IAC-04-IAA.5.12.3.06

A LEO SATELLITE POSTMISSION DISPOSAL STUDY USING LEGEND

J.-C. Liou
Lockheed Martin Space Operations, 2400 NASA Parkway, Mail Code C104, Houston, TX 77058, USA
Email: jer-chyi.liou1@jsc.nasa.gov

Nicholas L. Johnson
NASA Johnson Space Center, 2101 NASA Parkway, Mail Code SX, Houston, TX 77058, USA
Email: nicholas.l.johnson@nasa.gov

ABSTRACT

This paper summarizes results from two postmission disposal parametric analyses based on the high fidelity NASA orbital debris evolutionary model LEGEND. The first analysis includes a non-mitigation reference scenario and four test scenarios, where the mission lifetimes of spacecraft are set to 5, 10, 20, and 30 years, respectively, before they are moved to the 25-year decay orbits. The comparison among the five scenarios quantifies how a prolonged spacecraft mission lifetime decreases the effectiveness of the 25-year decay rule in the low Earth orbit region. The second analysis includes three 25-year decay postmission disposal scenarios where the mission lifetimes of spacecraft are set to 5 years but with disposal success rates set to 50%, 70%, and 90%, respectively. It illustrates how the postmission disposal success rate impacts the long-term debris environment. The conclusion of this paper is that a prolonged spacecraft mission lifetime and a lower postmission disposal success rate can have noticeable negative impact on the debris environment in the long run.

INTRODUCTION

Postmission disposal (PMD) has been recognized as the most effective way to limit the growth of future orbital debris populations[1-3]. The 1995 NASA Safety Standard 1740.14, *Guidelines and Assessment Procedures for Limiting Orbital Debris,* recommends placing a spacecraft or upper stage passing through the low Earth orbit regime (LEO, region of space below 2,000 km altitude) in an orbit in which atmospheric drag will limit its lifetime to less than 25 years after the completion of mission[4]. This postmission disposal practice has been known as the 25-year decay rule. However, a prolonged spacecraft mission lifetime will certainly decrease the effectiveness of the 25-year decay rule. In addition, the success rate of PMD has a direct impact on the environment as well. The objective of the study summarized in this paper is to quantify how future LEO orbital debris environment responds to different spacecraft mission lifetimes and different PMD success rates.

The tool used in this study is the NASA orbital debris evolutionary model, LEGEND[5] (a LEO-to-GEO Environment Debris model). It is a high fidelity physical model that is capable of simulating the historical as well as future near Earth debris environment. The parametric study in this paper includes a total of seven test cases based on selected PMD scenarios with different spacecraft mission lifetimes and with different PMD success rates. Details of the scenarios and the study results are presented in the following sections.

SPACECRAFT MISSION LIFETIME

The spacecraft mission lifetime test cases included a non-mitigation scenario and four PMD test scenarios. In all PMD scenarios rocket bodies, after launch, were moved to 25-year decay orbits or to LEO storage orbits (above 2,000 km altitude), depending on which option required the lowest change in velocity for the maneuvers. In the PMD scenarios the mission lifetimes of spacecraft were set to 5, 10, 20, and 30 years, respectively. At the end of the mission lifetime, each spacecraft was moved to either the 25-year decay orbit or to a LEO storage orbit, depending on which option required the lowest change in velocity for the maneuvers. In most cases, the 25-year decay orbit was the preferred choice for vehicles passing through LEO.

Five LEGEND simulations, one for each scenario, were completed. Each simulation included 30 Monte Carlo runs with a projection period of 100 years. Future launch traffic was simulated by repeating the 1995 to 2002 launch cycle. The solar 10.7 cm flux used in the orbit propagator included two components: short term projection (2003-2011, NOAA Space Environment Center), and long term projection (2012-2103). The long-term projection was a repeat of an average cycle derived from the Solar Cycles 19-23. Explosion probabilities of rocket bodies and spacecraft were based on an analysis of historical explosions between 1988 and 1998. Objects with non-zero explosion probabilities were classified, by origin and type, into nine categories. Each category was assigned a time-dependent explosion probability for up to 10 years (since launch). Collision probabilities among objects were calculated based on a fast pair-wise comparison algorithm[6]. Only objects 10 cm and larger were included in collision consideration.

The postmission disposal success rates for the four mitigation cases were all set to 90%. A simple procedure based on random numbers was used to determine whether or not postmission disposal for each vehicle was to be implemented successfully. If it failed, the vehicle was simply left in orbit.

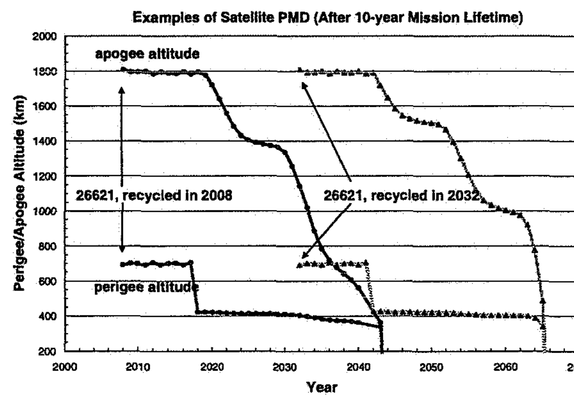

Fig. 1: Examples of spacecraft PMD after 10-year mission lifetime. After their perigee altitudes were lowered, both vehicles decayed in 25 years.

The 25-year decay orbit of a vehicle, at the end of its mission, was determined using a simple iteration process by reducing its perigee altitude. The end-of-mission orbit was propagated forward in time for 25 years. If the vehicle decayed, no modifications to its orbit were made. Otherwise, its perigee altitude was lowered by 5 km at a time and the new orbit was propagated for 25 years. The whole process was repeated until a new orbit that would result in the decay of the vehicle in less than 25 years was reached.

An example from the 10-year spacecraft mission lifetime simulation was given in Figure 1. This was a spacecraft launched in the year 2000 and it was repeated in future traffic cycle every 8 years (only 2008 and 2032 cases shown). Ten years after it was launched in 2008, its perigee altitude was lowered to just above 400 km. The new orbit caused the spacecraft to decay in 2043. The same vehicle launched in 2032 followed a similar pattern.

The spatial density distribution of 10 cm and larger objects in LEO at the end of the 100-year projection is shown in Figure 2. Each curve represents the average from 30 Monte Carlo runs. The spatial density distribution at the beginning of 2003 is also included as the dashed-curve near the bottom. When compared with the non-mitigation scenario, the four PMD cases all significantly reduce the growth of future debris populations. However, there are noticeable differences among different mitigation cases, especially around 800 km, 1,000 km, and 1,450 km altitudes. The spatial density increases with increasing spacecraft mission lifetime.

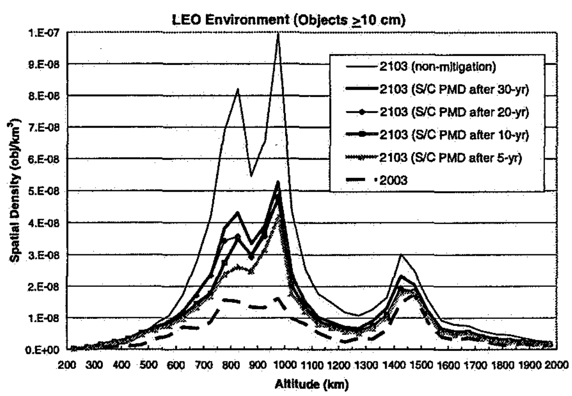

Fig. 2: Spatial density distribution of objects 10 cm and larger as a function of altitude at the end of future projection. The five curves, from top to bottom, are labeled in the same order as those in the key. The dashed-curve near the bottom represents the environment in 2003.

Note the 25-year rule mitigation scenarios always result in a slightly higher spatial density below 500 km altitude than the environment predicted by the non-mitigation scenario. This is a direct consequence of moving on-orbit rocket bodies and spacecraft to the 25-year decay orbits. Even with these increases, the magnitude of spatial density remains well below that of most other altitudes. In addition, active collision avoidance procedures ensure no risk to human space flight. The reversed trend below 500 km altitude is insignificant when one evaluates the overall positive impact of shorter spacecraft mission lifetime on the LEO environment.

The spatial density distribution of 1 cm and larger objects in LEO at the end of 100-year projection is shown in Figure 3. Qualitatively, the trend is similar to that in Figure 2, i.e., a prolonged spacecraft mission lifetime decreases the effectiveness of the 25-year decay rule. Note that for 1 cm debris the spatial density does not increase below 500 km.

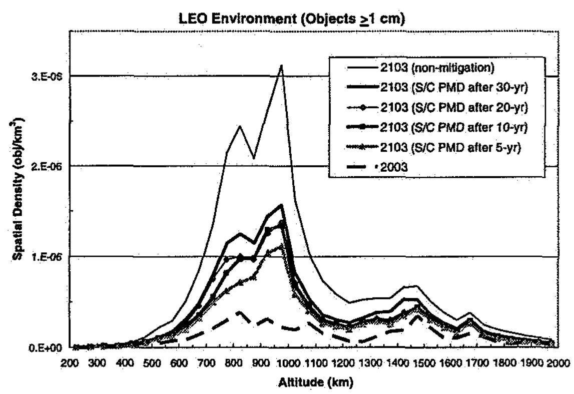

Fig. 3: Spatial density distribution of objects 1 cm and larger as a function of altitude at the end of future projection. The five curves, from top to bottom, are labeled in the same order as those in the key. The dashed-curve near the bottom represents the environment in 2003.

The effective numbers of objects, 10 cm and larger and 1 cm and larger, passing through LEO are summarized in Table 1. The effective number is defined as the fractional time, per orbital period, an object spends between 200 and 2,000 km altitudes. When compared with the non-mitigation scenario (case I), the 5-year spacecraft mission lifetime PMD scenario effectively reduces the LEO debris populations by more than half in 2103. This again reaffirms the general belief that postmission disposal is an excellent way to limit the growth of future debris populations, primarily by reducing the number of future collisions.

Table 1: Summary of spacecraft mission lifetime study.

Case	R/B PMD	S/C PMD after x year	Normalized N_{10cm}, 2103	Normalized N_{1cm}, 2103
I	no	no	1	1
II	yes	30	0.63	0.57
III	yes	20	0.56	0.49
IV	yes	10	0.54	0.47
V	yes	5	0.48	0.40

PMD SUCCESS RATE

The second parametric analysis included a non-mitigation scenario (identical to the one described previously), and three test scenarios where rocket bodies were moved to 25-year decay orbits or LEO storage orbits after launch and spacecraft were moved to 25-year decay orbits or LEO storage orbits after 5 years of mission. The PMD success rates for the three test scenarios were set to 90%, 70%, and 50%, respectively.

Following a procedure similar to that in the previous section, the result for each scenario is based on 30 Monte Carlo runs using LEGEND. Figure 4 shows the effective number of objects, 10 cm and larger, in LEO as a function of time during the projection period. The four curves show a clear and expected trend. While PMD scenarios all reduce LEO debris populations in the future, lower PMD success rate results in higher debris populations; and the differences among scenarios increase with time. The correlation between the PMD success rate and the effective number of objects in 2103 is close to a linear relationship. With increasing PMD success rate, the number of future collisions decreases.

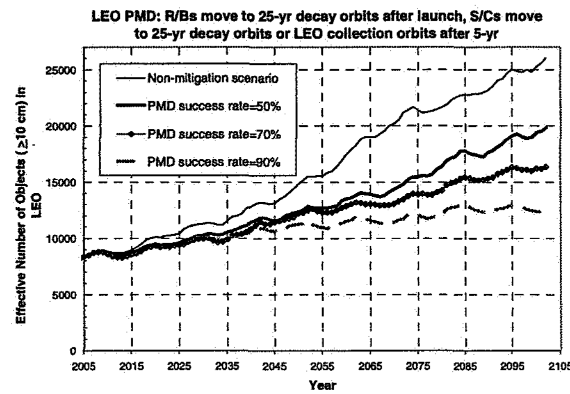

Fig. 4: Effective number of objects, 10 cm and larger, in LEO as a function of time. The four curves, from top to bottom, show the non-mitigation scenario and the three PMD scenarios with PMD success rates of 50%, 70%, and 90%, respectively.

The spatial density distributions of objects, 10 cm and larger, at the end of the projection period are shown in Figure 5. Similar distributions for objects 1 cm and larger are shown in Figure 6.

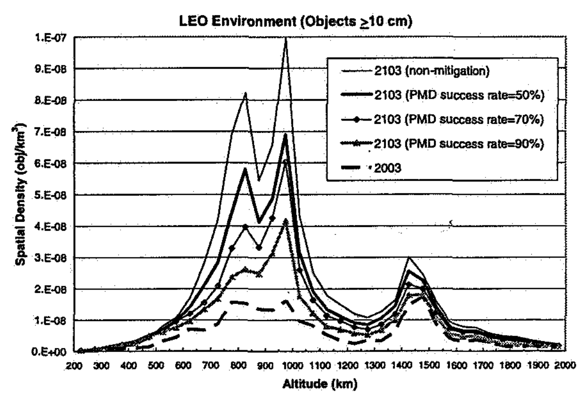

Fig. 5: Spatial density distribution of objects 10 cm and larger as a function of altitude at the end of future projection. The four curves, from top to bottom, are labeled in the same order as those in the key. The dashed-curve near the bottom represents the environment in 2003.

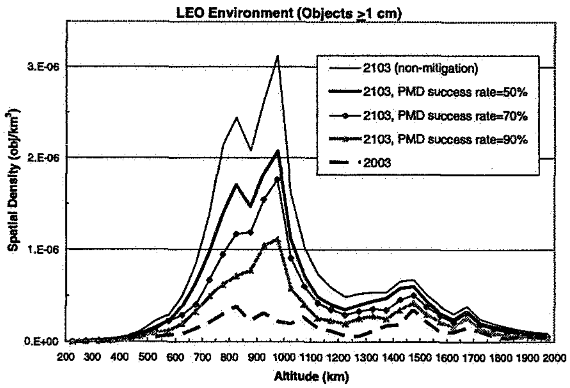

Fig. 6: Spatial density distribution of objects 1 cm and larger as a function of altitude at the end of future projection. The four curves, from top to bottom, are labeled in the same order as those in the key. The dashed-curve near the bottom represents the environment in 2003

Both Figures 5 and 6 illustrate how the effectiveness of the 25-year rule PMD is degraded by a lower PMD success rate. Even the difference between 90% and 70% scenarios is quite significant. The projected LEO environment in 2103, normalized to the non-mitigation scenario, is summarized in Table 2. The three PMD scenarios (cases II-IV) all reduce the LEO debris populations by 2103. However, as the PMD success rate changes from 90% to 50%, the reduction in debris populations changes from more than half to only about 25%.

Case	PMD	PMD success rate	Normalized N_{10cm}, 2103	Normalized N_{1cm}, 2103
I	no	no	1	1
II	yes	50%	0.76	0.73
III	yes	70%	0.63	0.58
IV	yes	90%	0.48	0.40

Table 2: Summary of PMD success rate study. N_{10cm} and N_{1cm} are the effective numbers of objects, 10 cm and larger and 1 cm and larger, respectively, in LEO.

SUMMARY

The two parametric analyses presented in this paper quantify two important factors in postmission disposal practices: length of spacecraft mission lifetime before the 25-year decay rule is applied and the postmission disposal success rate. Overall, the results show that indeed the 25-year decay rule, coupled with a high PMD success rate, is a very effective way to limit the growth of future debris populations in LEO.

Although the operational lifetime of many LEO spacecraft are less than five years, some notable exceptions exist, e.g., Landsats 4 and 5, SPOT 1, and HST. If the average operational lifetime of LEO satellites significantly exceeds five years, an alternative disposal policy could maintain the desired effect of the 25-year decay rule. This new policy would decrease the permissible postmission decay time as the mission duration increases, such that the sum remains 30 years, i.e., equivalent to the current 5 plus 25 years. For example, if a spacecraft is to remain operational for 12 years, then at the end of its mission, the vehicle should be placed in a PMD orbit such that it will decay in 18 years. In other words, the 25-year decay rule would be replaced by a new "30-year-in-orbit" rule.

A consequence of this "30-year-in-orbit" rule is that additional propellant might be needed for a spacecraft with a projected long mission time. A longer operational duration would require a shorter PMD decay orbit in the end which means a higher velocity change would be needed for the orbit maneuver. Therefore, the spacecraft would need additional propellant reserves.

Greater attention to expected satellite mission times would also be needed. Many satellites today are launched with "design" lifetimes which are artificially short for technical and programmatic reasons and which are routinely exceeded. The continued operation of numerous satellites without adequate PMD resources would necessarily lead to a degradation of the LEO environment.

REFERENCE

1. Opiela, J.N. and P.H. Krisko. Evaluation of orbital debris mitigation practices using EVOLVE 4.1. In *Space Debris 2001* (J. Bendisch, Ed), 209-219, 2002.
2. Krisko, P.H, N.L. Johnson, and J.N. Opiela. EVOLVE 4.0 orbital debris mitigation studies. *Adv. Space Res.* **29**, 9, 1385-1390, 2001.
3. Walker, R., C.E. Martin, P.H. Stokes, J.E. Wilkinson, and H. Klinkrad. Studies of space debris mitigation options using the debris environment long term analysis (DELTA) model. In *Space Debris 2000* (J. Bendisch, Ed), 305-314, 2001.
4. *Guidelines and Assessment Procedures for Limiting Orbital Debris*, NASA Safety Standard 1740.14, NASA Office of Safety and Mission Assurance, August 1995.
5. 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, 2003.
6. Liou, J.-C., D.J. Kessler, M.J. Matney, and E.G. Stansbery. A new approach to evaluate collision probabilities among asteroids, comets, and Kuiper Belt objects. *Proc. Lunar Planet. Sci. Conf.* **31**, 1828, 2003.