ANALYSING GLOBAL ACHIEVEMENTS IN ORBITAL LIFETIME REDUCTION AT THE END OF LEO MISSIONS

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ABSTRACT

The major driver for future debris proliferation, besides the intentional and unintentional release of objects, is the abundance of objects with large masses and sizes in orbit that could be involved in catastrophic collisions. Mitigation measures thus concentrate on the prevention of object release (explosions, mission-related objects, SRM (Solid Rocket Motor) exhaust products), the disposal of objects and active collision avoidance. As ESA's simulations show, the most effective means of stabilizing the space debris environment is the removal of mass from regions with high spatial densities. A limitation of the residence time of controlled objects in altitudes below 2000km to 25 years followed by either atmospheric re-entry or reboost to higher altitudes allows to limit the growth of object numbers in the densely populated LEO environment. This is the most relevant requirement for operations.

In this paper we look into the achievements of all spacefaring nations with respect to this requirement. For this purpose, ESA has developed a method to determine the operational status of running missions, by monitoring their manoeuvre activity with the help of the publicly available orbit data distributed by the US Strategic Command (USSTRATCOM). Missions that have been found to have terminated their operational life will be processed to determine the remaining orbital lifetime. The results will be presented in a statistical manner.

1 INTRODUCTION

The LEO altitude regime is the most frequently used region in space, and, today, the only region into which manned spacecraft are placed. As a consequence of the LEO traffic, the global maximum of the spatial density of space objects is found at around 800km altitude, where the influence of the atmosphere on the orbital lifetime is small. Despite of cleaning effects caused by the remainders of the higher atmosphere in altitudes up to several hundreds of kilometres, the population of space objects is steadily evolving due to the generation of more objects from new fragmentation events (approx. 5 per year) that over-compensate the decay of space objects.

The rising object numbers from about 60-70 annual launches enhance the probability of collisions in frequently used orbital regions. Today, it is a matter of great concern, that collisions could eventually become the main future source for new debris objects, possibly leading the space debris environment into a chain reaction, rendering some orbital regions with an unacceptable risk for operations (an effect first postulated by NASA's Donald Kessler in 1978) [1].

Since the first awareness of the problem in the early 1960s, the global dimension of this problem has not been understood until recent times. A first important step to an international application of debris mitigation measures was taken by the IADC (Inter –Agency Space Debris Coordination Committee) which was founded in 1993 as a forum for technical exchange and coordination on space debris matters. In 2002, the IADC published the "IADC Space Debris Mitigation Guidelines" [2] and presented them to the UNCOPUOUS Scientific & Technical Subcommittee. In the meantime, space agencies in Europe developed more technically specific guidelines named "European Code of Conduct" which was signed by ASI, BNSC (now UKSA), CNES, DLR and ESA in 2006 and which is building up on the work of the IADC. ESA refined this into requirements on Agency-level for mission procured after April 1st 2008 [3]. In parallel to these requirements, standardization of mitigation measures is important in order to achieve a common understanding of the required tasks leading to transparent and comparable processes. This is the task of normative international standardization bodies like ISO (Technical Committee 20 and Sub-Committee 14, e.g. ISO/WD 24113 Space Debris Mitigation [4]) and ECSS (European Cooperation for Space Standardization).

The recommended maximum residence time of space systems after completion of their mission is 25 years, a figure which is supported by all member agencies of the IADC, which is required by ISO-standard 24113, its adoption in ECSS-U-AS-10C, and most related national standards.

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2 MEASURES TAKEN IN ESA

The active reduction of the orbital lifetime for LEO objects to at least 25 years is a firm requirement for all ESA missions procured after April 1st 2008 (the day where ESA's mitigation requirements entered into force). All missions that have been procured before that date are encouraged to follow these requirements to the maximum possible degree possible. ERS-2, launched in 1995, after 16 years of successful operations, was the first ESA object that lowered its orbit at the end of the mission in 2011 in order to comply with the rule.

ERS-2 has an on-orbit mass of 2080kg and operated in 790km altitude at 98.6° inclination. The satellite concept is based on the re-utilization of the Multi-mission Platform, developed within the French SPOT program. This platform provides the major services for the satellite and payload operation, in particular attitude and orbit control, power supply, monitoring and control of payload status, telecommunications with the ground segment. At the time of launch, ERS-2 and its sister spacecraft ERS-1 were the most sophisticated Earth observation spacecraft ever developed and launched by Europe. These highly successful ESA satellites collected a wealth of valuable data on Earth's land surfaces, oceans, and polar caps and were called upon to monitor natural disasters such as severe flooding or earthquakes in remote parts of the world. Both ERS satellites were built with a core payload of two specialized radars and an infrared imaging sensor. ERS-2 included an extra instrument to monitor ozone levels in the atmosphere.

In July 2011, ERS-2 was retired and the process of deorbiting the satellite began. In 6 weekly blocks of several manoeuvre pairs, a permanent decrease of the altitude while maintaining a certain circularity of the orbit has been achieved. A circular orbit was desired due to a combination of requirements to clear the operational orbit, ground station coverage and platform constraints. Up to ca. 2 m/sec delta-v per burn at beginning of de-orbiting campaign, led to a semi-major axis drop by ca. 40 km a week, based on weekly pattern of 5 maneuvering days (Figure 1).

After that the target altitude was maintained while fuel depletion burns alternately increased and decreased eccentricity until tank pressure dropped below operational levels. The decommissioning of the ERS-2 satellite was successfully completed on 5 September 2011, after it reached the target circular orbit at around 570km altitude. This ensures that the re-entry on the atmosphere will be performed in less than 15 years. Although ESA's Space Debris Mitigation Requirements [3] are only applicable for missions procured after April 1st 2008, ERS-2 fully complied with the associated rules. Once placed in its final orbit, ERS-2 has been "passivated" (the batteries were disconnected and the communication system was switched off once all the fuel was depleted). Since September 5th, 2011 13:16 UTC, no telemetry data have been acquired.

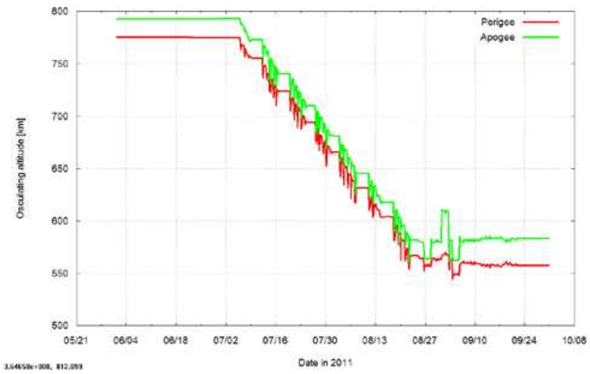

Figure 1. De-orbiting of ERS-2 during July, August and September 2011

3 GLOBAL EFFORTS (EXPECTATION)

While individual achievements in the field of orbital lifetime reduction measures are regularly reported by different operators of the world, a significant damping of the growth rate of the environment can only be achieved if efforts are taken globally. Such an overview on the global level of implementing lifetime control is important to reflect the acceptance of such rules in individual missions, to raise awareness and to discover unfavourable trends or developments early enough.

It should be noted that, for many missions, the implementation of such measures has a significant impact on the design of the space system. The design of space missions, from the formulation of requirements to the launch, can take 10 years or more in some cases. Typically spacecraft are operated between 1 and 13 years, before disposal actions are applied. The figure of 25 years as the recommended remaining lifetime has been first issued by the IADC in 2002, where a few years were required for this figure to propagate into the various national standards. Given all this, a global and strict implementation of this important measure cannot be expected to be seen at the time of writing. Still, many missions (payloads and upper-stages) are expected to already show a certain compliance rate since some time because of the selected mission orbit (e.g. < 600km) or because of an earlier adherence to this guideline. Hence, the curve showing the share of compliant LEO mission (see) is not expected to start from 0. It then seems likely that the share of space systems that successfully implements orbital lifetime reduction is further growing and reaches a saturation at around the year 2030.

In this paper, space systems that retired in 2010 and 2011 are analysed.

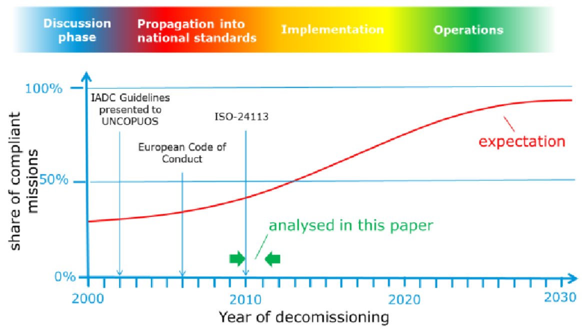

Figure 2. Expected trend in the adoption of lifetime reduction measures for space-systems injected in LEO

4 APPROACH

The principle idea of this analysis is to be independent of any direct information from the owners of space systems, but to rely on surveillance data that is available to registered users of the USSTRATCOM space-track service (i.e. TLEs) [5]. The TLEs will be used in order to identify the status of a mission. This will be followed by an independent estimation of the lifetime, which again does not make use of any data on the objects that cannot be derived from surveillance data. Hence, even the objects properties (e.g. area-to-mass ratio) will be derived from TLE data set histories where possible, and will only rely on ESA (non-surveillance-based) source otherwise.

While direct investigation, intelligence and communication with the owners of space system could increase the accuracy of the prediction, it might still be unbalanced as the request for such data might not be answered by anybody, nor can all owners be clearly identified and approached. Also surveillance data misses information on some objects, however, the corresponding information is also not expected to come from alternate sources. Therefore, the chosen approach seems to be the most balanced, simple, fair and therefore justified approach.

4.1 Assumptions and Constraints

The major difficulty is to identify whether an object has reached its end of life and thus is eligible for the analysis of orbital lifetime compliance. A number of conventions and assumptions have to be established for this purpose:

1. All orbit information is based on USSTRATCOM TLEs [5] (this is the only source of information that contains a global survey of all objects with standardized quality. No attempt will be made to use literature information on the capabilities, mission profiles etc. of payloads. The reason for this is that this information cannot be complete for all objects, while the usage of surveillance data allows an analysis on equal grounds for all objects)
2. All information on object mass is based on ESA's DISCOS database [6] (the data in DISCOS goes back to reliable sources, and own research, and has a proven and cross-validated content).
3. Spacecraft that have not shown a large orbit control capability have an operational lifetime of 10 years (since an EOL epoch for these objects cannot be detected from surveillance data, a standardized operational lifetime needs to be assumed. A value of 10 years seems to be a safe estimate, given that many of such small missions tend to have significantly shorter lifetimes. The capability of an objects to manoeuvre is determined from non-natural orbit changes over the operational lifetime. It might occur, however, that objects with manoeuvre capability fail directly after launch and never had the chance to exhibit manoeuvre capabilities. As there is no way to discriminate those from objects without manoeuvre capabilities, they would, in consequence, be considered as not manoeuvrable and having an operational lifetime of 10 years.)
4. Upper-stages perform the disposal manoeuvres (if any) immediately after injection (meaning that the orbit occupied by an upper-stage a few days after launch can be considered to be the EOL disposal orbit)
5. Re-entry vehicles (STS, Dragon, Progress, Soyuz-TM, ATV, Shenzhou, …) are not analysed (they are considered out of the scope because it is their mission to re-enter)
6. Space systems for which no TLE orbit information is published are excluded from the analysis (no reasonable analysis is possible, this not only covers classified missions, but also objects on an escape trajectory)
7. No object launched before 1990 is considered still operational in the year of analysis (such long lifespans are generally not achievable (one extreme exception might be Landsat 5 which was launched in 1984 and was still active in 2012). This assumption helps to limit the analysis to fewer objects)
8. Upper-stage de-orbit burns are only detected when sufficiently visible in the orbit data (Whenever upper-stages conduct burns after payload separation to reduce the remaining orbital lifetime, these burns usually occur shortly after injection. This makes it very difficult for a surveillance system to provide a full history of orbit sequences until decay for such short timeframes and very often the intermediate transfer orbit used by the upper-stage is not known. Sometimes it is not even known whether the upper-stage has been on the final orbit of the payload for a short-term or whether the payload performed the

final injection by itself. Hence, in many cases it remains doubtful whether the upper-stage re-entered naturally or via a dedicated de-orbit burn. The approach taken will consist of reporting only the obvious cases (e.g. a non-natural changes in the upper-stage orbit can be observed in historical surveillance data)

9. Lifetime estimates for highly eccentric orbits are sufficiently accurate (It should be noted that lifetime estimations for objects on highly eccentric orbits is a particular difficulty and associated with large uncertainties. For some individual upper-stages on GTOs, even the classification might not be adequate. However, since this report intends to uncover general trends and among several upper-stage on GTO, it is expected that proper statistical trends are preserved even when such predictions are limited.).
10. A re-orbit attempt is considered when the change in semi major axis is at least 1km until EOL (natural/unexplained effects can lead to noise in the history of the osculating semi-major axis that could even give the impression of a re-orbiting attempt. A screening window of 1km is assumed to be sufficient to safely discriminate real re-orbiting attempts from other effects)

4.2 Criteria

The assumptions outlined before lead to the following selection criteria in order to extract the object of concern for the particular year of analysis:

Upper-stages are analysed if they:

- Are launched in the year of analysis (i.e. immediate EOL is assumed)

And:

- Have a perigee altitude < 6000km at the time of reporting (to account for a possible lowering of the perigee of highly eccentric orbits due to orbital perturbation)

Payloads are analysed if they have a perigee altitude <2500km at the time of reporting and are launched after 1990 (i.e. we do not expect any object launched before 1990 to be still operational at the time of the report) and are either:

- Found to be manoeuvring in the year of analysis, but not during the subsequent year
- Not a re-entry vehicle (STS, Dragon, Progress, Soyuz-TM, ATV, Shenzhou, …)

Or:

- Found to have never manoeuvred and launched ten years before the year of analysis (i.e. ten years of operational lifetime assumed)

Or:

- If they are launched in the year of analysis and decayed in that year

For payloads a manoeuvre detection mechanism was implemented in order to determine the end of manoeuvrability (assumed to correspond to the end of operational life) and in order to detect de-orbiting attempts.

4.3 Object Classification

Objects will be classified according to their initial orbit as follows:

- Orbits <600km (LEO1): These orbits usually lead to a natural decay within 25 years for representative area-to-mass ratios (0.05-0.005m²/kg)
- Orbits 600km-1400km (LEO2): Objects in these orbits will, in most cases, have to apply active measures to reduce their remaining orbital lifetime after the operational phase. For objects with representative area-to-mass ratios (0.05-0.005m²/kg) it will be more fuel efficient to lower the orbit rather than attempting to achieve orbital altitudes above LEO
- Orbits >1400km (LEO3): For objects in these orbits it will be more fuel efficient to increase altitude to above 2000km for a permanent escape from the LEO region
- Other orbits: Such like MEO transfer orbits (MTO), GEO Transfer Orbits (GTO)

This classification makes sense because efforts to be done in the area of orbital lifetime reduction differ significantly for these regions. A global figure of success rate in this regard will have to be studied in relation to this orbit groups, where orbits between 600km and 1400km (LEO2) play a particular role as associated efforts are high and the environment contained therein is the most polluted.

Objects in these different LEO categories do not necessarily have to be on circular orbits. A few objects might transit in-between the 3 LEO regions. In this case, the perigee height will decide on the classification.

Objects will further be classified according to their nature:

- Upper-stage
- Payload with OCC (Orbit Control Capability)
- Payload without OCC

This provides the ground for an interesting analysis of the behaviour of the selection of target/injection orbits as a function of this classification.

4.4 Manoeuvre Detection

The algorithm used to detect manoeuvres in TLE derived time-series is described in detail in [7]. The method used here is essentially based on the moving window approach. The time and orbital-parameter dimensions of the window are allowed to vary automatically while processing the time-series, which makes this approach independent of the orbital-parameters selected for the detection of manoeuvres and reduces the fine-tuning effort required from an operator. The dimensions of the moving window are calculated directly from the time-series by techniques from robust statistics and harmonic regression.

It has to be noted that the detection performance of the algorithm is a function of the altitude regime and the type of manoeuvre. Along-track manoeuvres (i.e. typical orbit maintenance manoeuvres), in high altitudes are the most simple case for detections and manoeuvres of a few mm/s can be identified. Figure 3 gives an example for the semi-major axis of METOP-A between 21/1/2011 and 9/8/2011.

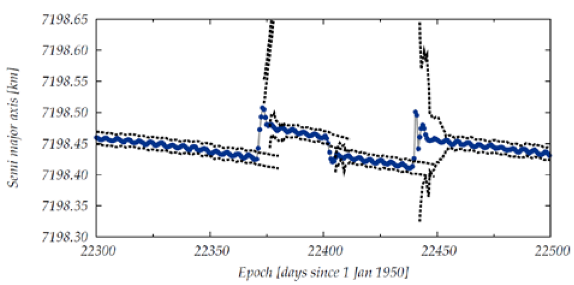

Figure 3: History of the semi-major axis [km] of METOP-A between 21/1/2011 and 9/8/2011 (blue dots) boundary of the moving window (black lines)7

The black lines mark the boundaries of the moving window. As some manoeuvres are of the same order of magnitude as the expected noise level of the series, the algorithm will ignore them. Larger manoeuvres, with a difference of a few meters in semi major axis, are correctly identified. Accordingly, performing manual checks is required [7].

It should also be noted that the sensitivity of the algorithm and also manual inspection has its natural limits in the quality of the underlying orbit data. Changes less than 10m (or even more for eccentric orbits) will not be detected as evidence for an orbit control capacity. Moreover, slow changes in the orbital parameters, e.g. by using electric propulsion for constellation maintenance, will look the same as long-term natural perturbations to the algorithm. Therefore, these objects are also excluded from orbit control capacity, as they don't demonstrate the potential for 1km semi-major axis change manoeuvres. When they do a slow re-orbiting manoeuvres within 10 years, they will eventually be classified correctly.

4.5 Orbital Lifetime Estimation

The next step, after identifying the end of mission life, is to determine remaining orbital lifetime. For this, the ballistic coefficient is fit to the orbit information (i.e. the decay rate) using a propagator (see Figure 4). Hence, the analysis is independent from any literature information on mass and area. With the obtained ballistic coefficient the initial lifetime estimate is performed by straight forward application of King Hele`s formulations [8]. Based on this initial estimate, a refined analysis is performed with different fidelity (and computing power) according to the outcome. If the initial estimate leads to lifetimes of less than 100 years, King Hele's formulations are applied iteratively. Semi-analytical propagation is applied if the initial estimate results into less than 1 year.

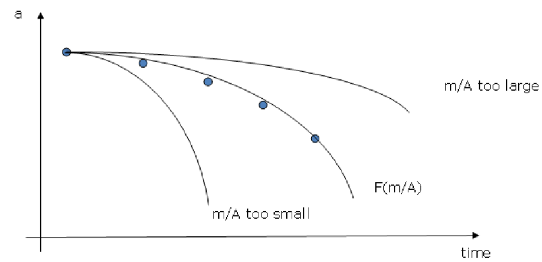

Figure 4: Iteration to fit a mass/area ratio into a history of orbital data

The lifetime estimation process is automated, and, to some degree, based on simplified assumptions. On top of this, the orbital lifetime predictions generally suffer from large uncertainties due to the impossibility to predict solar and geomagnetic activities over the next decades in an accurate way. Therefore, the lifetime estimates will not be given directly, but the objects will be classified in three lifetime classes:

- < 25 years: These are all lifetimes that are definitely shorter than 25 years, including objects that are already decayed at the time of analysis. A very safe cut-off value of 20 years from the estimated lifetime is used for this class
- ca. 25 years: a rather generous condition of the estimated lifetime of <40 years and > 20 years is used to account for the uncertainties and to avoid unjustified markings on missions that are close to the 25 year threshold
- > 25 years: This is for all remaining objects (hence, estimated lifetimes > 40 years)

It should be recalled again that lifetime estimations for objects on highly eccentric orbits is a particular difficulty and associated with large uncertainties. For some individual upper-stages on GTOs, even the classification might not be adequate. However, since this paper intends to uncover general trends and among several upper-stage on GTO, it is expected that proper statistical trends are preserved even when such predictions are limited.

5 RESULTS

5.1 Upper Stages

The results shall be analyzed first from the perspective of upper-stages in a statistical way. 115 upper-stages have been injected into potentially LEO-crossing orbits in the two analysed years (2010 and 2011) (see Table 1). 67 will decay (or have already decayed) within 25 years, another 8 are likely to decay in that time (see Figure 5). Apart from decaying, it is also interesting to note that a number of upper-stages select a GTO with sufficient clearance in the perigee altitude to the protected zone.

Table 1: Counts of upper-stages per orbit category injected in 2010 and 2011 as a f unction of their remaining orbital lifetime

Upper-stage injection orbit	Numbers		
	<25 y	ca. 25 y	>25 y
< 600km	43	2	0
600 - 1400km	9	4	16
>1400km	0	0	0
MTO	1	0	4
GTO	14	2	20
	67	8	40

Figure 6 shows the accumulated object mass of the 115 upper-stages for different target injection orbits. Obviously, most of the upper-stage mass is removed (either directly or naturally) for most direct LEO injection. Stages injected into transfer orbits tend to accumulate more mass with longer orbital lifetimes. Transfer orbits mostly interfere with the LEO regions, but the interference is limited to a small fraction of the orbital period.

We can state that more than half of the number and mass of the upper-stages respect the limitation of residence time in LEO. However, if we take a closer look at the particularly densely populated region of 600-1400km, where most of the collisions are expected to take place, we can observe the inverse situation.

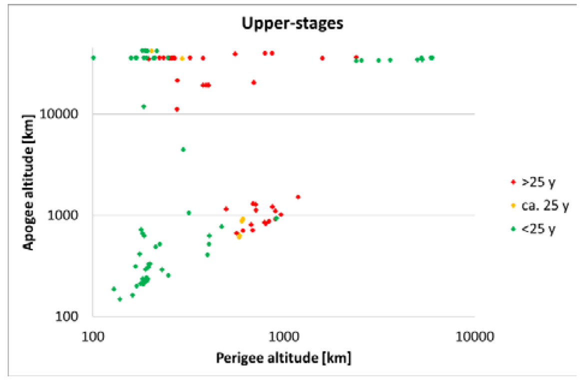

Figure 5: Initial apogee and perigee altitudes of upper-stages injected in LEO-intersecting orbits in 2010 and 2011

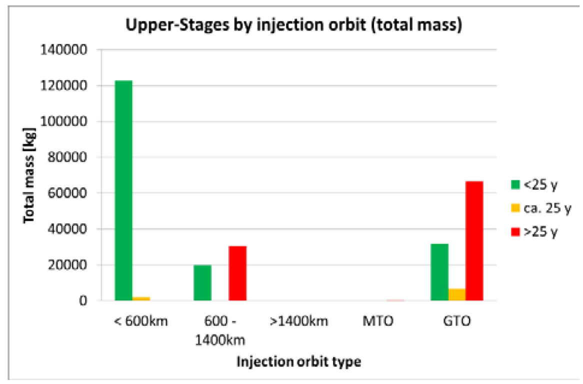

Figure 6: Cumulated upper-stage masses in different categories of LEO-intersecting orbits as a function of their remaining orbital lifetime

A similar picture results for the situation on GTOs: The LEO region can be cleared in both directions (perigee lowering and perigee raising) and both options are used. Although the 25 year lifetime limit applies to them strictly and the individual masses are usually large, their environmental impact on the LEO population is small due to the short residence times in LEO per orbit revolution.

The performance in the critical region of 600-1400km is thus the most relevant for the environment and amounts to about only 40% removal success in terms of numbers and mass.

Upper-stages reach their end-of-life typically quite quickly after injection. It is therefore difficult to observe whether any active de-orbiting measure has been performed, because the update rate of the available orbit information does not allow to resolve the various manoeuvres. However, 10 clear de- (or re-) orbiting attempts have been detected under these constraints.

5.2 Payloads

A total of 127 spacecraft have reached their end of life in 2010 and 2011. With the launch date being known, the operational lifetime can be computed. The number of spacecraft having orbit control capabilities (OCC) and therefore a determinable end of life allows for some meaningful statistics on the operational life of LEO satellites (see Figure 7). Operational periods show an interesting concentration at around 11 years with a mean value of 8 years and a median of 10 years.

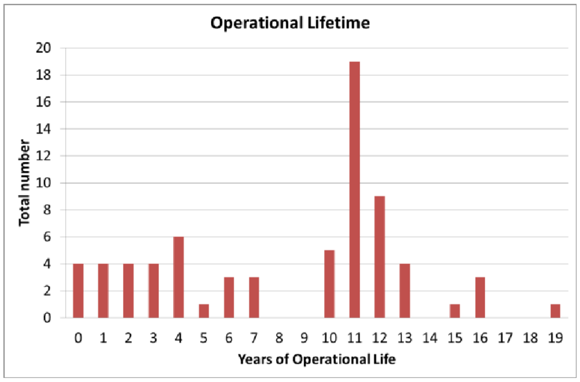

Figure 7: Estimated lifetimes for objects with orbit control capacity (OCC)

Table 2 reveals the performance in terms of orbital lifetime reduction. 9 payloads have been launched into orbits which are likely to comply due to natural effects alone. This is achieved in all but one case.

Table 2: Counts of payloads per orbit category that reached EOL in 2010 and 2011 as a function of their remaining orbital lifetime

Payloads	Numbers		
	<25 y	ca. 25 y	>25 y
< 600km	8	0	1
600 - 1400km	2	2	34
>1400km	5	1	19
Payloads without OCC	10	4	41
	25	7	95

The more interesting region between 600 and 1400km has seen a much worse performance in this regard than the corresponding upper-stages. Less than 10% in terms of numbers and (as Figure 8 shows) slightly more than 10% in mass have orbital lifetimes on the order of 25 years or less. In one case this is achieved by the selection of the operational orbit in combination of the area and mass of the object. Only 5 larger attempts to actively remove the objects at EOL with its own propulsion system have been detected. Only 3 of them were successful (their original orbits can be depicted from the green and yellow dots in Figure 8).

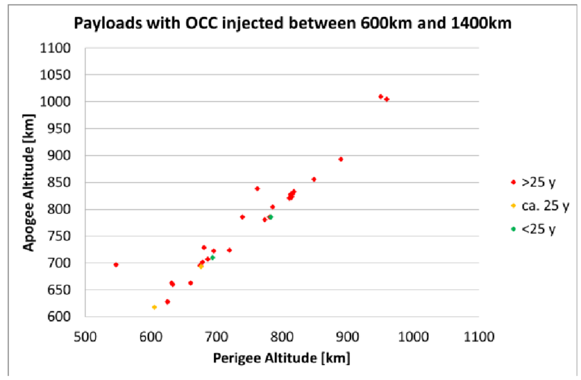

Figure 8: Initial apogee and perigee altitudes of spacecraft injected in orbits between 600 and 1400km

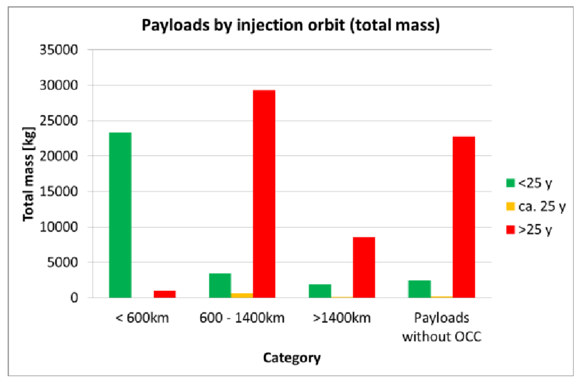

Figure 9: Cumulated spacecraft masses in different categories of LEO-intersecting orbits as a function of their remaining orbital lifetime

The 38 objects that reached EOL on orbits above 1400km have shown a remarkable performance. All of them have attempted a re-orbit (and a deorbit in case of 2 objects on GTOs not shown in Figure 10). These measures were successful in 6 cases.

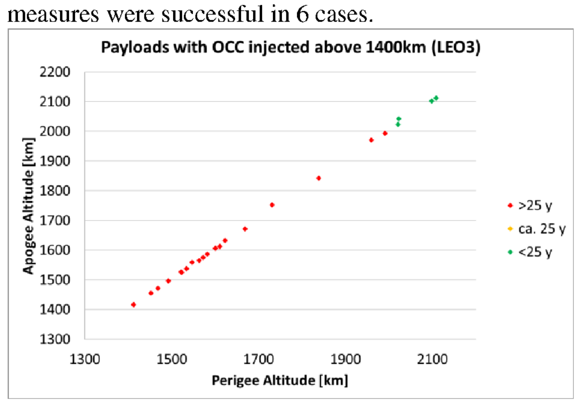

Figure 10: Current apogee and perigee altitudes of spacecraft injected in orbits above 1400km

Spacecraft without orbit control capacity should be launched into orbits from which they decay naturally. However, in 2010 and 2011, the objects of that type that reached EOL have been injected into all analysed types of LEO orbits. These types of objects are often launched as piggy-back payload and can therefore also be found on MEO and GEO Transfer Orbits (MTO and GTO).

Only about 20% of the object achieve a reduced lifetime of less than about 25 years (see Table 3). The mass associated with these objects is surprisingly high (see Figure 9). This might be partly explained by the fact that objects that failed immediately after injection might never have shown the capability to manoeuvre and therefore end up in this category.

Table 3: Counts of payloads without OCC per orbit category that reached EOL in 2010 and 2011 as a function of their remaining orbital lifetime

Payloads without OCC	Numbers		
	<25 y	ca. 25 y	>25 y
< 600km	7	0	5
600 - 1400km	2	4	23
>1400km	0	0	6
MTO	1	0	2
GTO	0	0	5
	10	4	41

6 CONCLUSIONS

About 10 years, after the IADC guidelines including the 25 year figure for recommended post EOL orbital residence time have been published, a first review of the implementation success based on available surveillance data has been performed. On average, 44% percent of the objects and 58% of the mass injected in LEO-intersecting orbits achieve the required lifetime reduction, where the performance of upper-stages in this regard is much better than for payloads.

The most critical region in LEO, between 600 and 1400km is used by about 40% of all object each year. On average only 24% of them (and 26% of the mass) achieve the required lifetime reduction. In some cases this achievement is reached without active intervention. Real de-orbiting or re-orbiting efforts have been detected in only 14% of the cases on average. In this regard, 2011 has been a better year than 2010 (see Table 4).

In summary, the actual performance in comparison to the expectation (Figure 2) is close to where it is expected to be. However, a detailed look reveals that the performance in the critical region between 600-1400km is far below average and needs to be improved.

Table 4: Statistics on global performance in 2010 and 2011

	2010	2011	Average
% of objects with reduced orbital lifetime	40%	48%	44%
% of mass with reduced orbital lifetime	50%	64%	58%
Between 600km and 1400km:			
% of objects that used this region	39%	41%	40%
% of lifetime reduction attempts	6%	21%	14%
% of objects with reduced orbital lifetime	20%	28%	24%
% of mass with reduced orbital lifetime	23%	27%	26%

7 LITERATURE

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