Revisiting the Effectiveness of Debris Mitigation by Back-Dating Fragmentation Events

Chris Ostrom(1), Phillip Anz-Meador(2), and John Opiela(2)

(1) NASA Johnson Space Center, Mail Code XI5-9E, 2101 NASA Parkway, Houston, TX 77058, USA
(2) Jacobs, NASA Johnson Space Center, Mail Code XI5-9E, 2101 NASA Parkway, Houston, TX 77058, USA

ABSTRACT
Since 1961, more than 250 satellites have fragmented while in orbit about the Earth, from very low Earth orbit out to the geostationary belt. The problem of orbital debris has been recognized since at least the late 1970s, with the institution of the NASA Orbital Debris Program Office (ODPO) in 1979 at the Johnson Space Center. Efforts to mitigate the growth of the orbital debris environment have mainly focused in two areas: the reduction and elimination of accidental explosions of spacecraft and rocket upper stages and the timely removal of spacecraft and rocket upper stages from orbit after completion of their missions. The ODPO continues to analyze the orbital population in orbit based on object type, mass, and other parameters of interest for characterizing the overall growth of objects in Earth’s orbit.

Of the 268 known fragmentation events, 46 have occurred more than ten years after the affected satellites’ launch. These long-delayed breakups increase the population of orbital debris on the date of fragmentation, but we can also consider that the debris generated during that event could be attributed to the launch date of that satellite. We will present here an analysis of the historical growth of the low-Earth orbit debris environment, removing intentional fragmentation events, and examine the effectiveness of mitigation measures (such as passivation and reducing post-mission orbital lifetime).

1 Introduction
Orbital debris has been a part of space history from the very start – with the launch of Sputnik-1 on 04 October 1957, its launch vehicle, also named Sputnik, an expended core stage, remained in orbit for two months. The Sputnik-1 payload ran out of battery power after 22 days, remained on orbit for a further three months, and decayed on 03 January 1958. After more than 6100 launches, the near-Earth orbital environment has changed significantly. Figure 1 shows the number of orbital objects in the US Space Command (SPACECOM) catalog (SATCAT) from 1957-2023; this chart frequently appears in the Orbital Debris Quarterly News as the “monthly objects in orbit chart.” It is immediately apparent that there are several features on this chart: large vertical lines, which represent on-orbit breakups (accidental or intentional explosions and collisions), and gradual descending sections, representing time spans where the number of objects decaying from orbit is greater than the number of those launched or generated from fragmentation events.
Fig. 1. Monthly Objects In Orbit Chart, showing the increase of the effective number of objects in orbit from 1957-2023. Populations, expressed as effective number (the portion of their orbital period spent in any of the defined spaces), are presented for the low Earth orbit (LEO), middle Earth orbit (MEO), geosynchronous orbit (GEO), and other Earth-bound orbits. MEO lies between the conventionally defined LEO and GEO spaces.

The first on-orbit breakup occurred in June 1961 (the Ablestar upper stage associated with the launch of Transit-4A), tripling the size of the SATCAT [1]. Since then, more than 270 other objects have fragmented in orbit, producing an estimated 23,000 cataloged pieces of debris. The rate of on-orbit breakups peaked in the 1980s at nearly 6 events per year (see Fig. 2, reproduced from [1], for an annual accounting of on-orbit breakup events), and has averaged above 4 events per year since the mid-1970s.

Fig. 2. Number of breakups occurring each year since 1957 (reproduced from [1]).
For this work, only accidental fragmentation events (explosions and collisions) are considered, as the intentional
destruction of satellites is not generally a controllable or predictable outcome before launch. After removing all
fragmentation debris associated with satellites that were intentionally broken up (either by explosion or collision)
and constraining the current analysis only to low Earth orbit (LEO), the trend seen in Fig. 3 emerges.

![Graph showing the effective number of objects on-orbit in LEO from 1957-2023, excluding any fragments resulting from deliberate destruction of satellites.]

Fig. 3. The effective number of objects on-orbit in LEO from 1957-2023, excluding any fragments resulting from deliberate destruction of satellites.

2 Historical Analysis and Orbital Debris Mitigation

The on-orbit chart seen in Fig. 1 is a product of three eras in spaceflight: first, a “Wild West” or “big sky theory”
era, starting in 1957 and ending approximately in the mid-1980s, in which it was assumed that any human behavior
could not have negative effects on the space environment due to the vast volume of Earth orbital and interplanetary
spaces; second, an “Age of Mitigation,” in which significant efforts were begun to reduce the generation of new
long-lived orbital debris, starting in the early 1980s and continuing to today; and the third, an era of large
constellations and other new classes of space operations, starting in the late 2010s. These three eras can be seen in
Fig. 1 as three different slopes in the LEO population – from the mid-1960s to mid-1980s, there is a near-constant
growth rate in LEO, due to both launch traffic and a steady rate of breakups in orbit. The mitigation era is
characterized by a sharp change in slope to nearly horizontal from the mid-1980s to the mid-2000s, after which
intentional and accidental collisions in LEO nearly doubled the population. As solar cycle 24 peaked in the mid-
2010s, the population in LEO decreased and appeared to level off, but the deployment of large constellations and the
proliferation of CubeSats has led to a potential new era in spaceflight.

2.1 Big Sky Era

The early years of spaceflight were characterized by an (assumed) understanding that unless satellites were
intentionally maneuvered for rendezvous, the probability of a collision between two orbiting objects would be
vanishingly small. As such, the intentional or accidental destruction of satellites near their operational orbits was
acceptable.

During this time, most satellites did not plan for controlled reentry at the conclusion of their mission, excepting
dedicated film or payload reentry vehicles and certain reconnaissance satellites that executed maneuvers to assure
destruction of all classified components. These satellites would remain in orbit for decades, potentially centuries,
increasing the potential for an accidental explosion due to some unforeseen fault or a catastrophic collision. Since
these missions also used higher operational altitudes than typical missions today, any fragmentation debris generated
would also be longer-lived than if a similar satellite were to experience a breakup now.
In 1973, a Delta upper stage fragmented on orbit for the first time, generating 20 cataloged fragments; eight more Delta upper stages would break up before the end of the decade [2]. These 10 breakup events would contribute nearly 1800 fragments to the SATCAT. Another major contributor, in terms of number of breakups, if not number of cataloged debris, is the Soviet/Russian SOZ (sistema obespecheniya zapuska, launch support system) propellant-settling, or “ullage,” rockets from the Proton launch vehicle. [2] These uillage motors were jettisoned after the ignition of the fourth stage of Proton rockets and have experienced an approximately 70% rate of fragmentation in independent flight.

2.2 Age of Mitigation

In the late 1970s and into the 1980s, government and industry began to recognize the potential for orbital debris to cause operational problems. McDonnell Douglas conducted an investigation into the fragmentations of the Delta upper stage and implemented mitigation measures (now standard practices termed “passivation”) that would deplete the propellants and depressurize spent rockets to mitigate the risk of explosion from the mixing of residual fuel and oxidizer [2]. Since the introduction of passivation measures for Delta, the rate of fragmentations decreased from 9% of launches to 1%; furthermore, the number of cataloged fragments per explosion decreased from nearly 180 to less than 20. Similarly, the root cause of SOZ explosions was determined in the early 1990s, and the issue was remedied. SOZ rockets continued to be separated from the Proton fourth stage until 2012 and have continued to fragment on orbit; at the time of writing, over 30 SOZ remain intact on orbit. The total number of on-orbit breakups over time, including and excluding the SOZ rockets, can be seen in Fig. 4 (reproduced from [1]). Spacecraft have also experienced fragmentation issues due to batteries and propulsion, both during and after completion of mission operations. Passivation measures began to be implemented for spacecraft in the 1980s and 1990s.

![Fig. 4. The cumulative number of on orbit breakups (as of 01 May 2022), with and without the SOZ breakups included.](image)

There are two facets to mitigating the generation of long-lived orbital debris: generation, which can be reduced by eliminating accidental explosions (among other things), and reducing the orbital lifetime of any debris, which can be done mainly by reducing orbital altitude. Since many satellites require (or prefer) higher altitudes to successfully achieve their missions, the reduction in orbital lifetime is typically achieved by conducting a post-mission disposal (PMD) maneuver. For example, many earth observation satellites operate between 700-1000 km in altitude. Typical satellites at this altitude would have a postmission orbital lifetime exceeding 100 years, potentially over 1000 years;
however, by reducing the perigee altitude (or perigee and apogee altitudes), the lifetime could be reduced to a point that would ensure space sustainability. This has been implemented by NASA, the U.S. Government, the Inter-Agency Space Debris Coordination Committee (IADC), the United Nations, and others as the “25 year rule” (that spacecraft and rocket bodies should ensure that the post-mission orbital lifetime should not exceed 25 years) [3].

2.3 Modern Era

From the start of the 21st century until the mid-2010s, the trend of the orbital debris environment (again, ignoring the intentional destruction of satellites) appeared to be near-zero growth, punctuated by a stair-step increase (the collision of Iridium 33 and Cosmos 2251 in 2009). The ‘background noise’ of constant breakups seemed to slow significantly, thanks to the mitigation measures begun nearly 20 years earlier. Despite this period of seeming calm, the introduction and proliferation of CubeSats (and smallsats in general) in the early- to mid-2010s started a new trend of super-linear growth in the on-orbit population. Then, in the late 2010s and early 2020s, multiple constellations began deploying and operating in LEO: SpaceX’s Starlink constellation mainly near 550 km altitude with more than 4000 satellites; and the OneWeb constellation near 1200 km altitude with 648 satellites on orbit.

This new era, with a large number of satellite deployments, may pose a challenge to the current orbital debris mitigation paradigm. The 2019 update to the US Government Orbital Debris Mitigation Standard Practices (ODMSP) included new language regarding the design and operation of large constellations and smallsats to help address these special classes of space operations [3].

2.4 Backdating

Backdating, a tool we propose to assess the efficacy of mitigation measures and re-analyze the history of fragmentations on orbit, assumes that fragments resulting from these events were actually generated at the time that the object was launched rather than the time of the breakup. Simply transforming the breakup dates from the actual fragmentation to the respective launch dates, generates Fig. 5. The breakup events that occurred in the 1990s, 2000s, 2010s, and even early 2020s (c.f. Fig. 2) can be seen as largely the result of objects launched in the 1970s and 1980s, which have remained on orbit for decades.

It is now possible to examine the fragmentation debris generated by backdating their creation; Fig. 6 shows the evolution of the cataloged population in LEO after removing the debris from intentionally fragmented satellites and backdating breakups to their respective launch dates. This figure can be contrasted with Fig. 3 above in one major
way – the near-constant slope that appears in Fig. 3 from the mid-1960s to around the year 2000 is seen in Fig. 6 as abruptly changing near the year 1990 to the same nearly flat trend that characterizes the Age of Mitigation. It is further apparent that the orbital population appears to decrease in the mid-2010s before the deployment of large numbers of smallsats and large constellations in LEO.

![Chart showing the increase of objects in LEO from 1957 to 2023, excluding any fragments resulting from deliberate destruction of satellites, and backdating breakup events to the launch date.]

**Fig. 6.** Chart showing the increase of objects in LEO from 1957 to 2023, excluding any fragments resulting from deliberate destruction of satellites, and backdating breakup events to the launch date.

### 3 Conclusions

The rate of fragmentation events in Earth orbit has decreased moderately since it peaked in the mid-1980s at over 6 per year. By examining only the contributions in low Earth orbit (LEO), removing intentional breakups, and backdating fragment generation to a satellite’s launch date, it is clear that satellites’ behavior has significantly changed, starting in the early-mid 1980s. Changes to the design of orbital hardware and operations reduced the probability of accidental on-orbit breakup. The orbital debris environment features fewer breakups of objects in higher LEO altitudes, even among those objects that have been on orbit for decades, and objects launched since the mid-1990s are typically in lower orbits than earlier satellites, either by initial orbit design or through the execution of postmission disposal maneuvers.

While the measures of passivation and the limitation of post-mission orbital lifetime have been effective in mitigating the growth of orbital debris in long-lived orbits, it is crucial to improve compliance with national and international standards, regulations, and guidelines. The introduction and proliferation of CubeSats (and smallsats in general) and large constellations in LEO present challenges to the traditional approach to managing the growth of the orbital debris environment solely through mitigation measures and reminds us that remediation (i.e., active debris removal) is a key future practice to ensure long-term space sustainability.

### References

