AN ACCIDENT WAITING TO HAPPEN? EXPECTED EVOLUTION OF GROUND HAZARDS DUE TO SPACE DEBRIS RE-ENTRY

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ABSTRACT

Several recent, widely publicised, uncontrolled re-entry events of intact space hardware highlight the potential risk to life on ground posed by the large number of derelict rocket bodies and large satellites not designed for demise in the Earth's atmosphere. In addition to the danger posed by these objects to sustained space activity while still in orbit, a better understanding of the cumulative likelihood of casualties over the coming decades may help inform international policy on debris removal, as well as steer the efforts being taken by public and private spacecraft operators to mitigate their own liabilities and potential damage to their public image.

The objective of this paper is to quantify the casualty risk and other ground hazards posed by existing and foreseen debris, with a view to encouraging governments and space operators to take proactive steps to remove large objects from orbit before the seemingly inevitable tragedy on ground occurs, thereby addressing the debris problem both in space and on-ground.

Predicted future ground hazard predictions from re-entering intact space hardware is executed with a foundation of examining and revising the historical results from space object re-entries over the last nearly 70 years. Known re-entries of derelict hardware since 1957 are compared against the limited amount of reported ground impact incidents. The number of objects that have re-entered as a function of mass and inclination relative to the growing Earth population is reviewed as a basis for potential future ground hazard. The number, mass, and inclination of objects already abandoned that will naturally re-enter in the next 50 years is combined with the forecasted growing number of operational and non-operational satellites that will be re-entering due to the technology refresh associated with large constellations.

Key assumptions that might alter the future ground impact hazard will be exposed: the ability to perform controlled re-entry, the application of active debris removal services, the trend toward larger operational payloads in LEO, potential new rocket bodies abandoned in conjunction with new high-LEO constellations, new design for demise features as well as recent concerns about demisability adding to atmospheric pollution.

Results identify key areas of potential future research in spacecraft design, re-entry demise modelling and end of life operations, highlighting active policy and operational steps which could be taken to mitigate the risks exposed.

1 INTRODUCTION

The danger posed to space operations through the proliferation of space debris in commonly used orbital regimes is now well known by space-faring nations and efforts of varying effectiveness are starting to be implemented to help ensure their sustainability. An additional urgency to mitigate this problem has arisen from the exponential rise in actively controlled satellites in the Low Earth Orbit (LEO) regimes, as commercial mega-constellations are being deployed and many more planned for the near future. Mitigation measures are primarily driven through regulations and guidelines, which are now being extensively revised in an attempt to keep up with this rapidly evolving environment. These regulations primarily target the design of new-generation satellites and launchers, together with supporting ground systems, to ensure they can effectively avoid generating debris in orbit and can be reliably disposed of at the end of their useful life. Space objects already launched or designed prior to the imposition of regulations into their requirements will continue to represent a higher risk to orbital sustainability throughout their lifetime in orbit. Indeed, the original top 50 list of objects with greatest space environment risk indicated 40 were launched before 2000. Even for the updated top 50 list (for ECSD) the number remained high at 34. [1]

While it is understandable that the focus of the space debris mitigation efforts has been on the in-orbit environment, the risks that re-entering objects pose to life and infrastructure on ground have been accepted to a significant degree and until recent years have only very sporadically come into the public consciousness through media reporting. Indeed, prioritising the removal of the object from orbit can be *viewed* as an acceptance of a risk

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of collateral damage in meeting the greater good. While space debris regulations and guidelines are typically attempting to reduce the risk to life on ground to a level of 1/10,000, this figure has not evolved over many years despite the exponential increase in the number of objects re-entering.

Some events have made headlines in recent years such as the 2024 re-entry of the ISS battery pack passing through the house of a Florida resident, fortunately, without causing injury (See Figure 1), [2], and the 2022 re-entry of a Long March 5B rocket which led to Spain temporarily closing airspace with an associated economic impact into millions of Euros.

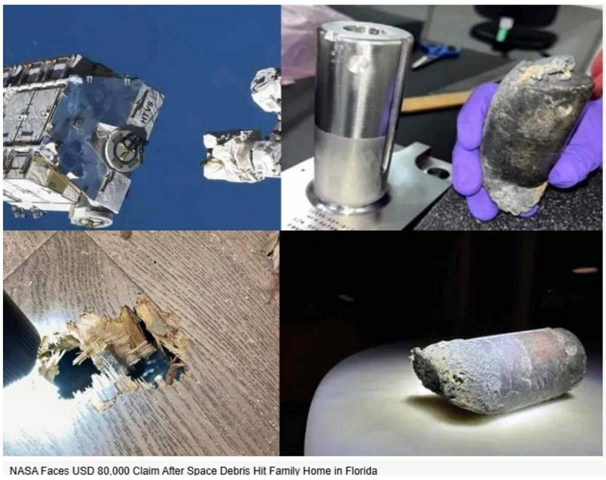

Figure 1. Space debris hits home in Florida, March 2024.

Despite such headlines regarding re-entry events, there has been little media attention and global public consciousness related to the number of space objects surviving re-entry through the Earth's atmosphere, passing in an uncontrolled manner through our airspace and striking the surface, be it oceans or land. It is expected that with increasing awareness about the frequency of these events, pressure will build to find solutions. If life is lost or significant infrastructure damage occurs, then one may expect the issue will be thrust into public awareness and governments and their space agencies forced into demonstrating action to prevent reoccurrence. Liability clearly lies with the "launching state" [3] and compensation claims could be high and potentially escalate existing political tensions between the country affected and the liable party for the debris.

With technologies existing for controlled re-entries and rapidly maturing for Active Debris Removal (to provide a controlled re-entry using a third-party service), the liability carried, both financial and legal, by space-faring nations could be very high. By raising awareness with international governments of this "accident" waiting to happen, the question is whether all reasonable measures to prevent this accident can be made before the lives are lost. Unfortunately, government action is normally galvanised by the foreseeable "accident" occurring, such as was the case with the 1989 Exxon Valdez oil spill. The threat of such an event had been realised during 1970s and 1980s, but the global shipping industry had resisted requirements for double-hull oil tankers (noting they also operate in an "area beyond national jurisdiction"). Only after this tragedy was a transition to double hulls required, first by the United States and then by the International Maritime Organization [4].

It is noted that the "double-hull" equivalent technological solutions to prevent space debris casualties on Earth mostly overlap with solutions which also mitigate the risks to in-orbit sustainability, namely using controlled re-entry for new-generation objects and using Active Debris Removal on large, heritage derelict objects and those objects still in operation, but incapable of being deorbited in an adequately safe manner.

This paper reframes the problem of space debris with the emphasis on casualty risk. The associated political and economic risks being taken by space-faring nations, may provide additional impetus and urgency to tackle both in-orbit sustainability and safe re-entry.

2 "What goes up…": A review of historical and expected uncontrolled re-entry events.

2.1 Overview

It is interesting to look at the historical re-entries to understand the risks society has been exposed to, as well as how the number of re-entries and associated risks may evolve in the future.

Pardini et al have performed extensive research on these issues with some key results reproduced and referenced below.

2.2 Historical Analysis

Figure 2 indicates casualty probabilities for both rocket bodies and spacecraft in the period 2010 to August 2023 [5].

It is noticeable that the risks increase beyond the previous years' levels in the most recent years, particularly in the case of the orbital stages.

An annual average casualty risk from the combined effect of re-entering orbital stages and spacecraft over this period is calculated to 3% with 70% of the risk associated to orbital stages. Over the 13 years analysed, this corresponded to a significant cumulative risk to life of over 18%. Crucially, the increase seen in latter years appears to be due to the start of the surge in space traffic and does not bode well for safety on Earth in the future.

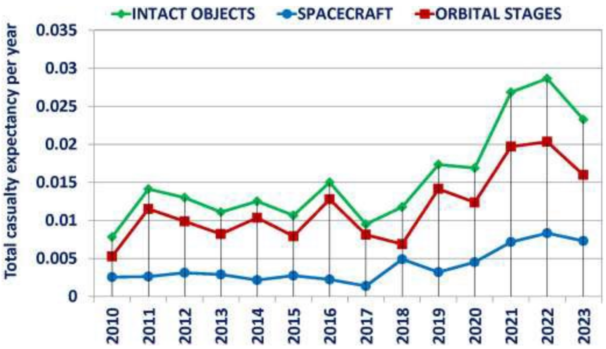

Figure 2.Casualty probability of uncontrolled re-entries of spacecraft, orbital stages, or both (intact objects) between 2010 and 2023

2.3 Impact of constellations in future evolution

There are several unknowns in assessing the future impact of constellations. While it seems the exponential growth of objects in space is set to continue, there is a clear opportunity to adapt the designs of such satellites to mitigate their impact on re-entry risk. What seems clear is that without any mitigation measures, the casualty risk from satellites will vastly surpass those of rocket bodies leading eventually to a *yearly* casualty risk in the order of 20% (based on a conservative assumption of 200 launches carrying 2000 satellites per year). If space traffic becomes much higher, it is estimated that this annual casualty risk figure could rise to 30%, for 4000 re-entries per year and 80% for 20,000 re-entries per year [6]. Note that each of the individual satellites are assumed to have a casualty risk significantly lower than the generally accepted casualty risk guidance of 1/10,000, but the cumulative effect renders this guidance ineffective. Proposals for establishing constellation mission-level casualty risk guidance are being made, such as 1/10,000 covering the cumulative effect of overall mission lifetime and each satellite component [7]. Note that we would suggest this would be better expressed as a yearly risk in order to avoid artificial engineering of constellation mission lifetime definitions to meet such a requirement. For example, one could declare all satellites launched in the next 20 years to be part of the same mission system or else say minor upgrades performed every 3 years to the same system constitute a new mission. Applying a 1/10,000 casualty guidance would clearly result in a higher annual casualty risk from the 3-year mission compared to the 20-year mission.

Identified mitigation measures could consist of improving the design for demise, using controlled re-entry to population-sparse regions, or Active Debris Removal to allow similar controlled re-entries. Improving design for demise may prove the most cost effective, but the concern about the cumulative impact of chemical substance release in the upper atmosphere is building [8]. Furthermore, compliance monitoring is difficult without the support of recognised external regulatory bodies. Controlled re-entry would add complexity to the satellite designs and therefore be a cost driver. Possibly, combined with choice of materials to *avoid* demise, it could mitigate adverse environmental effects. [9]. The application of ADR for constellations as a primary means of disposal would seem cost ineffective unless a large number of satellites could be collected by a single servicer. However, a significant number of satellites in a constellation are likely to suffer in-orbit failures, rendering them unable to initiate de-orbit manoeuvres, ADR may have a role as a backup in this case.

It is therefore imperative that mission analyses are performed to inform appropriate regulation, coupled with scientific assessments of the environmental risks and mitigation measures, as well as the engineering options to allow a compliant system design which ultimately mitigates these identified risks to society on Earth.

Indeed, if governments and industry fail to implement solutions, we risk a societal backlash against commercial constellations and potentially space activity in general.

3 RISKS POSED BY HERITAGE OBJECTS

3.1 Overview

Despite the potential impact of constellations on casualty risk, it is important not to lose sight of the risk posed by historical large, derelict objects in any mitigation solution. It must be taken into account that the side-effect of over 60 years of pioneering space activity has been to leave a large accumulated mass of rocket bodies and non-operational satellites in orbits which take decades to centuries to decay. The impact these will have on casualty risk is therefore hardly visible in the previously presented view of re-entries from 2000 to 2013.

Assuming that constellation risk is contained as discussed in the previous section, the regular re-entries of such small satellites should go relatively unnoticed by the general public. On the contrary, when a large object is due to re-enter in an uncontrolled manner and from which we can predict substantial survival of components toward the surface of the Earth, then this may cause unwelcome media attention, with associated reputational risks for the operators and nations involved, coupled with uncertainty for air traffic authorities, psychological impact on the general public and associated economic impacts through behaviour changes of such airlines and in the public at large.

Furthermore, the interference of the passage of decaying orbits of these large bodies through swathes of constellation satellites could be significant. While functional constellation satellites can manoeuvre away from well-tracked large objects, the risk of collision between uncontrolled debris objects is high and has the potential to leave a cloud of lethal non-tracked (LNT) objects interfering with the constellation orbits, thereby increasing the likelihood of a chain-reaction in collision events, i.e. the Kessler Syndrome.

It is likely that only a dedicated campaign of Active Debris Removal could mitigate these risks. Below we present our analysis of both the in-orbit risk and re-entry risk components of leaving these objects in orbit.

3.2 Risks posed during orbital decay

The criticality of operationalizing ADR is largely based upon the thousands of massive derelicts abandoned in LEO decades ago. *Table 1* depicts the current state of only ~660 of these nearly 3,000 objects that have been aggregated for decades. The four clusters are represented by the altitude at which these objects are centered and the total number of objects in each cluster. The annual collision rate within each cluster is determined and the median year of abandonment for each cluster is recorded. This is the year from which the calculation is conducted for the PC by (PCb) 2050 and 2075 (i.e., 25 years and 50 years from now, respectively). The table shows the PCb is greatest for Cluster 975 with a 39% probability of a collision by 2050 and 49% by 2075. The average mass of the objects in each cluster is then used to determine the number of cataloged fragments (i.e., # cataloged) that would be created by a center of mass-on-center of mass collision assuming a relative velocity of 12 km/s. Further, the number of LNT fragments between 1 and 10 cm (i.e., #1cmLNT) is estimated.

Cluster	Number of Objects	Collision Rate per year, CR	Median Year of Abandonment	**PCb 2050**	**PCb 2075**	Average Mass, kg	# catalog	**#1cmLNT**
775	145	0.00184	1982	0.12	0.16	1519	4557	45570
850	91	0.00136	1988	0.08	0.11	3202	9606	96060
975	350	0.00743	1984	0.39	0.49	1280	3840	38400
1450	78	0.0005	1982	0.03	0.05	1355	4065	40650

Table 1: The cumulative collision probability for clusters of intact derelict objects in LEO.

To assess the ramifications to the on-orbit population from these events occurring (i.e., number of LNT produced multiplied by the PCb), these fragment clouds are deposited in orbit and combined with the background 1 to 10 cm population as depicted by MASTER. For a standard smallsat with a collision cross-section of 4 m^2, the probability of collision for a 5-year span starting in the year 2050 is shown in Table 2 below. The smallsat is assumed to reside at 700 km, 900 km, and 1100 km. The results are tabulated by determining the PC for (1) one satellite being impacted once, (2) 100 satellites having one impact event, and (3) 1,000 satellites having 10 impacts. Each impact is assumed to terminate the mission of the spacecraft.

PCb 2050	1 sat / 1 collision	100 sat / 1 collision	1000 sat / 10 collisions
700	0.002	0.48	0.17
900	0.009	0.67	0.27
1100	0.005	0.39	0.12

Table 2: The likelihood of mission-terminating events for a typical smallsat at different altitudes in different configurations by 2050 depict the high certainty of a reduction in satellite reliability if ADR is not actively pursued.

Looking at 100 typical smallsats deployed to 900 km, the analysis shows there is a 67% probability that such a constellation would lose one satellite over a 5-yr mission in 2050 because of the addition of the LNT from breakups likely to occur by 2025. Further, if there were 1,000 satellites at 900 km, there is a 27% probability that 10 satellites would be lost over a five-year mission from collisions in the four clusters. Of course, these results would have to be scaled by the number of likely satellites at each of these altitudes. Note that the Chinese alone are planning on deploying more than 20,000 satellites to around 1,100 km altitude by 2040. Clearly, if this occurs and no ADR is performed on these massive derelicts, one could expect with high certainty that such constellations will lose many tens of spacecraft to the resulting fragment clouds.

The situation worsens if the analysis timeframe is extended out 50 years (i.e., to 2075), as depicted in *Table 3*.

PCb 2075	1 sat / 1 collision	100 sat / 1 collision	1000 sat / 10 collisions
700	0.002	0.49	0.20
900	0.010	0.73	0.31
1100	0.005	0.43	0.15

Table 3. By 2075, if ADR is not actively pursued, future constellations of spacecraft can be expected to lose tens of spacecraft from fragments generated by collisional breakups events involving "last century" derelicts.

It is not unreasonable to assume that each constellation spacecraft lost would be on the order of €1M. Note that estimates for satellite costs with lower production rates have been made at $55,000/Kg [10]. First, there will likely be other breakup events from explosions of rocket bodies (e.g., CZ-6A from 2024) and collisions between objects deposited in the last 20 to 30 years. For an estimated population of operational payloads in LEO by 2050 numbering in the tens of thousands, the loss rate can be seen to fairly easily start to approach a €B without considering more expensive spacecraft or other breakup events.

3.3 Risks posed upon re-entry

Table 4 below shows the number of large space objects (with individual casualty risks exceeding 1/10,000) expected to re-enter over the coming 50 years. *Table 5* shows the mass associated to these re-entries. While the number of derelict large satellites outnumbers those of rocket bodies, the mass of rocket re-entering rocket bodies is expected to be 2.4 times that of the large satellites over this period.

It is noteworthy that there are many more derelict large objects at higher altitudes (as was seen on the in-orbit risk table), which may take a century or more before re-entry, but nevertheless represent a significant future risk. Policy initiatives for funding investment on ADR will pay dividends for our descendants over the coming century.

Note also that the in-orbit and re-entry risks can be compounded – those objects not broken up through collision during their long descent will represent a large risk upon re-entry. Those objects which did suffer collision and break up may potentially represent a lower direct re-entry risk, but indirectly cause additional re-entry risks due to disabled satellites with which their debris has collided re-entering in an uncontrolled manner. Further analysis is needed to assess the extent of these risks.

Number of Objects	within 1 year	1- 5 years	5- 10 years	10 - 25 years	25-50 years	Total
Average Current Altitude	~400 km	400 - 500 km	500 - 550 km	550 - 615 km	615 - 675 km	
Rocket Body	32	67	37	88	46	**270**
Non-Operational Payloads	41	80	49	89	71	**330**

Table 4. Number of large objects due to re-enter in next 50 years

Mass (T)	within 1 year	1- 5 years	5- 10 years	10 - 25 years	25-50 years	Total
	~400 km	400 - 500 km	500 - 550 km	550 - 615 km	615 - 675 km	
Rocket Body	65	125	64	124	89	467
Non-Operational Payloads	20	50	23	40	35	168

Table 5. Mass of large objects due to re-enter in next 50 years

Casualty risks associated to the above assessment remain to be assessed but are assumed to be significant.

EUMETSAT, in close cooperation with ESA has already initiated a study on the Metop first generation satellites removal. Note in this case, not only would liability against casualty risk be mitigated, but additional lifetime can also be gained from the still operational satellites, which would be able to operate until failure instead of using half their fuel reservice to attempt an orbit lowering. [11]. Of course, for derelict objects, the owner will "only" be mitigating their liability.

4 CONCLUSIONS

It will be clear from this paper that the space sustainability of current and planned space activities is doubtful without rapid intervention to mitigate impacts. While in-orbit sustainability has been the focus of effort from the space community's regulatory and standardisation bodies and is showing progress in adapting satellite designs and operational behaviours, a closer look at the casualty risks expected in coming years highlights the need for an all-encompassing, holistic approach to risk assessment and mitigation measures.

While existing standards do point towards limiting an individual satellite's casualty risk to 1/10,000, it has been seen above that this is woefully inadequate for constellations of 1,000s to 10,000s of satellites. For the large number of derelict objects abandoned for decades, with casualty risks far in more than the accepted norm, we are in an unfortunate game of Russian Roulette. Eventually, one of the chambers of in the gun will contain the bullet. At some point, luck runs out.

Constellation sustainability depends on mitigation measures against their casualty risks being rapidly identified, implemented and enforced, be it design for demise, controlled re-entry of ADR, or a combination of the above.

Sustainability of space activities overall is doubtful without removal of the compound risks posed by the large, derelict objects from their in-orbit decay and eventual re-entry. An Active Debris Removal initiative is required, be it financed through a global fund, or through unilateral action from a coalition of concerned nations. A decision to fund this activity would gain the constituent nations immediate recognition as reliable global stewards of the environment. Furthermore, their industries will make major advances in technological prowess. Other nations are likely to join in the effort (be it coordinated or independently) in order not to be left behind.

Analysis of the appropriate ADR targets providing the most cost-effective risk reductions should be used to demonstrate the effectiveness. Reference [1] goes some way to addressing this. Comparison with the expected cost (financial and reputational) to space faring nations in terms of lost satellites and liability claims should easily illustrate the value of a derelict body ADR approach.

There is little time to lose on debate, the time for action is now.

5 REFERENCES

1. McKnight, D., Witner, R., Letizia, F., Lemmens, S., Anselmo, L., Pardini, C., Rossi, A., Kunstadter, C., Kawamoto, S., Vladimir Aslanov g , Juan-Carlos Dolado Perez h , Vincent Ruch h , Hugh Lewisi , Mike Nicollsj , Liu Jing k , Shen Dan k , Wang Dongfang k , Andrey Baranov l , Dmitriy Grishko m "Identifying the 50 statistically-most-concerning derelict objects in LEO," *Acta Astronautica, Volume 181, April 2021, Pages 282-291.*

2. https://arstechnica.com/space/2024/04/trash-from-the-international-space-station-may-have-hit-a-house-in-florida/

3. United Nations Office for Outer Space Affairs, (1971), Convention on International Liability for Damage Caused by Space Objects, *2777 (XXVI), https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/liability-convention.html*

4. Byers, M., Boley, A, Wright, E., (2023), Letter to Space Agency Leaders on reducing risks from uncontrolled reentries of rocket bodies and other space objects. *J. Space Safety Eng. 10 (2023) pp1–6.*

5. Pardini, C., Anselmo, L., (2024). On the need to assess and mitigate the risk from uncontrolled re-entries of artificial space objects in view of the current and future developments in space activities. *Acta Astronautica 219 (2024) pp662–669.*

6. Pardini, C., Anselmo, L., (2022). The Kinetic casualty risk of uncontrolled re-entries before and after the transition to small satellites and mega-constellations, *J. Space Safety Eng. 9 (2022) pp414–426.*

7. Ailor, W.H., Hazards of re-entry disposal of satellites from large constellations, *J. Space Safety Eng. 6 (2019) 113–121, doi: 10.1016/j.jsse.2019.06.005.*

8. Pardini, C., Anselmo, L., (2024), The increasing amount of human-made space objects re-entries into the Earth's atmosphere: thoughts on possible detrimental consequences. *45th COSPAR Scientific Assembly, 13-21 July 2024, Busan, South Korea, Scientific event PEDAS.1, Tuesday, July 16, 2024.*

9. Bonnal, C., Ott, A., (2024), Atmospheric reentry of orbital objects: Can "Design for Non-Demise" D4ND be the optimal solution? *International Conference on Space Debris and Sustainability - SDS 2024, Hong Kong, 5 December 2024.*

10. Maliga, K., Kunstadter, C., (2024), Risk Management Strategies Among Space Operators, *IAC-24-E6,4,10 x90347, 75th International Astronautical Congress (IAC), Milan, Italy, 14-18 October 2024.*

11. Monham, A., (2024), Mission Lifetime Optimisation with Self or Assisted Disposal, *Acta Astronautica 219 (2024), pp138-148.*