

AN UPDATE ON THE EFFECTIVENESS OF POSTMISSION DISPOSAL IN LEO

J.-C. Liou

NASA Orbital Debris Program Office, Houston, TX 77058, USA, jer-chyi.liou-1@nasa.gov

Paula Krisko

JETS/Jacobs Technology, Houston, TX 77058, USA, paula.krisko-1@nasa.gov

Orbital debris mitigation measures have been developed to reduce the growth of the future debris population by the international space community over the past two decades. A major component in the overall mitigation strategy is postmission disposal (PMD). A key PMD element for the low Earth orbit (LEO, the region below 2000 km altitude) satellites is the 25-year decay rule. It is intended to limit the long-term presence of massive intact objects - rocket bodies (R/Bs) and spacecraft (S/C) in the environment. The effectiveness of the 25-year rule was well demonstrated and documented during the development of the mitigation measures. The orbital debris population in LEO, unfortunately, has significantly increased since that time. The objectives of this paper are to provide an updated assessment based on the 2012 LEO environment and to highlight the importance of the global compliance of the 25-year decay rule.

I. INTRODUCTION

The accumulation of the orbital debris population and the threat from orbital debris to satellite operations have been recognized by the space community for decades. Figure 1 shows the historical increase of the objects tracked by the U.S. Space Surveillance Network (SSN) and placed in the satellite catalog. The top curve is the total and the population breakdown is represented by the four curves below the total. Fragmentation debris have dominated the population almost from the beginning and they are heavily influenced by major breakup events, such as the anti-satellite test conducted by China in 2007 and the accidental collision between the retired Cosmos 2251 and the operational Iridium 33 in 2009, and, to a lesser extent, solar activity which modulates the atmospheric drag. Among the 3500 or so spacecraft in space, only about 1100 are operational and the rest are simply orbital debris.

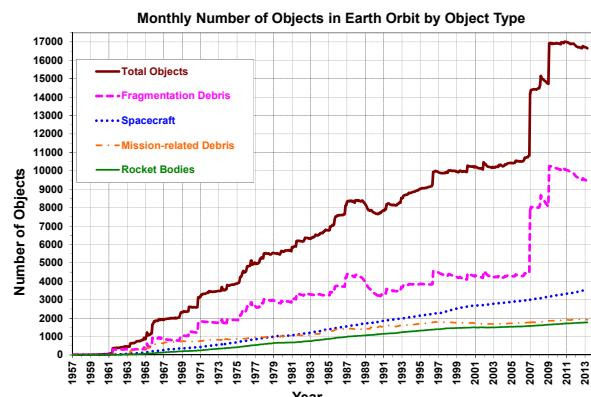


Fig. 1: Monthly increase of the catalogued population between 1957 and 2013. The top curve is the total and the population breakdown is shown by the four

curves below the total. About 57% of the 2013 catalogued objects are fragmentation debris.

The buildup of material in space is illustrated in Figure 2. The mass distribution is dominated by spacecraft (S/C) and rocket bodies (R/Bs). They account for approximately 54% and 42%, respectively, of the total mass in the environment. Although fragmentation debris dominate the number distribution, they only represent less than 3% of the total mass. The amount of material in Earth orbit exceeds 6500 tons as of 2013 and approximately 2700 tons of material is concentrated in low Earth orbit (LEO, the region below 2000 km altitude).

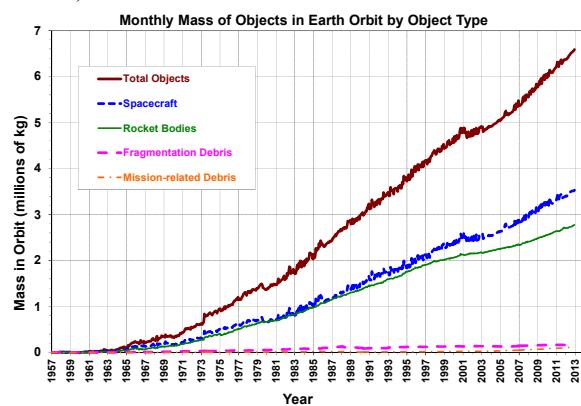


Fig. 2: Historical mass increase in the near-Earth space environment. The top curve is the total and the population breakdown is shown by the four curves below the total.

The trend of the top curve in Fig. 2 shows a steady increase of mass over time and there is no sign of slowing down. This is a serious problem because as

more material is added to the environment, the chances of accidental collisions among existing objects will increase in the future. More frequent collisions will generate more small debris to threaten the safety of operational satellites.

The international space community has attempted to address the orbital debris problem since the 1970s. Postmission disposal (PMD) mitigation measures, such as end-of-mission passivation to reduce potential explosions and the 25-year decay rule to limit the long-term presence of massive S/C and R/Bs in LEO, have been adopted by many space agencies, including members of the Inter-Agency Space Debris Coordination Committee (IADC), as part of the overall mitigation strategy to manage the orbital debris problem. The 25-year rule simple means to place a S/C or R/B at the end of its mission in an orbit where the atmospheric drag will limit its orbital lifetime to 25 years or less. The selection of 25-year was based on "This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit."¹ The effectiveness of using the 25-year rule to reduce the future debris growth was well documented during the development of the measure in the 1990s²⁻⁴. The objectives of this paper are to provide an updated study based on the 2012 environment and to highlight the importance of the global compliance of the 25-year decay rule.

II. STUDY SCENARIOS

Reliable future debris environment projection is an impossible task. Major uncertainties in environment simulations include the characteristics of future launches (orbit, mass, material, mission lifetime, etc), solar activities, explosions, and options for mitigation and potential remediation. There are two general approaches to handle the uncertainties. The first is to examine the extreme cases and then use the results to bound the problem. Examples of this approach include the assumptions of no future launch, no future explosion, or no mitigation measure. The second is to analyze nominal cases based on reasonable assumptions, such as repeating a typical launch cycle or repeating an average solar activity cycle. The choice really depends on the objectives of the simulations. Any projection results should only be considered as a benchmark to guide the expectation of the future environment under the assumed scenario⁵.

Future environment simulations usually follow a Monte Carlo (MC) approach where collision events are selected based on the collision probability of each likely event and the draw of a random number to determine if such an event would occur. Multiple MC simulations, ranging from tens to hundreds, are performed for the projection period. The MC results can be processed to

obtain the average and the standard deviations, but individual MC predictions can also be analysed for their distribution to gain additional insights of the projected environment.

The simulation tool for this study is NASA's state-of-the-art orbital debris evolutionary LEGEND (LEO-to-GEO ENvironment Debris) model^{6,7}. The model simulates the historical R/Bs, S/C, mission-related debris, and fragmentation debris based on documented launches and breakup events (explosions and collisions). For future projection, the model propagates the historical populations forward in time and uses a pair-wise collision probability evaluation algorithm and a MC method to simulate future collision activities. The NASA Standard Breakup Model is used to generate fragments after each collision. The model can adopt user-specified future launch traffic, post-mission disposal, and active debris removal options.

The study scenarios include the following. The simulations focus on the 10 cm and larger population in LEO. Historical simulation covers the period from 1957 to the end of 2011 and the future projection covers 2012 through 2212. The 2004 to 2011 8-year launch cycle is assumed to be representative of future traffic so this 8-year cycle is repeated during the projection period. All future S/C is assumed to have 8-year mission lifetime. No stationkeeping and no collision avoidance maneuver for operational S/C is allowed. Future solar activity is a repeat of an average cycle derived from Solar Cycles 18 to 23. The PMD scenarios include the following. No explosion for R/B and S/C is allowed in the future. Each R/B is moved a 25-year decay orbit after launch. Each S/C is moved to a 25-year decay orbit or a LEO graveyard orbit (depending on the least ΔV required for the two options) after 8-year of mission lifetime. The 25-year decay rule success rates for R/Bs and S/C are set to 0%, 10%, 50%, 75%, and 95%, respectively. A total of 100 MC runs are carried out for each success rate scenario and the results are analysed and presented in the next section.

III. STUDY RESULTS

The projected orbital debris population increases from the five test scenarios are presented in Figure 3. The effective number is defined as the fractional time, per orbital period, an object spends below 2000 km altitude. Each projection curve is an average of 100 MC simulations. Because of the averaging effect, sharp increases due to major collision events, such as the increase from the Iridium 33 and Cosmos 2251 collision shown in Figure 1, are smoothed out. Nevertheless, the average curves provide a good way to quantify the differences in the expected population growth from different projection scenarios. As expected, the no future explosion and no 25-year decay rule scenario projects the highest growth and the increase is nonlinear

for the next 200 years. The no explosion and 95% compliance of the 25-year decay rule leads to the slowest population increase in 200 years.

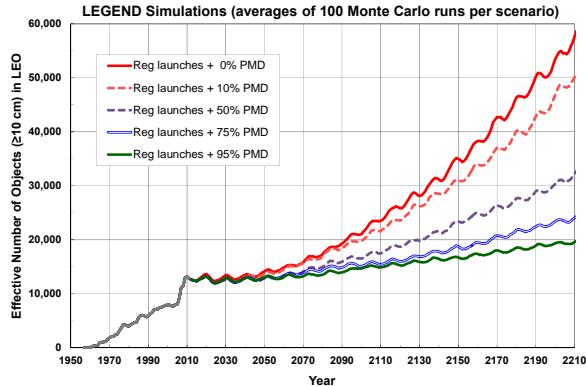


Fig. 3: Projected average population growth in LEO. Each projection curve is the average of 100 MC simulations. Implementation of the 25-year PMD rule can significantly reduce the future debris population increase.

When the 25-year decay rule is implemented at a 50% level, the average population increase is cut significantly. When it is implemented at a 95% level, the projected average population increase is limited to about 54% in 200 years. Table 1 summarizes the average 10 cm and larger objects in LEO at a 50-year interval for the five scenarios.

	2012	2062	2112	2162	2212
0%	12,866	15,088	23,720	38,294	58,692
10%	12,866	14,728	21,931	33,820	50,919
50%	12,866	13,610	17,633	24,730	32,767
75%	12,866	13,560	15,509	19,446	24,315
95%	12,866	13,319	14,954	17,225	19,795

Table 1: Average population increase for the 10 cm and larger objects in LEO at a 50-year interval from each study scenario.

A different parameter to characterize the future orbital debris environment is collision activities. There are two types of collisions – catastrophic and non-catastrophic. A catastrophic collision occurs when the ratio of impact energy to target mass exceeds 40 J/g. The outcome of a catastrophic collision, such as the collision between Iridium 33 and Cosmos 2251, is the total fragmentation of the target or targets involved and the generation of thousands of ≥ 10 cm debris and tens of thousands of millimetre-to-centimetre debris. A non-catastrophic collision occurs when the energy mass ratio involved is less than 40 J/g. The outcome of a typical non-catastrophic collision is minor damage to the target and the generation of a small amount of debris that has minimal contribution to population growth. The average

catastrophic collisions projected by the five scenarios are shown in Figure 4.

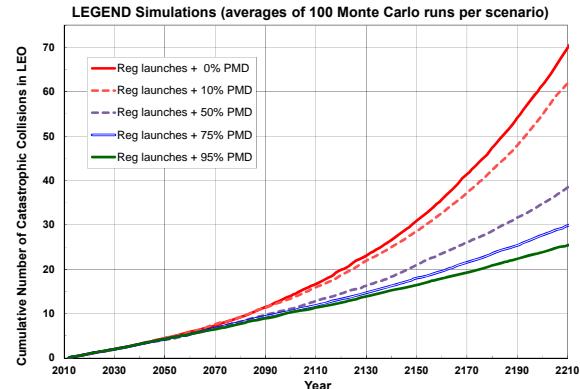


Fig. 4: Projected catastrophic collision activities in LEO from the five study scenarios. Each curve is the average of 100 MC simulations.

The numbers of catastrophic and non-catastrophic collisions from the study are summarized in Table 2. For the no future explosion and no 25-year decay rule scenario, an average of 71 catastrophic collisions are expected in LEO for the next 200 years. The no future explosion and 95% compliance of the 25-year decay rule scenario has the lowest number of catastrophic collisions. On average, only 26 such events are expected in LEO for the next 200 years. Although the number is significantly lower than 71, it still means an average of one catastrophic collision every 7.7 years. The threat from small debris (millimetre to centimetre) to operational S/C from such events on a regular basis cannot be overlooked.

	0%	10%	50%	75%	95%
cat	71	63	39	30	26
non-cat	76	65	37	24	19
total	147	128	76	54	45

Table 2: Average catastrophic and non-catastrophic collisions in LEO for the next 200 years as predicted by the five study scenarios.

Another important parameter to assess the seriousness of the orbital debris problem is the total mass of material in the environment. As shown in Figure 2, the historical mass increase between 1957 and 2013 has been quite steady. The no future explosion and no 25-year PMD rule projection follows a similar trend (Figure 5). The projected mass increase for this scenario is a direct reflection of the repeated traffic cycle (i.e., 2004 through 2011), especially the masses of the R/Bs and S/C, their mission altitudes, and their area-to-mass ratios. For the no future explosion and 95% compliance of the 25-year decay rule scenario, the mass is more or

less maintained at a constant level, although still higher than the beginning of the 2012 environment.

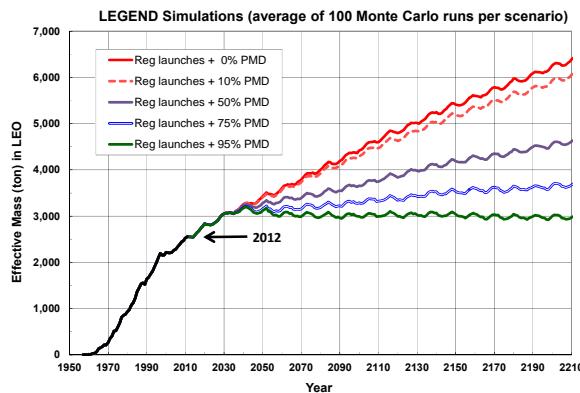


Fig. 5: Projected mass increase in LEO from the five study scenarios. The 2012 environment is indicated by the arrow.

IV. SUMMARY

Predicting the future debris environment is very difficult. The results are always sensitive to key assumptions adopted by the model, including future launches, future explosions, and solar activity. Nevertheless, one can make reasonable assumptions, define nominal scenarios, and then draw conclusions from the average results for effective environment management. This updated study again illustrates the effectiveness of using the 25-year decay rule to limit the future debris population growth in LEO. Mitigation measures, especially passivation and the 25-year decay rule are the first and the most cost-effective defense against future population growth in LEO. The benefits of compliance are clearly quantified in the study. The current global compliance rate of the 25-year decay rule for LEO R/Bs and S/C is significantly lower than 95%. It is critical for the international space community to fully implement the mitigation measures to better

protect the future environment. On the other hand, the study results also show that even with no future explosion and a global 95% compliance of the 25-year decay rule, the LEO debris population is expected to slowly increase and collision activities are expected on a regular basis in the next 200 years. To better manage the orbital debris problem and improve the safety of operational S/C in LEO, more aggressive measures, such as active debris removal, should be considered by the international space community.

REFERENCES

1. IADC Space Debris Mitigation Guidelines, IADC-02-01, available at <http://www.iadc-online.org>.
2. Krisko, P.H., N.L. Johnson, J.N. Opiela, EVOLVE 4.0 orbital debris mitigation studies, *Adv. Space Res.* 29, 1385–1390, 2001.
3. Opiela, J.N. and P.H. Krisko, Evaluation of orbital debris mitigation practices using EVOLVE 4.1, in: J. Bendisch (Ed.), *Space Debris 2001*, 2002, pp. 209–219.
4. Walker, R., C.E. Martin, P.H. Stokes, J.E. Wilkinson, H. Klinkrad, Studies of space debris mitigation options using the debris environment long term analysis (DELTa) model, in: J. Bendisch (Ed.), *Space Debris 2000*, pp. 305–314, 2001.
5. Liou, J.-C., A statistical analysis of the future debris environment, *Acta Astronautica* 62, 264–271, 2008.
6. Liou, J.-C., D.T. Hall, P.H. Krisko, and J.N. Opiela, LEGEND – A three-dimensional LEO-to-GEO debris evolutionary model. *Adv. Space Res.* 34, 5, 981–986, 2004.
7. Liou, J.-C., Collision activities in the future orbital debris environment, *Adv. Space Res.* 38, 9, 2102–2106, 2006.