STATUS OF THE SPACE ENVIRONMENT: CURRENT LEVEL OF ADHERENCE TO THE SPACE DEBRIS MITIGATION POLICY

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ABSTRACT

To counter an ever increasing number of man-made objects orbiting Earth which are endangering current and future space missions, the Space Debris Mitigation (SDM) guidelines, issued by the Inter-Agency Space Debris Coordination Committee (IADC), were first published in 2002. These guidelines were a model for various international and national standardisation and regulation activities on SDM. One part of the research conducted at the Space Debris Office at the European Space Operations Centre (ESOC) is to study and monitor the level of implementation of these guidelines. This report summarises the status of the near Earth space environment by illustrating the number of objects orbiting Earth. The current and historical environment is assessed, with a focus on the interference of the IADC protected regions, the Low Earth Orbit (LEO) and the Geostationary Orbit (GEO). It includes an estimate of the evolution of the collision risk of payloads and rocket bodies with space debris, computed with ESA's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) tool. And it illustrates the current level of adherence to the SDM guidelines in terms of end-of-life operations and the release of mission related objects.

Key words: Space Debris; Mitigation Guidelines; IADC.

1. INTRODUCTION

The space debris mitigation guidelines, published by the Inter-Agency Space Debris Coordination Commitee (IADC) in 2002 and revised in 2007, were introduced to reverse the trend of the ever increasing number of space debris, to mitigate the risk of collisions and to preserve the space environment for future generations [5]. In particular, two regions are protected by the guidelines; the Low Earth Orbit (LEO) and the Geostationary Orbit (GEO), subsequently referred to as $\mathrm{LEO}_{\mathrm{IADC}}$ and $\mathrm{GEO}_{\mathrm{IADC}}$ (see Table 2 for the definitions of those regions). Now, 15 years later, sufficient time has passed for the guidelines to propagate into national and international standards [6] and to be applied to recent space missions. It is of interest to see whether trends can be found indicating a broadening implementation of the guidelines. This reports shows some of the results produced by the Space Debris Office of the European Space Agency (ESA) on quantifying the level of adherence to the mitigation guidelines.

Herein, the historical and current environment in terms of numbers and collision risk is presented. At each reference epoch (1 January), every observed orbiting object was counted and a state was obtained from the Database and Information System Characterising Objects in Space (DISCOS) [3]. The collision risk is subsequently calculated using the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) tool [2]. More than 50,000 MASTER runs were performed in a highly automatic and distributed system. The results are presented per object type (see Table 1) and orbital class (see Table 2).

Then, two components addressed by the mitigation guidelines are discussed:

- the degree of implementation of end-of-life (EOL) manoeuvres in order to clear the protected regions;
- the number of released mission related objects (MROs).

Not being discussed in this report are the parts of the mitigation guidelines concerning the prevention of on-orbit collisions and fragmentations during and after normal operations.

2. CURRENT AND HISTORICAL STATUS OF THE SPACE ENVIRONMENT

2.1. Numbers

The number of observable objects orbiting Earth as of the reference epoch 1 January 2017 is almost 18500 (see Table 3). Each object counted was observed at least once in 2016, and is assumed to not have re-entered before the reference epoch. Almost two thirds of these objects

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Table 1. Object types

Type	Description
PL	Payload
PM	Payload Mission Related Object
PD	Payload Debris
RB	Rocket Body
RM	Rocket Mission Related Object
RD	Rocket Debris
UI	Unidentified

reside in LEO and nearly 5% in GEO. Additionally, objects on orbits crossing into the protected regions increase the traffic further (see Table 4); 394 objects cross both, LEO_{IADC} and GEO_{IADC} and 2629 objects penetrate into LEO_{IADC} only. A total of 2637 objects intersect with (and reside in) GEO_{IADC}. Table 4 also gives an idea of how long on average the crossing objects spend in the protected regions; the equivalent number of objects is calculated from summing up the dwell time fraction over all objects interfering the region. The dwell time fraction is defined as the total time an object spends in the protected region per orbit, divided by its orbital period. E.g. the 394+2629=3023 objects crossing LEO_{IADC} add an equivalent of 12638-12230=408 additional objects to the protected region. Thus each LEO_{IADC} crosser dwells on average 13.5% of its orbital period within LEO_{IADC}. Note that the velocities of these crossers are typically considerably higher at their respective perigees, compared to the objects fully residing in LEO_{IADC}.

Figures 1 and 2 show the evolution of the number of observable objects orbiting Earth, per object type and orbital classification respectively. The two steep increases after 2007 and 2009, are due to the Chinese anti-satellite (ASAT) test [9] and the Iridium 33/Kosmos 2251 collision [10]. The number of UIs is expected to rise dramatically with improved sensor capabilities.

2.2. Virtual Collisions

Using the MASTER tool allowed to estimate the space debris flux each of the PLs and RBs counted above receives over the course of one complete orbit. Only particles sized between 0.1-100 m in reference diameter were taken into account, as they generally correspond to the objects involved in so called catastrophic collisions, i.e. having an impact energy above 40 J/g. Multiplied with the cross sectional area of the object, and the time-frame of one year results in the number of virtual collisions each objects experiences in one year, under the assumption of a non-perturbed orbit. The *virtual* is added because these are not real collisions, but merely estimated ones, which give a measure of the collision risk for each object.

Table 5 shows the summed number of virtual collisions for PLs and RBs separately in each orbital class. Note that the collision risk is greatly underestimated, as collisions with particles smaller than 10 cm are ignored (most of which would result in non-catastrophic collisions [7]). At the same time it is slightly overestimated, as the capability of manoeuvering to avoid a probable collision is ignored. However only about a third of all PLs - ignoring human spaceflight - reaching EOL between the years 2000-2015 proved to have orbit control capability [4]. And the capability of manoeuvring alone does not protect against a collision; conjunctions also need to be predicted and appropriate measures taken in order to prevent a collision. The trend in Figure 2 shows that the likelihood of collision is on the rise[1]. LEO is by far at greatest risk to see a collision, with 0.15 virtual collisions in one year, or one virtual collision of a PL or RB with an object larger than 10 cm in 7 years. The following discussion is thus focused on LEO only. Within 10 years (after the rise induced by the ASAT test), the number of virtual collisions per year rose by 51.5%, while the number of PLs and RBs orbiting only rose by 33.7%, translating into a 14.3% increase of collision risk on average for each PL and RB. Within 20 years, the number of virtual collisions rose by 206%, while at the same time the number of PLs and RBs increased by 65.9%, meaning the individual collision risk increased on average by 84.6%, i.e. almost doubled.

Integrating the trend of the virtual collisions in LEO of the past 60 years results in 1.03 virtual collisions for PLs and 1.45 for RBs. More than half being accumulated within the past 10 years (0.56 for PLs and 0.72 for RBs respectively). So far, four collisions between catalogued objects have been reported in LEO [11].

3. END-OF-LIFE OPERATIONS

The mitigation guidelines state that an object reaching the end of operational mission should perform a manoeuvre to clear dense orbital regions by reducing its remaining orbital lifetime, preferably to zero. In LEO_{IADC}, the post-mission orbital lifetime shall be limited to 25 years or less. Objects in geosynchronous orbits, where no atmospheric drag acts to clean the region, shall relocate into an orbit that remains outside GEO_{IADC} for the foreseeable future (refer to [5] for a more technical description). Vessels related to human spaceflight are not taken into account for the synthesis of the results, as they tend to skew the results positively in terms of count and mass due to their objectives. Objects reaching EOL are binned into four different categories, depending on whether they performed an EOL manoeuvre and their respective orbits pre- and post-EOL manoeuvre:

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[1] The steep increase at the reference epoch 1 January 2007 is due to the ASAT test of 11 January 2007. The MASTER tool is population based, and for each calculation chooses the population which is closest to the reference epoch. In this case, the population from 1 February 2007 is - rather than the one from November 2006 - closer to the reference epoch of the majority of the selected states. Thus the estimate includes the short-term future.

Table 2. Orbit classifications, with semi-major axis a, eccentricity e, inclination i, perigee height h_p, apogee height h_a and declination δ. The units are km and degrees.

Orbit	Description	Definition		
LEO	Low Earth Orbit	$h_{p/a} \in [0, 2000]$		
GEO	Geostationary Orbit	$h_{p/a} \in [35586, 35986]$	$i \in [0, 25]$	
EGO	Extended Geostationary Orbit	$a \in [37948, 46380]$	$e \in [0, 0.25]$	$i \in [0, 25]$
GTO	GEO Transfer Orbit	$h_p \in [0, 2000]$	$h_a \in [31570, 40002]$	$i \in [0, 90]$
NSO	Navigation Satellites Orbit	$h_{p/a} \in [18100, 24300]$	$i \in [50, 70]$	
MEO	Medium Earth Orbit	$h_{p/a} \in [2000, 31570]$		
LMO	LEO-MEO Crossing Orbits	$h_p \in [0, 2000]$	$h_a \in [2000, 31570]$	
MGO	MEO-GEO Crossing Orbits	$h_p \in [2000, 31570]$	$h_a \in [31570, 40002]$	
HEO	Highly Eccentric Earth Orbit	$h_p \in [0, 31570]$	$h_a > 40002$	
LEO_{IADC}	IADC LEO Protected Region	$h_{p/a} \in [0, 2000]$		
GEO_{IADC}	IADC GEO Protected Region	$h_{p/a} \in [35586, 35986]$	$\delta \in [-15, 15]$	

Table 3. Number observed objects in geocentric orbit as of 1 January 2017.

	PL	PM	PD	RB	RM	RD	UI	Total
LEO	2300	113	5959	822	490	2474	72	12230
GEO	708	3	4	67	0	0	30	812
EGO	401	37	1	181	0	35	845	1500
GTO	60	10	10	217	49	214	312	872
NSO	230	1	0	70	2	0	0	303
MEO	52	53	8	16	2	5	37	173
LMO	90	47	130	207	221	590	307	1592
MGO	66	2	82	158	4	10	184	506
HEO	24	1	19	42	0	48	300	434
Other	30	3	0	4	0	0	26	63
Total	3961	270	6213	1784	768	3376	2113	18485

Table 4. Number observed objects in geocentric orbit penetrating into the protected regions, in absolute (abs) and equivalent (eqv) terms, as of 1 January 2017.

	PL	PM	PD	RB	RM	RD	UI	Total
both (abs)	19	1	20	73	15	122	144	394
LEO_{IADC} (abs)	2464	171	6118	1277	760	3326	743	14859
LEO_{IADC} (eqv)	2335	124	6050	871	528	2611	119	12638
GEO_{IADC} (abs)	864	37	41	281	15	148	1251	2637
GEO_{IADC} (eqv)	762	11	5	103	1	9	124	1016
none (abs)	652	63	74	299	8	24	263	1383

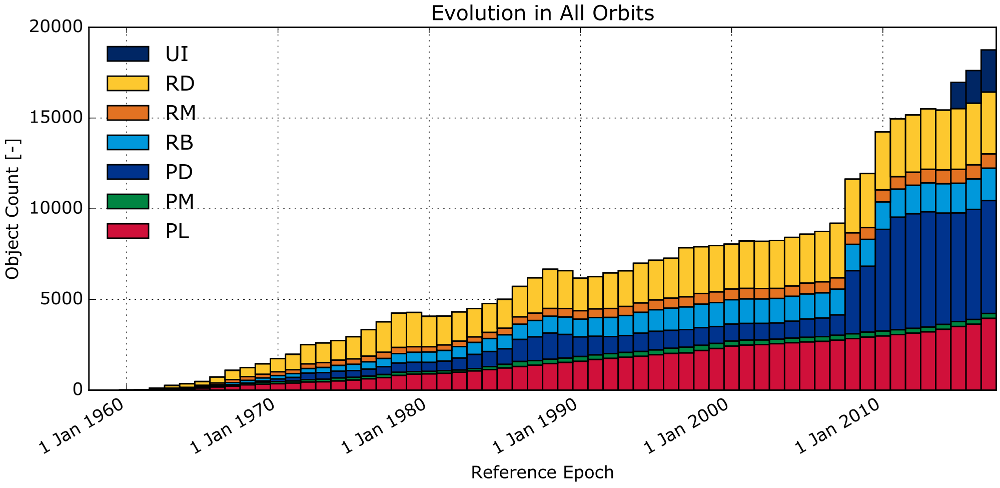

Figure 1. Evolution of the number observed objects in geocentric orbit by object type.

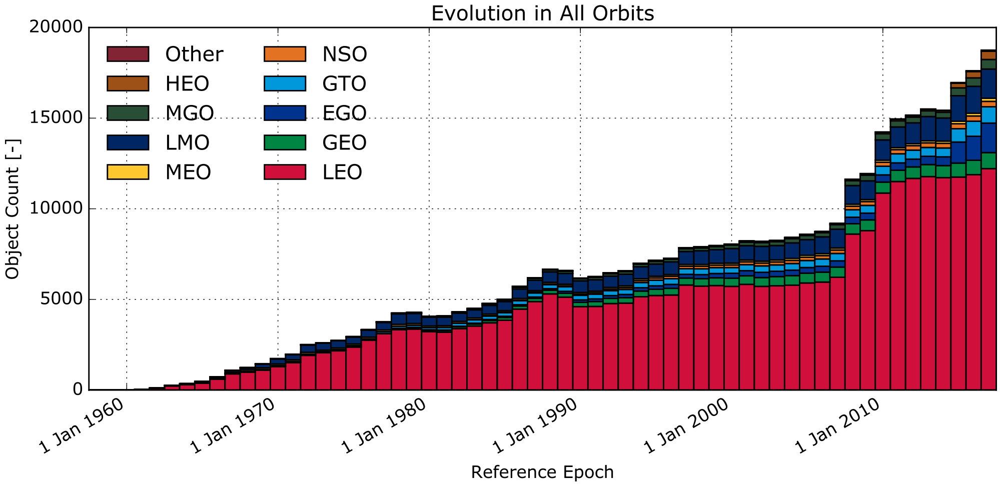

Figure 2. Evolution of the number observed objects in geocentric orbit by orbital class.

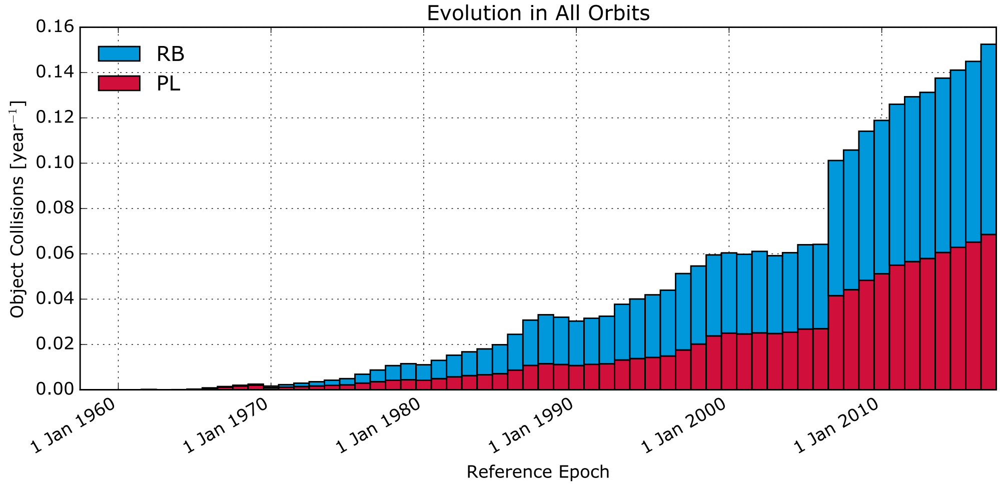

Figure 3. Evolution of number objects (sized 0.1-100 m) colliding with PLs and RBs on-orbit per year, according to the MASTER tool. Note that the increase in collision risk due to the ASAT test is evident already as of 1 January 2007, due to the way the tool chooses the resident populations.

Table 5. Cumulative number of virtual collisions of PLs and RBs with debris (sized 0.1-100 m) per year as of 1 January 2017, according to the MASTER tool.

	PL	RB	Total
LEO	6.8×10^{-2}	8.2×10^{-2}	1.5×10^{-1}
GEO	3.1×10^{-4}	1.6×10^{-5}	3.2×10^{-4}
EGO	3.9×10^{-5}	1.0×10^{-5}	4.9×10^{-5}
GTO	9.8×10^{-5}	6.2×10^{-4}	7.1×10^{-4}
NSO	5.4×10^{-6}	5.3×10^{-6}	1.1×10^{-5}
MEO	1.8×10^{-5}	4.8×10^{-6}	2.2×10^{-5}
LMO	5.1×10^{-4}	1.2×10^{-3}	1.7×10^{-3}
MGO	1.2×10^{-6}	9.2×10^{-6}	1.0×10^{-5}
HEO	7.8×10^{-6}	3.8×10^{-5}	4.6×10^{-5}
Other	1.6×10^{-6}	6.4×10^{-10}	1.6×10^{-6}
Total	6.9×10^{-2}	8.4×10^{-2}	1.5×10^{-1}

- **no attempt:** no manoeuvre was performed despite residing in a non-compliant orbit;
- **insufficient attempt:** the object performed a manoeuvre that failed to put it in a compliant orbit;
- **successful attempt:** the performed manoeuvre put the object into a compliant orbit (includes objects that performed a manoeuvre even residing in an already compliant orbit pre-manoeuvre);
- **naturally compliant:** without performing a manoeuvre, the object is compliant due to an orbital lifetime limited to less than 25 years by atmospheric drag (only applicable in $\mathrm{LEO_{IADC}}$).

In-depth description of the methodology used to determine the EOL of LEO objects can be found in [8]. For a more detailed summary of the results given here for GEO objects, please refer to [1].

Figures 4 to 6 show the relative evolution of those categories for PLs (relative count and mass) and RBs (only relative count as the mass trend is qualitatively the same) in $\mathrm{LEO_{IADC}}$ reaching EOL. The pluses in the figures show a 10-year moving average of the compliant objects (i.e. the sum of the objects categorised as successful attempt and naturally compliant). The following paragraph only takes into account $\mathrm{LEO_{IADC}}$ objects reaching EOL in the last 10 years of analysis, i.e. 2006-2015 for PLs and 2007-2016 for RBs. $\mathrm{GEO_{IADC}}$ objects are discussed in the next paragraph. 49.9% of all PLs are naturally compliant and did not perform an EOL manoeuvre. Of the other half (taking it as 100%), only 6.7% successfully implemented a manoeuvre complying with the guidelines. Another 10.4% tried to do so but failed to comply with the 25-years rule. As for the remaining 82.9% (or 41.5% of all PLs), no attempt to comply with the guidelines was performed. In absolute terms, 53.3% are compliant. The last two years could suggest an improvement in behaviour, but looking at the evolution of the compliant mass (Figure 5), it becomes evident that the count figure is skewed by a change in the PL launch trend. The steep increase in naturally compliant category for the years 2014 and 2015 is due to the large numbers of cubesats introduced in the previous years mostly into orbits low enough, or with area-to-mass ratios high enough, to decay within 25 years. In terms of mass, 60.3% are compliant in the same time-range, consistently sloping downward in the 10-year moving average. RBs more successfully clear $\mathrm{LEO_{IADC}}$. Again, about half (49.4%) of the RBs are in orbits which are naturally compliant and no EOL manoeuvre was performed. Of the other half (taking it as 100%), 43.9% implemented a successful and another 13.6% an insufficient manoeuvre. The remaining 42.6%[2] (or 21.5% of all RBs) did not attempt to adhere to the guidelines. In absolute terms, 71.6% are compliant. The share of RBs actively clearing $\mathrm{LEO_{IADC}}$ is on the rise, but mostly at the expense of already naturally compliant RBs. The relative number of non-compliant RBs remains almost constant around 29%.

Figure 7 shows the compliance trend for PLs in $\mathrm{GEO_{IADC}}$. The following discussion only considers the ones residing in $\mathrm{GEO_{IADC}}$ and reaching EOL between 2007-2016. 66.1% successfully raised their orbits high enough above $\mathrm{GEO_{IADC}}$. Another 23.2% tried to do so, but failed, leaving only 10.7% or 1 in 9 PLs that did not attempt a clearance manoeuvre. The share of objects successfully implementing an EOL manoeuvre is - leaving out the year 2015 as an outlier - on the rise but seems to saturate at around 75%. Note that on average, only 16.8 PLs reached EOL each year in this period, making the figures prone to large variances.

4. RELEASE OF MISSION RELATED OBJECTS

The mitigation guidelines state that no debris, such as camera covers and de-spin weights, should be released during normal operations for both PLs and RBs. Figures 8 and 9 show the evolution of released mission related objects in number and mass for PLs and RBs respectively. The number of released MROs from PLs decreased drastically towards the end of the cold war down to and remaining at 5.6 per year (or 0.661 tons) averaged over the past 10 years. RBs however continue to release MROs at significant levels; over the past 10 years, they released on average 35.4 objects (or 10.741 tons) per year. The numbers presented here are to be interpreted as a lower limit only. From orbit dynamics alone it is difficult to distinguish between the intentional and non-intential release of space debris.

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[2] Parts do not sum to unity due to rounding errors.

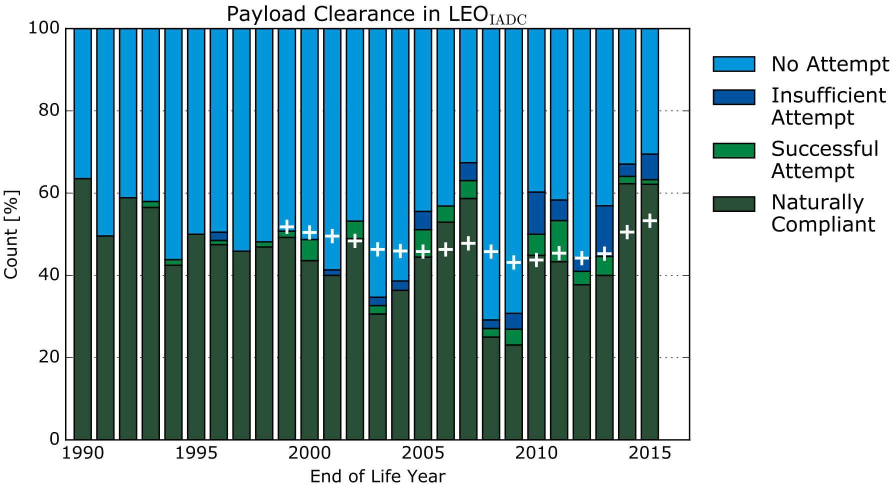

Figure 4. Evolution of compliance of PLs (not related to human spaceflight) in LEO_{IADC}. Pluses show the 10-year moving average of compliant objects (i.e. the naturally compliant ones and the ones performing a successful EOL manoeuvre).

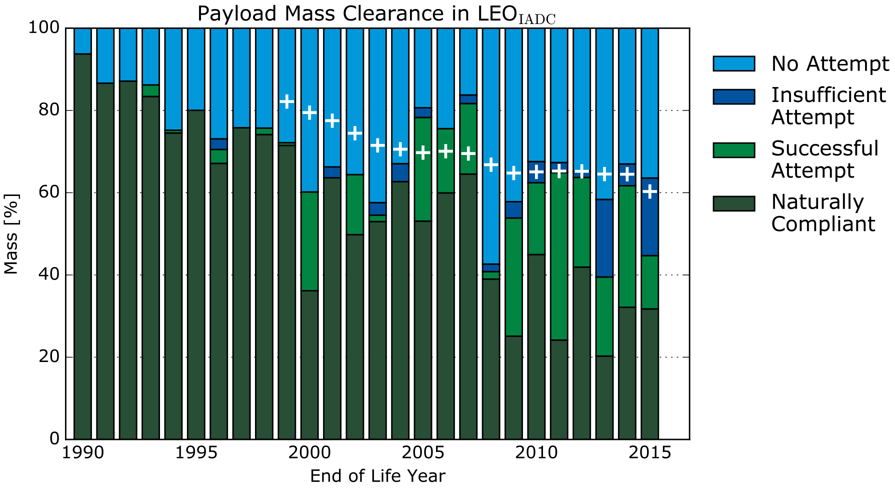

Figure 5. Evolution of compliant mass of PLs (not related to human spaceflight) in LEO_{IADC}.

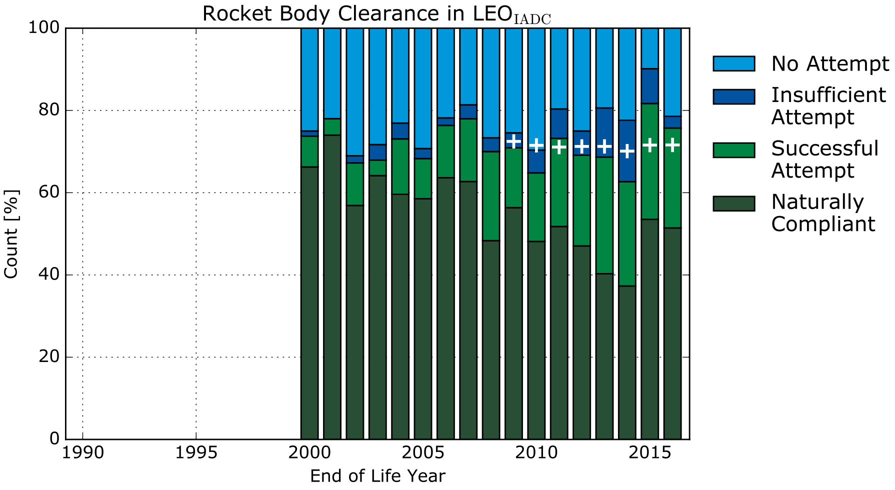

Figure 6. Evolution of compliance of RBs in LEO_{IADC}.

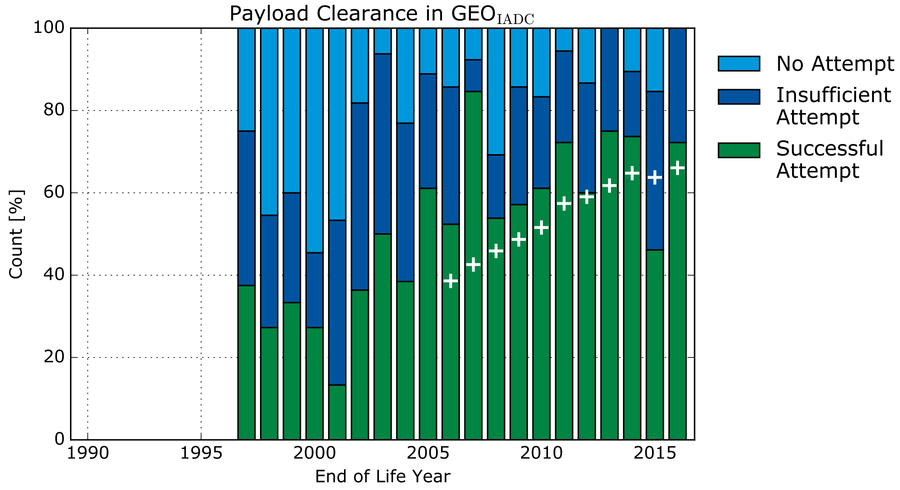

Figure 7. Evolution of compliance of PLs in $\mathrm{GEO_{IADC}}$. Pluses show the 10-year moving average of compliant objects (i.e. the ones performing a successful EOL manoeuvre)

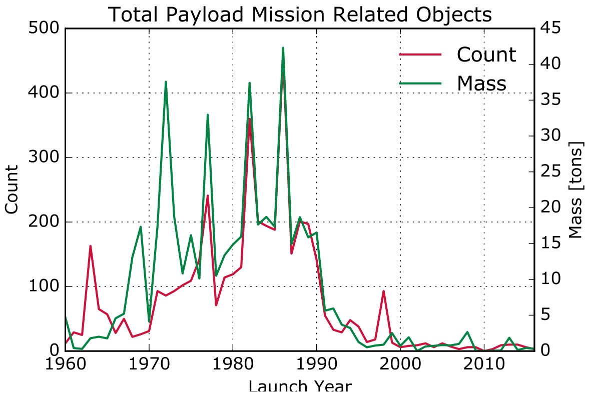

Figure 8. Release of PL MROs.

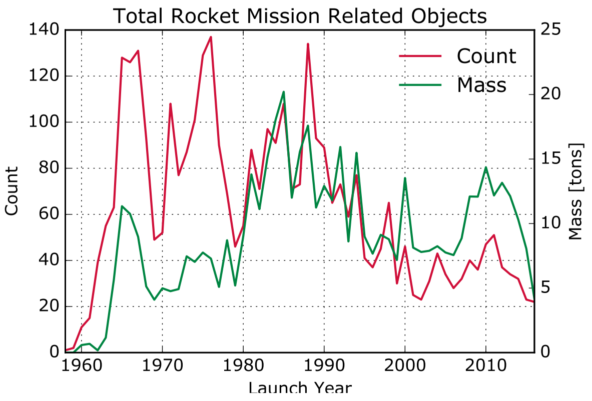

Figure 9. Release of RB MROs.

5. CONCLUSIONS

The historical and current status of the space environment was presented in terms of numbers and collision risk. It was shown that the likelihood of a collision of a PL or RB with an object larger than 10 cm is increasing faster than the total number of PLs and RBs. Currently one such collision is predicted to occur every 7 years, but the frequency is likely to increase in the near future.

Furthermore, the current level of adherence to the space debris mitigation guidelines was presented. To summarise:

- 53.3% of the PLs and 60.3% of the PL mass reaching EOL in $\mathrm{LEO_{IADC}}$ between 2006-2015 are compliant. In terms of mass, this share is constantly sloping downward;
- 71.6% of the RBs reaching EOL in $\mathrm{LEO_{IADC}}$ between 2007-2016 are compliant, a fraction virtually unchanged for 8 years in a row despite an increased EOL manoeuvre activity;
- 66.1% of the PLs reaching EOL in $\mathrm{GEO_{IADC}}$ between 2007-2016 are compliant, tendency rising but possibly saturating;
- the number of released PL MROs reached low levels already before the year 2000, but continues to be significant for RBs.

The level of adherence 15 years after the introduction of the mitigation guidelines is sobering, the only exception being the clearance of PLs in $\mathrm{GEO_{IADC}}$. The environment around Earth, especially in $\mathrm{LEO_{IADC}}$ is continuing to get more hostile almost every year. The goal of the mitigation guidelines - to preserve the Earth environment for future generations - is still beyond reach.

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