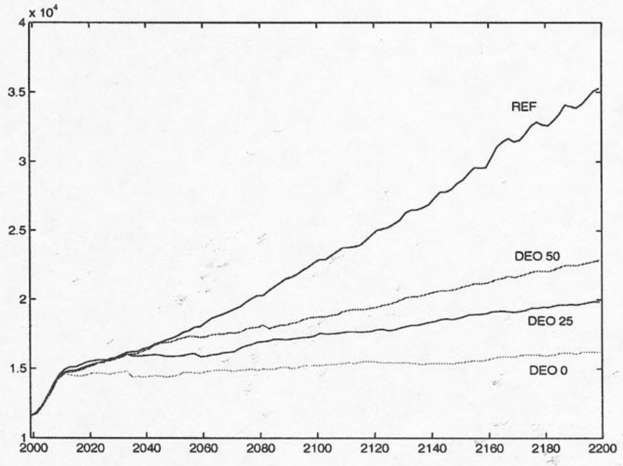

Figure 1. Number of objects larger than 10 cm, in LEO, in the reference case (REF), in the case of immediate de-orbiting at end-of-life (DEO_0) and 25 (DEO_25) and 50 years (DEO_50) disposal orbits

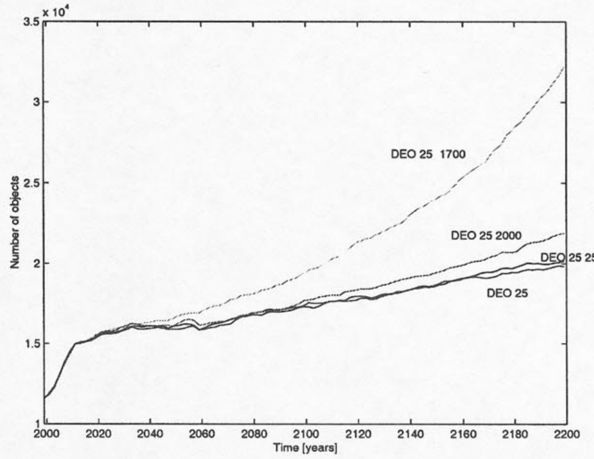

Figure 2. Number of objects larger than 10 cm for the scenarios where the disposal into 25-years residual lifetime orbits is coupled with the re-orbiting into three different graveyard zones.

In Fig. 1 the number of objects with diameter larger than 10 cm, for the 3 cases with the de-orbiting into orbits with different residual lifetime, is shown, with respect to the reference case. We note that, as pointed out before, in the REF case there is a steady growth in the number of particles; the number of objects in this case is ~ 40 % higher than in the three mitigated cases. The growth actually almost stops only in the immediate de-orbiting scenario, even if it is strongly mitigated also for the other two cases. The plots for the 1 cm particles shows a similar behavior with the growth of the population still present in all the scenarios, even thought with the number of objects in the DEO_50 scenario reduced to ~ 50 % with respect to the REF case. On the other hand the objects larger than 1 m are completely stabilized, and even slightly decreasing, for the three mitigated scenarios. Fig. 2 shows the number of objects larger than 10 cm for the scenarios in which the disposal into 25-year residual lifetime orbits is coupled with the re-orbiting into three different graveyard zones,

tion with the disposal into 25-year residual lifetime orbits. As shown in [6] the adoption of an artificial limit for the perigee discriminating between objects to be re-orbited or de-orbited is not realistic and could lead to misleading results; therefore the choice between de-orbiting and re-orbiting is automatically performed by the code, according to the lowest ΔV required by the necessary maneuver.

Several things should be pointed out at this stage. The DEO_25_1700 case results in a number of objects that is ~ 40 % higher than the other cases; this already indicates that, as will be pointed out also in Sec. 5, such a low storage zone is not convenient for the debris mitigation purpose. Then we note that the DEO_25 and DEO_25_2500 give almost the same result (the same is true both for objects larger than 1 cm and 1 m): this warns us that, as we will see in Sec. 4, the highest storage region is actually almost not used, with our simulated traffic scenario. Finally, it is worth noting that, due to the accumulation of objects in the graveyard zones (and the subsequent collisions), the population of objects larger than 10 cm is growing, with different paces, in all the 3 scenarios with the adoption of the storage zones.

This clearly, shows that, if the aim is only the limitation of the debris growth, the scenarios were only the de-orbiting is considered (and particularly the immediate de-orbiting one) should be chosen. On the other hand we will see in the next Section that this is not easy to do from a practical point of view.

4. ΔV COST

By using a realistic traffic scenario, such as the one we simulated in our calculations, it is possible to establish how the theoretical mitigation measures behave with respect to practical issues related to mission costs and operations.

Table 1 is a summary of the maneuvers performed to realize the mitigation measures described in Sec. 2. The number of satellites de-orbited or re-orbited and the average ΔV required for these maneuvers are listed. In particular the global average ΔV, the ΔV required by satellites in almost circular LEOs and the one required by satellites in highly elliptical orbit is separated. In the three cases where only the de-orbiting is foreseen, the decreasing number of de-orbited spacecraft (many objects reenter by themselves within the longer time spans of 25 or 50 years) and the decreasing $\overline{\Delta V}$ required with the longer residual lifetime, can be noted. A savings of ~ 30 % is obtained going from DEO_0 to DEO_25, while going to a 50-year residual lifetime represents a limited, ~ 6 %, savings (due mainly to the non linear decrease of the atmospheric density with altitude).

Whenever the possibility to use a super-LEO storage zone is introduced the picture changes. First

	DEO_0	DEO_25	DEO_50	DEO_25_1700	DEO_25_2000	DEO_25_2500
De-orbited satellites	9970	9450	8070	4070	6900	9330
$\overline{\Delta V}_{deo}$ [m/s]	260 ± 116	181 ± 103	170 ± 100	78 ± 48	143 ± 88	175 ± 97
Highly elliptic	1470	1680	1670	1490	1510	1680
$\overline{\Delta V}_{ell}$ [m/s]	45 ± 20	33 ± 19	30 ± 19	27 ± 10	28 ± 12	32 ± 18
LEO	8500	7770	6400	2580	5390	7650
$\overline{\Delta V}_{LEO}$ [m/s]	302 ± 72	213 ± 83	199 ± 84	107 ± 36	176 ± 71	206 ± 78
Satellites moved to graveyard				4940	2740	570
$\overline{\Delta V}_{gr}$ [m/s]				119 ± 46	179 ± 55	304 ± 24
Highly elliptic				180	160	
$\overline{\Delta V}_{gr-ell}$ [m/s]				54 ± 22	79 ± 18	
LEO				4760	2580	570
$\overline{\Delta V}_{gr-LEO}$ [m/s]				121 ± 45	185 ± 50	304 ± 24

Table 1. Number of de-orbited and re-orbited satellites and ΔV required for the respective maneuvers. $\overline{\Delta V}_{deo}$ is the average ΔV required to de-orbit a satellite into a disposal orbit with the given residual lifetime, $\overline{\Delta V}_{ell}$ is the average ΔV required to de-orbit a satellite originally in a highly elliptical orbit and $\overline{\Delta V}_{LEO}$ is the average ΔV required to de-orbit a satellite originally in a nearly circular orbit in LEO. $\overline{\Delta V}_{gr}$ is the average ΔV required to re-orbit a satellite into a given graveyard zone, $\overline{\Delta V}_{gr-ell}$ is the average ΔV required to re-orbit a satellite into an elliptic orbit inside the graveyard zone (coming from an originally highly elliptic orbit with apogee already above the graveyard limit). $\overline{\Delta V}_{gr-LEO}$ is the average ΔV required to re-orbit a satellite into a circular orbit inside the graveyard zone, coming from a LEO orbit completely below the graveyard limit.

maneuvers rises accordingly. The 1700 km zone is energetically very close to most of the LEO satellites and is therefore widely used. This greatly reduces the ΔV cost of the mitigation measures but, on the other hand, introduces serious problems on the collision risk side, as will be pointed out in Sec. 5. At the other extreme, we note that the storage zone above 2500 km is actually too far, from an energetic point of view, from most of the the LEO spacecraft. Only ~ 3 spacecraft per year are moved inside this zone. This of course means that the accumulation problems of the 1700 km zone are not present, but also means that there is basically no saving with respect to the purely de-orbiting case DEO_25. In between lies the case DEO_25_2000; as it will be shown in Sec. 5 the accumulation problems are still relevant, but greatly reduced by the lower number of satellites that are re-orbited (about half of those re-orbited in the DEO_25_1700 case).

5. COLLISION RISK ANALYSIS

stricted graveyard region may cause, on the long run, an increase of the collision risk in those zones. Fig. 3 shows the number of collisions between objects larger than 10 cm in LEO (between 0 and 3000 km) for the three scenarios with the adoption of the super–LEO storage zones, compared with the DEO_25 case (the lines for the DEO_25 and the DEO_25_2500 case are the lowest ones and are almost coincident, confirming again that the highest storage region is almost not used). The large increase in the collisions observed in the DEO_25_1700 case is due to more than 200 collisions expected in the storage region in the next two centuries. A highly non linear pace of the number of collisions is noticeable. The results shown in Fig. 3 confirm the long term hazard related to the use of the super-LEO storage zones. This risk is sensitive to the width of the storage region (here assumed to be 100 km), clearly growing if smaller regions of space are assumed. On the other hand may it be not realistic to assume too large storage regions, since it is reasonable to expect that a satellite operator would seek the minimum ΔV required to accomplish a given mitigation measure, thus reaching an altitude close to the lowest limit of the storage region.

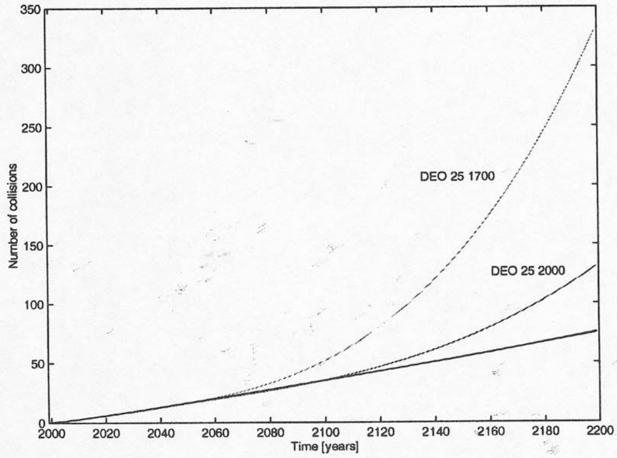

Figure 3. Expected number of collisions between objects larger than 10 cm in LEO (between 0 and 3000 km) in four different mitigated scenarios. The lowest line is actually composed by the superposition of the DEO_25 and the DEO_25_2500 cases, giving almost coincident results.

As pointed out in Sec. 1, the de-orbiting of satellites to elliptic disposal orbits, with a given residual lifetime, increase the number of objects crossing the orbit of sensible LEO spacecraft. In particular the ISS ($a \sim 6830$ km, $e \sim 0$, $i \sim 52°$) can be affected by this additional population of crossing particles. Fig. 4 shows the number of collisions against objects larger than 1 cm (i.e. projectiles capable of penetrating the protective shields) at the ISS altitude. First it should be pointed out that the probabilities are still quite low in all the 4 cases. Nonetheless, it can be noted that now the mitigation measures, that have proven useful in reducing the global population growth in LEO, act in the opposite way with respect to the collision risk on the ISS. The only scenario that reduces the risk is the immediate de-orbiting one, while in the other 2 mitigated cases the de-orbited objects cause an increase in the collision risk; e.g. the DEO_25 case exhibits an $\sim$ 50 % increase with respect to the REF case. On the other hand it should be noticed that, while in the DEO_25 case the pace is almost linear, in the REF case, after about 100 years the pace turns non linear, a possible warning of a collisional cascade under way. Since they imply a lower number of de-orbited satellites (see Tab. 1), the scenarios with the mixed de-orbiting–re-orbiting strategy show a lower collision rate with respect to those seen in Fig. 4; e.g. the DEO_25_2000 scenario gives way to $\sim$ 50 % less collisions, in the 200-year investigated time span, than the DEO_25 case.

With the help of the parameter space introduced in [7] we can visualize the increase in the collision risk for the ISS orbit, due to the de-orbiting measures. In Fig. 5 the *running population* (i.e. the population of objects introduced in space after the beginning of the simulation) larger than 1 cm, is plotted in the E vs. $\cos I$ space, for the DEO_0 case, in the year 2196,

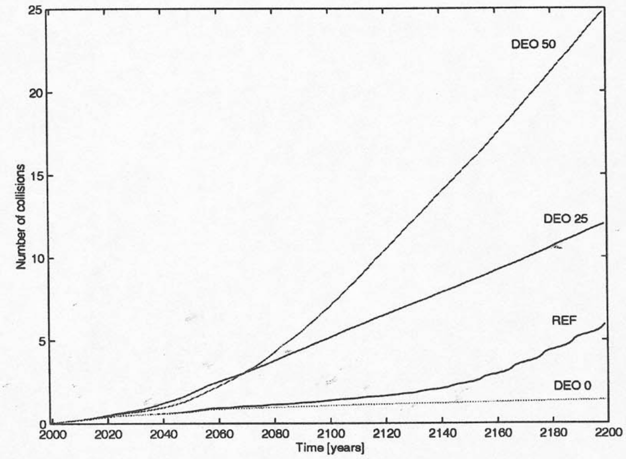

Figure 4. Expected number of collisions against objects larger than 1 cm at the ISS altitude (i.e. in the altitude shell between 450 and 500 km) in the reference case and in the cases where only the de-orbiting is foreseen.

y^{-1} (lower thick black curve) and 3.15×10^{-11} m^{-2} y^{-1} (upper thick grey curve); assuming a cross section of ~ 400 m^2 and a population of the order of 10^5 objects larger than 1 cm, these values mean a collision rate around 1% year^{-1} and 0.1 % year^{-1} on the ISS. The four subplots refer to different impact velocities: the upper left plot shows particles impacting at $\sim$ 5.4 km/s (i.e. $\sim$ 20631 J for a 1 cm particles), the upper right plot shows particles impacting at $\sim$ 7.6 km/s and the two lower subplots include particles impacting at $\sim$ 9.4 and $\sim$ 10.8 km/s, respectively. Fig. 6 is the same as Fig. 5, but for the DEO_50 case.

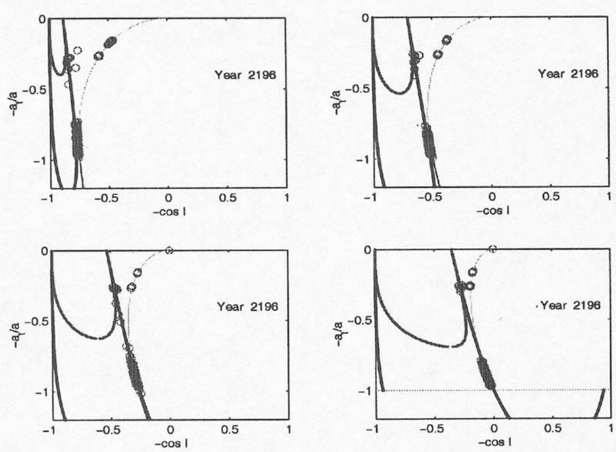

Figure 5. Visualization of the collision risk against particles larger than 1 cm on the ISS orbit in the year 2196, in the plane a_t/a versus $\cos I$ (where a_t and a are the semimajor axis of the target and of the projectile, respectively, and I is the relative inclination between the orbital planes of the target and of the projectile), for the DEO_0 scenario. The four subplots, from the upper left to the lower right, refer to impact velocities of 5.4, 7.6, 9.4, 10.8 km/s,

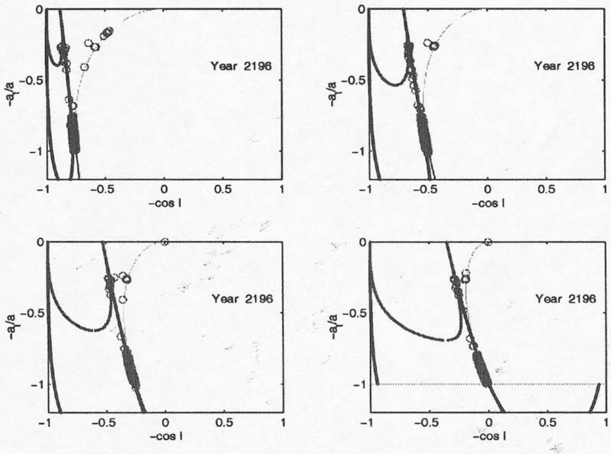

Figure 6. The same as in Fig. 5 but for the DEO_50 scenario.

Comparing the two Figures, it can be noted in Fig. 6 (e.g. in the 10.8 km/s subplot) the growing population of objects crossing the ISS orbit, having high relative velocity and non-negligible impact probability. They have the semimajor axis larger than the ISS one and the perigee nearly tangent to the ISS one (most of the points lie on the tangency condition line, partially coincident with the highest isoprobability curves in all the subplots). These objects are coming mostly from the de-orbiting maneuvers: in fact comparing, e.g., the 7.6 km/s subplots in Fig. 5 and in Fig. 6, it can be noted how the consistent population of objects with a_t/a between ~ 0.8 and ~ 0.3 visible in Fig. 6, is nearly absent in Fig. 5. Most of these objects have intrinsic collision probabilities in excess of 1.58×10^{-10} m^{-2} y^{-1}.

6. CONCLUSIONS

The need for measures to reduce the growth of debris in LEO is presently well understood.

We showed how the de-orbiting of the upper stages and the spacecraft at end-of-life (together with the stop of the in orbit explosions) is able to considerably reduce or even stabilize the population of orbiting debris. The use of different super-LEO graveyard zones will still guarantee a reduced growth pace, but with the risk of an accumulation of spacecraft and of an increased collision risk, in zones of space close to the presently crowded LEOs. In particular the use of the lowest proposed graveyard zone, above 1700 km, gives way to a dramatic increase in the number of catastrophic collisions in the graveyard region, in the next decades. Therefore the adoption of the graveyard zones could be a short sighted solution, even though useful from an energetic point of view.

In fact, in Sec. 4 the cost in term of ΔV related to the different proposed mitigation measures has been analyzed. The de-orbiting of spacecraft into orbits with a residual lifetime of 25 years and the re-orbiting into a super-LEO storage zone above 2000 km, appears a reasonable compromise between practical mission operation issues and space debris management issues. The cost analysis has been done assuming conventional impulsive thrusters. The adoption of electric propulsion systems could change the ΔV requirements, by lowering significantly the amount of propellant needed to perform a given maneuver [2]. The problems and the advantages related to the adoption of this propulsion system will be further investigated in a future work.

We also analyzed the evolution of the collision risk for the ISS due to the adoption of the simulated mitigation measures. The de-orbiting of many LEO spacecraft into elliptical orbits with a few decades of residual lifetime causes a significant increase in the number of particles crossing the ISS orbit and, consequently, in the risk of damaging collisions.

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