ACTIVE DEBRIS REMOVAL FOR LEO MISSIONS

B. Bastida Virgili [(1)], **H. Krag**[(1)]

[(1)] ESA Space Debris Office, ESOC/ESA, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany
Email: benjamin.bastida.virgili@esa.int, holger.krag@esa.int

ABSTRACT

There is consensus that the future evolution of the space debris environment in the LEO (Low Earth Orbit) regime is not stable and that active debris removal (ADR) is necessary to control the growth rate. First ADR mission designs are being intensively discussed and significant effort is put into the identification of suitable removal candidate objects.

In this paper we analyze the effect of ADR on the long term evolution of the space debris environment in LEO in different scenarios using ESA's Debris Environment Long Term Analysis (DELTA) model (with variations on the implementation of the mitigation measures, on the traffic models and evolution, on the removal selection criteria and on the solar flux). For each of the scenarios we derive a list of candidates based on the objects involved in catastrophic collisions. A combined list is then created with the objects which appear repeatedly in the different scenarios. Finally, this list is used as input for ADR simulations and the effectiveness of the removal is evaluated in terms of number of objects reduced and number of collisions avoided.

1 INTRODUCTION

The number of human made objects in space has undergone a steady increase since the beginning of spaceflight. The fear that the future environment growth might be dominated by collisions, rather than by launches and explosions, was expressed already decades ago. In response to this, the IADC (Inter-Agency Space Debris Coordination Committee) formulated a set of mitigation requirements that were issued in 2002 [1]. These requirements aimed at a limitation of the growth rate rather than at a reduction of the object population below the current numbers. These IADC guidelines recommend the spacecraft to perform collision avoidance maneuvers while operational, and to be passivated and perform a re-orbit or de-orbit maneuver in order to be outside from the LEO protected regions in less than 25 years at the end of their operational life.

As shown in recent studies done with different environment prediction tools from various agencies (NASA, ESA, …) [2, 3, 4, 11], the current environment will grow, even in the case of no further mission deployments (i.e. a "no further release scenario"), as can be seen in Fig. 1.

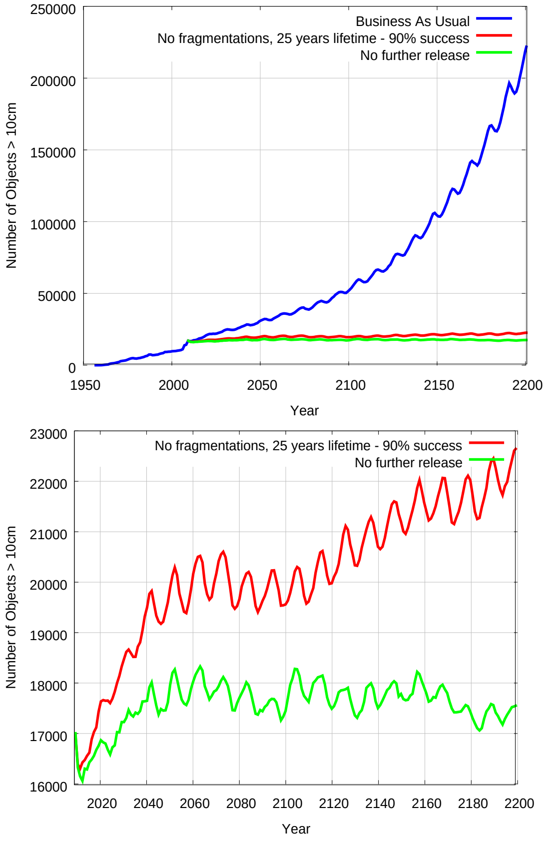

Figure 1. (top) Future evolution of the number of objects in LEO in a Business as Usual (BAU) scenario, in a no-further-release scenario and in a Partial Mitigation scenario with 90% accomplishment of mitigation measures. (bottom) Focus on the two last scenarios.

In Fig. 1 we also observe the environmental evolution in a scenario where 90% of the new objects launched in space follow the IADC mitigation guidelines, which confirms that even in an optimistic level of adoption of the mitigation guidelines a linear growth is to be expected. However, the comparison with the BAU scenario, where the growth is exponential, shows the necessity and urgency of applying the mitigation guidelines for all the future launches. The growth in all the scenarios is mainly due to collisions caused by fragments generated by other collisions (so-called feedback collisions). This observed instability indicates that the existing and currently proposed mitigation

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

measures are not sufficient to stop the increase of the collision rate, even when they are strictly implemented. It has to be noted that all the models have to predict the future, with the associated uncertainties that this process introduces.

To stabilize the environment, the idea of actively removing objects from space has been raised. Active debris removal (ADR) implies missions with the capability to interact with passive spacecraft or rocket bodies in order to reduce their remaining orbital lifetime. Obviously, such efforts are only acceptable if all mitigation measures proposed by IADC are strictly followed [5]. First ADR mission designs are intensively discussed and ESA can become one of the first actors on ADR through the Clean Space initiative. The analysis of optimal environment remediation strategies has just begun, but in parallel, mitigation measures might have to be intensified as well for a balance of activities that leads to effective results. Furthermore, the selection and ranking of targets by their deployment orbit and their physical properties needs to be optimized.

Although the IADC formulated the mitigation requirements in 2002, the actual evolution of the population during the last 10 years and the relatively low number of attempts to significantly shorten the orbital lifetime of LEO objects that operated above 600km altitude [6] has brought the situation to a point where ADR is necessary even to stabilize the growth of the population, as different studies have shown in the last years [2, 3, 4].

As it is clear that ADR is necessary, previous studies have looked into optimal target orbital regions for ADR or for other criteria to select the possible removal targets, while others have looked at the effect of varying the start epoch for ADR activities, and at the effect of the number of objects to be removed per year [2,5].

2 DELTA (Debris Environment Long-Term Analysis)

ESA's Debris Environment Long Term Analysis (DELTA) model is one of the models that contribute to the IADC studies on long term evolution, which have already been used to derive the mitigation guidelines and have also proven the need for ADR. DELTA was developed by QinetiQ and has been modified by ESA to add the active debris removal capabilities. 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 years. 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.

DELTA uses an initial space object population as input and forecasts the evolution of all objects larger than 10cm in size for our studies. The population is described by representative objects, evolved with a fast analytical orbit propagator which takes into account the main perturbations. The initial population has been extracted from ESA's MASTER-2009 (Meteoroid and Space Debris Terrestrial Environment Reference) model [13]. DELTA uses 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. This is one of the main causes for uncertainties in the results, as varying the future traffic models has a big impact, and there is no certainty on the actual evolution of the space activity in the future. The collision event prediction is done by using a target centered approach, developed to stochastically predict impacts between all objects within the DELTA population [7, 8, 9]. The fragmentation, or break-up, model used is based on the EVOLVE 4.0 (NASA) break-up model [10]. The future solar flux evolution has a strong effect on the results, as the atmospheric drag is the main factor for the natural decay of objects and is correlated to it. ESA has its own solar and geomagnetic activity prediction model (SOLMAG), which uses data from past solar cycles to predict the future ones. Different solar activity predictions have been used within DELTA in order to check their effect and to have valid and conclusive results with different future evolutions.

3 GENERATING A LIST OF CANDIDATES FOR REMOVAL

During the last 4 years, many different simulation scenarios have been run in DELTA in the scope of different studies for IADC and for conferences, as well as for maintenance and improvement of the software. Initial populations extracted from MASTER (for 1st May 2006 and, once available, 1st May 2009) were used, where an identifier allows to trace back the objects to the real ones in the catalog. The population of 2009 contains 250 objects more that can be assigned to objects of the catalog, as compared to the one of 2006. Therefore, we have checked the results of each of the simulations (each having a significant number of Monte-Carlo (MC) runs) and generated a list with the objects which are implied in catastrophic collisions. We have then counted in how many of the MC runs of each simulation this happens, so that a ranking and statistics are generated per simulation. Afterwards, a combined list has been produced including the results of all of the simulations, following the same approach, so that we have global ranking. In this list we have filtered out, in order to have valid statistics, those objects which have not been involved in collisions in simulations which had at least 100 MC runs.

3.1 Simulation cases used as background

We have used the results of 84 different simulations to generate the list, all of them with a propagation time span of 200 years in the future. From these, 21 are based on a “no-further-release” scenario, a situation where the initial population is propagated and only the collisions are responsible for the increase of the population, as no explosions occur and no new objects are added in space. 7 are based on a “Business-As-Usual” scenario, where the launch traffic for the future is based on that of the past 8 years, explosions continue to happen, also based on their occurrence the past, and no mitigation measure is applied. 21 are based on a “partial mitigation” scenario, where the future launches are based on the past, no explosions occur, and the mitigation requirements from IADC guidelines are applied. 17 are based on the propagation of new explosion or collision clouds through the initial population, in order to see the effect of a particular event in the global evolution. The rest of the simulations had as objective testing the improvements and upgrades of DELTA.

The differences between the simulations which are based on the same scenario are the possible initial population (2006 or 2009), the solar flux prediction used, the rate of accomplishment of the mitigation requirements, the variation of the launch rates, and the application of various ADR concepts.

In fact, there are 29 simulations where ADR has been tested in combination with different scenarios. The variations are the number of objects removed per year (3, 5, 10 or 20), different year for the missions’ start, and different criteria for the selection of the objects to be removed (based on mass, on area, or on a defined region of space).

4 STATISTICS OF THE LIST

The global ranking contains 1850 objects, associated to real objects from the catalog, having a probability above 1% of being involved in a catastrophic collision. The vast majority of these objects are payloads (P/L) and rocket bodies (R/B), as stated in Tab. 1. It is surprising that the number of P/L involved in collisions is higher than that of R/B, although this situation changes for higher probability levels. It is also important to remember that the catalog has around 12000 objects in LEO at the current epoch (April 2013), from which almost 9000 are fragments.

Table 1. Type of objects in the ranking above a given probability threshold (P/L: payload, R/B: rocket body, MRO: mission-related objects, Frag: fragments)

	P/L	R/B	MRO	Frag.	**Total**
>1%	1045	660	135	10	1850
>5%	60	66	9	1	136
>7%	12	22	3	0	37
Top10 (>9.5%)	2	8	0	0	10

In Fig. 2 we can observe the distribution, in 0.5% probability bins, of the objects according to the probability. As could be expected, the growth in number of objects is almost exponential when reducing the probability. The fact that under 2% there is a stabilization (and even decrease), is due to the filtering out of the cases with less than 100 MC runs.

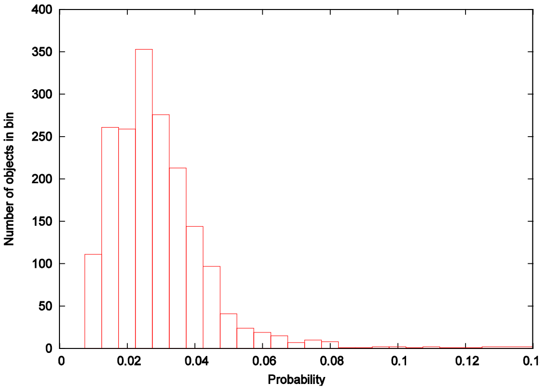

Figure 2. Histogram of distribution of objects in the ranking according to probability of being involved in a catastrophic collision.

The top-10 objects have a probability of collision above 9.5%. Moreover, the object on the top of the list has a collision probability of 13.8%. The eight R/B in this top-10 are from the same family, with masses between 8 and 9 tons. Six of them are in an altitude around 850 km and inclination around 71 deg, while the other two are in a Sun-synchronous inclination at 815 km and 1000 km respectively. The two payloads are in Sun-synchronous orbits and have masses of 8 and 4 tons respectively. In total, these 10 objects represent a mass of almost 80 tons and an average cross-section of 370 m^2.

However, as can be seen in Fig. 3, there is not a clear relation between the probability of collision and the area or the mass of the object (except for the few objects in the top risk region). So it is clear that performing an ADR based solely on area or mass will not be the most effective way. The mass of all the objects in the list sums up to 1800 tons (from the total mass in LEO which is around 2500 tons).

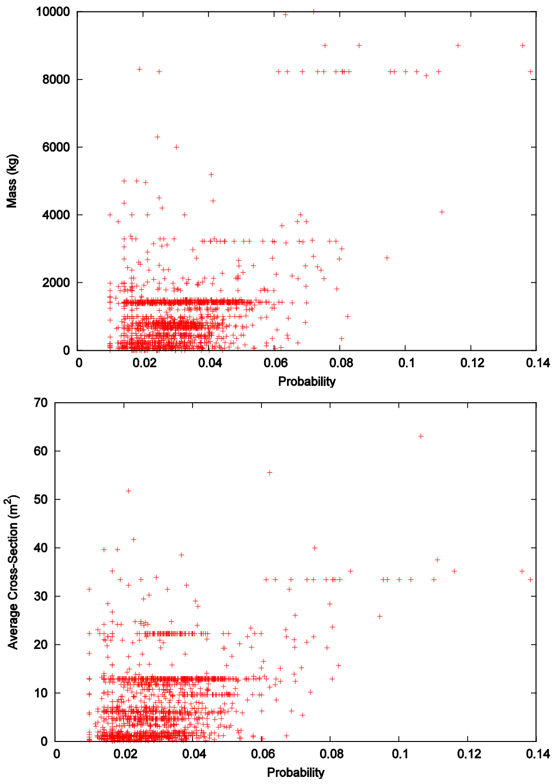

Figure 3. Mass (top) and average cross-section (bottom) vs. probability for the objects in the ranking.

The orbital distribution (mean altitude versus inclination) and the respective probability can be observed in Fig. 4. There are clearly regions with a higher concentration of objects having higher probabilities, where it could be possible to perform ADR missions which would remove more than one object per mission more efficiently, as was already discussed in [2].

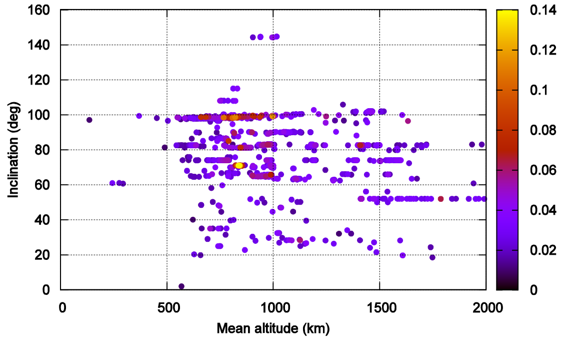

Figure 4. Orbital distribution (mean altitude vs. inclination) with the corresponding probability (color code) of the objects in the ranking.

5 ADR ON OBJECTS OF THE LIST

The objective of generating a global ranking is to have a different criterion as the ones used in previous studies to select the candidates for ADR. The method of generation of this list, which combines many different scenarios and takes into account 200 years of propagation, provides an overview which is independent of the scenario itself.

To demonstrate the relevance of the list, we have simulated ADR scenarios by selecting the objects from the list according to their ranking. We have chosen as reference scenario the one that has been used for the IADC comparison study [11]. It means a propagation of 200 years, starting with the MASTER-2009 population on 1st May 2009 above 10 cm, a high solar flux prediction, the implementation of the lifetime limitation of 25 years with 90% of success, no new explosions on orbit, a launch traffic based on that of 2001-2009, and an operational life for new payloads of 8 years. In this scenario, based on 100 MC runs, ESA results predicted 35 collisions to happen, an average increase of 22% of the population after 200 years, and 75% of the runs having a final population above the initial one (in number of objects). This is an optimistic scenario because studies [14] show that for the past years the compliance rate with the mitigation guidelines is around 30%, and there are still explosions in orbit every year. However, we have selected this scenario as it is the one used for the IADC study and as it has international recognition.

For the ADR scenarios, we have simulated the removal of 1 or 5 objects per year (ADR1 or ADR5), and starting the ADR missions 15 years after the epoch of the population (i.e. in 2024) because the technology is not yet ready to perform ADR missions and we expect that we will have to wait at least 10 more years before a real ADR mission is launched. We have also considered removing the same quantity of objects as in the 1 object per year scenario, but condensed in 35 years with 5 objects removed per year (ADR5L). For each of the cases, we have performed 40 MC runs.

The evolution of the population for the three scenarios as well as for the reference case can be seen in Fig. 5, whereas the cumulative number of catastrophic collisions is shown in Fig. 6. We can observe that in all the cases the population evolves below the reference case, as do the collisions. The feature that the number of objects is slightly above the reference for the first 25 years is an artifact of the averaging and not significant. However, once the ADR missions start, we see a decrease on the number of objects compared to the reference.

In addition, in ADR1, the final population is above the initial one, but with a smaller increase than the reference. In this case we also observe that the number of collisions is almost the same as for the reference during the first 120 years and only afterwards decreases. However, the collisions which occur produce fewer objects, thus being not so critical for the environment.

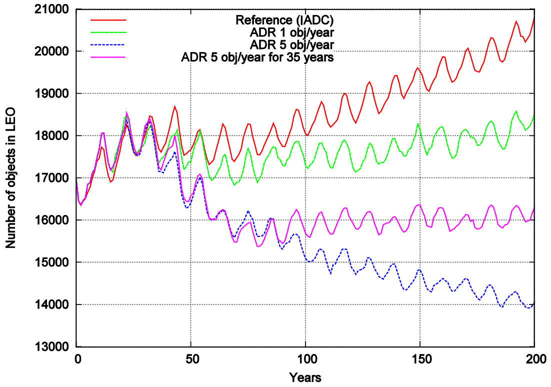

Figure 5. Evolution of population above 10 cm in LEO for the reference scenario and for the ADR scenarios selecting 1 and 5 objects per year starting in 2024 (15 years after the simulation start) from the ranking, with no end date for the ADR (ADR1, ADR5) or with only 35 years of ADR missions (ADR5L).

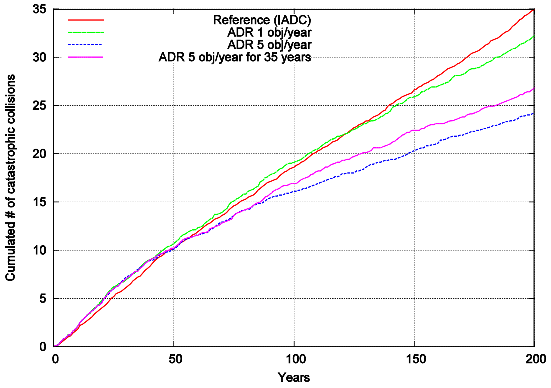

Figure 6. Cumulative number of catastrophic collisions for the reference scenario and for the ADR scenarios selecting 1 and 5 objects per year starting in 2024 (15 years after the simulation start) from the ranking, with no end date for the ADR (ADR1, ADR5) or with only 35 years of ADR missions (ADR5L).

In order to measure the effectiveness of the ADR missions, two quantifiers were proposed [2, 12]. The first, which we call ORF (Object Reduction Factor), indicates the relation between the number of objects removed and the reduction, due to the ADR, in the total number of objects compared to the reference scenario. The second, which we call CRF (Collision Reduction Factor), gives the relation between the number of objects removed and the reduction in the number of catastrophic collisions. In Tab. 2 we see these factors for the tested ADR scenarios.

Table 2. Quantitative results for the ADR scenarios selecting 1 and 5 objects per year starting in 2024 (15 years after the simulation start) from the ranking, with no end date for the ADR (ADR1, ADR5) or with only 35 years of ADR missions (ADR5L).

	1 obj/yr	5 obj/yr	5 obj/yr for 35y
Reduction in # objects (a)	2450	6760	4500
Reduction in # collisions (c)	2.7	10.6	8.1
# AR objects (b)	173	802	163
ORF (a/b)	14.16	8.43	27.61
CRF (b/c)	64.07	75.66	20.12
Population growth (%)	9.3	-17.1	-3.8
Years with AR missions	185	185	35

The two factors show the importance of removing the objects on the top of the list first. In fact, the ADR1 scenario, although not being able to stop the population growth, is far more effective than ADR5 scenario. This has been the motivation to perform the third simulation scenario (ADR5L), and the results in this scenario are much better than in the other ADR cases, with a much higher effectiveness in the ORF and in the CRF. In addition, the overall population stabilizes, as we can observe in Fig. 5. Furthermore, we note that the evolution of the population, and of the collisions, follows that of ADR5 for more than 40 years after the end of the removal missions, which is 50 years after the beginning of the simulation. This result underlines the importance of removing the objects in the top of the list first and in a fast way.

Although in the ADR1 simulation the removal of 1 object per year is performed, we note from the results in Table 2 that as a matter of fact, only 178 objects where removed after 185 years, whereas we would expect 185 objects to be removed. Similarly for the ADR5, only 803 objects are removed after 185 years instead of the expected 925. This is due to the fact that some of the objects in the list may have already decayed or they could have been involved in a catastrophic collision by the time they would be selected for removal, and in this case we skip them. This points to the importance of starting the ADR as soon as possible and to perform it as fast as possible, so that no collisions occur caused by the objects we wanted to remove.

In order to have a further comparison, we have recovered the results from [2] and showed them in Tab. 3. In that case, the reference scenario was a no-further-release and the ADR of 5 objects per year starting at the beginning of the simulation. The ADR was performed in selected orbital regions, in a combination of the regions, or by area or mass. It is for this reason that the comparison should focus only on the two quantifiers and not on the absolute numbers.

Table 3. Quantitative results from [2], for ADR in 1000km-82°, in 800km-99°, in 850km-71°, for multi-region ADR (switch to a different region of the 3 specified before after every removal mission), and for ADR selecting by mass or by area in any place of LEO.

	(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
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
ORF (a/b)	7.77	9.16	36.32	8.77	5.26	5.28
CRF (b/c)	55.41	42.95	40.91	64.68	120.48	125.00
Population growth %	-0.64	7.25	4.43	-15.63	-25.84	-26.12
Years with AR missions	75	53	19	150	200	200

The comparison shows that ADR5L is more efficient in terms of CRF in all the cases. However, the ORF is not the most effective for one of the studied cases in [2]. The exception is the removal in the region around 850 km altitude and 71 deg inclination, which is the region where we find 6 of the top 10 objects in the ranking. The reason is that these objects are removed faster (because the ADR missions in [2] start the same year as the simulation starts) from the environment than in the current simulation.

In order to verify this hypothesis, which was also analyzed in [2], we have performed two more simulations. In these we reproduce the same conditions as for the ADR5L scenario, but delaying the start of the ADR missions another 25 and 50 years respectively (ADR5L-2049, ADR5L-2074).

The evolution of the population for these two new scenarios, compared to that of an earlier start of ADR, can be seen in Fig. 7, while the cumulative number of catastrophic collisions is shown in Fig. 8.

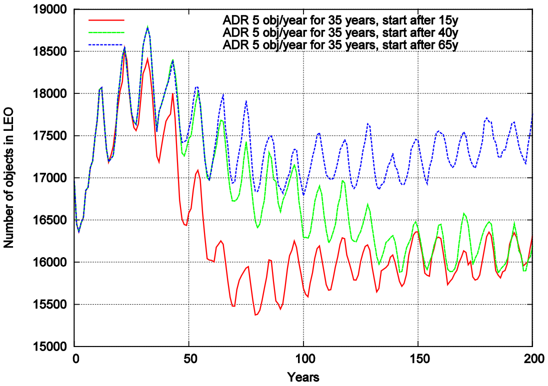

Figure 7. Evolution of population above 10 cm in LEO for the ADR scenarios of 5 objects per year selecting the objects from the ranking, starting in 2024 (ADR5L), in 2049 (ADR5L-2049) and in 2074 (ADR5L-2074), with only 35 years of ADR missions.

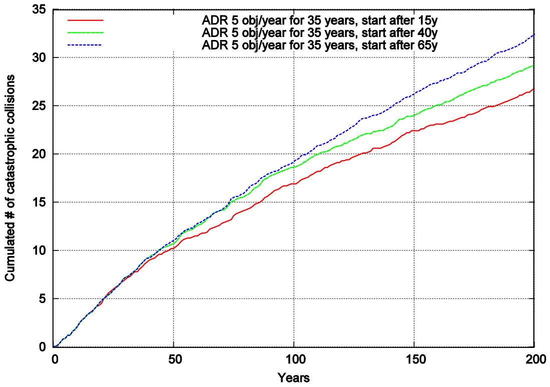

Figure 8. Cumulative number of catastrophic collisions for the ADR scenarios of 5 objects per year selecting the objects from the ranking, starting in 2024 (ADR5L), in 2049 (ADR5L-2049) and in 2074 (ADR5L-2074), with only 35 years of ADR missions.

The results show the expected behaviour: The earlier the ADR missions start, the better will be the evolution of the environment and fewer collisions will occur. In case of a later start, some objects which are in the list get involved in catastrophic collisions before the time of their removal arrives, with catastrophic consequences for the environment.

However, one could look at Fig. 7 and get the false impression that starting ADR missions later is not really a problem, since the final population for ADR5L-2049 reaches the same number as for ADR5L. The explanation for this is again that the objects which we intended to remove get involved in catastrophic collisions, but their orbits are low enough so that the fragments decay in around 100 years. In the ADR5L-2074, the situation is the same, but the extra objects implied in collisions are in a higher altitude, thus the fragments do not decay in the propagation timeframe. However, if we look at 50 or 100 years from the start of the simulation the situation is different, with always more objects if the ADR missions start later. What is important for a satellite operator is the safety of his spacecraft and how much propellant will be needed for collision avoidance manoeuvres, and this situation gets clearly worse as the ADR missions start later.

6 CONCLUSION

We have developed a novel way of generating a ranking of the objects candidates for ADR, based on selecting the objects being involved in a catastrophic collision from old environment simulations and ranking them according to the number of MC runs where they collide, yielding a probability of collision. This list is quite close to other lists independently obtained, with the main difference being that the lifetime of the objects is implicitly considered in the computation of the probabilities. The resulting list has been used as input for the selection of ADR candidates in a few simulation scenarios and the results show the effectiveness of this removal strategy in order to stabilize the population. We showed that removing only a small percentage of objects on the top of the list (less than 10%, corresponding to 170 objects) has a significant impact on the evolution of the environment. Nonetheless, the ADR missions have to start as soon as possible.

However, and more important, is the fact that ADR is only beneficial when the mitigation guidelines are correctly implemented by all space fairing nations. In any other situation, ADR would be inefficient as new debris will take the place of the ones removed. This has been addressed theoretically in [5] and we plan to show simulation results in the near future. In this study, we had considered an optimistic case with 90% compliance to the mitigation guidelines.

In addition, ADR missions are not yet a reality because many difficulties, both technically and politically, have to be overcome. ESA, with its Clean Space initiative, is working to improve the situation and to be able to perform a demonstration mission of ADR in the years to come.

7 REFERENCES

1. IADC. "IADC Space Debris Mitigation Guidelines". 2002.
2. B. Bastida Virgili, H. Krag. "Strategies for Active Removal in LEO." *Proceedings of the 5th European Conference on Space Debris*. 2009
3. J.-C. Liou. "An active debris removal parametric study for LEO environment remediation." *J. Adv. Space Res*. 2011. doi:10.1016/j.asr.2011.02.003
4. H. Lewis et al. "The Space Debris Environment: Future Evolution". *CEAS 2009 European Air and Space Conference, Manchester, UK.* 26 - 29 Oct 2009
5. B. Bastida Virgili, H. Krag. "Analyzing the Criteria for a Stable Environment". *AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, USA. AAS11-411.* 2011
6. H. Krag, T. Flohrer, S. Lemmens. "Consideration of Space Debris Mitigation Requirements in the Operation of LEO Missions". *In Space Operations: Experience, Mission Systems & Advanced Concepts, Progress in Aeronautics and Astronautics. AIAA, Reston, VA, USA,* 2013.
7. R. Walker, C.E. Martin et al. "Analysis of the effectiveness of space debris mitigation measures using the Delta model". *Adv. Space Res. Vol. 28, No. 9, pp 1437-1445.* 2001
8. C.E. Martin, R. Walker, H. Klinkrad. "The sensitivity of the ESA DELTA model". *Adv. Space Res. Vol. 34, pp 969-974.* 2004
9. R. Walker, C.E. Martin. "Cost-effective and robust mitigation of space debris in Low Earth Orbit". *Adv. Space Res. Vol. 34, pp 1233-1240.* 2004
10. N.L. Johnson et al. "NASA's new breakup model of evolve 4.0". *Adv. Space Res. Vol. 28 No. 9, pp 1377-1384.* 2001
11. J.-C. Liou et al. "Stability of the Future LEO Environment – An IADC Comparison Study". *Proceedings of the 6th European Conference on Space Debris*. 2013
12. J.-C. Liou, N.L. Johnson. "A sensitivity study of the effectiveness of active debris removal in LEO". *Acta Astronautica. 64, 236-243*. 2008.
13. M. Oswald et al. "Upgrade of the MASTER Model". *Final Report ESA contract 18014/03/D/HK(SC)*. 2006.
14. H. Krag, S. Lemmens, H. Klinkrad. "Analysing Global Achievements in Orbital Lifetime Reduction at the End of LEO Missions". *Proceedings of the 6th European Conference on Space Debris*. 2013