Post-Print

This is the accepted version of:

S. Frey, S. Lemmens, B. Bastida Virgili, T. Flohrer, V. Gas
Impact of End-Of-life Manoeuvres on the Collision Risk in Protected Regions
Acta Astronautica, Vol. 138, 2017, p. 417-422
doi:10.1016/j.actaastro.2017.06.012

This is an accepted manuscript version of an article published in Acta Astronautica. Copyright of the final editor version with Elsevier Ltd.

Citation: S. Frey, S. Lemmens, B. Bastida Virgili, T. Flohrer, V. Gass, Impact of End-of-Life Manoeuvres on the Collision Risk in Protected Regions, Acta Astronautica 138 (2017) 417-422

DOI: 10.1016/j.actaastro.2017.06.012

Impact of End-of-Life Manoeuvres on the Collision Risk in Protected Regions

Stefan Frey
Swiss Space Center on Secondment to the European Space Agency (ESA), Germany, stefan.frey@esa.int

Stijn Lemmens
European Space Agency (ESA), Germany, stijn.lemmens@esa.int

Benjamin Bastida Virgili
European Space Agency (ESA), Germany, benjamin.bastida.virgili@esa.int

Tim Flohrer
European Space Agency (ESA), Germany, tim.flohrer@esa.int

Volker Gass
Swiss Space Center, Switzerland, volker.gass@epfl.ch

The Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines, issued in 2002 and revised in 2007, address the post mission disposal of objects in orbit. After their mission, objects crossing the Low Earth Orbit (LEO) should have a remaining lifetime in orbit not exceeding 25 years. Objects near the Geostationary Orbit (GEO) region should be placed in an orbit that remains outside of the GEO protected region. In this paper, the impact of satellites and rocket bodies performing End-of-Life (EOL) orbital manoeuvres on the collision risk in the LEO and GEO protected regions is investigated. The cases of full or partial compliance with the IADC post mission disposal guideline are studied. ESA's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model is used to compare the space debris flux rate of the object during the remaining lifetime estimated for the pre-EOL-manoeuvre and for the post-EOL-manoeuvre orbit. The study shows that, on average, the probability of collision can be significantly decreased by performing an EOL-manoeuver.
Keywords: EOL Manoeuvres, Debris Flux, Mitigation Guidelines

1. Introduction

The collision between the operational Iridium 33 and the defunct Cosmos−2251, that resulted in the creation of over 2000 observable fragments [1, 2] highlighted the dangers originating from objects left in space, in particular in already crowded regimes. The Space Debris Mitigation Guidelines, issued by the Inter-Agency Space Debris Coordination Committee (IADC) in 2002, and revised in 2007, define two protected regions: the Low Earth Orbit (LEO) protected region, up to 2000 km, and the Geostationary Orbit (GEO) protected region at an altitude range of $h_{geo} \pm 200$ km and a declination range of $\pm 15°$, where $h_{geo} = 35786$ km [3].

In order to protect these regions, the guidelines recommend the prevention of on-orbit collisions and to limit the debris released during normal operations. They further recommend to passivate stored energy to minimise potential break-up and to perform Post-Mission Disposal (PMD) upon reaching mission End-of-Life (EOL). For LEO, the spacecraft, subsequently called Payload (PL), or the Rocket Body (RB) should be left in an orbit, such that the remaining lifetime does not exceed 25 years. For GEO, the PL should be re-orbited into an orbit sufficiently above the protected region, such that it remains cleared from the region, taking into account solar radiation pressure, luni-solar and geopotential perturbations.

Hundreds of objects have already performed such an EOL-manoeuvre. The contribution of this work is to quantify the effect of these manoeuvres on the cumulative number of collisions with space debris in the protected regions. The collision probability is analysed by calculating the debris flux the manoeuvering object is exposed to for its remaining lifetime, or up to 1 January 2055. Estimated for both the evolution of the pre-EOL-manoeuvre orbit as well as the post-EOL-manoeuvre orbit enable a comparison between the two scenarios. The results are presented statistically.

2. Methodology

The analysis can be described in three parts, all of which are explained in more detail in the following subsections. In the first, the source and the criteria for the selection of the objects are described. Subsequently, the selection process of the pre- and post-EOL-manoeuvre states is outlined. Lastly, the propagator used for the evolution of those states and the tool and settings to estimate the debris flux the objects are exposed to are presented.

2.1 Object selection

The selection of the PLs and RBs used throughout the analysis is based on the following criteria:

(a) not related to human spaceflight;

(b) reached end of mission;

(c) resided in or crossed the LEO or GEO protected regions before implementing an EOL-manoeuvre;

(d) performed a fully or partially successfull EOL-manoeuvre.

The sources for the objects performing such an EOL-manoeuvre are two-fold. In case of the LEO objects, the source is ESA's Database and Information System Characterising Objects in Space (DISCOS) [2] which contains the results of manoeuvre detection method based on USSTRATCOM's Two-Line-Elements (TLE) [4]. The ones performing a direct re-entry manoeuvre and the ones performing a re-/de-orbit manoeuvre without subsequent activity are considered. Additionally, DISCOS contains data on the destination orbit for objects without available TLE data. For PLs, the destination orbit is defined as the mission orbit. For RBs, it is defined as the orbit where the RB separates from upper stages or from the last PL it carries. In LEO, the data ranges studied are 1990-2014 and 2000-2015 for PLs and RBs, respectively. In case of the GEO objects, the results from all the annual *Classification of Geosynchronous Objects* reports [5] are used, which contain PLs performing EOL manoeuvres dating from 1999-2015. The precise date of the manoeuvres is not used here for either source, only the respective year is considered, subsequently refered to as activity year.

2.2 State Selection

Two states are selected for each object which are representative for the pre- and the post-manoeuvre state respectively. The main source of the states are again TLEs, which are stored in DISCOS. To avoid the selection of an outlier, the following process is implemented:

(a) get all TLEs within a given interval (excluding the EOL-manoeuvre, i.e. for pre-manoeuvre: the interval consists of the 30 days ahead of 1 January of the activity year, post-manoeuvre: the interval consists of the 90 days after 1 February of the year after the activity year);

(b) remove all the TLEs which are followed by another TLE less than half the orbit period later [4];

(c) fit a fourth order polynomial to the mean motion, n, the eccentricity, e, and the inclination, i, using iteratively re-weighted least squares for robustness against outliers;

(d) calculate the Mahalanobis distance, d_i, defined as $d_i^2 = \vec{r}_i^{\,T} C^{-1} \vec{r}_i$, for each state i using the residual $\vec{r}_i = (\Delta n_i, \Delta e_i, \Delta i_i)^T$ and the sample covariance C of all residuals;

(e) select state $i = \operatorname{argmin}_i d_i$, to assure that a state most consistent with the other states is selected.

For some objects, none or less than five TLEs are available, e.g. for the objects performing a direct re-entry. In case the pre-manoeuvre state is missing, it is replaced by the destination orbit for the given object from DISCOS. In case the post-manoeuvre state is missing, a check whether the object has re-entered before 1 February of the year after the activity year is performed. If yes, no propagation is done for the post-manoeuvre state. If not, the object is assumed to be missing and discarded from the analysis.

2.3 Propagation and Flux Analysis

To simplify the routines, and with enough computational power at hand, only one propagator with one set of parameters is used for all the objects, independent of the orbital regime. Both states are propagated even if real observations are available. This ensures the equal treatment of the evolution of the hypothetical and the real state of the object. The propagator is a fully numerical, Runge-Kutta 7(8) integrator with variable step-size taking into account perturbations from the geopotential (8×8), the atmosphere (NRLMSIS-00), the solar radiation pressure (modelled with conical Earth shadow) and the Moon and Sun third bodies.

To calculate the collision risk each object is exposed to after the end of its mission, the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model [6] is employed. For a given state and historical or future epoch, MASTER estimates the space debris flux, man-made and natural, an object experiences for different future scenarios and debris sizes. For this analysis, the business as usual scenario (i.e. averaged launch traffic and adherence to mitigation guidelines from 2001−2009) is used and only man-made chaser objects with diameter between 0.1−100 m are considered, i.e. decommissioned PLs and RBs, large explosion and collision fragments as well as launcher and mission related objects. The input states for the flux analysis are the propagated states, for both pre- and post-manoeuvre cases starting from the first post-manoeuvre epoch. It must be noted here that in case no post-manoeuvre state is available, the flux might be underestimated, as immediate re-entry is assumed, which is not always the case. The resulting fluxes are weighted with the time spent in the given orbit configuration and the object average cross-section and integrated over the whole time span to obtain an estimate of the total number of debris objects the PL or RB collides with.

The pre- and post-EOL-manoeuvre orbits are propagated, and their fluxes accumulated, until re-entry or 1 January 2055. This limit is imposed by the flux analysis tool, which predicts the near Earth space environment until this epoch. The beneficial long-term effect of a compliant EOL-manoeuvre is thus underestimated, as many of the objects would - given the pre-EOL-manoeuvre states - continue to dwell on-orbit and be exposed to space debris beyond the year 2055 for decades to come.

The results are grouped into LEO and GEO. The LEO objects are further subdivided into PLs and RBs.

3. Results

Table 1 summarises the total cumulative number of collisions experienced by all the objects within their respective groups, for the pre- and post-manoeuvre scenarios (marked via the indices $_{pre}$ and $_{post}$ respectively). In addition, the number of objects involved, the total cross sectional area and total dwell time on orbit are listed. The total numbers are driven by a few objects clearing highly populated orbital regions. To give a feeling about the distribution of reduction of collision probability over all the objects, Table 1 also contains the 25%, 50% and 75% quantiles of the individual relative changes in number of collisions, $\Delta N^i/N^i_{pre} = (N^i_{post} - N^i_{pre})/N^i_{pre}$, where i indicates the i-th object in each group. Figs. 2, 3 and 4 show, for each group, the evolution of the pre- and post-manoeuvre states as well as the cumulative number of collisions for each object, for both states, during its lifetime until re-entry or until 1 January 2055.

Table 1: MASTER number of collision analysis results for the three groups, with number of objects, n, total area, A, cumulative time on-orbit (until re-entry or 1 January 2055), t, total cumulative number of collisions, N, the total change in cumulative number, $\Delta N = (N_{post} - N_{pre})$, and the quartiles of the individual relative changes, $Q_\alpha = Q_\alpha\{\Delta N^i/N^i_{pre}\}$.

	LEO		GEO
	PLs	RBs	PLs
n [−]	86	171	199
A [m^2]	849	3089	5250
t_{pre} [years]	2897	4785	9095
t_{post} [years]	2470	2705	9095
N_{pre} [−]	0.21	0.61	0.0068
N_{post} [−]	0.12	0.16	0.0017
ΔN [−]	−0.09	−0.45	0.0051
ΔN [%]	−43%	−74%	−74%
$Q_{25\%}$ [−]	−100%	−100%	−82%
$Q_{50\%}$ [−]	−74%	−100%	−76%
$Q_{75\%}$ [−]	−22%	−44%	−71%

3.1 PLs in LEO

In LEO, a total of 86 PLs - or less than 10% of all PLs reaching EOL in non-compliant LEO orbits since 1990 - performed an EOL-manoeuvre. For 23 of those objects, no post-manoeuvre state can be found after the activity year, thus, they have either directly re-entered or within a short time span in the year of activity. A total cross-sectional area of 849 m^2 was moved with the PLs performing such a manoeuvre. The total dwell time on-orbit, until re-entry or 1 January 2055, of these 86 objects could be reduced from 2897 to 2470 years.

The manoeuvre overview (see Fig. 2a) reveals that many of the considered PLs with a pre-EOL-manoeuvre perigee above 1000 km (i.e. Globalstar constellation satellites) do not follow the IADC PMD mitigation guidelines, but re-orbit, to clear the mission orbits, as far as their remaining fuel takes them. PLs with perigee below this altitude tend to de-orbit, but not all of them decay within 25 years. Despite this, the total number of collisions with objects larger than 10 cm is reduced by 0.09 from 0.21 to 0.12, or relatively by 43%. This reduction figure would increase if the analysis interval was selected to be longer.

71% of the total reduction comes from 7 PLs only (see Tab. 2 and Fig. 1), performing large manoeuvres out of the very congested region in the altitude band from 690 to 820 km. The SPOT satellites [7–9] achieve low individual relative reductions due to the fact that in this

Table 2: PLs in LEO with the highest absolute reduction of individual number of collision, ΔN^i, ordered by the international COSPAR designator.

COSPAR	Name	ΔN^i	
1982-072A	Landsat 4	−0.0063	−80.8%
1986-019A	SPOT 1	−0.0084	−47.6%
1990-005A	SPOT 2	−0.0090	−54.8%
1995-021A	ERS-2	−0.0131	−92.5%
1997-030C	Iridium 9	−0.0073	−99.8%
1997-082D	Iridium 48	−0.0074	−99.9%
1998-017A	SPOT 4	−0.0112	−37.2%

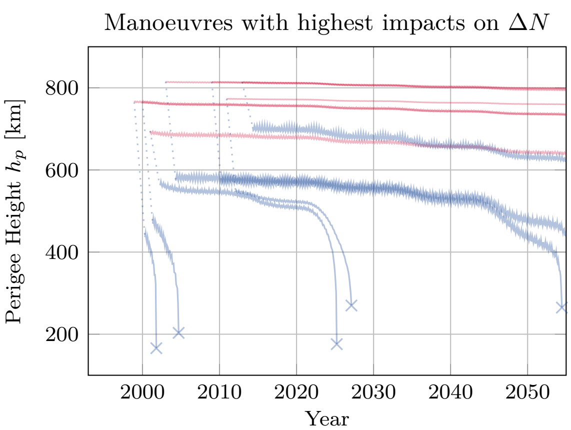


Fig. 1: Evolution of the pre- (red) and post- (blue) manoeuvre orbits for the PLs with the highest reduction in absolute number of collisions. Crosses and pluses signal a re-entry. From left to right, ordered by date of manoeuvre: Iridium 48, Iridium 9, Landsat 4, SPOT 1, SPOT 2, ERS-2, SPOT 4.

analysis they are predicted to remain in orbit for about 40 years or more after performing the EOL-manoeuvre. Landsat 4 [10], ERS-2 [11] and the Iridium satellites [12] achieve individual reduction rates of more than 80% in number of collisions. All the contributions of the remaining 79 PLs seem small in comparison, but only in terms of absolute reduction in collision risk. Individually, roughly one quarter reduces the exposure to space debris by 100% (i.e. direct re-entry), another quarter reduces it by 74% or more and the PLs in the third quartile remove it by 22% or more.

If only PLs are considered that are compliant with the 25 years rule - i.e. less than 4% of all PLs reaching EOL in non-compliant orbits - the reduction in number of collisions is 0.047 from 0.052 to 0.005, or relatively speaking by more than 90%.

3.2 RBs in LEO

As of the year 2000, a total of 171 RBs - or about half of all the RBs reaching EOL in non-compliant LEO orbits - performed an EOL-manoeuvre. For 87 of those objects, no post-EOL-manoeuvre state can be found after the activity year, thus, they have either directly re-entered or within a short time span in the year of activity.

The cross-sectional area being involved in those manoeuvres accumulate to a total of 3089 m^2. By performing the manoeuvres, they reduce their on-orbit dwell time from 4785 to 2705 years, and the total number of collisions with objects larger than 10 cm by 0.45 from 0.61 to 0.16, or relatively by 74%. In terms of individual collision risk, more than 3/4 of all RBs achieve a reduction of exposure to debris by 44% or more.

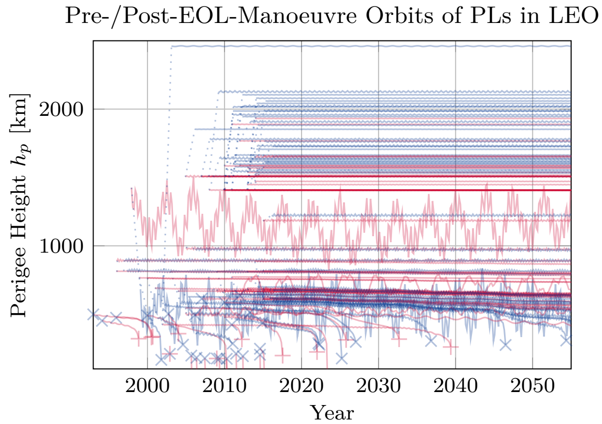
With 80% the largest share of the reduction comes from the more than 50% of RBs performing a direct re-entry, thus immediately clearing the congested region. The median individual risk reduction is therefore 100%. A much smaller part of the absolute reduction in number of collisions are the objects in GEO Transfer Orbit (GTO), performing perigee raise manoeuvres to clear the LEO protected region (see Fig. 3a), which is not conform with the mitigation guideline. These two groups of RBs can be inspected visually in Fig. 3b, as the upper and lower of the two strands, the upper one being thinned out in the middle plot due to the missing post-EOL-manoeuvre orbits and the lower one being 2-3 order of magnitudes lower due to the fact that GTOs spend less time in congested regions than objects fully residing in LEO.

25 RBs increased their exposure to space debris, adding a total of 0.043 in number of collisions. This can have multiple reasons; apogee raise due to passivation, or failed re-orbit, or too small perigee lowering manoeuvres (as only the time window until 2055 is considered).

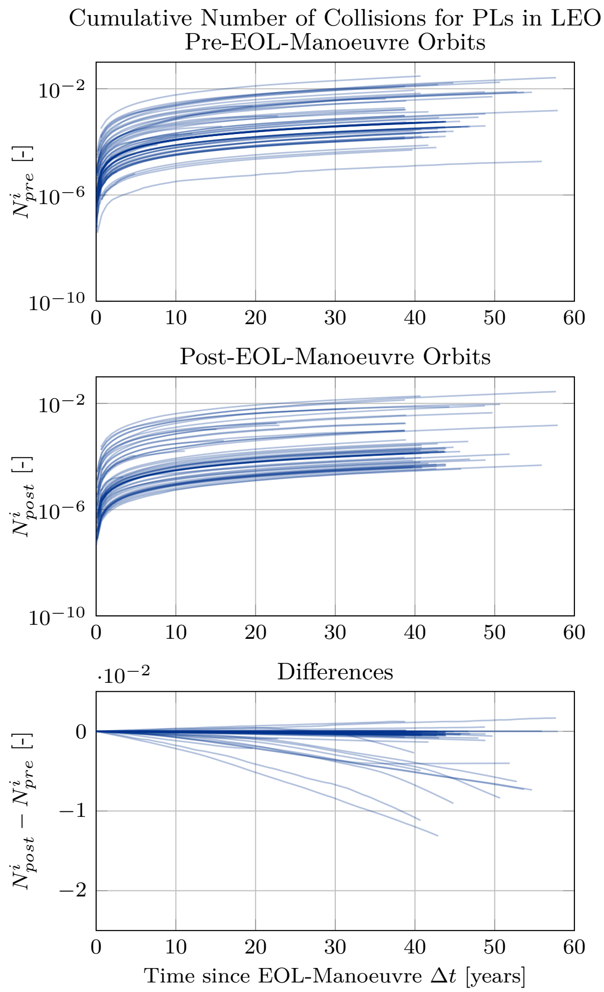
If only compliant RBs are considered, the number of collisions is reduced by 0.48, from 0.50 to 0.02, which translates into a reduction of collision risk by more than 95%. The share of these RBs as of the total number of RBs reaching EOL in non-compliant orbits since 2000 is 38%.

3.3 PLs in GEO

In GEO, 199 objects performed an EOL-manoeuvre since 1999, with various degrees of success (Fig. 4a). This corresponds to 81% of all the PLs reaching EOL. For all of them, a post-manoeuvre state can be found. The total time spent on-orbit is the same for the pre- and post-manoeuvre states as none re-enters. The total average cross sectional area involved is 5250 m^2. As they move out of the GEO protected region, they reduce the

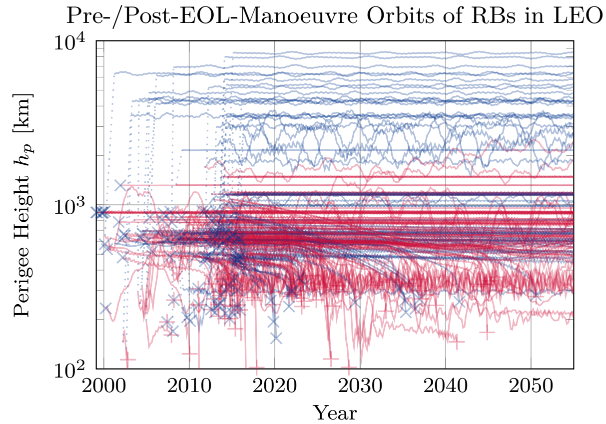


(a) Evolution of the pre- (red) and post- (blue) manoeuvre orbits. Crosses and pluses signal a re-entry.

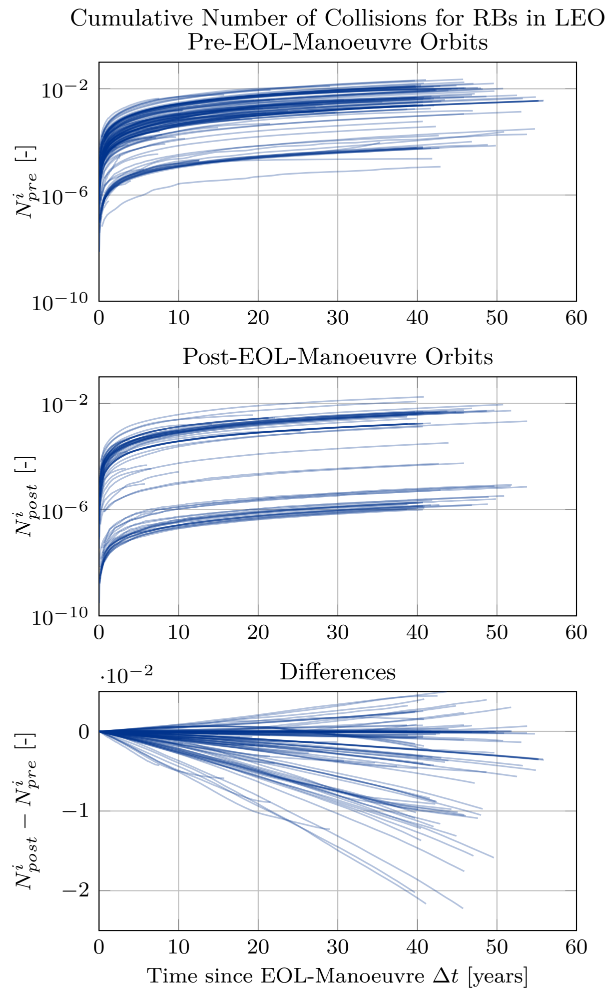


(b) Cumulative number of collisions in the pre- (upper) and post- (middle) manoeuvre scenarios and the absolute difference.

Fig. 2: Pre- and post-manoeuvre orbits and number of collisions for PLs initially in or crossing LEO.



(a) Evolution of the pre- (red) and post- (blue) manoeuvre orbits. Crosses and pluses signal a re-entry.



(b) Cumulative number of collisions in the pre- (upper) and post- (middle) manoeuvre scenarios and the absolute difference.

Fig. 3: Pre- and post-manoeuvre orbits and number of collisions for RBs initially in or crossing LEO.

total number of collisions with objects larger than 10 cm by 0.0051 from 0.0068 to 0.0017, or relatively by 74%, for the given analysis interval.

The number of collisions is two orders of magnitude smaller, compared to the situation in LEO. However, the consequences of a catastrophic collision in GEO would be much more severe, as there is no natural sink eventually clearing the objects. The time frames involved to see effects on the projected number of collisions with such a small difference is out of the scope of this study.

Contrary to the situation in LEO, the manoeuvres in GEO are very conform, which can be seen from the quartiles of the individual changes that are very close to each other.

4. Discussion

Previous studies [13–15] on the evolution of the number of collisions in LEO, involving objects larger than 10 cm and studying PMD levels of 0% and 50%, predict 12-14 collisions (where the number of fragment on fragment collisions - which are not considered in the current study - was found to be small), within the next 50 years. Both types of collisions are included in those studies; catastrophic and non-catastrophic, the former being defined as having a ratio of impactor kinetic energy to target mass of 40 J/g or higher. The ratio found between the two types of collisions were found to be around $50-60\%$.

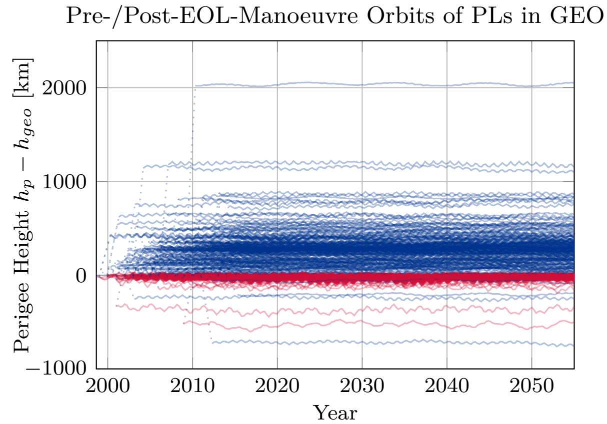
In roughly the same interval, the LEO objects studied in this report reduced the number of projected collisions by 0.54, which is well within the noise ($< 5\%$) of the projected numbers. Thus, no significant improvement for the resident population can be expected due to the already implemented EOL-manoeuvres.

More interesting is the question about combined impact of future EOL-manoeuvres, assuming

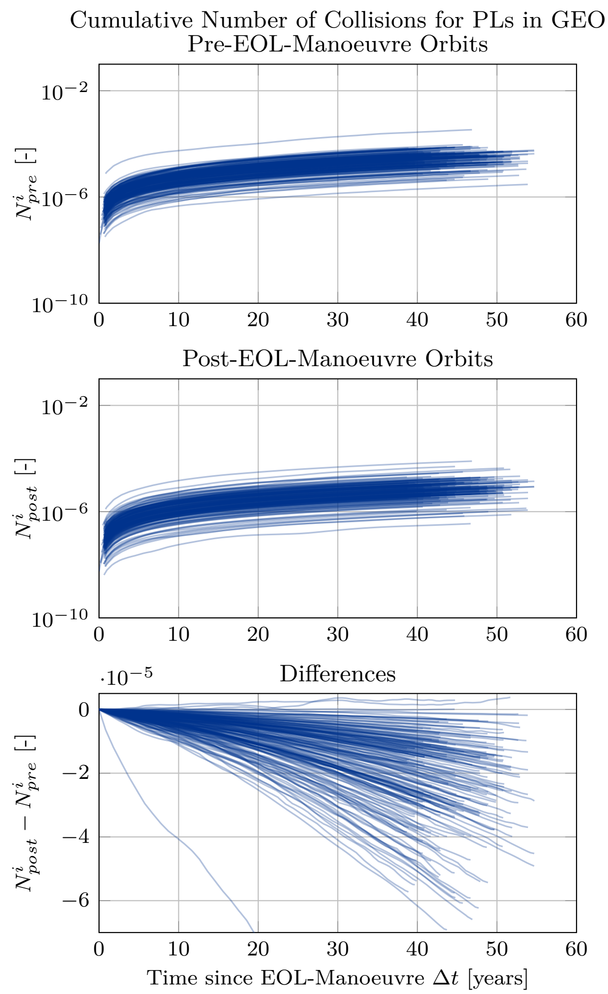
a) continuation of the current levels of EOL-manoeuvres (compliant and non-compliant) referred to as the business-as-usual (BAU) scenario;

b) improved adherence of 90% to the PMD mitigation guidelines, referred to as the 90%-PMD scenario.

The projection is done by calculating the average reduction of number of collisions in a 10 years span for objects reaching EOL within a 10-year interval. The average studied analysis interval (projection from manoeuvre up until 1 January 2055) for both PLs and RBs is roughly 45 years (in fact the average intervals are 45.3 and 44.3 respectively). To get the average reduction for a 10 years projection span, the number of collisions reported in the previous section need to be weighted by $\frac{10}{45}$. All the PL EOL-manoeuvres performed within the past 25 years are considered. For RBs, the interval is 15 years.



(a) Evolution of the pre- (red) and post- (blue) manoeuvre orbits.



(b) Cumulative number of collisions in the pre- (upper) and post- (middle) manoeuvre scenarios and the absolute difference.

Fig. 4: Pre- and post-manoeuvre orbits and number of collisions for PLs initially in or close to GEO.

To average the numbers for a 10-years interval, again a weight of $\frac{10}{25}$ and $\frac{10}{15}$ for PLs and RBs is applied. Then, the average is multiplied by the contributions of each decade $d = 1, 2, ..., 5$ towards the following 50 years, or mathematically speaking, multiplied by $5(5 + 1)/2 = 15$. To simplify comparison between the two scenarios, immediate effect of the PMD is assumed.

a) BAU

The total change in number collisions until 1 January 2055 was found to be −0.09 for PLs and −0.45 for RBs. Thus, the average change in number of collisions for the following 10 years for objects launched in a 10 year interval is $-0.09\frac{10}{45}\frac{10}{25} = -0.008$ for PLs and $-0.45\frac{10}{45}\frac{10}{15} = -0.067$ for RBs, or a combined reduction of 0.075. If the same launch trend is assumed for the next 50 years, the number of averted collisions becomes $15 \times 0.075 = 1.125$. Therefore, if current levels of adherence to the PMD guideline is continued, only one projected collision (or half a catastrophic one) can be averted within the next 50 years, out of 12 to 14.

b) 90% PMD

If only the compliant objects are considered, the total change in number of collisions up to 1 January 2055 is −0.047 for PLs and −0.48 for RBs. Assuming the share of compliant objects could be raised to 90%, i.e. a $\frac{90}{4} = 22.5$ manifold increase from 4% for PLs, and a $\frac{90}{38} = 2.4$ manifold increase from 38% for RBs, and assuming the same reduction as for the compliant-only objects studied in this report, the average change in number of collisions in the next 10 years, would be $-0.047\frac{10}{45}\frac{10}{25}\frac{90}{4} = -0.094$ for PLs and $-0.48\frac{10}{45}\frac{10}{15}\frac{90}{38} = -0.168$ for RBs, or a total of 0.262 for a 10-year interval window. This is a +250% improvement over the BAU scenario. Thus, assuming same launch trends, 3.94 collisions (or two catastrophic ones) can be averted in the next 50 years, which would be a significant contribution in keeping LEO population numbers stable. It has to be noted here that the fluxes were calculated in MASTER using its BAU scenario. The effect on the absolute reduction might therefore be slightly overestimated, as less objects would be present for possible collisions in an environment with improved levels of PMD. The estimated averted ~4 collisions scales well with the difference of roughly 2.5 collisions between 0% and 90%-PMD scenarios found in [14]. Still, a considerable number of collisions takes place, leading to an increase of the number of objects in space [16].

5. Conclusions

This study shows that the individual benefit of implementing an EOL-manoeuvre in reducing the risk of colliding with space debris is large. It is evident that commercial users (e.g. constellation and GEO satellite operators) are already clearing their operational orbits. Unfortunately, today, from a global perspective, and in particular in LEO, too few objects implement an EOL-manoeuvre compliant with the IADC mitigation guidelines in order to make a significant difference in the number of expected collisions and collisions fragments produced thereof.

The efforts of conducting PMDs will have to be increased, in terms of numbers as well as impact, if the clear benefits for the individual spacecraft are to be raised to gains for the entire protected region.

References

[1] L. Anselmo and C. Pardini. Analysis of the consequences in Low Earth Orbit of the collision between Cosmos 2251 and Iridium 33. In *Proceedings of the 21st International Symposium on Space Flight Dynamics*, 2009.

[2] T. Flohrer, S. Lemmens, B. Bastida Virgili, H. Krag, H. Klinkrad, N. Sanchez, J. Oliveira, and F. Pina. DISCOS - current status and future developments. In *Proceedings of the 6th European Conference on Space Debris*, 2013. `https://discosweb.esoc.esa.int`.

[3] Steering Group and Working Group 4 of the Inter-Agency Space Debris Coordination Committee. *IADC Space Debris Mitigation Guidelines*, 2007. Action Item number 22.4.

[4] S. Lemmens and H. Krag. Two-line-elements-based maneuver detection methods for satellites in low earth orbit. *Journal of Guidance, Control and Dynamics*, 37:860, 2014.

[5] T. Flohrer and S. Frey. Classification of geosynchronous objects. Technical Report 18, 2016. European Space Agency, Darmstadt.

[6] S. Flegel, J. Gelhaus, M. Möckel, C. Wiedemann, and D. Kempf. Maintenance of the ESA MASTER-model. Final Report of ESA contract 21705/D/HK, 2010. `https://sdup.esoc.esa.int`.

[7] F. Alby. Spot 1 end of life disposition manoeuvres. *Advances in Space Research*, 35:1335, 2005.

[8] A. Moussi, X. Pena, D. R. Delmas, S. Christy, F. Tavera, F. Riclet, J. P. Chognard, and P. Rebiere. Spot 2 end of life - disposal manoeuvres. SpaceOps Conference, 2010, Huntsville, Alabama, United States.

[9] Spot 4 undertakes new mission before being de-orbited. http://www.intelligence-airbusds.com/en/4612-spot-4-undertakes-new-mission-before-being-de-orbited. Accessed: 2017-05-05.

[10] National Aeronautics and Space Administration. GEOS 2 and Landsat 4 retired. In *Orbital Debris Quarterly News, Volume 6, Issue 3*, 2001.

[11] H. Krag, T. Flohrer, and S. Lemmens. Consideration of space debris mitigation requirements in the operation of LEO missions. SpaceOps Conference, 2012, Stockholm, Sweden.

[12] R. E. Penny jr. Iridium (tm) - debris mitigation practices. In *SPIE Proceedings*, volume 1951, 1993.

[13] J.-C. Liou. Collision activities in the future orbital debris environment. *Advances in Space Research*, 38:2102, 2006.

[14] National Aeronautics and Space Administration. An updated assessment of the orbital debris environment in LEO. In *Orbital Debris Quarterly News, Volume 14, Issue 1*, 2010.

[15] H. G. Lewis, G. G. Swinerd, and R. J. Newland. The space debris environment: future evolution. *The Aeronautical Journal*, 115:241, 2011.

[16] Working Group 2 of the Inter-Agency Space Debris Coordination Committee. *Stability of the Future LEO Environment*, 2013. Action Item number 27.1.