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MITIGATION RULES COMPLIANCE IN LOW EARTH ORBIT

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ABSTRACT

Space debris mitigation is one of the French Space Operations Act objectives, through the removal of non-operational objects from populated regions. At the end of their mission, space objects are to be placed on orbits that will reduce collision hazards with other spacecraft or debris. This paper presents our investigations on mitigation guidelines compliance in Low Earth Orbit (LEO) by space operators from 2000 to 2013. We are particularly interested in studying the expected decrease of the mid and long-term collision risk in LEO, through the application of the 25 years rule or the reaching of a graveyard orbit above this region.

We have identified space objects ending their mission during the period of interest and estimated their orbital lifetime. We obtain a global compliance rate and analyze its evolution over a 14 years period.

1. INTRODUCTION

Since the very beginning of the space era, human activities have led to place into orbit more than forty thousand space items. These objects are of a great variety, going from several tons spacecraft to Cubesats. However, less than 7% of orbiting objects are still considered today as operational. This implies that the in-orbit population is mainly dominated by space debris of various sizes, rather than active spacecraft, and their growing number increases the probability of collision hazards, as illustrated by the loss in 2009 of the operational Iridium-33 satellite after the collision with the inactive Kosmos-2251. Such dramatic events create a large amount of new debris, corrupting durably the given space area, as already expressed by Kessler et al. in 1978 [1].

Therefore, space debris mitigation becomes a topic of primary importance for the preservation of the space environment and for the space systems operations safety, especially in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). Objects removal from these regions once their missions are terminated is today a common practice to mitigate the growth of the debris population. In the last two decades, several actions have been under-

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Figure 2. Spatial density as a function of altitude in protected region A

Once we have computed the mitigation guidelines compliance rate for LEO objects orbiting the Earth, we can use these statistics together with the long-term projections of the Earth’s satellite population and the expected evolution of the Post-Mission Disposal (PMD) compliance rate, in order to evaluate if the efforts made to increase the global compliance with mitigation guidelines in LEO are already noticeable, and if such efforts are good enough to guarantee the long term sustainability of space activities.

1.1. Expected increase of the PMD compliance

Even if the number of objects orbiting the Earth has increased steadily since the launch of the first satellite in space, mainly due to new launches or explosions, the global dimension of the problem affecting the long term sustainability of space activities has not been understood until recent times.

Starting in the 90s, such awareness has motivated new initiatives to limit the proliferation of space debris. However, national mitigation guidelines were not published until 2002 [4]. This means that most satellites and rocket bodies orbiting presently the Earth have never been designed to be compliant with such guidelines.

Hopefully, new treaties and laws such as the FSOA, as well as other initiatives to come, will start to have a significant impact on the compliance to mitigation guidelines in the years to come.

1.2. Long term projection of the Earth’s satellite population

In the last decade, space debris modeling has been used intensively to analyze the way in which the Earth’s satellite population will evolve in the long term as a function of a given number of endogenous and exogenous variables, as for example the global compliance of the spacecraft and rocket bodies with the mitigation guidelines.

Such long-term simulations can be used to define the critical values of a group of variables (e.g. Post Mission Disposal compliance rate, frequency of explosions …) in order to guarantee the long term sustainability of space activities, or to analyze the sensitivity of the model to a modification in one of these variables.

Fig. 3, excerpted from [5], depicts the long-term evolution of the LEO population of objects larger than 10 cm, between 2009 and 2200, as a function of the PMD compliance rate and under the following assumptions:

- **Initial Population**: ESA’s MASTER reference population \( \geq 10\text{cm} \) residing in, or passing through, the LEO region on 1st May 2009.
- **Launch Traffic**: The observed 2001–2009 launch traffic cycle, is repeated throughout the simulation.
- **Satellite Properties**: Operational lifetime of satellites is set to 8 years. No station keeping or collision avoidance maneuvers are considered.
- **In-Orbit Explosion**: No future explosions are assumed.
- **Solar activity**: 200 years variable solar activity projection.

The PMD compliance rate presented in Fig. 3 refers to the percentage of objects in LEO, initially not compliant with the 25 years rule, performing a deorbit maneuver at the end of their operational lifetime. As we can see, the PMD compliance rate has a huge impact on the population evolution. It is therefore relevant to try to estimate its real value.
2. METHODOLOGY

In order to compute the global compliance to mitigation guidelines of spacecraft and rocket bodies in Low Earth Orbit (LEO), we have proceeded in several steps:
- Identification of the space objects with perigees altitude lower than 6000 km, even if they have already reentered the Earth’s atmosphere, from the USSTRATCOM’s SATCAT database [6];
- Detection of the End of Mission (EoM) date for the previous selected objects;
- Estimation of the physical parameters (i.e. Drag Area to Mass ratio and Reflecting Area to Mass ratio);
- Computation of the compliance rate with the mitigation guidelines in accordance with the FSOA:
  • Orbital lifetime < 25 years;
  • Non-interference with the LEO region (perigee altitude > 2000 km) during 100 years.

2.1. Identification of the objects

In order to select the objects to include in our study, we have used the SATCAT database of the USSTRATCOM as well as the Union of Concerned Scientists (UCS) database of operational satellites [7]. The period of interest we considered goes from the 1st January 2000 to 31st December 2013.

The SATCAT database contains more than 39,000 entries on the 1st January 2014. From this database, we have removed all the objects matching one of the following criteria:
- Satellites and Rocket Bodies (R/B) launched before the 1st January 1980 (we consider a maximum mission of 20 years for these objects);
- Objects that have reentered before the 1st January 2000;
- Objects flagged as DEB in the database, except for specific objects identified as SYLDA, SPELDA, SPELTRA, BREEZE-M DEB (TANK/ADAPTOR);
- Objects related to human space flight (MIR, ISS, Space Shuttle, Soyuz, Progress, ATV, HTV, Dragon, Cygnus, Shenzhou);
- Objects with perigee higher than 6000 km.

From the UCS database, we have identified all the satellites flagged as operational, by the 1st January 2014 (1153 objects), and we have removed them from the study. Once all these filters have been applied, there are 2528 objects left. Amongst these objects 1504 are satellites and 1024 are rocket bodies.

2.2. Identification of the end of mission date

The detection of the end of mission date is done as follows:
- Spacecraft: Detection of maneuverability and end of maneuverability of a spacecraft via the development of a maneuvers detection algorithm. This algorithm is based on the time series analysis of orbital data on a moving window approach [8].
- Rocket Body: In our study we suppose that the EoM of a launcher element (R/B) happens just after the launch. As a re- or de-orbit maneuver can be performed after injection, we consider that the orbit occupied by the launcher element 30 days after launch corresponds to its disposal orbit.
For non-maneuverable satellites (*i.e.* satellites with orbital data presenting no maneuver in the studied timespan), we perform a bibliographic research in order to define their EoM date. For the objects with no available information, we assumed fixed mission duration:
- 1 year for Cubesats;
- 4 years for COSMOS satellites;
- 10 years for Molniya and ORBCOMM FM satellites;
- 3 years for UNISAT and MEGSAT satellites.
Non-maneuverable International Laser Ranging Service (ILRS) satellites have been excluded from the study, as their mission continues as far as they stay in orbit. This will not affect much the results of our analysis, as we count only 15 objects of this type.

Fig. 7 & 8 show respectively the yearly evolution of satellites and rocket bodies reaching EoM between 2000 and 2013.

### 2.2. Identification of the end of mission date

The detection of the end of mission date is done as follows:

- Objects related to human space flight (MIR, ISS, Space Shuttle, Soyuz, Progress, ATV, HTV, DRAKE, SPELTRA, BREEZE-M DEB (TANK/ADAPTOR);
- Objects flagged as DEB in the database, except for specific objects identified as SYLDA, SPELDA, etc.;
- Objects that have reentered before the 1st January 2014 (1153 objects), and we have removed them from the study.

Once all these filters have been applied, there are 2528 objects left. Amongst these objects 1504 are satellites (83% of the objects), and we have estimated physical parameters of the selected objects, which is extensively described in [8], is based in a two-stage process:

- Computation of an initial \( \frac{S_{\text{drag}}}{m} = \frac{S_{\text{ref}}}{m} \), by the application of the conservation of energy principle, under the following assumptions:
  - The only dissipative force acting on the object is drag;
  - The object has a randomly tumbling attitude, therefore its geometry is considered as spherical;
  - The rotation speed of the atmosphere can be neglected.

- Computation of a more accurate estimate of \( \frac{S_{\text{ref}}}{m} \) and \( \frac{S_{\text{drag}}}{m} \) ratios, by the decomposition of the temporal evolution of semi-major axis and eccentricity as a function of conservative and dissipative forces.

To validate the estimation of the surface to mass ratios, we used French launcher elements, for which we know very well the physical properties. Fig. 9 depicts the relative error of estimation for all French launcher elements, as well as launcher elements with perigees lower than 500 km.
Two major conclusions were drawn from the data depicted in Fig 9:

1. The higher the perigee is, the harder it is to estimate the drag force, and therefore the higher is the relative error. The red bar at minus 100% relative error is the consequence of this lack of observability.
   a. The estimation error, also containing the atmospheric model error, is in most cases in the ±30% interval for perigee altitudes lower than 500 km;
   b. Objects with perigee altitudes higher than 500 km are most of the time not compliant with the 25 years rule, so the high estimation error for this subset of objects has no impact on our conclusions.

2. For objects with perigee altitude lower than 500 km, the estimation error is centered in 0%, so the conclusions are not biased due to a systematic over- or underestimation of the physical parameters.

Once our estimation method is validated, we can compute the physical parameters for spacecraft and launcher elements considered in the study.

2.4. Mitigation guidelines compliance

The compliance to the mitigation guidelines, both the respect of the 25 years rule and the non-interference with the LEO region (perigee altitude > 2000 km) during 100 years, is done using STELA [9], which is the reference software used to check the compliance of disposal orbits with the good practices attached to the FSOA. This compliance is verified following two different approaches:

- FSOA approach:
  - **LEO objects**: propagation from the end of mission date with a constant equivalent solar activity [9];
  - **HEO objects**: propagation, from the end of mission date, using a statistical approach [10], and a solar activity built by the random combination of the five past solar cycles and a random date in the first cycle for the phasing.

- Variable solar activity (VAR) approach:
  - **LEO objects**: propagation from the last available TLE with the NOAA-DAS solar activity prediction;
  - **HEO objects**: propagation, from the last available TLE, using a statistical approach [10], the NOAA-DAS solar activity until 2019, and a random combination of the five past solar cycles for the rest.

For the VAR approach, the time lapse between the end of mission date and the last available TLE is carefully taken into account in the total orbital lifetime. Concerning the statistical approach, as it is clearly explained in [10], we do not perform only one lifetime computation, but a Monte-Carlo draw composed of \( N \) orbital propagations since one lifetime computation is very sensitive to initial conditions for HEO. Once the Monte-Carlo simulation is done, we conclude that the object is compliant only if its orbital lifetime is shorter than 25 years with a 90% probability. In our Monte-Carlo simulation, we vary the following parameters:

- Ballistic Coefficient (±20% variability);
- Solar Activity Projection.

3. RESULTS OF THE STUDY

In the previous section, we have described the method and the different algorithms that we have developed and used within this study. Those algorithms have mainly two objectives:

- Identifying the End of Mission date of the satellites, by detecting their end of maneuverability;
- Computing their compliance to mitigation guidelines, once the physical properties of the objects have been estimated.
The first objective will help us analyze the number of objects arriving to EoM yearly during all the period of study (Fig. 11), as well as to subdivide the population in two subsets:
- Spacecraft with Orbit Control Capabilities (OCC);
- Spacecraft without OCC.
This subdivision is of key importance to the discussion of compliance with mitigation guidelines that involve a de- or re-orbit maneuver.

The second objective will help us draw a figure of the global compliance to mitigation guidelines, either thanks to a de- or re-orbit maneuver, or by the natural decay of the space object from its operational orbit.

As it can be observed from Fig. 11, 37% of the satellites reaching EoM between 2000 and 2013 and 33% of rocket bodies launched during the same period of time are already compliant with the 25 years rule mitigation guideline.

### 3.1. Satellites compliance

As presented in paragraph 2.2, the detection of the EoM of satellites is linked with the detection of the end of maneuverability. The analysis done in order to detect the end of maneuverability gives us all the information needed to distinguish satellites with OCC from satellites without OCC.

From Fig. 12 it can be observed than more or less half of the spacecraft population have orbit control capabilities. From the sub-population with OCC, only 27% of the objects (corresponding to 12% of the whole spacecraft population) performed an EoM maneuver.

In addition to the total number of EoM maneuvers, the temporal evolution of the number of EoM maneuvers between 2000 and 2013 constitutes important information, as it reflects the efforts made by operators to be compliant with mitigation guidelines.
gation guidelines, and in particular with the 25 years rule, can be done either with EoM maneuvers or with the selection of the operational orbit. Therefore, all the satellites with and without OCC must be taken into account for the computation of the mitigation guidelines compliance rate.

Figure 14. Global statistics on the spacecraft population between 2000 and 2013

On Fig. 14, the out of study percentage makes reference mainly to spacecraft with very sparse data. As can be observed from this figure, a total of 59% compliance to FSOA mitigation guidelines is estimated for the 2000–2013 period. A detail of the mitigation guidelines compliance as a function of the year is given in Fig. 15.

Figure 15. Number of satellites compliant with the FSOA between 2000 and 2013

If we focus on the spacecraft population with Orbit Control Capabilities, we observe from Fig. 16 that 46% of this subset is compliant with mitigation guidelines, either via an EoM maneuver or by natural decay. As a consequence, 54% of this subset is not compliant, even if some of them (6%) made an effort to try being compliant via an EoM maneuver.

Figure 16. Global statistics on the spacecraft population with OCC between 2000 and 2013

A detailed representation of the mitigation guidelines compliance as a function of the year for satellites disposing of OCC is given in Fig. 17.

Figure 17. Number of satellites with OCC compliant with the FSOA between 2000 and 2013

3.2. Launcher elements compliance

As presented in paragraph 2.2, we consider for launcher elements that its EoM happens just after the launch. In order not to be perturbed by aberrant data due to maneuvers or to errors linked with initial orbit determination, we compute the physical parameters of the launcher elements using orbital data released one month after the launch. This thirty days period is then taken into account for the computation of the residual lifetime of the launcher element.

As a consequence, we do not have any information concerning the percentage of launch elements with Orbit Control Capabilities (OCC). Therefore, only global statistics on the mitigation guidelines compliance of launcher elements are given hereafter.
3. Influence of the disposal orbit

The compliance with the 25 years rule is a direct function of the disposal orbit and drag area to mass ratio for both satellites and launcher elements. The disposal orbit is either the operational orbit if no maneuver is performed at the end of the mission, or the new orbit reached after a deorbit maneuver.

4. CONCLUSION

We have presented in this paper an analysis of the compliance rate of satellites and launcher elements with the mitigation guidelines from 2000 to 2013. The main results that we obtained are:

- The global compliancy rate is 59% for satellites and 60% for launcher elements;
- The percentage of spacecraft performing a re- or deorbit maneuver at the end of their mission is equal to 12%;
The most noticeable observations made during our study are therefore the following:

1. There is no clear trend of improvement over the years in terms of global compliance with the mitigation guidelines;
2. Most space objects rely on natural decay to meet mitigation rules;
3. The compliancy rate of spacecraft performing an active deorbit maneuver is slightly increasing over time;
4. Most objects performing a deorbit maneuver are doing so on a best effort basis, as they were designed and launched before mitigation guidelines were adopted.

According to these observations, a great effort is still needed in order to guarantee the sustainability of space activities by the application of mitigation guidelines. We hope that an initiative such as the French Space Operations Act will help to improve the security of space operations activities in the future.

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6. REFERENCES


Progress in space safety lies in the acceptance of safety design and engineering as an integral part of the design and implementation process for new space systems. Safety must be seen as the principle design driver of utmost importance from the outset of the design process, which is only achieved through a culture change that moves all stakeholders toward front-end loaded safety concepts. Superb quality information for engineers, programme managers, suppliers and aerospace technologists.

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Safety Design for Space Systems, Chinese Edition
Elsevier 2011

Space Safety Regulations and Standards
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Safety Design for Space Operations
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