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Impact of End-of-Life Manoeuvres on the Resident Populations 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@esa.int

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 time 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 long-term impact of both satellites and rocket bodies performing End-of-Life (EOL) orbital manoeuvres on the resident populations of 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. ESA's Debris Environment Long-Term Analysis (DELTA) tool is used to estimate the evolution of the space debris environment vis-à-vis the implementation, or not, of EOL manoeuvres. The study shows that, on average, an EOL-manoeuver significantly decreases the flux rate an object encounters, which in turn decreases the probability of a collision. However, the impact on the resident populations is of a low significance due to the small fraction of objects currently performing EOL manoeuvres.
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 in two ways. On the one hand, the effect on the objects themselves is analysed by calculating the debris flux the object is exposed to for its remaining lifetime, or up to 1 January 2055, for the pre-EOL-manoeuvre orbit as well as the post-EOL-manoeuvre orbit. On the other hand, a global analysis estimates the combined effect of these EOL manoeuvres on the resident LEO and GEO populations. The results of both of these studies are presented statistically.

2. Methodology

The analysis can be described in five parts, all of which are explained in more detail in the following subsections. As the first two, the selection processes for the objects and the pre- and post-manoeuvre states are described. Subsequently, the propagator used for the evolution of those states is explained. Lastly, the two tools and settings to estimate the debris flux the objects are exposed to, and the effect of the manoeuvres on the resident population 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 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. The data dates back to 1980 and 2000 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 back to 1999. The precise date of the manoeuvres is not used here for either source, only the respective year is listed, 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: 30 days interval ahead of 1 January of the activity year, post-manoeuvre: 90 days interval 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 $i = \text{argmin}_i\, d_i$, 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 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

The pre- and post-EOL-manoeuvre orbits, are propagated to 1 January 2055. This limit is imposed by the flux analysis tool, which predicts the near Earth space environment until this epoch.

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. 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.

2.4 Flux Analysis

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 orbit 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. 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 until 1 January 2055 or re-entry.

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

2.5 Impact on Resident Population Analysis

In order to quantify the effect the EOL manoeuvres have on the resident populations, ESA's DELTA tool [7] is used. This tool analyses the long term evolution of the future debris environment, taking into account collisions with space debris in a probabilistic manner. Again, the chaser objects considered are objects with diameter above 10 cm and the initial population of PLs, RBs, explosion and collision fragments and launch and mission related objects is taken from MASTER. Business as usual concerning launch traffic is assumed (averaged over the years 2005 – 2013), but without taking into account any further fragmentations due to explosions.

Four scenarios are executed: the pre-manoeuvre and the post-manoeuvre situation for LEO and GEO respectively. As DELTA starts from a single epoch, all the states are propagated to 1 January 2017. The initial epoch set in DELTA is 1 January 2013, and the environment is propagated for 200 years to capture collisional feedback effects. In case a re-entry is detected during propagation, it is removed from the population in the respective scenario. The two LEO cases are comprised of the results of 48 Monte Carlo runs each and the two GEO cases of 40 Monte Carlo runs each.

3. Results

Table 1 summarises the total cumulative fluxes experienced by all the objects within their respective groups, for the pre- and post-manoeuvre scenarios. In addition, the total mass and total average cross section that is being moved by the EOL manoeuvres is listed. Figs. 1, 2 and 4 show, for each group, the evolution of the pre- and post-manoeuvre states as well as the cumulative fluxes each object is exposed to, in both states, during its lifetime until re-entry or until 1 January 2055.

Table 1: MASTER debris flux analysis results for the three groups, with number of objects, N, total mass, m, total area, A, cumulative time on-orbit (until re-entry or 1 January 2055), t, total cumulative flux for the pre-EOL-manoeuvre scenario, ϕ_{pre}, total cumulative flux for the post-EOL-manoeuvre scenario, ϕ_{post} and the relative total cumulative flux difference, $\Delta\phi = (\phi_{post} - \phi_{pre})/\phi_{pre}$.

	LEO		GEO
	PLs	RBs	PLs
N [−]	86	171	199
m [tons]	180	321	320
A [m^2]	849	3089	5250
t_{pre} [years]	2897	4785	9095
t_{post} [years]	2470	2705	9095
ϕ_{pre} [−]	0.21	0.61	0.0068
ϕ_{post} [−]	0.12	0.16	0.0017
$\Delta\phi$ [−]	−43%	−74%	−74%

Table 2 lists the results from the DELTA analysis for the four scenarios and Figs. 3 and 5 depict the results temporally and spatially for selected scenarios. The other Figs. are omitted, as the pre- and post-EOL-manoeuvre scenarios show very similar behaviour.

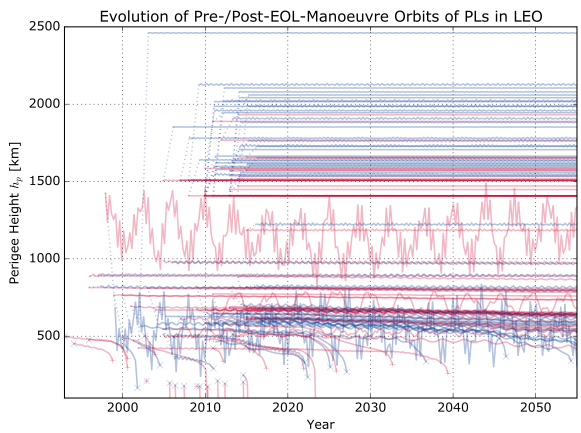
3.1 LEO

In LEO, a total of 86 PLs and 171 RBs performed an EOL-manoeuvre. For 23 and, respectively, 87 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.

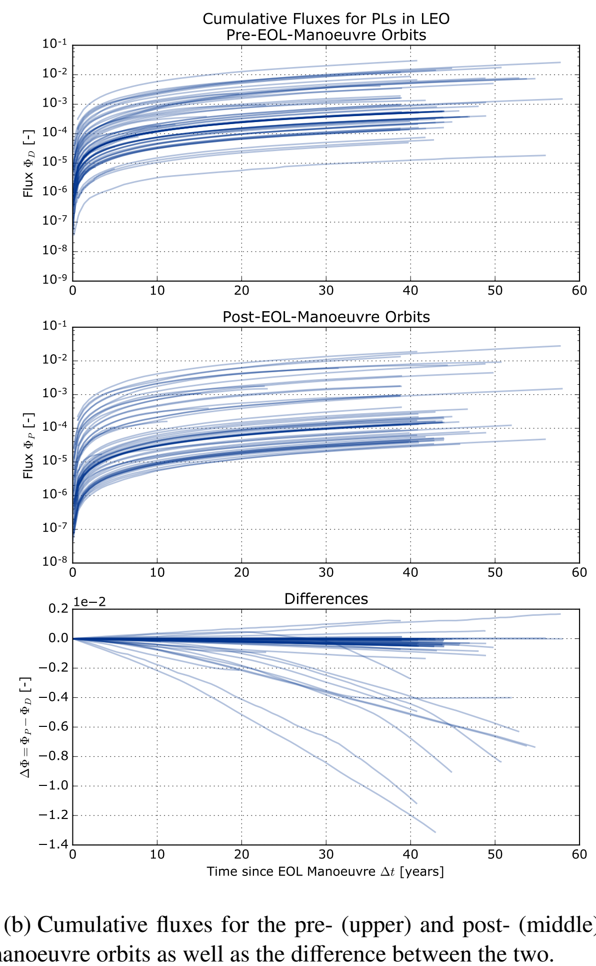
A total mass of 180 tons and a total cross-sectional area of 849 m^2 were moved with the PLs performing an EOL-manoeuvre. The total dwell time on-orbit, until re-entry or 1 January 2055, of these 86 objects could be reduced from 2897 to 2470 years. The total experienced debris flux in this group and for the same time span is reduced from 0.21 to 0.12 objects larger than 10 cm, or relatively by 43%.

The 171 RBs performing an EOL-manoeuvre accumulate to a total mass of 321 tons and 3089 m^2 total average cross sectional area. By performing the manoeuvres, they reduce their on-orbit dwell time from 4785 to 2705 years, and their total accumulated debris fluxes from 0.61 to 0.16 objects larger than 10 cm, or relatively by 74%.

The DELTA anaysis estimates 122.9 catastropic col-

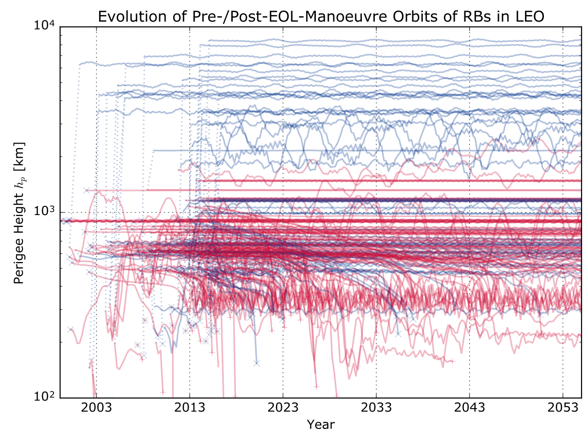


(a) Evolution of the pre- (red) and post- (blue) manoeuvre orbits. Crosses and pluses signal a re-entry.

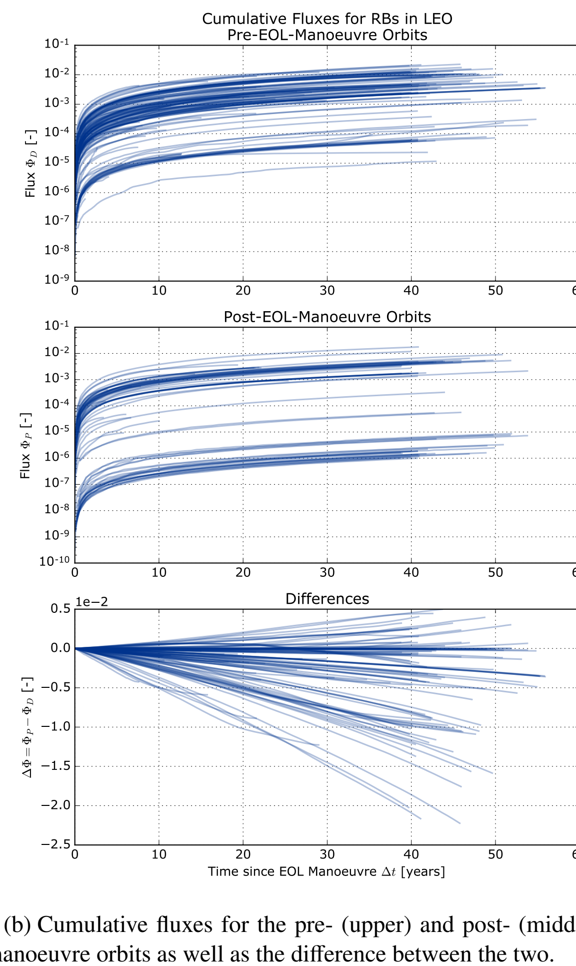


(b) Cumulative fluxes for the pre- (upper) and post- (middle) manoeuvre orbits as well as the difference between the two.

Fig. 1: Pre- and post-manoeuvre orbits as well as cumulative fluxes 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 fluxes for the pre- (upper) and post- (middle) manoeuvre orbits as well as the difference between the two.

Fig. 2: Pre- and post-manoeuvre orbits as well as cumulative fluxes for RBs initially in or crossing LEO.

Table 2: DELTA results for the four scenarios, after 200 years, with the average number of catastrophic collisions, N_c, the average number of collision fragments, N_f, and the respective sample standard deviations, σ_c and σ_f.

Scenario	N_c	σ_c	N_f	σ_f
LEO: pre	122.9	21.7	42626	8838
LEO: post	127.7	19.3	43887	9450
GEO: pre	1.2	1.2	1905	1261
GEO: post	1.4	1.3	2630	1865

lisions, with a sample standard deviation of σ_c = 21.7 for the pre-EOL-manoeuvre scenario, resulting in 42626 (σ_f = 8838) collision fragmentation objects. In the post-EOL-manoeuvre scenario, 127.7 (σ_c = 19.3) catastrophic collisions lead to 43887 (σ_f = 9450) fragmentation objects. Fig. 3 shows the evolution of the number of fragments and objects over time for the pre-EOL-manoeuvre scenario.

3.2 GEO

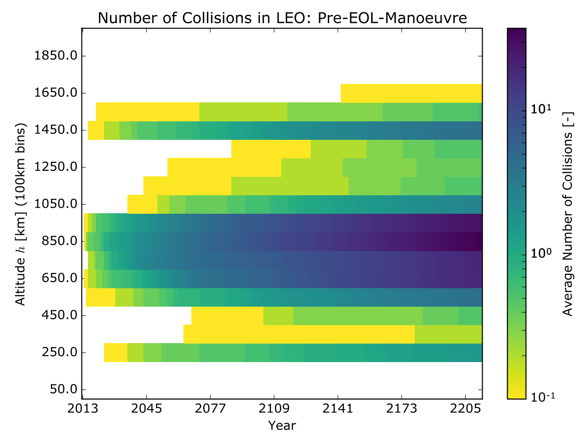
In GEO, 199 objects performed an EOL-manoeuvre with various degrees of success (Fig. 4a). For all of them, a post-manoeuvre state can be found. The total time spent on-orbit is the same for the pre- and post-manoeuvre states as none re-enters. The total mass of those objects accumulates to 320 tons, and the total average cross sectional area to 5250 m^2. As they move out of the GEO protected region, they reduce the total number of incident debris flux larger than 10 cm from 0.0068 to 0.0017, or relatively by 74%, for the given analysis interval.

The DELTA analysis estimates 1.2 catastrophic collisions in GEO, with a sample standard deviation σ_c = 1.2 for the pre-EOL-manoeuvre scenario, resulting in 1905 (σ_f = 1261) collision fragmentation objects (Fig. 5). In the post-EOL-manoeuvre scenario, an estimated 1.4 (σ_c = 1.3) catastrophic collisions lead to 2630 (σ_f = 1865) fragmentation objects.

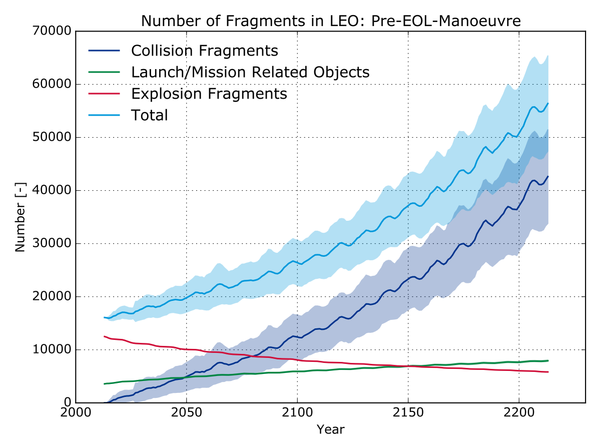
4. Discussion

4.1 LEO

The manoeuvre overview plot (see Fig. 1a) reveals that many of the considered PLs with a pre-EOL-manoeuvre perigee above 1000 km 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, they achieve, on average, a significant reduction of

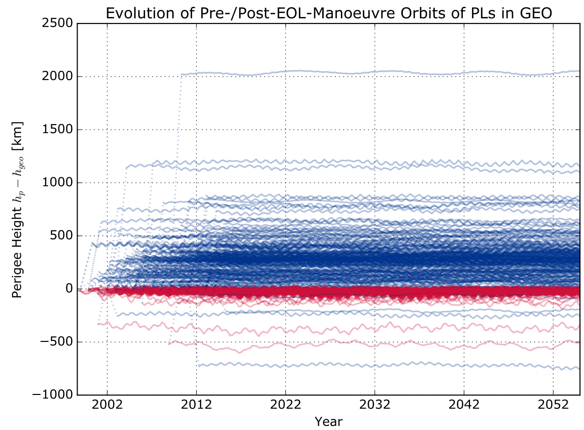


(a) Average number of collisions as a function of time and altitude. After 200 years, the highest number of on average 37.4 catastrophic collisions occur within 850 ± 50 km.

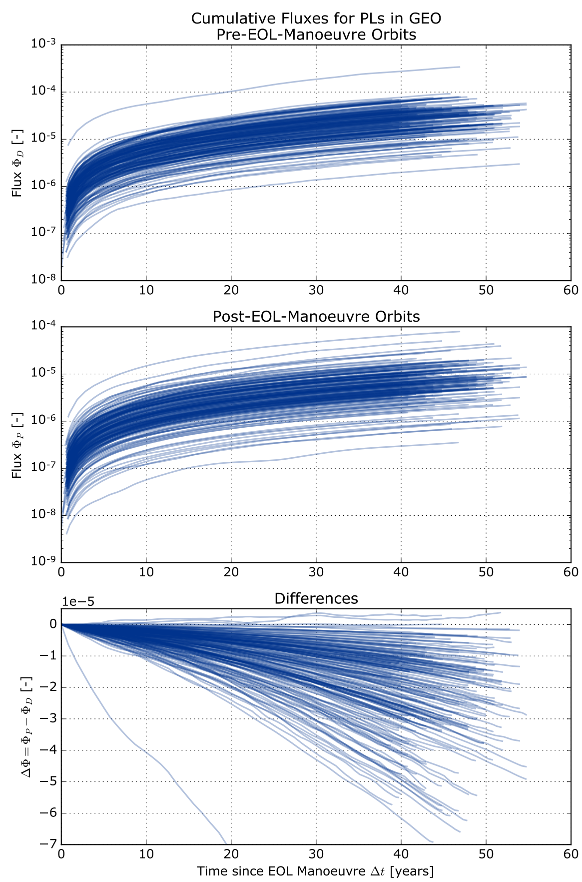


(b) Evolution of the average number of fragments, plus/minus one sample standard deviation.

Fig. 3: Evolution of the number of collisions and objects averaged over the Monte Carlo runs for the LEO, pre-EOL-manoeuvre scenario.

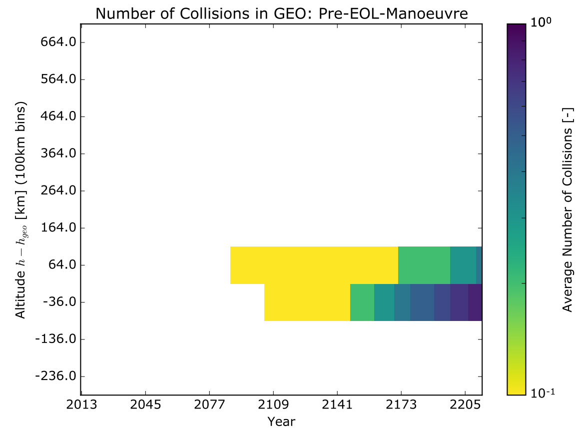


(a) Evolution of the pre- (red) and post- (blue) manoeuvre orbits.

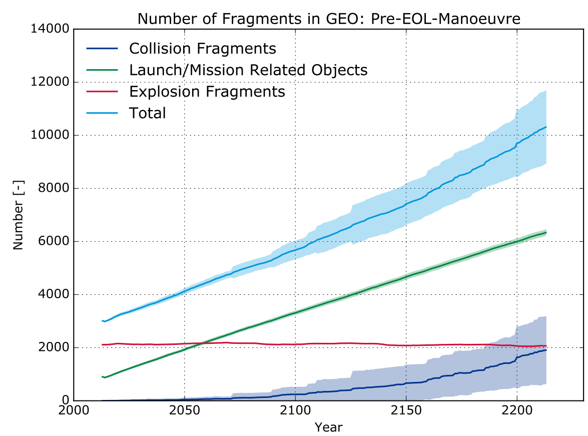


(b) Cumulative fluxes for the pre- (upper) and post- (middle) manoeuvre orbits as well as the difference between the two.

Fig. 4: Pre- and post-manoeuvre orbits as well as cumulative fluxes for PLs initially in or close to GEO.



(a) Average number of collisions as a function of time and altitude.



(b) Average number of fragments, plus/minus one sample standard deviation.

Fig. 5: Evolution of the number of collisions and objects averaged over the Monte Carlo runs for the GEO, pre-EOL-manoeuvre scenario.

43%, or in other terms, they are as individual objects 2/5 less likely to be involved in a collision after performing the manoeuvres. This reduction figure would increase if the analysis interval was selected longer, even though ironically, it would increase the most with direct re-entries.

For the RBs, the beneficial effect on the individual objects is even more pronounced. This arises from the fact, that many RBs implement a direct re-entry strategy, thus immediately clearing the congested region. Another reason are the objects in GEO Transfer Orbit (GTO), performing perigee raise manoeuvres to clear the LEO protected region (see Fig. 2a), which is not conform with the mitigation guideline. On average, after performing the manoeuvre, the objects are 3/4 less likely to collide with space debris in their remaining lifetime, or until 1 January 2055.

The DELTA analysis turns out to be insufficient for comparison of the two scenarios. The number of Monte Carlo runs executed, 48, is not high enough to reflect very small differences in the initial population, as the signal to noise ratio is still too low. The 257 objects performing an EOL-manoeuvre, many of those manoeuvres not compliant with the mitigation guidelines, constitute less than 2% of the more than 13000 observable objects which reside in or cross LEO (as of 1 January 2016 [2]).

To highlight that an increased level of PMD does make a significant change, two additional DELTA scenarios are compared, isolating the effect of the PMDs from the increasing number of launcher and mission related objects. Fig. 6 shows the evolution of the number of fragments in LEO for the two scenarios: one with 0% PMD and one with 90% PMD (in the sense of the mitigation guidelines). No further explosions and no release of launcher and mission related objects are considered. While the number of collision fragments increases exponentially for the 0% PMD case (to $N_c = 42157, \sigma_c = 7683$ after 200 years), it seems to stabilise for the 90% PMD case ($N_c = 12567, \sigma_c = 3647$).

What the DELTA results do show is that the current (from 2005 – 2013) level of adherence to the mitigation guidelines is insufficient, as it leads to the exponential growth of number of collision fragments.

4.2 GEO

In GEO, the situation is very different, as the experienced fluxes are 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 likelihood of colliding with a debris piece is significantly decreased, on average, by

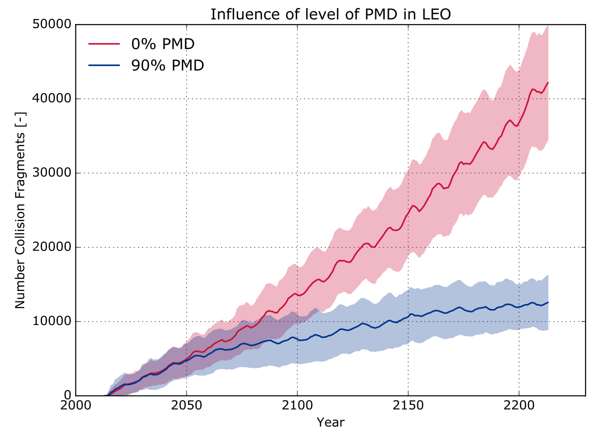


Fig. 6: Evolution of the number of collision fragments for two different levels of PMD.

3/4 after implementing an EOL-manoeuvre, for the analysis interval considered.

Concerning the DELTA results, the same is true as for the LEO scenarios. The number of Monte Carlo runs, 40, is insufficient for comparison. But even here, the current level of adherence to the mitigation guidelines are insufficient, concerning the growing number of collision fragments, with severe long-lasting consequences for the future use of the GEO region.

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. This not only protects the object itself, but also the protected environment it operates in. It is evident that commercial users (e.g. 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 if the clear benefits for the individual spacecraft are to be raised to gains for the entire protected region, and that our goal of making space accessible to all countries does not create a restricted region in the process.

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