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Energetic Cost and Viability of the Proposed Space Debris Mitigation Measures

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At the international level several mitigation measures are proposed to reduce and minimize the debris growth in Earth orbit. The deorbiting of payloads and upper stages at the end of their operative lifetime is one of the most favored options. The spacecraft should be deorbited either directly into the atmosphere or into disposal orbits with selected residual lifetimes (for example, 10, 15, 25, and 50 years) as a result of air drag. The possible introduction of storage zones (both in low Earth orbit and in geostationary Earth orbit) is also discussed. The effects of the different mitigation measures on the long-term evolution of the debris population are analyzed. The need for deorbiting to stabilize the debris population and stop its growth is confirmed. The introduction of low-Earth-orbit (LEO) storage zones is still able to reduce significantly the growth of the number of objects, even though it does not stop it. On the other hand, the adoption of such storage zones might only delay the problem. In particular, the use of the lower proposed storage zone, above 1700 km, will give way, in the next decades, to an increased number of collisions in LEO as a result of the accumulation of a large number of objects in that region. Whereas the only way to guarantee a long-term stability of the environment will be to adopt only the deorbiting mitigation measures, it is shown that a mixed strategy, involving deorbiting to 25-year residual lifetime disposal orbits and reorbiting to a storage zone above 2000 km, appears to be the best compromise between the debris mitigation problem and the practical operational issues (that is, in terms of ΔV required to accomplish the maneuvers).

Nomenclature

A/M	=	area over mass ratio of a spacecraft, m^2/kg
C_r	=	solar radiation pressure coefficient
g	=	acceleration of gravity, m/s^2
H	=	altitude of the storage orbit above the geostationary ring, km
I_{sp}	=	specific impulse of a spacecraft engine, s
m_p	=	mass of propellant needed for a maneuver, kg
m_0	=	initial spacecraft mass, kg
R	=	m_p/m_0
r_{apo_fin}	=	apogee radius of the final orbit in an Hohmann transfer, km
r_{apo_ini}	=	apogee radius of the initial orbit in an Hohmann transfer, km
r_{apo_trans}	=	apogee radius of the transfer orbit in an Hohmann transfer, km
V_{apo_fin}	=	velocity at the apogee of the final orbit in an Hohmann transfer, m/s
V_{apo_ini}	=	velocity at the apogee of the initial orbit in an Hohmann transfer, m/s
ΔV	=	change in orbital velocity required by a change of orbit, m/s
$\overline{\Delta V}_{deo}$	=	average ΔV required to deorbit a satellite, m/s
$\overline{\Delta V}_{ell}$	=	average ΔV required to deorbit a satellite originally in a highly elliptical orbit, m/s
$\overline{\Delta V}_{gr}$	=	average ΔV required to reorbit a satellite into the storage zone, km/s
$\overline{\Delta V}_{gr-ell}$	=	average ΔV required to reorbit a satellite into an elliptic orbit inside the storage zone, coming from an originally highly elliptic orbit with apogee already above the storage limit, m/s
$\overline{\Delta V}_{gr-LEO}$	=	average ΔV required to reorbit a satellite into a circular orbit inside the storage zone, coming from a low Earth orbit completely below the storage limit, m/s
$\overline{\Delta V}_{LEO}$	=	average ΔV required to deorbit a satellite originally in a nearly circular orbit in low Earth orbit, m/s
μ	=	mass of the Earth times the gravitational constant G

Introduction

THE overcrowding of the circumterrestrial space is posing growing problems to the space agencies and satellite operators worldwide. Beyond the approximately 9000 objects cataloged by the U.S. Space Command, tens of thousands of centimetric debris pollute the space around the Earth. Most of the centimetric objects presently in space are debris coming from past explosions that destroyed rocket upper stages and satellites.

Several studies (for example, see Refs. 1–4) showed that, if no action is taken, the debris growth could continue, even possibly reaching, in certain altitude bands, a chain reaction status where more objects are produced by collisions than those removed by air drag. To reduce the debris growth and minimize the collision risk for space assets, several mitigation measures have been proposed at the international level.[5,6] Within the international panels, such as the Inter Agency Debris Committee (IADC), these mitigation measures are actively discussed to find a common understanding on the most viable and efficient ones. When dealing with this problem, the consequences that a given measure might have on the mission budget and on the mission operational procedure have to be primarily considered. Some of the mitigation measures, even if quite effective in terms of debris reduction, are shown to be too demanding in terms of propellant expenditure to be actually implemented.

The purpose of this paper is to asses the effectiveness of different mitigation measures in limiting the debris growth, taking into account the practical implementation of these measures. This is done by analyzing these measures also in terms of their impact on the missions' ΔV budget.

In the next section a very short review of the most commonly proposed mitigation measures is given. Then the methods adopted in the present simulations are described. Finally, the results of the

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simulations under the point of view both of the debris reduction effects and of the cost in terms of propellant are discussed.

Mitigation Measures

From previous studies[7–9] 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 in-orbit explosions, responsible for the majority of the centimetric and larger debris presently in orbit. This stopping of the explosion events in orbit can be obtained first by ending all of the intentional explosions. Then the passivation of all of the spacecraft after they have 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 types of explosions.

On the other hand, the stopping of the explosions alone, although able to significantly 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 low-Earth-orbit (LEO) space at the end of their operative lifetime.[7–9] The most obvious and effective measure would be to send the spacecraft directly into the atmosphere. Nonetheless the direct sink of old spacecraft into the atmosphere would require in many cases a large propellant expenditure, incompatible with 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 deorbiting into the atmosphere (0 years residual lifetime) to 50 years residual lifetime. NASA,[10] the Japanese National Space Development Agency (NASDA),[11] and the French Centre National d'Etudes Spatiales (CNES)[12] proposed in their Space Debris Mitigation Standards the mean 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 International Space Station (ISS). On the other hand, such a disposal strategy requires two maneuvers to reach the final circular orbit, starting from a generic higher one. To reach an elliptic disposal orbit, a single maneuver to lower the perigee is required, with a savings in propellant.

Because for objects with perigee above approximately 1400 km deorbiting 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 the most crowded LEO zones, that is, above approximately 2000 km. Again the various space agencies actually proposed different regions with NASA suggesting 2500 km, CNES 2000 km, and NASDA 1700 km (Ref. 6). The effect of these different altitudes will be investigated and commented in the next section. It is worth stressing that the adoption of the storage orbits is to be debated further because of the uncertain long-term effects of the accumulation of objects in a LEO region.[13]

For the geostationary ring the reorbiting of spacecraft in the super-geostationary orbit (GEO) disposal zone (approximately 300 km above the ring, with the exact altitude depending on the actual cross-sectional area of the spacecraft) is widely accepted. The IADC proposed an altitude for the storage orbit above the GEO ring given by the formula

$$H = 235 + (1000 \cdot C_r \cdot A/M) \tag{1}$$

Actually the national space agencies proposed slight modifications of Eq. (1) in their Safety and Mitigation Standards but which do not change much the overall picture. In this study the IADC formula[6] was implemented.

To study the effectiveness of these mitigation measures, the Space Debris Mitigation (SDM) 2.1 software package was used. SDM is highly detailed software for study of the long-term evolution of the space debris population developed in the last several years under European Space Agency and Italian Space Agency contracts.[4,14] The software allows the simulation of complex scenarios involving detailed modeling of the future launch traffic, explosions, and collisions, along with many options to simulate suitable mitigation measures. In particular the possibility to deorbit the satellites, at the end of a given operative life, into an orbit with a selected residual lifetime has been implemented. The elements of the disposal orbit, which ensures the selected residual lifetime with respect to the effect of the air drag, are calculated. The calculation accounts for the actual area over mass ratio of each spacecraft, either with an approximate analytical method or with a more accurate, slightly more CPU-demanding, numerical one. Similarly the possibility to send the satellites at the end of life into a selected super-LEO or super-GEO storage zone is implemented. For a detailed description of the software, see Ref. 14.

In version 2.1 of the software, the ΔV related to the deorbiting or reorbiting maneuvers can be estimated. Presently, an impulsive maneuver is simulated. Moreover, a minimum energy transfer between coplanar orbits (that is, Hohmann-like transfers and no changes of inclination) is always performed, as described in the next section.

ΔV Calculation

To account for all of the possible deorbiting or reorbiting maneuvers required to comply with the mitigation scenarios described in the preceding section, a few cases have to be considered.

Whenever it is desired to immediately deorbit a satellite into the atmosphere or to put it into an elliptical disposal orbit having a selected residual lifetime, a maneuver to lower the perigee of the orbit is performed. This maneuver is done by a burn at the orbit apogee, so requiring a ΔV:

$$\Delta V = |V_{\text{apo\_ini}} - V_{\text{apo\_fin}}| \tag{2}$$

The preceding expression equals

$$= \sqrt{\mu}\left|\left(\frac{2}{r_{\text{apo\_ini}}} - \frac{1}{a_{\text{ini}}}\right)^{\frac{1}{2}} - \left(\frac{2}{r_{\text{apo\_ini}}} - \frac{1}{a_{\text{fin}}}\right)^{\frac{1}{2}}\right| =$$

Note that $r_{\text{apo\_ini}}$ equals $r_{\text{apo\_fin}}$:

$$= \sqrt{\mu}\left|\left[\frac{1}{a_{\text{ini}}}\left(\frac{1-e_{\text{ini}}}{1+e_{\text{ini}}}\right)\right]^{\frac{1}{2}} - \left[\frac{1}{a_{\text{fin}}}\left(\frac{1-e_{\text{fin}}}{1+e_{\text{fin}}}\right)\right]^{\frac{1}{2}}\right| \tag{3}$$

The suffixes ini and fin always refer to the orbital elements of the initial and final orbits.

Another possible mitigation strategy might require the deorbiting on a lower circular orbit having a selected residual lifetime. In this case starting from a generic elliptical orbit, two maneuvers are necessary. First a burn at the apogee of the initial orbit is needed to lower the perigee, sending the spacecraft to a transfer orbit:

$$\Delta V_A = |V_{\text{ini\_elliptic@apo}} - V_{\text{trans@apo}}|$$

$$= \sqrt{\mu}\left|\left(\frac{2}{r_{\text{apo\_ini}}} - \frac{1}{a_{\text{ini}}}\right)^{\frac{1}{2}} - \left(\frac{2}{r_{\text{apo\_ini}}} - \frac{1}{a_{\text{trans}}}\right)^{\frac{1}{2}}\right| \tag{4}$$

where $r_{\text{apo\_ini}} = r_{\text{apo\_trans}}$ (the suffix trans now refers to the parameters of the transfer orbit). Then a second burn is required, at the perigee of the transfer orbit, to circularize the final orbit:

$$\Delta V_B = |V_{\text{trans@peri}} - V_{\text{circular\_fin}}|$$

$$= \sqrt{\mu}\left|\left(\frac{2}{a_{\text{fin}}} - \frac{1}{a_{\text{trans}}}\right)^{\frac{1}{2}} - \sqrt{\frac{1}{a_{\text{fin}}}}\right| \tag{5}$$

So that, finally, the total required ΔV is

$$\Delta V = \Delta V_A + \Delta V_B \tag{6}$$

The same applies, with a reversed sequence of maneuvers, if a reorbiting into an upper storage zone is sought, starting from a lower orbit completely outside the storage zone.

If the spacecraft orbit has instead the apogee already inside the storage zone, only one maneuver is needed. With this maneuver, performed at the apogee of the initial orbit, the perigee is raised inside the storage zone. Similar to Eq. (3), the following is obtained:

$$\Delta V = |V_{\text{fin\_elliptic@apo}} - V_{\text{ini\_elliptic@apo}}|$$
$$= \sqrt{\mu}\left|\left[\frac{1}{a_{\text{fin}}}\left(\frac{1-e_{\text{fin}}}{1+e_{\text{fin}}}\right)\right]^{\frac{1}{2}} - \left[\frac{1}{a_{\text{ini}}}\left(\frac{1-e_{\text{ini}}}{1+e_{\text{ini}}}\right)\right]^{\frac{1}{2}}\right| \tag{7}$$

Simulation Scenarios and Results

The efficiency of the different mitigation measures has been investigated by simulating several scenarios with SDM. In the reference scenario, code-named REF, a constant rate of 80 routine launches per year is assumed. The routine launches consist of objects not related to constellations or large structures, such as the ISS. The orbital distribution of the payloads and (optional) upper stages mimics that of past years. The rocket upper stages are supposed to be left in orbit until the year 2005. After that date the upper stages are immediately deorbited after the end of their mission. This assumption might not be completely realistic, but the issue of the disposal of upper stages is still open. For them, anyway, it appears more reasonable to assume always an immediate deorbiting instead of a delayed one because of 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 is simulated. These constellations include some already operational (for example, IRIDIUM and GLOBALSTAR), others in the advanced planning phase (for example, TELEDESIC) and others purely hypothetical, introduced in order to have constellation-related traffic covering a 100-year time span (Table 1). The explosion rate, of about five explosions/year, again mimics the experience of the past several years. A collisional fragmentation threshold of 40,000 J/kg for satellites and of 60,000 J/kg for upper stages has been assumed.

Some mitigation measures have been included already in the REF case because, as already stated, there is a general agreement on their efficiency: the explosions are supposed to stop in the year 2010, and the GEO satellites are reorbited in the super-GEO storage orbit at an altitude above the GEO ring given by Eq. (1).

Building on the REF case, the following mitigated scenarios have been simulated: first, DEO_0 is the same as REF, but, starting in the year 2010, the LEO satellites are immediately deorbited into the atmosphere at the end of life (set to 10 years on average). Second, DEO_25 is the same as REF, but, starting in the year 2010, the LEO satellites are deorbited into a circular disposal orbit with a residual lifetime of 25 years at the end of life. Third, DEO_50 is the same as DEO_25, but now the residual lifetime is set to 50 years. Then the last two cases have been simulated, assuming elliptic (as opposed to circular) disposal orbits with 25- and 50-year residual lifetimes. The two new scenarios are therefore code-named DEO_25_ELL and DEO_50_ELL, respectively. Then three scenarios including the adoption of the LEO storage zones have been simulated. First, DEO_0_1700 is the same as DEO_0, but now all of the satellites with perigee higher than 1400 km are reorbited, at end of life, into a LEO storage zone above 1700 km. Second, DEO_0_2000 is the same as DEO_0_1700 but with the LEO storage zone above 2000 km. Third, DEO_0_2500 is the same as DEO_0_1700 but with the LEO storage zone above 2500 km.

The limit of 1400 km for the perigee of the objects to be sent into the LEO storage is the one generally adopted to discriminate between the fate of the satellite to be removed on the basis of an approximate calculation. However, especially for a high LEO storage zone (for example, 2500 km), in many cases it might be more energetically convenient to send the objects with perigee around 1400 km down, toward reentry, than up into the storage zone. This advantage of the deorbiting maneuver is probable in particular when the disposal orbit has a medium to long residual lifetime, that is, if the disposal orbit does not require a very low perigee. Therefore, to check the accuracy of the 1400-km assumption and to simulate more realistic cases the last scenarios have been repeated, allowing the code to look for the best maneuver, in terms of lower ΔV, between the deorbiting toward immediate reentry and reorbiting in the LEO storage zone. With the same convention of the preceding scenarios, these new cases are code named DEO_0_1700_AUTO, DEO_0_2000_AUTO, DEO_0_2500_AUTO, DEO_25_1700_AUTO,

Table 1 Orbital elements and a few characteristics of the simulated satellite constellations

Constellation name	a, km	e	i, deg	Satellites in orbit	Spacecraft mass, kg
Iridium	7,158	0.0	86.4	78	575
Globalstar	7,792	0.0	52.0	56	450
Orbcom	7,203	0.0	45.0	48	43
Skybridge	7,835	0.0	55	64	800
Ellipso	10,561	0.347	116.5	10	174
Ico	16,733	0.0	45.0	12	2,600
Teledesic	7,528	0.0	98.2	324	300
WB-LEO-1	7,728	0.0	47.0	72	1,200
WB-LEO-2	7,828	0.0	47.0	72	1,300
WB-LEO-3	7,928	0.0	47.0	72	1,400
WB-LEO-4	8,028	0.0	47.0	72	1,500
WB-LEO-5	8,128	0.0	47.0	72	1,600

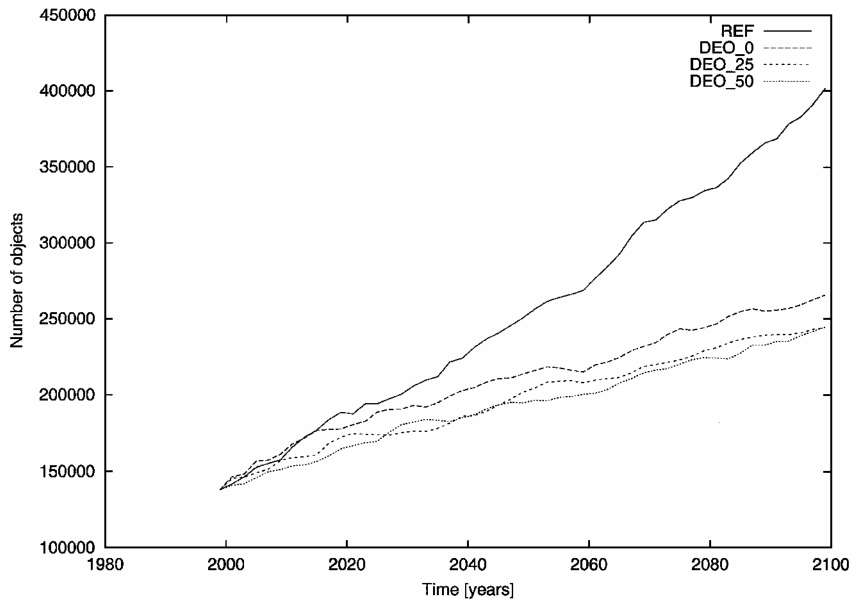

Fig. 1 Number of objects larger than 1 cm in the reference case (REF) with respect to the cases of immediate deorbiting at end of life (DEO_0), 25 (DEO_25), and 50-year (DEO_50) disposal orbits.

DEO_25_2000_AUTO, and DEO_25_2500_AUTO, respectively. In all of the scenarios, the initial population was composed by the objects with mass larger than 1 mg included in the ESA MASTER 99 model.[15]

Efficiency of the Mitigation Measures

First the effect of the simulated mitigation measures on the growth of the debris population will be analyzed. The debris evolution is driven by a number of stochastic events, such as explosions and collisions. These stochastic features depend on the choice of the seed for the random number generator. To establish the typical long–term "systematic" trends of the evolution process, it is necessary to average the outputs of many similar Monte Carlo runs obtained with the same input parameters but different random-generator seeds. All of the figures in this section are obtained averaging the results of 20 runs of SDM. From this averaging process a mean value and a standard deviation are obtained. Therefore in all of the results shown next there is an intrinsic statistical uncertainty that nonetheless does not mask the general trend shown by the average. All of the figures refer, if not otherwise specified, to the altitude band from 0 to 3000 km, in order to include also the region of the storage zone above 2500 km.

In Fig. 1 the number of objects with diameter larger than 1 cm, for the three cases with the deorbiting into orbits with different residual lifetimes, is shown with respect to the reference case. As pointed out before, in the REF case there is a steady growth in the number of particles. The number of objects in the REF case is about 30% higher than in the three mitigated cases. The three mitigated scenarios give comparable results, and, also for them, a growth in the 1-cm population is still present, even though much reduced. Consider now the objects larger than 10 cm (Fig. 2). The effect of the mitigation measures becomes more apparent. In the REF case the growth is constant throughout the simulated time span. On the other hand, in the mitigated scenarios, after the end of the explosions, around the year 2010 the growth is almost stopped. The mitigated cases are again comparable, and the important aspect is that now the situation appears stabilized. Figure 3 shows how the adoption of the mitigation measures stops the growth of the objects larger than 1 m. The population stabilizes on different levels, according to the residual lifetime adopted for the disposal orbits.

Figures 1–3 referred to the cases where the satellites were moved to circular disposal orbits. Figure 4 shows the number of objects larger than 10 cm in the scenarios with 25-year circular and elliptic disposal orbits. (Both have been calculated with the numerical

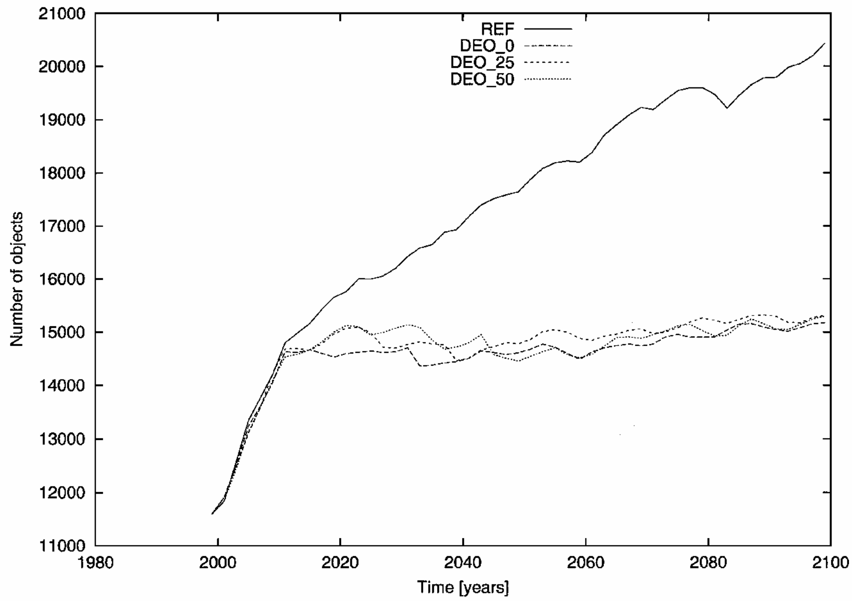

Fig. 2 Same as Fig. 1, but for objects larger than 10 cm.

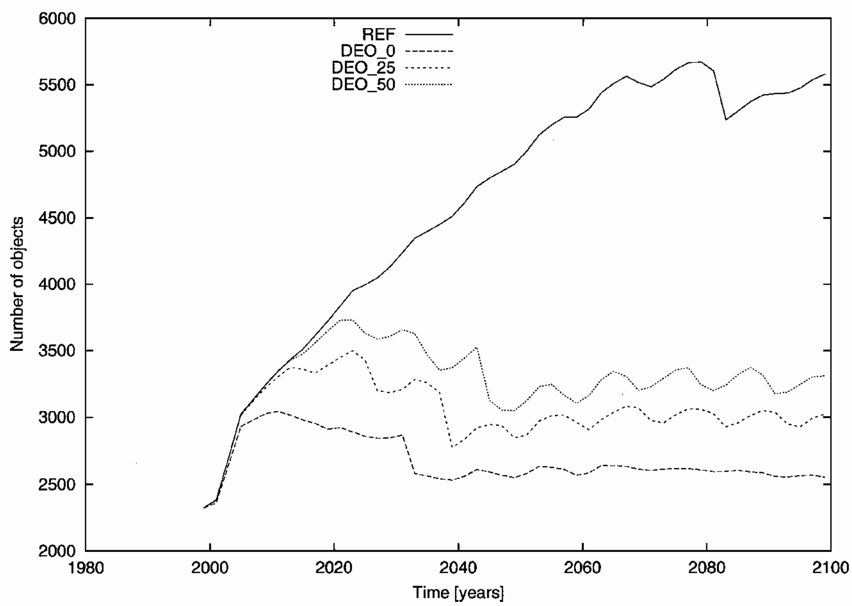

Fig. 3 Same as Fig. 1, but for objects larger than 1 m.

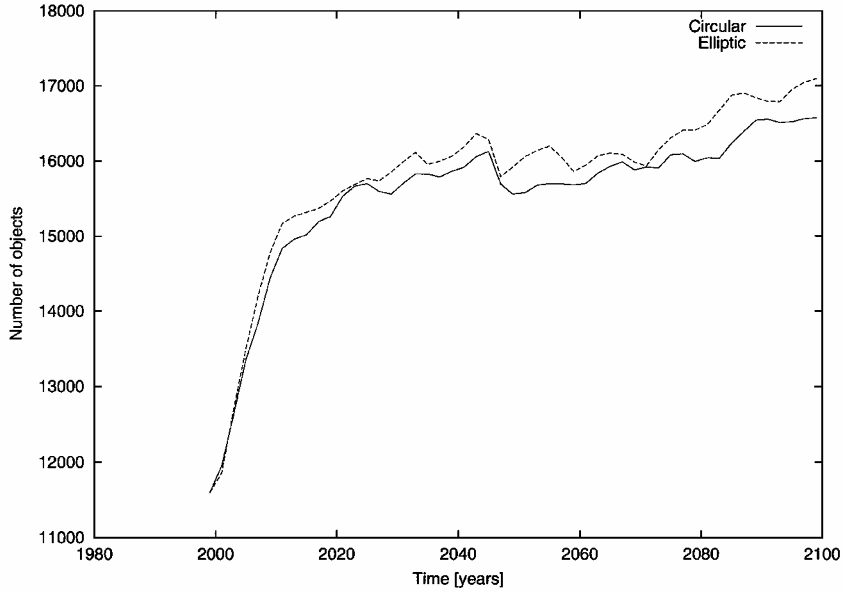

Fig. 4 Number of objects larger than 10 cm in the DEO_25 and DEO_25_ELL cases, that is, for circular vs elliptic 25-year lifetime disposal orbits.

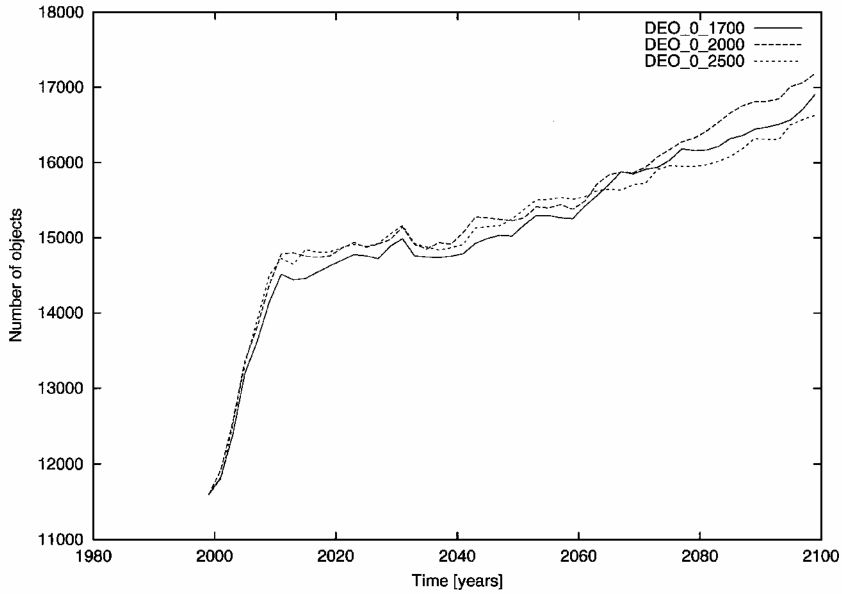

Fig. 5 Number of objects larger than 10 cm for the scenarios with immediate deorbiting of spacecraft with perigee lower than 1400 km and reorbiting into three different storage zones for spacecraft with higher perigee.

method, which accounts for a slight difference between the curves drawn in this figure and those of Fig. 2, which have been calculated with the analytical method; see the description of the SDM code in the preceding section). In terms of the debris growth, the use of a circular or elliptic disposal orbit produces comparable effects. On the other hand, in the next section it will be shown how the elliptical option is much favored from the energetic ΔV point of view. For this reason in all of the following cases, only the deorbiting to elliptical disposal orbits will be considered.

Figure 5 shows the number of objects larger than 10 cm for the three cases where the satellites having perigee lower than 1400 km are immediately deorbited at end of life and those with perigee higher than 1400 km are sent into three different storage zones. In terms of the total number of debris in LEO up to 3000 km, the three scenarios give again comparable results, apparently suggesting that the altitude of the storage zone is not a significant issue. The altitude of the storage zones will be shown to have different consequences whenever examined in terms of collision probabilities in the next decades (Figs. 6–8) and in terms of ΔV. With the accumulation of objects in the storage zones (and the subsequent collisions), as opposed to what was seen in Fig. 2, the debris larger than 10 cm keep growing, even though at a low pace. Similar results are obtained if the objects larger than 1 cm and 1 m are considered.

Therefore, if the only aim is the limitation of the debris growth the scenarios where only deorbiting is considered have to be chosen. On the other hand, in the next section it will be shown that the use of only deorbiting might not be convenient from a practical point of view.

As will be shown in the next section, the adoption of a fixed threshold for the perigee, discriminating between the spacecraft to be deorbited and those to be reorbited, is not a realistic assumption. Therefore, the following figures refer to the scenarios where the choice between deorbiting and reorbiting is automatically performed by the code, according to the lowest ΔV required by the necessary maneuver.

Figure 9 is similar to Fig. 5, but now the less ΔV demanding maneuver is chosen between deorbiting and reorbiting. The behavior is similar to that of the case with fixed threshold, but here slightly larger numbers for all of the three cases can be noted. These increased numbers are because, as it will be shown in the next section, the reorbiting maneuver becomes often more energetically convenient, so that more objects are accumulated into the storage zones. Figure 10

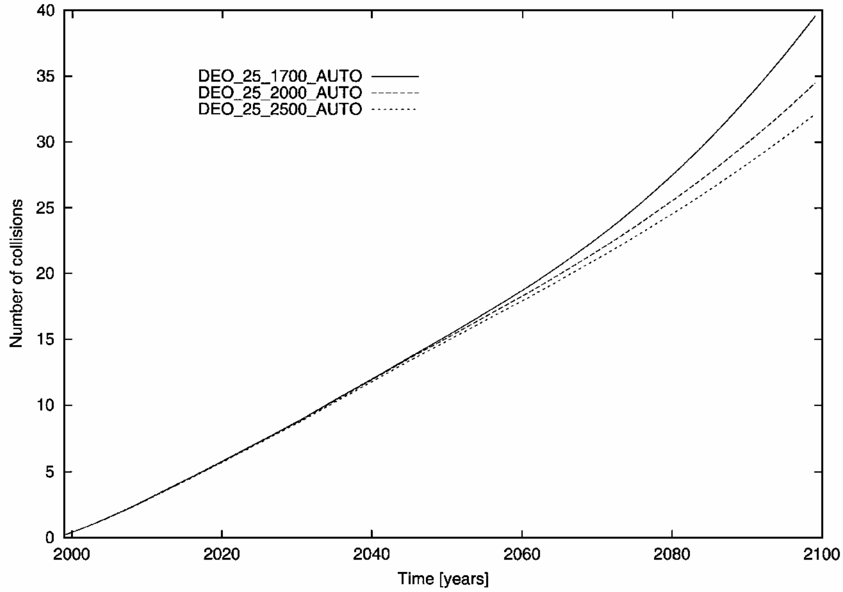

Fig. 6 Cumulative collision probability between objects larger than 10 cm with the adoption of the three different storage zones and of the 25-year residual life disposal orbit.

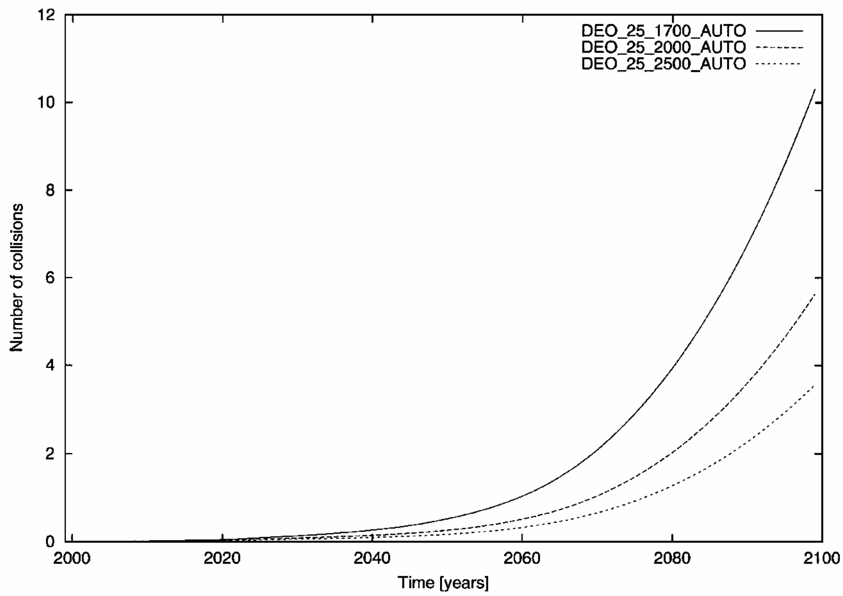

Fig. 7 Same as Fig. 6, but for the altitude band between 1700 and 3000 km.

is the same as Fig. 9, but now the disposal orbit has a 25-year residual lifetime. The pace of the debris growth is similar in the two figures. In Fig. 10, note that the three cases are now closer because the reorbiting and deorbiting solutions are energetically closer. In fact, the 25-year disposal orbit is easier to reach than the immediate deorbiting option. A similar result is obtained for the 1-m objects. Figures 9 and 10 show the number of objects larger than 10 cm in the cases where the same storage zones are considered, along with different residual lifetimes for the disposal orbits. Comparing these two figures, note how the final number of objects larger than 10 cm is not much influenced by the use of the two different types of disposal orbits. In particular, the adoption of a 25-year lifetime just slightly increases the final number of particles for the 2500-km storage orbit, with respect to the immediate deorbiting case. This behavior was already noted studying the scenarios where the 1400-km fixed threshold was imposed on the perigee (for example, see Fig. 2).

Figure 11 shows the number of objects larger than 1 m (that is, mainly satellites and upper stages) in the DEO_0_2500 and DEO_0_2500_AUTO cases. The reason for the large difference is that, when the very demanding maneuver necessary to immediately deorbit a satellite is required, the choice of the storage zone becomes more energetically convenient. Therefore more satellites accumulate in the storage zones, giving way also to additional collisions (discussed later).

From the results shown in Figs. 1–5 and 9–11, one could draw two obvious conclusions. First, the sooner the deorbiting is performed the better it is for the debris environment. Second, if the adoption of a LEO storage zone is foreseen the choice of the altitude of the storage has little influence on the 100-year evolution of the debris population. In the next section the first conclusion is shown to hardly face the reality of cost-effective space operations.

The second conclusion is put into a different perspective by the results shown in Figs. 6–8. In Fig. 6 the cumulative collision probability (that is, the expected number of collisions) over 100 years between objects larger than 10 cm is shown. The scenarios with the three different adopted storage zones are compared. With our choice of the fragmentation thresholds, a collision between objects larger than 10 cm leads to the complete destruction of the target. It can be noted how the accumulation of objects in the lower storage zones leads to an increased collision probability in LEO with the three scenarios now clearly separated. This increased risk is more apparent

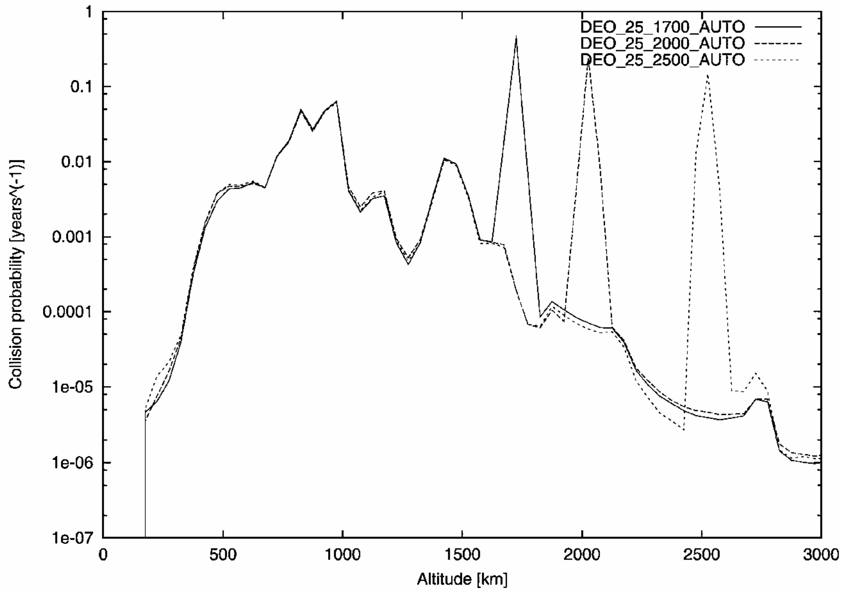

Fig. 8 Collision probability, as a function of altitude between particles larger than 10 cm in the year 2100 for the scenarios with different storage zones and 25-year residual life.

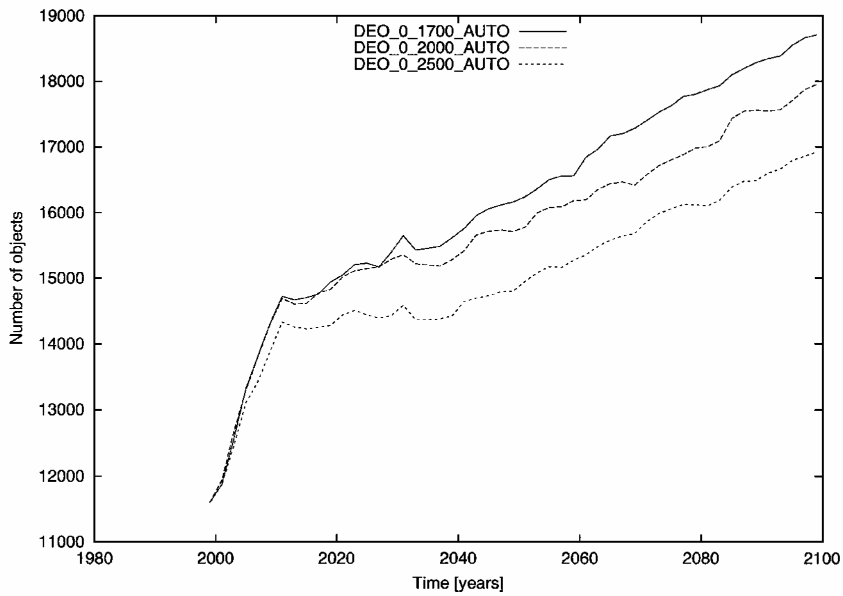

Fig. 9 Same as in Fig. 5, but now in the scenarios where the choice between reorbiting and deorbiting is made on the basis of the lowest ΔV maneuver.

if the cumulative collision probability is shown for the altitude band between 1700 and 3000 km (Fig. 7). The responsibility of the objects reorbited into the storage zones for the increased number of expected collisions is shown. In particular, the storage zone above 1700 km is clearly the most dangerous in the long run.

Figure 8 shows the collision probability in year 2100, as a function of altitude. The peaks corresponding to the simulated storage zones exceed the values of any other altitude. This figure confirms the danger posed by the accumulation of the objects in the LEO storage zones, for the long-term stability of the debris environment. The decreasing altitude of the peaks with growing altitude of the storage zones confirms the results of Fig. 7. Under the light shed by Figs. 6–8, the results of Fig. 12 can be interpreted. In Fig. 12 the number of objects larger than 1 cm in three scenarios with different storage altitudes is shown. The increase, around the year 2070 in the case with a 1700-km altitude storage zone, could be the sign of the collisions starting to take place as a result of the accumulation of objects. To prove this statement clearly, an analysis on a longer time span is needed.[13] Figures 6–8 warn that the future exploitation of the altitude bands devoted to the storage of reorbited spacecraft could be jeopardized if not completely compromised.

ΔV Cost

By using a realistic traffic scenario, such as the one simulated in this paper, it is possible to establish how the theoretical mitigation measures act "in the real world" (that is, how they can face the reality of cost-effective space operations). As noted, the immediate deorbiting of the spacecraft of course would ensure the best results in terms of debris mitigation. These results are depicted in the DEO_0 scenario. In this case approximately 4900 satellites are directly sent into the atmosphere, immediately after the end of life, within the 100-year time span. This deorbiting is done by a single maneuver performed at apogee, with a ΔV given by Eq. (3). The average ΔV required by these deorbiting maneuvers is $\overline{\Delta V} = 248 \pm 111$ m/s. Out of these 4900 spacecraft, 850 are satellites in highly elliptical orbits (Molnyia and GTO) for which a $\overline{\Delta V} = 49 \pm 23$ m/s is required, and 4050 are satellites in LEO with a $\overline{\Delta V} = 289 \pm 69$ m/s. The smaller maneuver required by the highly elliptical orbits is caused by their low perigee altitude. In addition to these deorbited satellites, about 2650 geostationary satellites are reorbited into the storage orbit with $\overline{\Delta V} = 9 \pm 0.0008$ m/s. This value is the same for all of the simulated scenarios. (No differences in the GEO mitigation measures have been examined.)

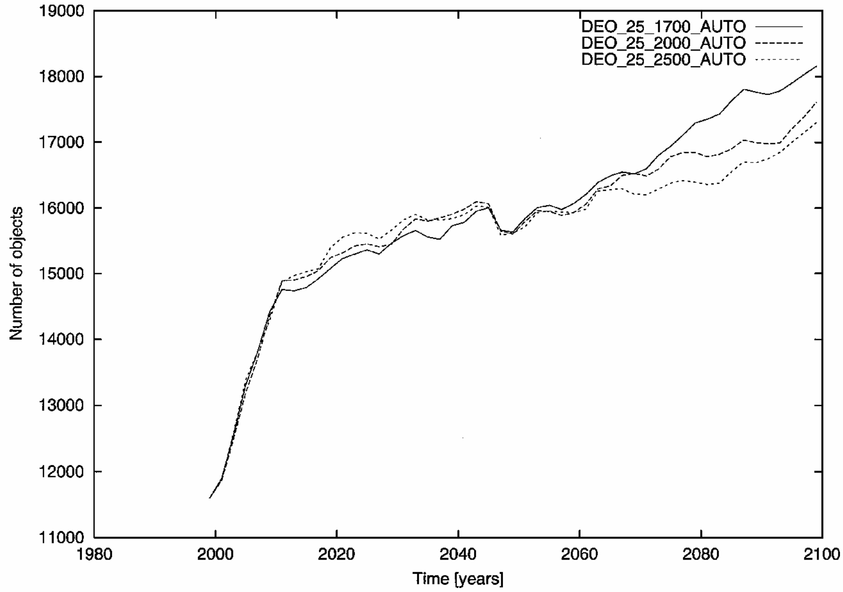

Fig. 10 Same as in Fig. 6, but with the residual lifetime of the disposal orbit set to 25 years.

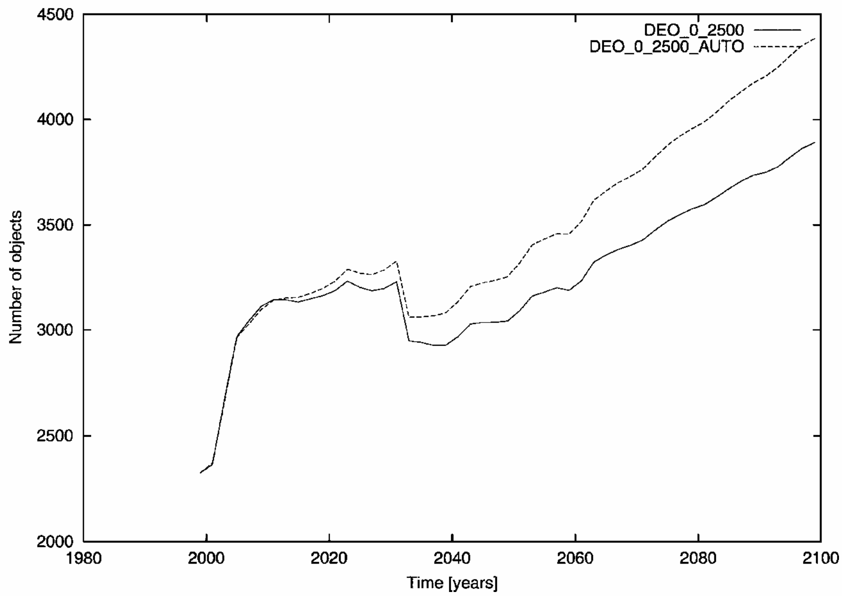

Fig. 11 Number of objects larger than 1 m with immediate deorbiting at end of life and storage zone above 2500 km. Comparison between the DEO_0_2500 and DEO_0_2500_AUTO cases.

As shown in the preceding section, the deorbiting into orbits with a residual lifetime of 25 years gives comparable results in terms of the debris growth, with respect to the case of immediate deorbiting. First, consider the case in which the satellite is moved to a circular disposal orbit (DEO_25), that is, the case described by Eq. (6). In this case about 4850 satellites are deorbited; 18% are in highly elliptical orbits with $\Delta V = 2268 \pm 397$ m/s and 82% are in LEO with $\Delta V = 286 \pm 140$. It is quite obvious that trying to move a satellite from a highly elliptical orbit into a low circular orbit is not a clever way to handle the problem, and the huge ΔV testifies to this. Moreover this case is disadvantageous, even for LEO satellites, with respect to the 0 residual lifetime case. On the other hand, consider the scenario (DEO_25_ELL) where the satellites are sent into an elliptical disposal orbit. Out of the about 4850 deorbited objects, the 17% originally on highly elliptical orbits require a $\Delta V = 35 \pm 19$ m/s, whereas the 83% originally in LEO require a $\Delta V = 201 \pm 79$ m/s. Therefore, in this more realistic case a significant improvement of about 28% for the highly elliptical orbits and of about 30% for the LEO ones is noted, with respect to the DEO_0 case.

Going to the cases with a residual lifetime of 50 years, a further reduction is obtained in the values of the ΔV. In the DEO_50_ELL scenario the ΔV required to deorbit the spacecraft in highly elliptical orbits reduces to 31 ± 19 m/s. For the LEO satellites in the circular disposal case the ΔV becomes 253 ± 140 m/s, whereas in DEO_50_ELL it becomes 187 ± 83 m/s, with about a 7% savings with respect to the DE0_25_ELL case. Remember that the almost exponential profile of the atmospheric density makes, accordingly, highly nonlinear the difference in semimajor axis (and therefore in ΔV) of the disposal orbits of the different lifetime cases. The savings obtained when moving from 25- to 50-year residual lifetime are therefore limited. This finding suggests the keeping of the more stringent option of a lower residual lifetime to avoid a possible overcrowding of the LEO region as a result of a large number of long-lived disposed spacecraft.

The preceding results point out that the idea of deorbiting the old spacecraft into circular LEOs, even though this might present some advantages from the point of view of debris management, is definitely not convenient from the operational point of view. These operational disadvantages are the reason why in all of the following cases, simulating the use of LEO storage zones, only deorbiting into elliptical orbits will be assumed.

If the possibility to reorbit the highest LEO satellites into a storage orbit is introduced, the ΔV situation again changes significantly. Table 2 summarizes the results of the scenarios where the satellites are either sent directly into the atmosphere after the end of life if their perigee is lower than 1400 km, or they are reorbited into a storage orbit if their perigee is higher than 1400 km. As pointed out in the preceding section, three different storage zones have been considered: above 1700 (DEO_0_1700), 2000 (DEO_0_2000), or 2500 km (DEO_0_2500). First, as expected, raising the limit of the storage zone increases the required ΔV accordingly. As shown in Fig. 7, the 1700-km limit for the storage zone, although obviously advantageous from an energetic point of view, could represent a danger from the point of view of the safe exploitation of LEO space if many spacecraft are left in that zone during the next decades. All of the satellites moved into the storage zones, in these three scenarios, were originally orbiting in nearly circular LEOs. In fact the limit on the perigee excludes all of the highly elliptical orbits that have their perigee below 1400 km. Therefore all of the satellites in highly elliptical orbits are deorbited, which is not necessarily a good choice from an energetic point of view. The results for the deorbiting are almost the same in the three cases because what is different between these scenarios is only the limit of the storage zone. All of the objects with the perigee below 1400 km are deorbited, and these objects have the same characteristics in the three cases. These results can be compared with those referring to the scenarios where only the deorbiting was foreseen. The scenarios with storage zones above 1700 and 2000 km are favored, in terms of ΔV, with respect to the immediate deorbiting one (DEO_0). For the storage zone above 1700 km, the caveat about the growing risk of accumulation of spacecraft in that area holds. The DEO_0_2000 scenario still allows a savings of about 16% with respect to the DEO_0 case. On the other hand, the DEO_0_2000 requires about 18% more ΔV than the case where only the deorbiting to a disposal orbit with residual lifetime of 25 years (DEO_25_ELL) is performed. Comparing Figs. 2 and 5, note how the disposal into a 25-year lifetime orbit gives better results even from the debris management point of view with respect to the case DE0_0_2000. Therefore, even with the adoption of the storage

Table 2 Summary of the deorbiting and reorbiting maneuvers in the fixed perigee threshold scenarios

Maneuver type and ΔV	DEO_0_1700	DEO_0_2000	DEO_0_2500
Satellites moved to storage	1195	1313	1034
ΔV_{gr}	101 ± 39	214 ± 52	408 ± 56
Deorbited satellites	3549	3683	3573
ΔV_{deo}	210 ± 101	207 ± 102	206 ± 102
Highly elliptic	808	874	851
ΔV_{ell}	50 ± 25	49 ± 23	49 ± 24
LEO	2741	2809	2722
ΔV_{LEO}	258 ± 57	257 ± 57	255 ± 58

zones, the immediate deorbiting of spacecraft is still energetically less convenient than the delayed reentry option. Already at this point the storage zone above 2500 km appears too far, from an energetic point of view, from most of the orbits with perigee in the LEO region.

As already explained, to have a more realistic simulation of the deorbiting/reorbiting scenarios the possibility to choose automatically between the less expensive option, in terms of ΔV, between reorbiting into a storage zone or deorbiting into a disposal orbit has been implemented. The scenarios simulated with this automatic choice considered two different residual lifetimes (0 and 25 years) and three different storage zones (again above 1700, 2000, and 2500 km).

Comparing Table 3 with the values of the cases with no reorbiting and with Table 2, first the increased number of objects sent into the storage zones above 1700 and 2000 km can be noted. The zone above 2500 km appears definitely not convenient from an energetic point of view. In particular the lowest storage zone at 1700 km becomes widely used (especially if coupled with the immediate deorbiting option), leading to the accumulation problems discussed in the preceding section. The ΔV in Table 2 have, on average, values lower than the corresponding ones in Table 2. A kind of even redistribution of the values between reorbiting and deorbiting can also be noted. Compared to the case DEO_0, the DEO_0_2000_AUTO option offers an approximate 17% savings in ΔV.

The last three columns of Table 3 show that the adoption of the 2000-km storage zone, coupled with the 25-year lifetime disposal orbits, reduces the average ΔV for all of the required maneuvers (deorbiting and reorbiting) to about 150 m/s. This value represents an approximate 13% savings with respect to the DEO_25_ELL case, where only the deorbiting was done. Therefore the DEO_25_2000_AUTO case appears the best compromise between mission design and operational constraints and safeguarding the space environment. Figure 13 shows the change in orbital elements (semimajor axis and eccentricity) performed by all of the deorbiting and reorbiting maneuvers in this scenario. The peak in the semimajor axis around the storage limit can be noted. The global lowering of the semimajor axis and the increasing of the eccentricity for the deorbited objects is also noticeable.

Finally remember that, for a given ΔV maneuver, the required amount of propellant is given by

$$R = 1 - \exp\{-[\Delta V/(I_{sp} \cdot g)]\} \tag{8}$$

Therefore, assuming a typical specific impulse of 250–300 s, a ΔV of 200 m/s, for example, requires between 8 and 7% of the spacecraft mass as propellant. That is, looking at Table 3, for a satellite of about 1000 kg, the implementation of the mixed mitigation measure "25-year disposal + 2000 km storage zone" would imply the use of

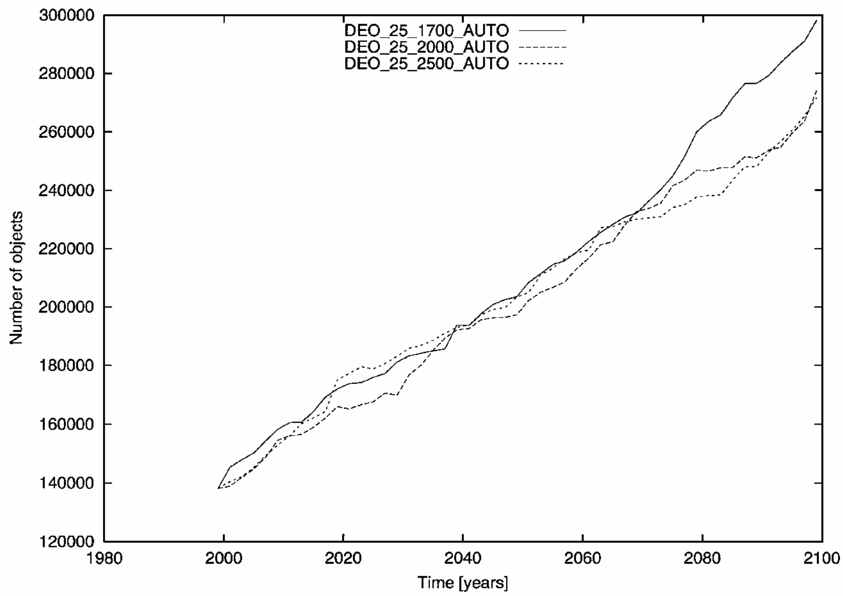

Fig. 12 Same as Fig. 10, but for particles larger than 1 cm.

Table 3 Summary of the deorbiting and reorbiting maneuvers in the ΔV optimized scenarios

Maneuver type and ΔV	DEO 0_1700 AUTO	DEO 0_2000 AUTO	DEO 0_2500 AUTO	DEO 25_1700 AUTO	DEO 25_2000 AUTO	DEO 25_2500 AUTO
Satellite moved to storage	2664	2161	339	1962	1106	151
ΔV_{gr}	153 ± 71	232 ± 60	330 ± 32	119 ± 42	193 ± 57	302 ± 28
Highly elliptic	87	81	0	66	70	0
ΔV_{gr-ell}	55 ± 3	80 ± 2	——	54 ± 3	79 ± 2	——
LEO	2577	2080	339	1896	1036	151
ΔV_{gr-LEO}	156 ± 70	239 ± 53	330 ± 32	122 ± 41	200 ± 50	302 ± 28
Deorbited satellites	2180	2742	4532	2705	3656	4719
ΔV_{deo}	148 ± 81	178 ± 89	237 ± 107	100 ± 61	137 ± 83	167 ± 93
Highly elliptic	777	751	852	782	826	849
ΔV_{ell}	45 ± 20	45 ± 20	50 ± 23	30 ± 13	30 ± 13	35 ± 19
LEO	1403	1991	3680	1923	2830	3870
ΔV_{LEO}	205 ± 26	228 ± 41	280 ± 63	129 ± 49	168 ± 68	197 ± 76

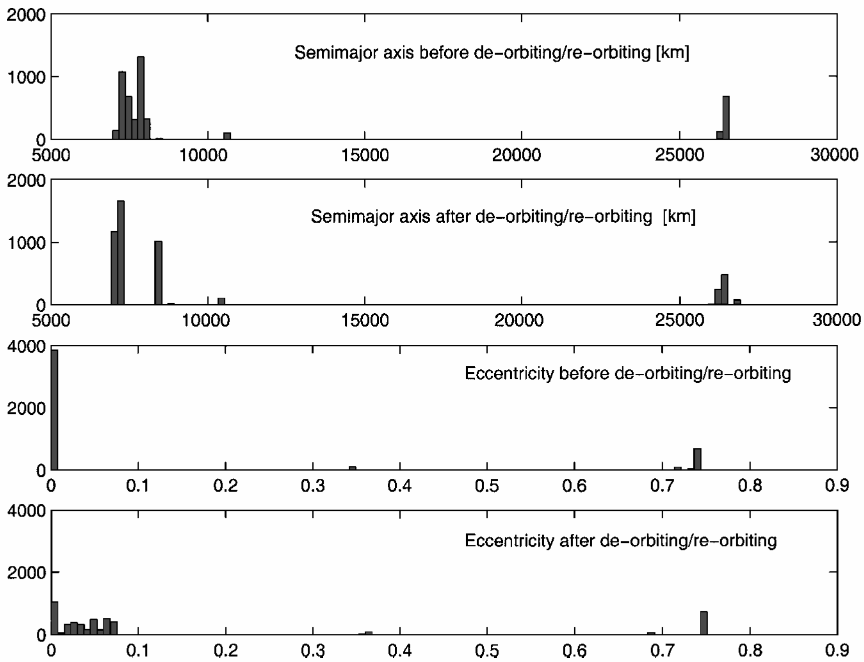

Fig. 13 Change in the semimajor axis and eccentricity of the population of deorbited or reorbited objects in the DEO_25_2000_AUTO scenario.

about 80 kg of propellant as a maximum. In Ref. 5 it is noted that, for example, a French Spot satellite, devoted to Earth observation, carries about 150 kg of propellant for its entire lifetime. Taking into account these numbers, the best possible strategy for the removal of spacecraft at end of life from the crowded LEO regions has to be sought to cope with the needs of the different missions.

From Table 3 and Eq. (8) it can be pointed out that still a significant amount of propellant is required to comply with the proposed mitigation measures. All of the preceding calculations have been done assuming conventional impulsive thrusters. The adoption of electric propulsion systems could change the picture by lowering the amount of propellant needed to perform a given maneuver.[16] For example, in Ref. 5 it is pointed out that to deorbit a satellite from a 1500-km altitude circular orbit the adoption of the electric propulsion would lead to a savings of ~80% of propellant mass. The problems (such as longer disposal time or efficiency of the thrusters in presence of atomic oxygen in LEO) and the advantages related to the adoption of this propulsion system will be further investigated in a future work.

Conclusions

The need for measures to reduce the growth of debris in LEO is presently well understood. The deorbiting of the upper stages and the spacecraft at end of life (together with stopping in-orbit explosions) is shown to stabilize the population of orbiting debris. The use of different LEO storage zones will still guarantee a low 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.

Therefore the adoption of the storage zones, even though useful from an energetic point of view, could be a shortsighted solution. In the last section the cost in terms of ΔV related to the different proposed mitigation measures has been analyzed. If practical considerations have to be considered, beyond the fundamental debris minimization issue the adoption of a mixed strategy with the disposal of spacecraft into orbits with a residual lifetime of 25 years and the reorbiting into a LEO storage zone above 2000 km appears to be a compromise between practical mission operation issues and space debris management issues. Nonetheless the hazards related to the adoption of such a mixed policy, as a result of the accumulation of objects in the storage zone, must be again stressed. Ideally, the storage zones could be only a temporary solution, before technological improvements (such as a widespread electric propulsion onboard the spacecraft) could make the deorbiting of all of the spacecraft viable.

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