STRATEGIES FOR ACTIVE REMOVAL IN LEO

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1. ABSTRACT

Some recent studies on the future evolution of space environment suggest that the number of objects in orbit might be unstable [1, 2]. Instability means that the population of objects in space will grow even when no further objects are added to space (i.e. no launches, no fragmentation events). This growth is mainly due to collisions caused by fragments generated by other collisions (so-called feedback collisions). This kind of instability indicates that the existing and currently proposed mitigation measures are not sufficient to stop the increase of space debris even when they are strictly implemented. In the past years, the idea of actively removing objects from space has been raised in order to improve the tendency. Active removal (AR) implies robotic missions with the capability to dock to completely passive spacecraft or rocket bodies and to bring them into an orbit with significantly reduced lifetime.

It can be expected that the evolution of the environment depends very much on the orbital region in which the removal missions will operate and on the type of objects removed. However, existing studies on active removal have not yet identified target regions and candidate objects so far. Another important factor will be the time in which removal activities begin. It is probable that the number of missions per year or decade can be reasonably limited when the time distribution is optimized. So far there seems to be no real attempt to identify such key parameters. In this paper these key factors will be analyzed.

2. INTRODUCTION

This study analyses the effect of AR for various removal mission scenarios in the space environment for objects larger than 10 cm, which is the limiting size for the tracking of objects by the US Space Surveillance Network. This analysis is done based on a no-further-release scenario, which considers launches and explosions to stop. This scenario constitutes a "best case" of evolution because only the objects already in space are taken into account, and in an explosion free environment. If AR is not effective in this scenario, it is not going to be effective in the real environment. In a validation phase, other scenarios will be considered. The business-as-usual (BAU) scenario reflects a future evolution where the launches and explosions follow the same traffic model of the last 8 years, with the inclusion and maintenance of constellations (Iridium, Orbcomm and Globalstar), and with no mitigation measures implemented. Variations can be done in the BAU scenario to include mitigation measures as passivation, de-orbiting in 25 years of payloads and rocket bodies below 1300 km of altitude and re-orbiting to a graveyard orbit.

This study is conducted in the LEO (low-earth orbit) region (from 120 km to 2000 km of altitude) for a time span of 200 years (from 2006 until 2206). The original population for the study is derived from the MASTER-2005 population. At the beginning of 2006, there were about 14000 objects larger than 10 cm orbiting or intersecting the LEO region. From these, about 2000 were operational payloads, 2000 more were rocket bodies and operational debris, and the rest were explosion fragments (around 10000). However, 86% of the mass of objects in LEO corresponds to the payloads and rocket bodies, which cover only 15% of the cross-sectional area. The explosions, collisions and launches that have occurred since 2006 have increased the population in a significant way which is not reflected in the study.

The tool used in the study is the ESA Debris Environment Long-Term Analysis (DELTA) software, developed by QinetiQ. The most recent available version is v3.0, completed in February 2006. DELTA is a three-dimensional, semi-deterministic model, which in its entirety allows a user to investigate the evolution of the space debris environment and the associated mission collision risks in the low, medium and geosynchronous Earth orbit regions over the future. DELTA is able to examine the long-term effects of different future traffic profiles and debris mitigation measures, such as passivation and disposal at end-of-life. This version has been modified to add the active debris removal capabilities. The current version is therefore v3.1.

DELTA uses an initial population as input and forecasts all objects larger than 1 mm in size. The population is described by representative objects, evolved with a fast analytical orbit propagator which takes into account the main perturbation sources. The high fidelity of the DELTA model is ensured by using a set of detailed future traffic models for launch, explosion and solid rocket motor firing activity. They are each based on the historical activity of the eight preceding years (1997-2004). The collision event prediction is done by using a target centered approach, developed to stochastically predict impacts for large target objects (mass higher than 50 kg) within the DELTA population. The fragmentation, or break-up, model used is based on the EVOLVE 4.0 break-up model [3].

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The sensitivity of the environment's evolution to the solar flux has been analyzed, since a higher solar flux causes a faster natural reentry of objects leading to a different conclusion on the stability of the environment. For this study, the future solar flux was predicted based on an analysis of all the ancient solar cycles.

First DELTA simulations confirm the instability of the population in LEO. In the BAU scenario without mitigation, an average of 1 million objects larger than 10 cm would be in the LEO region by 2206. The de-orbiting and passivation measures help controlling the population's growth, but after 200 years there would be about 57,000 objects in LEO. If full mitigation was implemented, this population would be reduced to about 30,000 objects. In the no-further-release scenario the population would grow 18%, as shown in fig. 1.

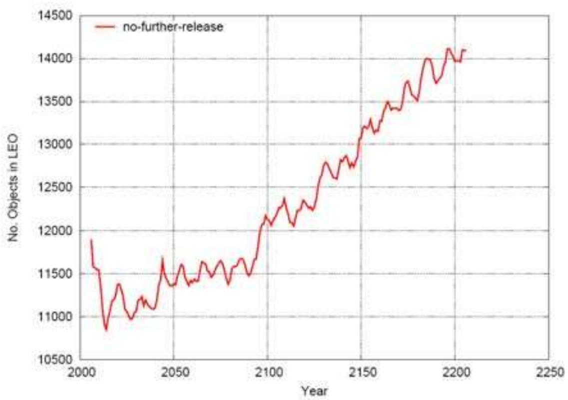

Figure 1. Population evolution in LEO above 10cm in the no-further-release scenario

3. CHARACTERIZATION OF THE LEO ENVIRONMENT

Collisions are the only reason for the growth of the population in the no-further-release scenario. In DELTA, the collision risk is calculated using a target-centered approach, defining as target all the objects with mass over 50 kg. The main parameter to determine whether a collision is catastrophic (thus generating new fragments) or not-catastrophic is the energy-to-mass ratio (EMR):

$$EMR = \frac{0.5 M_p v_{imp}^2}{M_t} \quad (1)$$

The threshold between catastrophic and non-catastrophic is assumed to be 40 kJ/kg. In the worst situation, where the maximal encounter velocity (v_{imp}) can attain 17,5 km/s and the minimum target mass (M_t) is 50 kg, the impactor mass (M_p) found implies a diameter around 4 cm to have a catastrophic collision. The study only considers objects above 10 cm, which is the limiting size for tracking. Therefore, some catastrophic collisions are not going to be simulated.

As the collision probability is a function of the object's cross section, large objects are main candidates for active removal. The most relevant object types hereunder are payloads and rocket bodies, while operational and fragmentation debris are less interesting for three reasons:

- In most cases they have smaller cross-sections than intact objects
- The geometry is unknown, which generates high burdens for the feasibility of a retrieval action
- Low mass implies a low number of fragments generated when a collision occurs

Payloads in LEO fulfill various types of missions. Accordingly, the payload size and shape can vary significantly. Various attitude control types are used, and most of the payloads have solar panels. The most typical payload in LEO is a telecommunication mission with a cylindrical shaped body using 3-axis stabilization and two solar panels. For rocket bodies the mission is irrelevant, the shape is mostly cylindrical, solar panels are not present and the objects are mostly 3-axis stabilized. This large number of commonalities and the fact that a nozzle is an inherent feature make upper stages interesting candidates for active removal.

Fig. 2 and fig. 3 display the distribution of payloads and rocket bodies in LEO according to their area and mass. Rocket bodies tend to be larger, but because they consist of a large volume of empty tanks, their mass distribution seems to follow similar characteristics to those of the payloads.

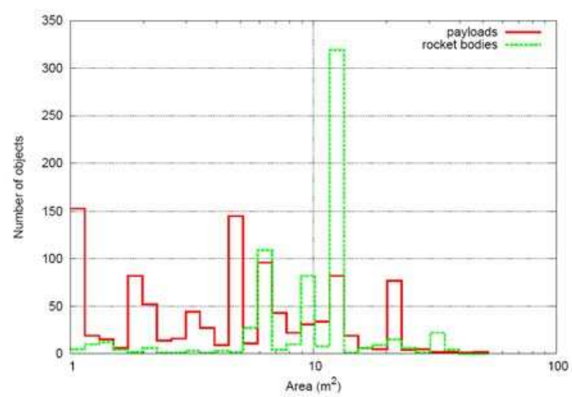

Figure 2. Number of payloads and rocket bodies distributed by area in LEO

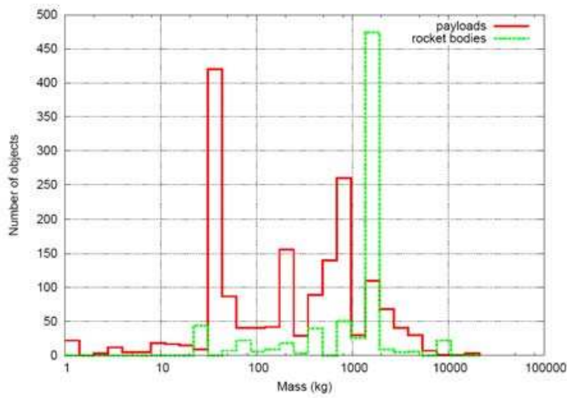

Figure 3. Number of payloads and rocket bodies distributed by mass in LEO

4. IDENTIFICATION OF REMOVAL MISSION TARGETS

In a first approach to active removal missions, based on the no-further-release scenario, the simplest strategies are the selection of the objects by their mass or area in any orbit of the LEO region, taking the biggest ones first. However, these strategies are far from a real mission because the objects removed are in different zones of space. Thus a removal vehicle would consume more than accepted to retrieve them, or else one mission per object would be required. In consequence, further optimization is necessary.

A detailed study on the collisions, catastrophic or not, permits to identify their source, their distribution in space (altitude, inclination, eccentricity) and in time, the characteristics of the colliding objects (mass, area, diameter), as well as the EMR and the velocity of the collision. This knowledge helps to identify groups of objects which are reachable in one or more missions, and also the zones where an active removal seems to be more necessary.

The design of an active removal mission is not in the scope of this study. However, a realistic region is defined for operating a spacecraft able to remove more than one object per mission. Therefore, a margin of 100 km in semi major axis, of 1 degree in inclination and of 10 degrees in RAAN (right ascension of ascending node) is allowed. The geometry of the debris to be removed has to be previously known in order to easily manipulate them. For this reason, only defunct payloads and rocket bodies (upper stages) are considered for removal.

Fig. 4 shows the distribution of the catastrophic collisions in altitude and inclination after 200 years in the no-further-release scenario.

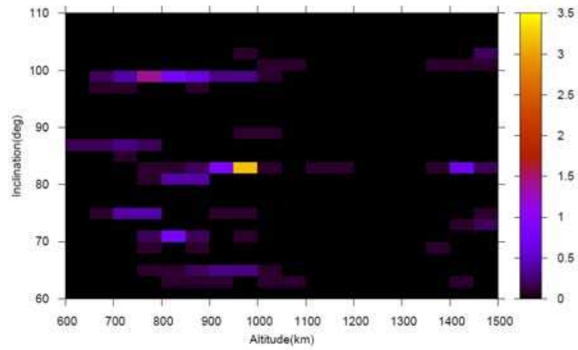

Figure 4. Number of catastrophic collisions vs. altitude vs. inclination of the targets after 200years in the no-further-release scenario

Based on the analysis of the collisions, as well as on the object properties, some regions have been selected as candidates for active removal:

- alt = 1000km±100km, inc = 82°±1°

In this region the largest number of catastrophic collisions will occur in 200 years. It seems to be less frequently used today but the objects in this region have a long orbital lifetime. Moreover, the spatial density is high and it keeps on growing. 290 objects are susceptible to be removed inside the orbital region defined above. Most of them are satellites from the same constellation, which could facilitate the removal. The problem could be the almost equally dispersed nodal lines.

- alt = 800km±100km, inc = 99°±1°

The inclination of this region corresponds to sun-synchronous orbits, used for many applications. 140 objects fulfill the criterion in this region. The whole altitude band is almost equally used and the satellites are of different types and shapes, which could make the removal difficult. However, the economic profit of using these orbits makes active removal interesting.

- alt = 850km±100km, inc = 71°±1°

This region contains 40 objects of high cross-section and high mass. Some of the future catastrophic collisions occur here. These collisions generate a lot of fragments due to the high mass, spreading across a highly populated altitude, and the high area increases the probability of collision. The removal of these big objects is therefore recommended.

Two more regions appeared to be interesting but have been rejected for some reasons:

- alt = 750km±100km, inc = 86°±1°

This region is mainly used for a telecommunications constellation, Iridium, and a removal mission could be easily implemented. However, in the current scenario, the predicted number of collisions in this region is not significant and consequently an AR mission would not improve the evolution of the environment. Nevertheless, the collision between Iridium-33 and Cosmos-2251 on February 10, 2009 occurred in this region and generated more pollution. Therefore it could become necessary to consider also this zone for AR.

- alt = 1400km±100km, inc = 82°±1°

This region contains a considerable number of intact objects, most of them satellites of a military constellation. However, the high altitude of this region makes a removal mission expensive and difficult to realize. In addition, the number of collisions predicted is not significant and the growth in the spatial density is low enough to decide not to study AR in this region.

5. COMPARISON OF THE EFFECTIVENESS OF REMOVAL STRATEGIES

The reference scenario to compare the effectiveness of the removal strategies is the one of no-further release of objects in space after 2006. The first strategies tested consist of selecting the targets ranked by mass or by area (starting with the most massive or the largest objects and continue with 5 objects per year). The optimized strategies concentrate on the three regions chosen in section 4 separately. Finally, a combined multi-region strategy is analyzed, in which AR missions are send to all three regions.

Each scenario is carried out with a 200 year projection period and 20 Monte Carlo runs. With this number of runs, dispersion under 7% from the average mean can be assured. Active removal is implemented to start in 2006 and 5 objects are removed each year in a single mission, until no more objects are found in the region. The assumption of an immediate removal of the selected objects is taken, which is the best type of active removal, and the missions are considered to have instantaneous effects (i.e. the 5 objects disappear from space at the same time). For the removal inside the selected regions, the RAAN is set to 100°±10° as initial assumption. If more than 5 objects are inside the region, the ones with highest mass are removed first. Tab. 1 condenses the limits in altitude, inclination and RAAN of the selected strategies (the multi-region changes after every mission to the next region out the three proposed).

Table 1. Altitude, inclination and RAAN limits for the selected strategies

	removal by mass	removal by area	(1000km,82deg)	(800km,99deg)	(850km,71deg)
altitude(km)	0-2000	0-2000	900-1100	700-900	750-950
inclination(deg)	0-180	0-180	81-83	98-100	70-72
RAAN(deg)	0-360	0-360	90-110	90-110	90-110

Fig. 5 shows the evolution in time of the effective number of objects above 10 cm in LEO. To quantify the effectiveness of each strategy after 200 years, tab. 2 shows the number of objects removed for each strategy, the reduction in the number of objects due to AR compared to the reference scenario, and the relationship between them. This relation means for example that for every object removed in the multi-region strategy, a reduction of 8.77 objects is gained after 200 years. It shows also the increase or decrease in % over the initial population and the time taken until all the objects are removed.

The no-further-release scenario predicts a growth of 18% in the population in the next 200 years. The three scenarios in which AR is individually applied to the selected regions are able to reduce the population's growth but not to stop it. However, the multi-region AR is able to stabilize the population and reduce the number of objects in LEO with a limited number of missions. The two other scenarios, with selection according to a mass or area ranking in any region of LEO, seem to work better, but the overall number of objects removed is much larger because the missions are not optimized. In fact, with the mass selection strategy, in 200 years 1000 payloads and rocket bodies with mass above 450 kg will have been removed and with the area selection strategy, 1000 objects with cross-section above 3.08 m^2.

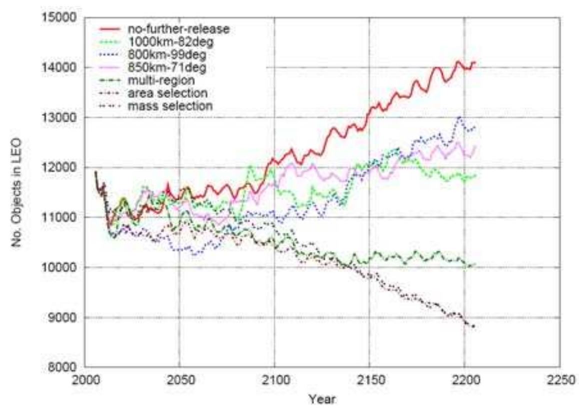

Figure 5. Evolution of population above 10cm in LEO for no-further-release scenario, for AR in 1000km-82°, for AR in 800km-99°, for AR in 850km-71°, for multi-region AR (switch to different region after every mission), and for AR selecting by mass or by area in any place of LEO.

Table 2. Objects removed, reduction in number of LEO objects and population growth after 200 years for the proposed AR strategies, and removal time.

	(1000km,82deg)	(800km,99deg)	(850km,71deg)	multi-region	removal by mass	removal by area
Reduction in # objects (a)	2238.73	1298.18	1634.61	4025.94	5257.61	5276.95
# AR objects (b)	288.15	141.75	45.00	459.20	1000.00	1000.00
Object reduction/AR objects (a/b)	7.77	9.16	36.32	8.77	5.26	5.28
Population growth %	-0.64	7.25	4.43	-15.63	-25.84	-26.12
Years with AR missions	75	53	19	150	200	200

Another way to measure the effectiveness of AR is to examine the collision activity as a function of time (fig. 6). The no-further-release scenario shows a linear growth for the cumulative number of collisions, reaching 20.7 in 200 years. All the other scenarios have a better tendency, as expected. To quantify the effectiveness of each strategy in a 200 years period, tab. 3 shows the number of objects removed for each strategy, the reduction in the number of catastrophic collisions due to AR compared to the no-further-release scenario, and the relationship between them. This relationship shows for example that for every 64.68 objects removed in the multi-region strategy, a reduction of 1 collision appears after 200 years.

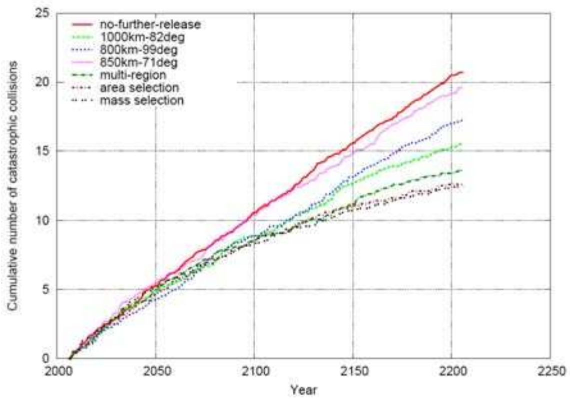

Figure 6. Cumulative number of catastrophic collisions for no-further-release scenario, for AR in 1000km-82°, for AR in 800km- 99°, for AR in 850km-71°, for multi-region AR (switch to different region after every mission), and for AR selecting by mass or by area in any place of LEO.

Table 3. Objects removed and reduction in number catastrophic collisions after 200 years for the proposed AR strategies.

	(1000km,82deg)	(800km,99deg)	(850km,71deg)	multi-region	removal by mass	removal by area
Reduction in # collisions (c)	5.20	3.30	1.10	7.10	8.30	8.00
# AR objects (b)	288.15	141.75	45.00	459.20	1000.00	1000.00
AR objects/collision reduction (b/c)	55.41	42.95	40.91	64.68	120.48	125.00

This analysis of the results shows that an active removal of a few objects in selected regions is more effective than a general selection based just on the objects' mass or area. In addition, in the simulation of the AR missions in the selected regions some constraints were imposed to make them more realistic, while the mass or area selection ignored the fact that realistic missions have a limited activity range in terms of inclination, altitude and RAAN. It can be confirmed that the selected regions play an important role for the evolution of the space environment and that AR is a possible way to stabilize the environment and reduce the number of objects in LEO. Quantitatively, the removal in the 850km-71° region is the most efficient, with the best ratio of collision and objects reduced to the objects removed. However this strategy is unable to stop the growth of the population. The multi-region strategy, less efficient but promising, is consequently a good option as it reduces significantly the population and still has twice the efficiency of the mass or area selection strategies. Nonetheless, the removal of a large number of objects seems to be far from feasible and the time of removal is longer than expected since not all missions can remove 5 objects, due to the limitations of the operating range. Therefore, a second step will be studied in the following in order to avoid unnecessary missions.

6. ROBUSTNESS OF THE PROPOSED STRATEGIES

Once the effectiveness of AR in selected regions is validated, some variations are made in the original scenarios to test their robustness and continue with the optimization process. The starting date of active removal missions is varied to study the effect of delays in the development of active removal missions. Also the number of objects removed per mission is modified, to check its impact in the evolution of the environment.

As an exemplary study case, the analysis is focused in the region of 1000 km altitude and 82 degrees inclination since this is the region where more objects can be removed (290 object meet the criteria) and the impact of the removal is more visible in the results, as seen in the precedent section. The RAAN constraint is removed in this example (i.e. the selection does not take into consideration the RAAN of the object) in order to avoid missions in which the target of 5 objects is not reached, thus being able to effectively compare the situations.

Fig. 7 and fig. 8 display the evolution of the population and the number of collisions when AR starts in different epochs (2006, 2020, 2040, 2060 and 2080) with a removal rate of 5 objects per year. The results show that delaying the start of the active removal missions will lead to a decrease of the effectiveness of AR after a certain turn-over point in a few decades. From the simulations, the three cases starting up until 2040 are quite similar and only a slight increase between them appears for those starting later. However, the strategies starting AR in 2060 or later are less efficient and the situation progressively worsens.

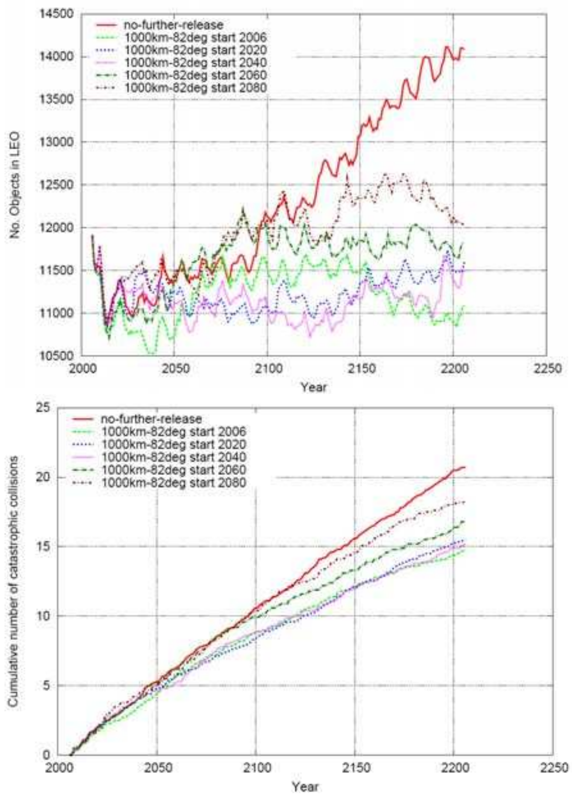

Figure 7 and 8. Evolution of population above 10cm in LEO and cumulative number of catastrophic collisions for AR in 1000km-82° of 5 objects/year starting in 2006, 2020, 2040 and 2080.

Fig. 9 and fig. 10 display the evolution of the population and of the number of collisions for the variation of the number of objects removed per year (1, 3, 5, 10 and 20), with the removal starting in 2006. The results are almost identical for removal rates of 5 objects/year or more. In fact, there are 290 objects fulfilling the conditions for AR in this region, corresponding to 58 years of AR missions at 5 objects/year, meaning that the end of the removal is foreseen in 2064. It seems that there is also a turn-over point in the number of objects removed per year above which further optimization effects become negligible. This seems to be the case at 5 objects/year. The rate of 3 objects/year seems to be worse in terms of collisions, but as the first objects removed are those with higher mass, the collisions generate fewer fragments and after 200 years the number of objects is only 5% higher than in the simulations where more objects are removed. One object/year seems to be insufficient to satisfy the active removal objectives, as the removal is too slow and not all the objects in this region are removed (although the objects with highest mass are).

The two turn-over points are related: if AR missions start later in time, more objects will have to be removed to have the same effectiveness, thus increasing the cost or complexity of the missions. This means that efforts will have to be intensified as the later AR missions begin, the harder it becomes to avoid a cascading effect with exponential growth of the population.

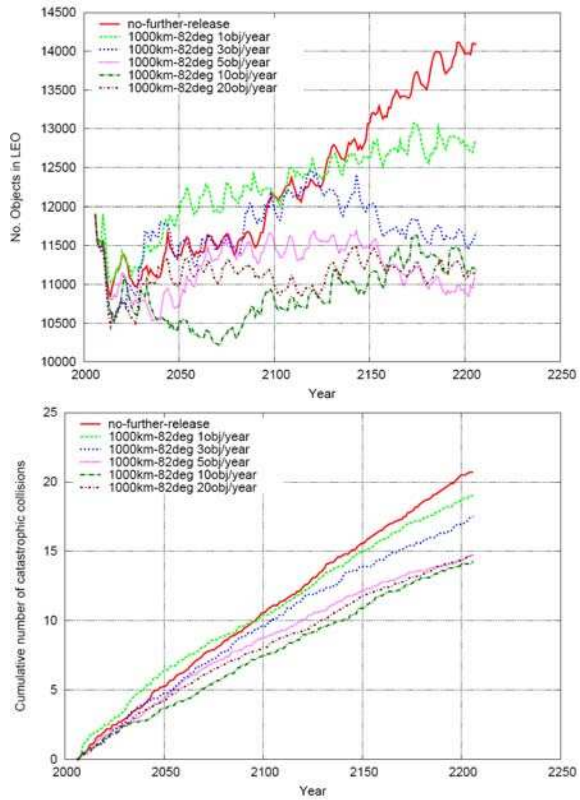

Figure 9 and 10. Evolution of population above 10cm in LEO and cumulative number of catastrophic collisions for AR in 1000km-82°, starting in 2006, of 1 object/year, 3 objects/year, 5 objects/year, 10 objects/year and 20 objects/year.

Having seen the influence of the starting time and the removal rate, the last step of the optimization process consists on applying the results to the best AR strategy analyzed, the multi-region approach. The difference between the scenarios studied in this chapter and the multi-region strategy of section 5 consists on the RAAN margin assumptions. In reality, the RAAN variation that a spaceship is able to reach through drift depends on the altitude, on the inclination and on the time spent in orbit:

$$\frac{d\Omega}{dt} = -\frac{3}{2} J_2 n \left(\frac{R_e}{p} \right)^2 \cos i \qquad (2)$$

Focusing on the three selected regions and executing one mission per year (i.e. considering that the mission's duration can be up to one year), the reachable RAAN band is ±50° for the 1000km-82° region, ±20° for the 800km-99° region and ±70° for the 850km-71° region.

The objects in the regions are then selected and removed taking into account the optimization of the ΔV consumption. This scenario is much more realistic and it reduces the number of missions with few objects, therefore taking less time to remove the targeted objects. In order to limit the number of missions even further and avoid extra costs, the minimum mass for a removed object is fixed to 1000 kg. This AR strategy is tested based on the no-further-release scenario, starting in 2006, and removing 5 objects per year.

In addition, a variation on this strategy is done, starting the active removal at the more realistic date of 2020. Finally, to be even more realistic, it is considered that a mission meant to remove 5 objects can not actively de-orbit them. Instead, it is assumed that a device accelerating the natural decay process is attached onto the targets (tether, balloons, sails …). It is further assumed that the decay will take 25 years.

The results in terms of number of objects (fig. 11) and number of collisions (fig. 12), as well as the quantitative results in tab. 4 show that even the more realistic scenario fulfills its objectives, reducing the number of missions, thus the objects removed, in less time and without a significant increase in the final number of objects and collisions. The efficiency of these strategies is consequently much better than in the first proposed strategies. The strategy with a lifetime limitation of 25 years and starting in 2020, the one closest to a possible AR mission, does not differ too much from the one with immediate removal, and it is able to stabilize and reduce the population.

Table 4. Quantitative results for the tested multi-region strategies (AR in 3 regions, changing the region after every mission, removal of 5objects/year): starting in 2006 with fixed RAAN (100°±10°) and no mass limit; with mass limit of 1000kg and reachable range RAAN selection; starting in 2006 and in 2020, and with lifetime limitation of 25 years starting in 2020.

	multi-region (fixed RAAN)	r. range RAAN, start 2006	r. range RAAN, start 2020	r. range RAAN, start 2020, lifetime 25 years
Reduction in # objects (a)	4025.94	3500.09	3065.50	2899.24
Reduction in # collisions (c)	7.10	6.60	6.30	5.20
# AR objects (b)	459.20	237.60	236.40	235.80
Object reduction/AR objects (a/b)	8.77	14.73	12.97	12.30
AR objects/collision reduction (b/c)	64.68	36.00	37.52	45.35
Population growth %	-15.62	-11.07	-7.57	-6.02
Years with AR missions	150	60	60	60

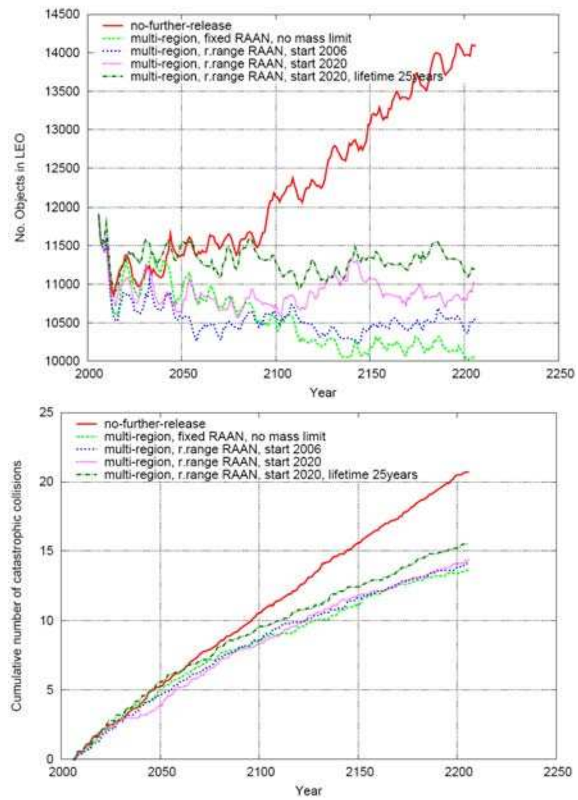

Figure 11 and 12. Evolution of population above 10cm in LEO and cumulative number of catastrophic collisions for multi-region AR with fixed RAAN (100°±10°) and no mass limit, and with mass limit of 1000kg and reachable range RAAN selection, starting in 2006 and in 2020, and with lifetime limitation of 25 years.

In a final analysis, the multi-region AR strategy is checked in a realistic background scenario based on full mitigation (passivation, de-orbiting of objects below 1300 km of altitude and re-orbiting of objects above it) and AR starting in 2020, replacing the no-further-release scenario. In this case, the premises taken are those of the precedent section (no mass limitation and RAAN fixed at 100°±10°) because the objective is to analyze the impact of a realistic background scenario compared to the previous analyses.

The results (fig. 13 and 14) show that AR is also useful in this case, reducing by half the increase of the number of objects compared to the full mitigation scenario without AR, although the difference is not that large in terms of collisions. Active removal will have to be intensified in reality in another optimization process similar to the one done in the no-further-release scenario in order to fully stop the growth. Nonetheless, the selected AR strategy makes already an improvement to a realistic scenario.

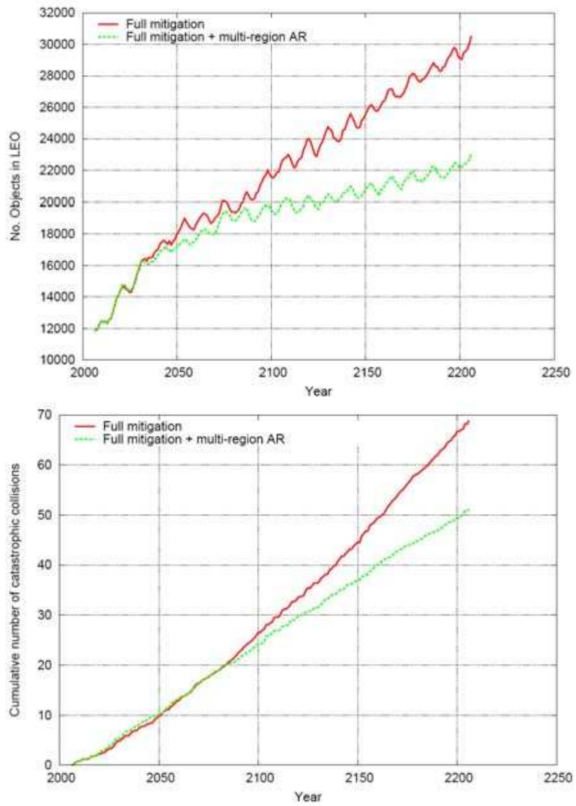

Figure 13 and 14. Evolution of population above 10cm in LEO and cumulative number of catastrophic collisions for full mitigation scenario starting in 2020, and with full mitigation and multi-region AR starting in 2020.

7. CONCLUSION

The previous sections proved that the number of objects in LEO will grow if no active measures are taken, even in the best (although not realistic) case of evolution of the environment. AR can be an efficient way to control this growth, as it is able to stabilize it and even reduce the population. An optimized selection of the strategy for AR improves the effectiveness of the removal missions. Some factors as the time of start of AR missions and the removal ratio play an important role for this efficiency.

The feasibility of AR missions, both technically and politically, is still under study. However, the recent collision between two satellites must be an inflexion point towards a consensus on the realization of AR missions as well as on the full implementation of the mitigation measures. Further studies are required considering the actual population of objects in LEO and taking also into account objects between 1 and 10 cm in size, which can be responsible for some catastrophic collisions. Other more realistic evolution scenarios such as BAU with mitigation must be further studied in detail to verify the results of this study.

8. REFERENCES

1. Liou, J.-C. & Johnson, N.L. (2008). Instability of the present LEO satellite populations. *Advances in Space Research.* 41, 1046-1053.
2. Liou, J.-C. & Johnson, N.L. (2008). A sensitivity study of the effectiveness of active debris removal in LEO. *Acta Astronautica*. 64, 236-243.
3. Martin, C.E. (2006). DELTA 3.0 Technical Note. ESA/ESOC Contract 18014/03/D/HK