



# IAA Situation Report on Space Debris - 2016

*Editors:*  
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**International Academy of Astronautics**



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## Table of Contents

Preamble and executive summary.....	5
1. Introduction .....	9
2. Current status of the space debris environment .....	13
2.1. Current situation .....	13
2.2. Consequences of collisions.....	14
2.3. Distribution of debris per orbital regime.....	15
2.4. Contributors to orbital debris environment.....	19
2.5. Debris collision risk assessments.....	23
3. Measurements .....	27
3.1. High level requirements.....	27
3.2. Existing technologies and technical means for space debris observation .....	28
3.3. Existing and currently developed techniques for space debris observations....	30
3.4. Existing practices for international cooperation in the field of space debris measurements .....	38
3.5. Existing gaps and multidisciplinary issues.....	39
4. Space situational awareness systems .....	43
4.1. Introduction .....	43
4.2. USA.....	45
4.3. Russia .....	48
4.4. France .....	53
4.5. Germany .....	54
4.6. ESA .....	55
4.7. Japan .....	56
4.8. Commercial Space Operations Center (ComSpOC®).....	58
4.9. Other sources of orbit data and conjunction services.....	59
5. Collision avoidance .....	61
5.1. In-orbit collision avoidance .....	61
5.2. Satellite owner/operator collaborative collision avoidance .....	63
5.3. Collision risk mitigation in mission design and disposal .....	65
5.4. Collision avoidance at launch.....	65
5.5. International standards and best practices.....	66
6. Hypervelocity impact effects and protection.....	69
6.1. Introduction .....	69
6.2. Hypervelocity impact effects on spacecraft .....	69
6.3. Experimental studies to investigate the effects of impacts on satellite components.....	70
6.4. Light-gas gun accelerators: workhorses for experimental impact testing .....	75
6.5. Shielding investigations for spacecraft .....	76
6.6. Risk assessment methodology for spacecraft .....	78
6.7. On-orbit impacts and analysis of returned spacecraft surfaces.....	81
6.8. Concluding remarks .....	83

7. Reentering space objects .....	85
7.1. Background .....	85
7.2. Reentry location/time determination .....	86
7.3. Hazardous objects.....	93
7.4. Statistics on reentries .....	95
7.5. Reentry survivability analyses .....	97
7.6. Policy issues.....	99
7.7. Solutions .....	99
8. Future environment .....	103
8.1. Historical orbital debris environment .....	103
8.2. Future orbital debris environment.....	106
9. Space debris mitigation.....	115
9.1. General objective of space debris mitigation guidelines.....	116
9.2. Protected regions .....	116
9.3. Mitigation measures .....	118
9.4. Post mission disposal measures .....	119
9.5. Prevention of on-orbit collision .....	120
9.6. Global implementation of mitigation measures.....	121
10. Debris remediation.....	125
10.1. Introduction .....	125
10.2. Methods for Lethal NonTrackable (LNT) debris and Catalogued Fragments (CF) .....	126
10.3. Intact Derelict Objects (IDO) .....	127
11. Legal aspects of space debris .....	139
11.1. Introduction .....	139
11.2. The UN space treaties and space debris .....	139
11.3. The relevance of non-legally binding instruments .....	143
11.4. The future: debris remediation.....	145
11.5. National legislation .....	145
11.6. Conclusion .....	145
12. International aspects.....	149
12.1. Towards an international recognition of the space debris issue .....	149
12.2. Major events that raised public awareness on debris.....	150
12.3. Addressing the debris issue .....	150
13. Synthesis and further References.....	157
13.1. Synthesis.....	157
13.2. Overall logic of works .....	157
13.3. To know more.....	162
Appendixes .....	165
1. List of contributors to the Study Group 5.14/ “IAA Space Debris Situation Report – 2016” .....	165
2. List of acronyms.....	166
3. IAA – A brief description .....	16



## Preamble

This fifth report on orbital debris sponsored by the IAA is being issued at a time when so many aspects of the space environment are changing. There are an increasing number of countries operating in space; a more diverse suite of satellites and launchers and an influx of commercial investment into current and future space operations. Unfortunately, in addition to the enhanced benefits that these systems provide mankind, there is also more orbital debris threatening the new activities in space. This situation report has been written to provide a comprehensive, yet concise, coverage for the nontechnical reader of the many dimensions of orbital debris.

As a result of the complex measurements and modeling across a diverse range of topics timestamps are provided for vetted data that are inconsistent (i.e., not the same year) across the "Situation Report". This fact highlights the multi-disciplinary, international dimensions of the community collaborating to identify, characterize, and manage risks posed by orbital debris. It is also critical to understand that this "Situation Report" format was specifically selected to avoid having to make recommendations for research or action. This report primarily provides a snapshot of the important dimensions of space debris upon which mission- and country-specific recommendations may be based.

## Executive summary

Orbital debris is a growing concern to all spacefaring organizations and to society at large; however, the only thing clear about this space environmental issue is that there is much ambiguity as to the current state of affairs and how this threat to space flight safety and sustainable space operations will evolve.

There is ambiguity as to the number of objects in orbit. Figure 1 below shows the sources of orbital debris relative to how we can measure, model, and characterize the debris environment. We can now only reliably and directly see and catalog objects above about 10 cm in low Earth orbit (LEO) by radar systems and objects 80 cm and larger in geosynchronous orbit (GEO) using primarily optical telescopes. Periodic surveys are also conducted by various radars at worldwide level, capable of detecting fragments as small as 6 mm up to 1,000 km.

In their vast majority, the objects currently monitored in LEO are debris from over 200 breakup events that created many tens of thousands more objects too small to be sensed but are still deleterious to spacecraft operations. Impacts from objects as small as 5 mm are likely to disrupt or terminate a satellite's operations. However, fragments smaller than 5 mm can only be modeled by returned exposed surfaces from spaceflight (e.g., *Long Duration Exposure Facility [LDEF]*, *Space Shuttle*, *Hubble Space Telescope*, *EuReCa*, etc.) which provide limited insights into the actual environment as these are only periodic samples from the 350 to 600 km altitude. In addition, there have been few returned samples with impacts of particles greater than 1 mm but from the totality of samples it was found that the number of debris impacts exceeded the number of micrometeoroid impacts in most size ranges; this could be determined thanks to chemical analysis of impactors after recovery.

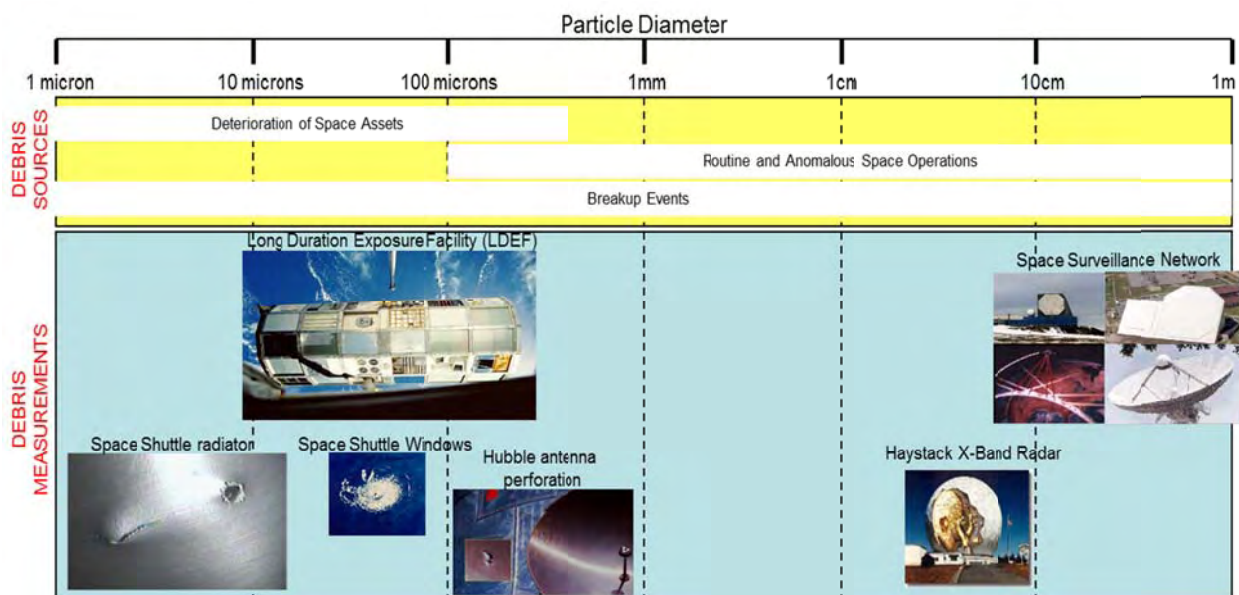


Figure 1: Sources of orbital debris and observation means

While the primary source of the cataloged population is driven by breakup events and routine space operations, the nontrackable population is also enhanced by the deterioration of space assets. This disintegration of the surface of spacecraft is due to a variety of phenomena: ultraviolet radiation weathering the surface, micrometeoroid impacts cratering the surfaces, atomic oxygen eroding surfaces, and thermal flexing. These factors peak in LEO but due to the dynamic and small nature of the hazard from these tiny particles it is difficult to model, and thus, avoid this portion of the debris population even though impacts by particles as small as 10 microns in diameter have resulted in the need to replace windows on the *Space Shuttle*<sup>1</sup>.

In addition to the ambiguity in the measurement of the actual on-orbit debris population, we have significant uncertainty about how the debris population will evolve over time. Figure 2 below shows the evolution of the number of catalog debris objects thus far in the space age. As stated earlier, to be in the “catalog”<sup>2</sup> objects in LEO are typically 10 cm in diameter or larger, and in GEO typically 80cm in diameter or larger. The components of the space population start with rocket bodies that have been abandoned in orbit after they have served their purpose of deploying a payload. Mission-related debris includes smaller objects that are released in routine deployment sequences such as lens covers, fairings, etc. Spacecraft represents payloads, both operational and dead (i.e., non-operational). Lastly, fragmentation debris comprises objects that have been generated from explosions and collisions in space. Explosions may be localized such as battery casing ruptures or catastrophic such as conflagration of propellants left on-board. The numbers are modulated by solar activity (increasing atmospheric drag in LEO), debris mitigation policies (reducing debris deposited and likelihood of rocket body explosions), breakup events, and launch rates.

After nearly a decade of positive returns from debris mitigation efforts from the 1990's through the early 2000's, two breakups in 2007 and 2009 increased the population by 40% in two short years. The plot Figure 2 “Fragmentation debris” shows that much of the

<sup>1</sup> During the course of the *Shuttle* program, the windows were exposed to an equivalent of 2 years in orbit conditions and on average there were 1-2 windows replaced each roughly week-long mission.

<sup>2</sup> The “catalog” is shorthand for the Satellite Catalog of objects maintained by the Joint Space Operations Center (JSpOC).

fragmentation debris is removed from orbit by atmospheric drag as evidenced by the significant reduction in fragmentation debris from 2009 to present. This bodes well for keeping the short-term collision hazard under control at the lower altitudes of LEO (i.e., less than 650 km).

However, the steady accumulation of derelict rocket bodies and payloads has produced a steady rise of the mass in orbit, as seen in Figure 3. The total mass in orbit is currently estimated to be about 7,500,000 kg.

These massive objects provide the potential source for tens of thousands of fragments in the future. For example, if two 1,000 kg rocket bodies were to collide in LEO, it is estimated that the collision would produce about 4,000 trackable objects and over 100,000 lethal, yet nontrackable (i.e., > 5 mm), fragments<sup>3</sup>.

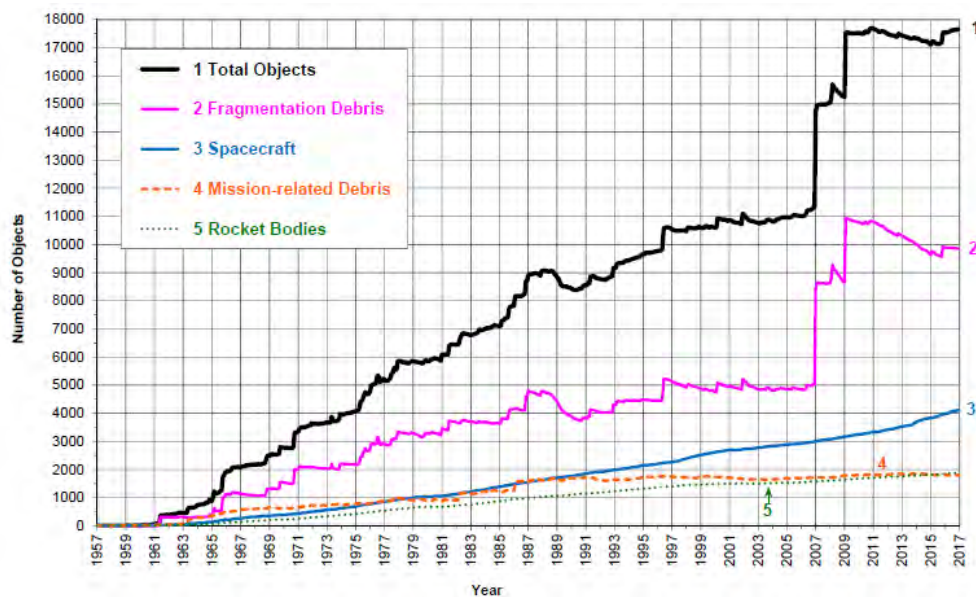


Figure 2: Evolution of the number of objects in orbit [NASA<sup>4</sup>]

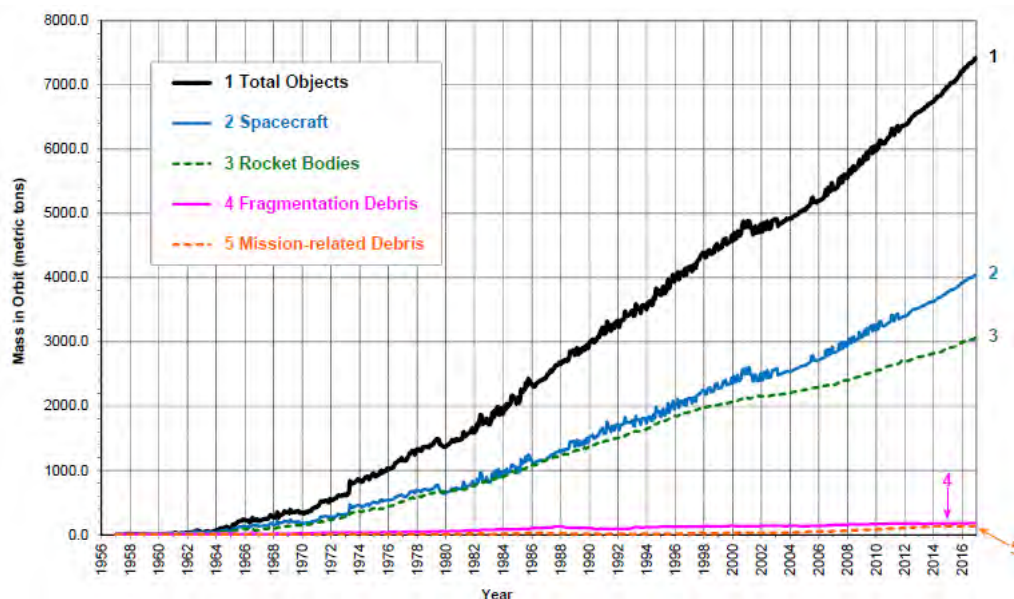


Figure 3: Evolution of the mass of objects in orbit [NASA<sup>4</sup>]

<sup>3</sup> This calculation is based on the two catastrophic collisions that have occurred in space (Fengyun-1C and Iridium/Cosmos) and is consistent with the NASA Breakup Model.

<sup>4</sup> <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv21i1.pdf>



The potential for a cascading series of collisions of objects creating fragments that in turn trigger more collisional breakups has been termed the “Kessler Syndrome”. While regions in LEO have mathematically exceeded the critical density of objects to assure that this will occur, it is unclear how and how fast this phenomenon will manifest itself. With only four known examples of two cataloged objects colliding and only one of these being catastrophic, it is difficult to predict the sequence of events in the coming years or decades.

As a result, further analysis has examined likely scenarios and these efforts have highlighted that debris mitigation guidelines will be insufficient to prevent the onset of cascading breakup events. This does not mean that debris mitigation guidelines and practices should be revoked, if anything, this implies that debris mitigation efforts should be consistently implemented in compliance with existing guidelines. This has spurred the community to study how Active Debris Removal (ADR) can be engineered and executed to reduce the mass of debris in orbit that might be involved in future catastrophic collisions. Related analyses have examined other ways to reduce the probability of massive derelicts from colliding on orbit by nudging them out of harm’s way before they can collide.

Unfortunately, these debris remediation options have technical, operational, and policy challenges that are amplified by the ambiguity in collision dynamics in the short-term (i.e., hours to days) and long-term (i.e., years to decades) periods.

Supporting these increased long-term debris evolution modeling efforts and coordinating amongst many more space operators, there has been a growing emphasis placed on Space Situational Awareness (SSA) through more complete measurement campaigns (both remote and *in situ*) and dedicated assets (such as radars and telescopes) to characterize the debris population. In the last few years, existing ground-based assets have been networked and combined into more robust networks. In addition, many new systems have been deployed on the ground and in space to enhance the ability of spacefaring countries to understand the evolution of the debris population.

Looking forward, it is critical that:

- Every spacefaring entity be diligent about not adding to the current debris population,
- More emphasis be placed on improving international space situational awareness to monitor increased space activity, and
- Eventually some forms of debris remediation may have to be deployed to minimize the probability that abandoned massive objects will collide. Such collisions would add to the existing collision hazard and possibly make routine space operations unreliable.

The “Situation Report” begins with an introduction providing context to the evolution of the topic of space debris over the space age then a quick examination of the current status of the space debris environment. After these two foundational sections, key capabilities are covered in detail following a logical sequence of topics: gaining new knowledge (measurements and space situational awareness), characterizing risk (collision avoidance, protection, reentering debris, and modeling the future), and then finally managing the debris risk (mitigation, remediation, and legal/international issues). There is some redundancy or overlap between the chapters to allow them to be read independently, however, the reader is encouraged to read the entire report to gain the most complete awareness of the space debris situation.

# 1. Introduction

The objective of the “*IAA Space Debris Situation Report*” is to be *the* reference paper at the international level on the topic of orbital debris.

Orbital Debris (OD) is an increasing concern to satellite operators, aerospace engineers, space lawyers, insurance underwriters, scientists, and policymakers worldwide. Events over the last two decades have amplified concerns that this environmental hazard will increasingly become a central issue in the decades to come. This is exacerbated by the growing globalization of space and the number of ways mankind depends increasingly on space based systems for basic necessities of life (e.g., banking, navigation, weather predictions, climate monitoring, etc.).

IAA has been working for more than 20 years on the topic of orbital debris, aiming at raising the global consciousness on this critical subject, wishing to enhance the understanding of the situation for decision makers. Each IAA report / paper has provided a quality chronicle of this evolving space environmental hazard transiting through the stages of Recognition (1993) - Characterization (2001) - Mitigation (2005) - Remediation (2013). These documents have both catalyzed action and documented international efforts along this journey.

While the IAA documents have focused on specific issues most relevant to their time of publication and other documents have concentrated on specific technical issues, there is a need for an understandable and comprehensive description of the current state of orbital debris and related technologies, capabilities, and models. The goal of this “*Situation Report*” is to provide a baseline understanding of the diverse dimensions of orbital debris for any scientific, engineering, policy, regulatory, or legal person. The “*Situation Report*” will likely have to be updated every few years or as events dictate due to the dynamic nature of this space environmental hazard.

## A history of IAA orbital debris contributions

In the past, several key “*Position Papers*” from IAA have been published and acted as revealing reference papers at the time of their release.

In 1993, the first “*IAA Position Paper on Space Debris*” was compiled by the Ad Hoc Expert Group of the IAA which was a component of IAC Committee on Safety, Rescue, and Quality [1.1]. This document was created concurrently with the formation of the Inter-Agency Space Debris Coordination Committee (IADC). Three documents followed in rapid succession related to the content of this report: NASA Safety Standard 1740.14 – Guidelines and Assessment Procedures for Limiting OD (1995) [1.2]; NASDA STD-18, Space Debris Mitigation Standard (1996) [1.3]; and CNES Space Debris Mitigation Standard (1999) [1.4].

### ***Debris scorecard at time of this report:***

*> ~7,700 cataloged objects in orbit*

*> ~120 breakups on orbit to date*

1  
9  
9  
3

Three families of options were identified in this report as depicted in the Figure 1.1 below:

- category I: do immediately - require minimal technology development or cost
- category II: consider later - require moderate technology development and/or cost
- category III: consider later - require significant technology and cost

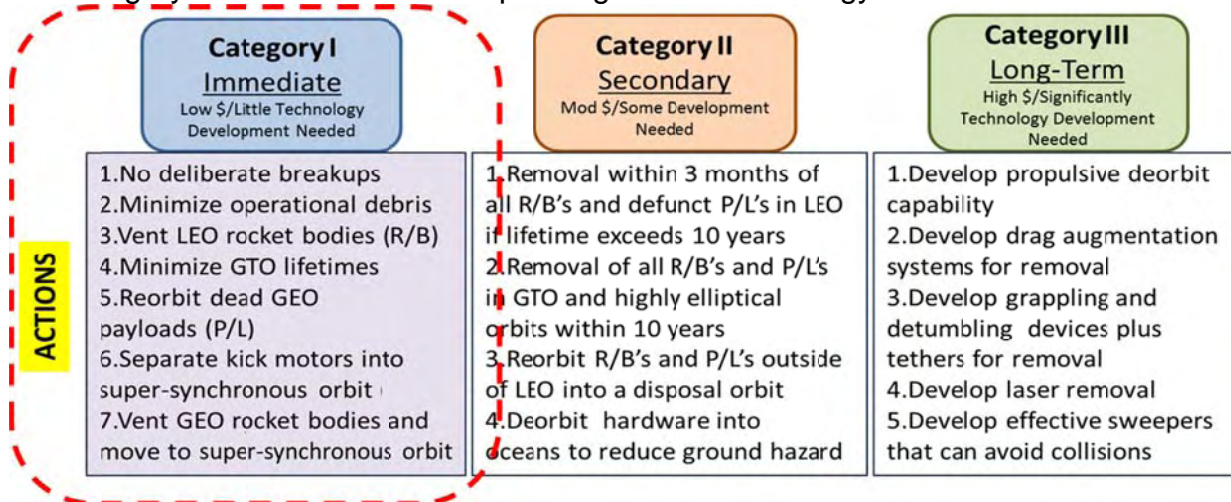


Figure 1.1: Options identified in the 1993 IAA Position Paper

In 2001, a general revision of the 1993 Position Paper was issued by the Space Debris Subcommittee of the IAA accounting for new results of space debris research, the evolving space debris environment, and international policy developments [1.5].

### ***Debris scorecard at time of this report:***

- > ~8,700 cataloged objects in orbit
- > ~160 breakups on orbit to date

2  
0  
0  
1

During this time the first quantitative analysis examining the potential cascading effect of the debris population was presented galvanizing the debris community. In addition, for the first time multiple spacefaring countries contributed mightily to the debris discussions by establishing or strengthening research institutes and contributing to the emerging area of orbital debris best practices, guidelines, and policies.

### ***Debris scorecard at time of this report:***

- > ~10,300 cataloged objects in orbit
- > ~180 breakups on orbit to date

2  
0  
0  
5

In 2005, the “Position Paper on Space Debris Mitigation” was released [1.6], with the subtitle “Implementing zero debris creation zones” It focused on debris mitigation. The paper clearly made a call for the aerospace community to stop adding to the existing debris population. It outlined operational procedures for compliance with evolving space debris mitigation guidelines for low Earth orbit (LEO) and geosynchronous orbit (GEO). LEO and GEO were to be protected by “zero debris creation” mandates. LEO was considered as up to 2000 km while GEO was defined as  $\pm 200$  km altitude and  $\pm 15^\circ$  latitude from the GEO arc.

Three simple, yet powerful, rules to mitigate debris creation were suggested: minimize debris releases, eliminate energy sources (after use), and remove from orbit after operational use.

***Debris scorecard at time of this report:***

- > ~16,600 cataloged objects in orbit*
- > ~210 breakups on orbit to date*

2  
0  
1  
3

In 2013, the “*Position Paper on Space Debris Remediation*” was published [1.7]. It was determined that debris mitigation guidelines would not be sufficient to control growth of orbital debris. The aerospace community was challenged to actively remove massive derelict objects as the next level of defense to managing the debris environment (i.e., debris remediation).

A wide variety of technologies are under consideration for the challenging mission of Active Debris Removal (ADR) that will remove massive objects in cluttered orbits. For LEO, the objects would be reentered and if at GEO moved to higher disposal orbits. ADR will not be easy as one must grapple, (possibly) despin, and then move/remove the object. There are many potential mechanisms to move/remove derelict objects such as propulsive tugs, drag-enhancement devices, solar sails, electrodynamic tethers, etc.

Removing of objects from orbit does not end the risk posed by orbital debris. Depending on the mass and construction of a space object, it may or may not have significant mass survive to the ground posing a personal casualty or property damage risk. As a result, ADR mechanisms that provide a controlled reentry capability are preferred. Significant research and operational modeling is being conducted to minimize the likelihood that reentering space debris poses a risk to people and objects in the air (e.g., commercial airliners) or on the ground.

There is now a dedicated IAA Study Group (SG 5.10) working to produce a “*Position Paper on policy, legal and economic issues in orbital debris removal*” [1.8]. It will build upon the technical framework of the 2013 “*IAA Cosmic Study on Space Debris Environment Remediation*” to determine operational issues to fielding ADR options. It will address key questions in three broad fields:

- Policy: Is it a space commons or alternative venue for international politics?
- Legal: What is debris and who defines remaining utility of an object?
- Economic: Is active debris removal cost-effective?

It is important to identify the relationship between the space debris and Space Traffic Management (STM), especially as these are two topics addressed by separate IAA publications<sup>5</sup>.

This space debris situation report provides a technical status of the debris environment plus tools and techniques applied to assess the evolution of this important space environmental component. Space traffic management focuses on the rules of the road for space systems to operate in the shared space domain and comprises a much broader scope than space debris. Space debris is one of many background hazards that are considered by STM and also one of many outcomes that STM strives to minimize contributing to through the proper execution of STM principles.

<sup>5</sup> IAA Cosmic Study on Space Traffic Management, September 2005,



As such, this situation report on space debris provides part of the baseline understanding that STM practitioners will have to consider in developing a globally effective STM concept of operations.

The debris scorecard at the end of 2016 is provided showing that despite all our efforts the space debris growth continues.

***Debris scorecard at time of this report:***

*> ~17,700 cataloged objects in orbit*

*> ~300 breakups on orbit to date*

2  
0  
1  
6

## References

- [1.1] IAA Position Paper on Orbital Debris, IAA 1993, ISBN-2-9508153-1-6
- [1.2] NASA Safety Standard 1740.14 – Guidelines and Assessment Procedures for Limiting OD (1995)
- [1.3] NASDA STD-18, Space Debris Mitigation Standard (1996)
- [1.4] CNES MPM-51-00-12 Exigences de sécurité – Débris Spatiaux (Space Debris Mitigation Standard) (1999)
- [1.5] IAA Position Paper on Orbital Debris, Edition 2001, ISBN-2-9516787-0-3
- [1.6] Position Paper on Space Debris Mitigation, “*Implementing Zero Debris Creation Zones*”, IAA 2006, ISBN-2-9516787-7-0
- [1.7] Position Paper on Space Debris Environment Remediation, IAA 2013, ISBN-978-2-917761-30-4
- [1.8] Position Paper on Policy, Legal and Economic Issues in Orbital Debris Removal, IAA, to be published



## 2. Current status of the space debris environment

Six decades of space flight activities since the launch of *Sputnik-1*, in 1957, have generated a significant human-made particle environment in Earth orbits that is referred to as "space debris".

The Inter-Agency Space Debris Coordination Committee (IADC) defines space debris as "*all man-made objects including fragments and elements thereof, in Earth orbits or re-entering the atmosphere that are non-functional*".

The sizeable population of space debris must be considered in launch system, payload and mission designs to ensure space operations with an acceptable, low risk of losing or degrading a mission, or of suffering casualties during human space flight. Likewise, payloads and orbital stages must be designed, operated, and disposed of in such a way that they do not further deteriorate the space debris environment, or pose an unacceptable risk to the ground population or air traffic during re-entries.

### 2.1. Current situation

To describe the current space debris environment, a snapshot of the orbital population of space objects in 2013 will serve as a reference.

It is the product of more than 5,250 launches and more than 300 on-orbit break-ups that led to more than 17,854 objects by March 2017 which are accessible through the unclassified catalog of the US Space Surveillance Network (SSN) (see Figure 2.1).

Approximately 6,000 more objects are systematically tracked, but are either classified, or are not yet correlated with a launch or deployment event. All SSN catalog objects combined represented some 7,500 tons of on-orbit mass in 2017.

Several ten tons of further material from different sources is expected to exist at sub-catalog sizes, below diameters of 10 cm.

Only 6% or 7% of the catalog entries are operational spacecraft (1,100 to 1,200), while 28% are non-functional but intact objects, and 64% are fragments, mainly resulting from explosions, but also from recent in-orbit collisions. 75% of the catalog objects are in low Earth orbits (LEO), 7% are in or near geostationary orbits (GEO), and 18% are in highly eccentric orbits (HEO), medium Earth orbits (MEO), or other orbit classes.

Since 2007 the SSN catalog has experienced two significant step increases:

- On January 11<sup>th</sup> 2007, the Chinese *Feng Yun 1C* satellite was intercepted in an ASAT (Anti-Satellite) test, generating 3,433 catalog objects of which 3,050 were still in orbit 6 years later;
- On February 10<sup>th</sup> 2009, the first accidental hypervelocity collision between two intact catalog objects (*Iridium 33* and *Cosmos 2251*) generated 2,296 cataloged fragments in two separate clouds, of which 1,740 were still in orbit 4 years later.

Both of these events have produced a long-lasting increase in spatial object densities and in collision risk at altitudes between 750 km and 900 km.

## 2.2. Consequences of collisions

The risk of collision-induced catastrophic fragmentations or mission-terminating impacts is the highest in the Low Earth Orbit (LEO) regime. It exceeds the risks in other orbit regions, including the Geostationary Orbit (GEO) by at least 3 orders of magnitude. As a consequence, the following analysis will concentrate on the collision risk levels for the *International Space Station (ISS)*, as an example of a manned LEO platform, and on the collision risk levels for a typical remote sensing spacecraft, on a Sun-synchronous orbit, as an example of a robotic LEO platform.

The concepts of active protection (shielding) and passive protection measures (avoidance maneuvers), and their effectiveness as a function of debris size will be discussed as possible risk mitigation measures for the specific debris environment of given operational orbits at 350 km altitude and 51.1° inclination for the *ISS*, and at 780 km altitude and 98.5° inclination for an Earth observation mission.

Roughly 36% of the entire mass in orbit is concentrated in the LEO regime, within just 0.3% of the operationally used volume from LEO up to super-GEO altitudes.

Debris risk mitigation through collision avoidance, passive protection, and end-of-mission disposal turns out to be a necessary but insufficient condition to maintain an acceptable space debris environment.

Long-term projections indicate that even drastic mitigation measures, such as an immediate, complete halt of launch and release activities will not result in a stable LEO debris environment [2.1], [2.2], [2.3], [2.4], [2.5].

Catastrophic collisions between existing space hardware of sufficient size, will within a few decades, start to dominate the debris population sources, and lead to a net increase of the space debris population, also at sizes which may cause further catastrophic collisions. A self-contained collisional cascading process in the LEO regime may hence ultimately lead to a run-away situation (the so-called “*Kessler syndrome*”), with no further possibility of control through human intervention. The only way to prevent the on-set of collisional cascading is to prevent collisions between large derelicts which may be enabled through active removal of mass from orbit.

Apart from the systematically trackable catalog population of space objects, there is a much larger population of sub-catalog debris objects than can disable or seriously degrade a space mission.

The related objects can only be observed in a statistical manner, by means of research radars, telescopes, and *in situ* detectors. Based on orbital and physical characteristics of the observed debris, and based on ground test benchmark data, debris environment models can be established that compose an image of the current environment from a replicate of historic launch, release, and break-up events.

One of the leading debris models, ESA’s MASTER software (Meteoroid and Space Debris Terrestrial Environment Reference [2.6], [2.7]), will be used in the following risk assessments.

MASTER represents the current space debris environment and has been validated with ground and space-based measurements. It agrees reasonably well with NASA's ORDEM<sup>6</sup> (Orbital Debris Engineering Model) model, which is a completely independent development.

Both models suffer from uncertainties around object sizes of 1 mm which is due to a lack of measurement data in this size range [2.9]. An in-depth technical discussion of underlying theories and analysis techniques is provided by [2.10] and will not be repeated here.

The resident mass in operationally used orbit regions around the Earth is to 99.95% dominated by human-made space debris, totaling approximately 7,500 metric tons in the year 2017. Only a few tons of additional materials within the same reference volume originate from natural meteorites, with most probable sizes of about 200  $\mu\text{m}$ . As a consequence, space debris dominates the risk for operational space missions and will be in the focus of the following discussion.

### **2.3. Distribution of debris per orbital regime**

Within one decade after the first space launch, the annual launch rates reached a level of more than 120 at the end of the 1960's.

As a consequence of reduced Russian/Soviet space activities at the end of the 1980's, annual launch rates have reached a minimum of 52 by year 2005, and then increased to the current level of about 80 to 90 per year<sup>7</sup>. By March 2017 there were some 5,250 successful launches (out of 5,600 launch attempts) that deployed 7,478 payloads (from which 4,262 are still in orbit), 5,481 rocket stages (1,973 in orbit), and another 8,010 mission-related objects (MRO) (1,257 in orbit) (see Table 2.1).

These intact objects account for most of the in-orbit mass of about 7,500 tons. However, they only account for 37% of the space object population by number that can be routinely tracked by operational surveillance networks.

Out of 17,854 objects of the US Space Surveillance Network (SSN) catalog in March 2017, the dominant space debris population contributed 10,362 trackable objects (58%).

With 12,621 objects (71%) the vast majority of the SSN catalog resides in low Earth orbits (LEO), below altitudes of 2,000 km, another 751 objects (4%) are in the vicinity of the geostationary ring (GEO), at altitudes of  $35,786 \pm 200$  km and inclinations of  $0^\circ \leq i \leq 15^\circ$ , and the remaining objects are distributed across medium Earth orbits (MEO, including semi-synchronous orbits of navigation constellations), GEO transfer orbits (GTO), highly eccentric orbits (HEO), high-altitude orbits beyond the GEO regime (HAO), and Earth escape orbits (ESO).

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<sup>6</sup> <https://www.orbitaldebris.jsc.nasa.gov/modeling/engrmodeling.html>

<sup>7</sup> 82 successful orbital launches in 2016

Orbit classification	Payloads			Rocket Bodies			Total
	Intact	MRO	Debris	Intact	MRO	Debris	
LEO	2,328	123	6,292	840	497	2,541	12,621
GEO	687	2	4	58	0	0	751
EGO	351	32	3	140	0	35	561
NSO	229	1	0	70	2	0	302
LMO	90	47	139	211	226	736	1,449
GTO	72	10	18	234	51	246	631
MGO	64	3	147	156	4	21	395
MEO	52	53	12	16	8	15	156
HEO	42	3	27	45	4	50	171
ESO	26	3	0	20	1	0	50
HAO	20	0	0	2	0	0	22
IGO	16	0	0	0	0	0	16
GHO	6	3	0	9	0	0	18
UFO	1	1	0	0	0	0	2
Not classified	278	148	39	172	35	37	709
Total Count	4,262	429	6,681	1,973	828	3681	17,854

*Table 2.1: Orbital distribution of US Space Surveillance Network catalog objects in orbit in March 2017 according to ESA's DISCOS database [2.7].*

*(MRO = mission-related objects, associated with payloads and rocket bodies; LEO = low Earth orbits, GEO = near-geostationary orbits, EGO = extended-geostationary orbits, NSO=Navigation Satellites Orbits, LMO = LEO-MEO, GTO = GEO transfer orbits, MGO = MEO-GEO, MEO = medium Earth orbits, HEO = highly eccentric orbits, ESO = Earth escape orbits, HAO = high-altitude super-GEO orbits, IGO = inclined geostationary orbits, GHO = GEO-super GEO, UFO=unclassified orbits)*

Figure 2.1 shows the historic evolution of the catalog population. The US Space Surveillance Network has a cataloging size threshold that ranges from about 10 cm in the LEO regime to about 1 m in the GEO ring. Related routine observations are performed by a network of radars for LEO and low MEO altitudes and by globally distributed electro-optical telescopes for the remaining part of MEO up to GEO altitudes.

For the dominant LEO catalog population Figure 2.2 shows the altitude distribution of objects, with the primary maximum from 700-875 km, a secondary maximum close to 975 km, and a third peak in the 1,400-1,500 km region.

Since the vast majority of catalog objects are on near-circular orbits (with more than 50% of the eccentricities smaller than 0.01), the depicted, resident-probability-weighted, mean altitude distribution is very similar to the actual perigee and apogee altitude distributions.

Figure 2.3 shows that the inclination distribution of LEO orbits is driven by mission and launch constraints, with distinct, preferred inclination bands around 65°, 74°, 82°, 90°, and 98°.

Figure 2.4 illustrates how the altitude and inclination distributions of catalog objects are correlated.

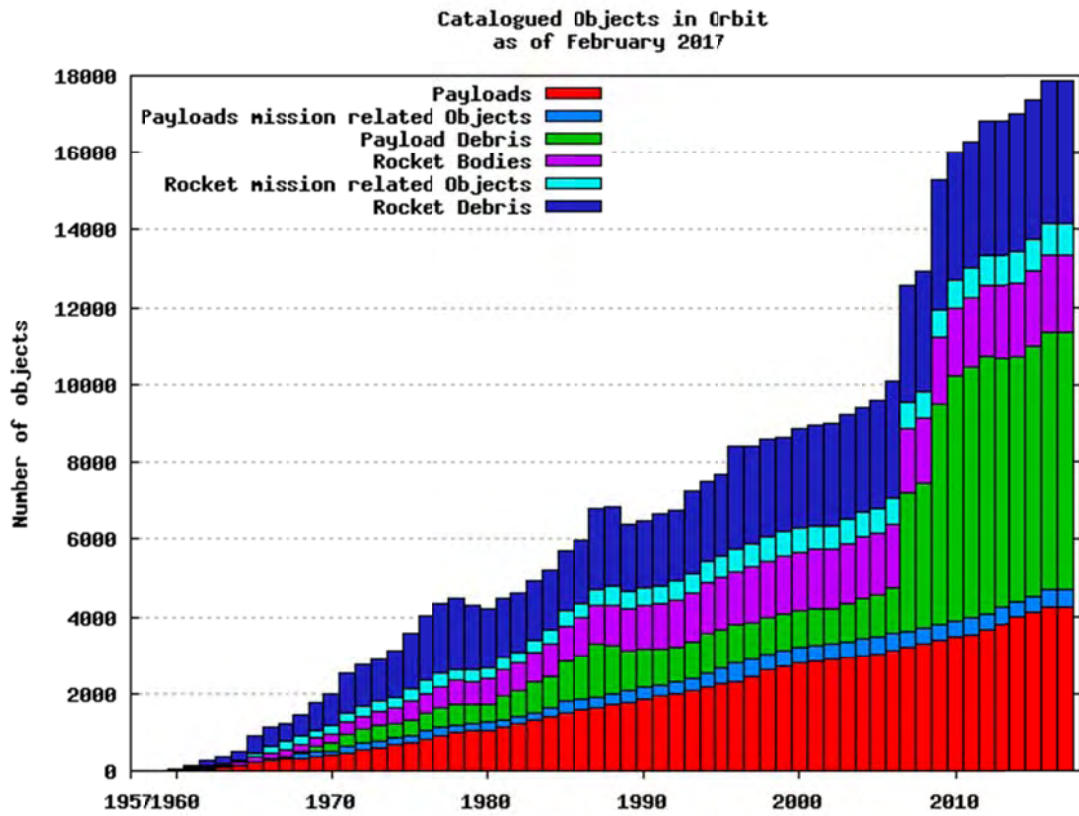


Figure 2.1: Historic evolution of the US SSN catalog of trackable space objects through February 2017.

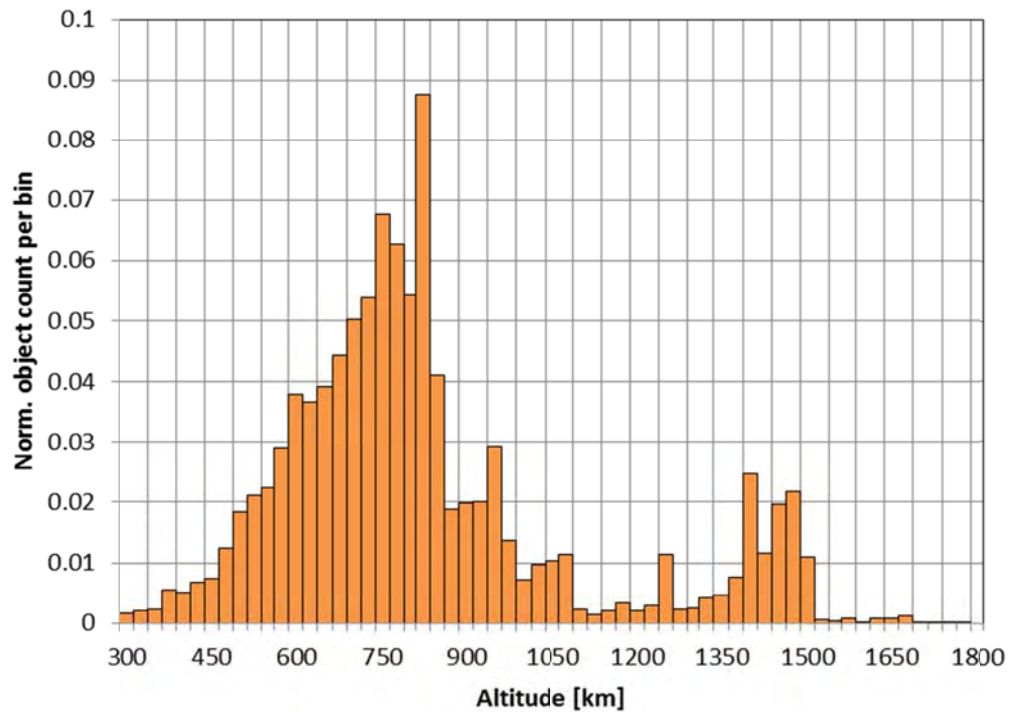


Figure 2.2: Altitude distribution of catalog-size objects (>10 cm) in low Earth orbit (LEO) in October 2015. The normalized count is in fractions per 25 km altitude bin for a total of 12,385 objects.



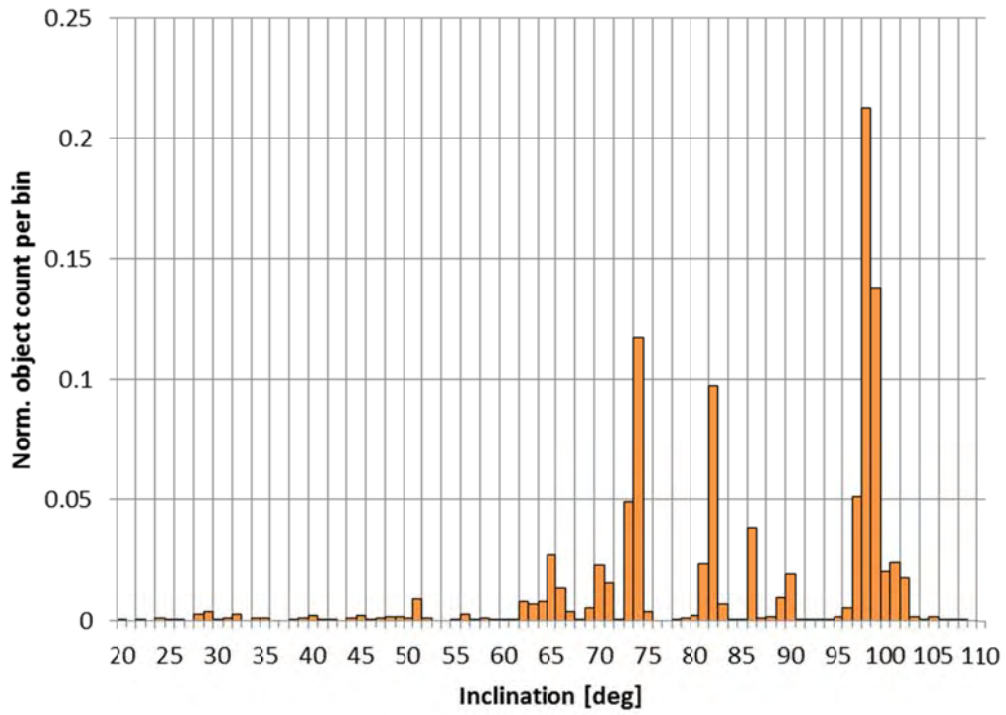


Figure 2.3: Inclination distribution of catalog-size objects (>10 cm) in low Earth orbit (LEO) in October 2015. The normalized count is in fractions per  $1^\circ$  orbit inclination bin for a total of 12,385 objects.

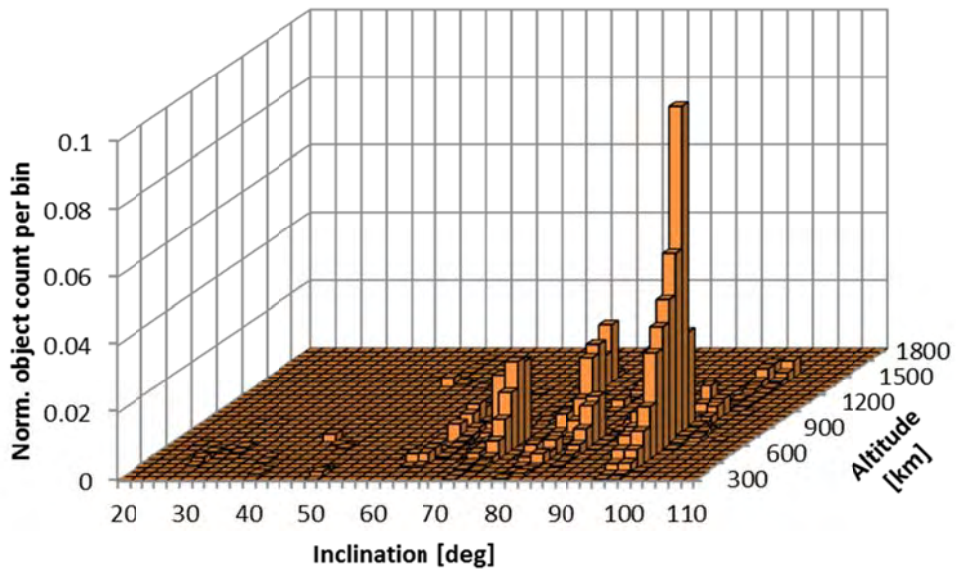


Figure 2.4: Inclination and altitude distribution of catalog-size objects (>10 cm) in low Earth orbit (LEO) in October 2015. The normalized count is in fractions per bin of  $2^\circ \times 50$  km for a total of 12,385 objects.

## 2.4. Contributors to orbital debris environment

The evolution of the space debris population is simply a balance of sources and sinks. There are only two means for debris to be removed (i.e., sinks): atmospheric drag (at very low altitudes) or retrieval (which will be discussed later in this report). However, there are many sources (i.e., contributors). First, space debris caused by fragmentation events are the most prolific source of catalog objects, with a contribution of 58% to the trackable population in March 2017.

In the course of space history, some 300 on-orbit fragmentation events were inferred from the detection of new objects and from the correlation of their determined orbits with a common source.

The dominant break-up causes are believed to have been deliberate explosions or collisions (dominated by an ASAT test that destroyed *Feng Yun 1C* in January 2007), propulsion-related explosions, battery explosions, and 4 known accidental collisions (the *Cosmos 1934* spacecraft with a *Cosmos 926* MRO in December 1991, the *Cerise* spacecraft with what is thought to be an *Ariane H-10* fragment in July 1996, a Thor stage with a *CZ-4B* stage fragment in January 2005, and *Cosmos 2251* with *Iridium 33* in February 2009).

About 37% of all break-ups were of an unknown cause, and another 23% are assessed to have been deliberately induced. With the exception of three known GEO explosion events (an *Ekran-2* satellite in 1978, a *Titan III-C Transtage* in 1994, and a *Briz* upper stage in 2016), all known fragmentations occurred on orbits passing through LEO altitudes, with about 83% of the orbits entirely within LEO, and with 15% on highly eccentric trajectories passing through LEO [2.10].

Object name	Launch date	Max. count	COSPAR	Sat. no.	Assessed cause
	Event date	Curr. count	H <sub>b</sub> [km]    H <sub>a</sub> [km]	i [deg]	Object type
<i>Feng Yun 1C</i>	1999/05/10	3,433	1999-025A	25730	deliberate
	2007/01/11	,2850	843    863	98.64	payload
<i>Cosmos 2251</i>	1993/06/16	1,668	1993-036A	22675	collision
	2009/02/10	1,102	843    863	98.64	payload
<i>Pegasus 4<sup>th</sup> stage</i>	1994/04/19	754	1994-029B	23106	propulsion
	1996/06/03	83	584    819	81.97	rocket body
<i>Iridium 33</i>	1997/09/14	628	1997-051C	24946	collision
	2009/02/10	344	776    791	86.39	payload
<i>Cosmos 2421</i>	2006/06/25	509	2006-026A	29247	unknown
	2008/03/14	0	389    415	65.04	payload
<i>Ariane 1 3<sup>rd</sup> stage</i>	1986/02/22	499	1986-019C	16615	propulsion
	1986/11/13	33	803    833	98.61	rocket body
<i>OV 1/LCS 2</i>	1965/10/15	474	1965-082B	1640	propulsion
	1965/10/15	33	658    761	32.17	payload
<i>CZ 4B 4<sup>th</sup> stage</i>	1999/10/14	431	1999-057C	25942	unknown
	2000/03/11	206	727    744	98.54	rocket body
<i>Thor Agena D 2<sup>nd</sup> stage</i>	1970/04/08	376	1970-025C	4367	unknown
	1970/10/17	235	1,013    1,049	99.62	rocket body
<i>PSLV 4<sup>th</sup> stage</i>	2001/10/22	372	2001-049D	26960	unknown
	2001/12/19	75	550    674	97.90	rocket body

Table 2.2: On-orbit break-up events with highest counts of cataloged fragments, and their contributions by March 2017.

Table 2.2 shows a list of the 10 most significant in orbit break-ups, sorted by the number of cataloged fragments. Eight of these top ten events occurred on orbit inclinations of  $90^\circ \pm 10^\circ$ , mainly at altitudes of  $800 \text{ km} \pm 50 \text{ km}$ . Since the orbit inclination is a very stable parameter, directly linked to the orbit momentum and only marginally affected by orbit perturbations, it strongly governs the latitude distribution of resulting spatial object densities.

Figure 2.5 indicates that the highest concentration of catalog-size objects is at high latitudes  $\delta$ , where  $\delta \approx i$ , with  $i$  being the inclinations of break-up orbits. As a consequence, catastrophic collisions between catalog objects are most likely at high latitudes in densely populated altitude bands.

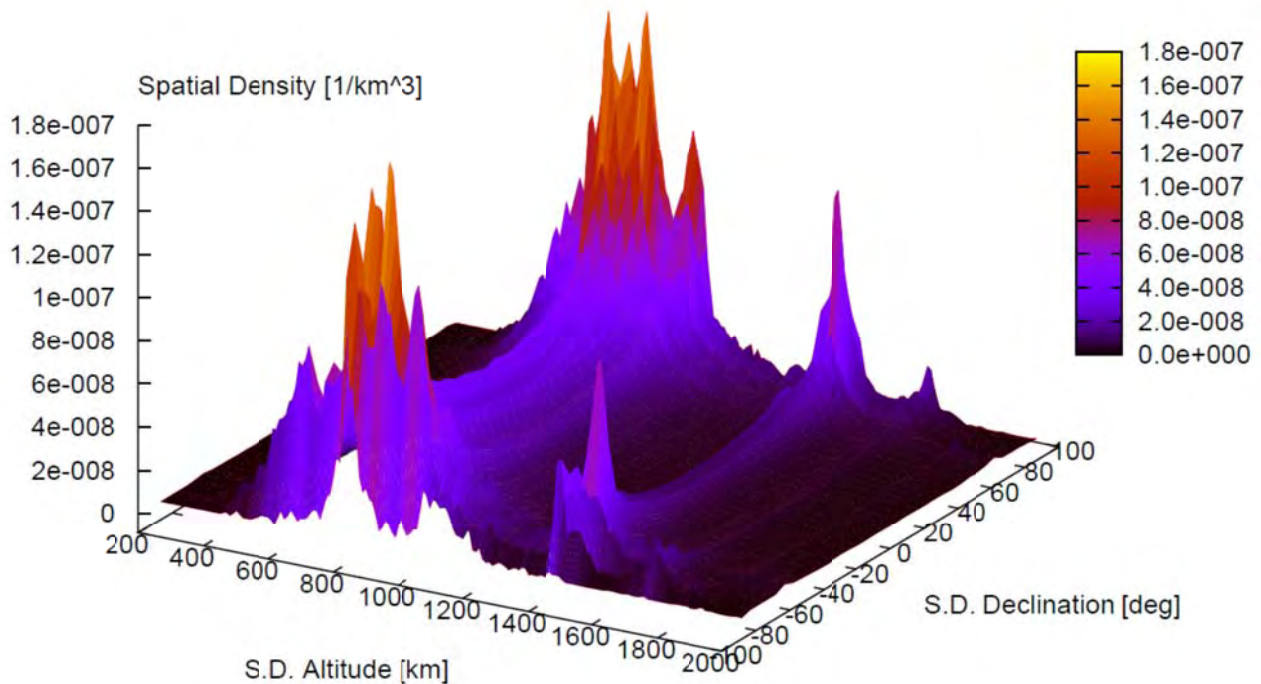


Figure 2.5: Spatial density distribution of catalog-size objects (>10 cm) in low Earth orbit (LEO) in 2009, as a function of altitude and declination [2.7].

Fragmentation debris from in-orbit explosions and collisions dominate the space debris population down to the cm-size regime (see Table 2.3). The most significant breakup-related, relative increase of the catalog population occurred in 1961, when the first accidental explosion in space of an *Ablestar* injection stage more than tripled the catalog population from 110 to almost 400.

The most significant absolute growth of the catalog so far occurred in January 2007, when the *Feng Yun 1C* kinetic ASAT test increased the orbital population by +34% (3,433 trackable fragments), and in February 2009, when the accidental collision between *Cosmos 2251* and *Iridium 33* increased it by +22% (2,296 trackable fragments).

Today's population of trackable and non-trackable objects can be reproduced by space debris environment models, such as ESA's MASTER-2009 model [2.7].

Such models consider historic launch and release events, known in-orbit fragmentations, known solid rocket motor firing events, intentional releases of NaK coolant liquid from *Buk* reactors of Soviet *RORSAT* satellites, unintentional releases of surface degradation products (MLI and paint flakes), and the generation of ejecta and spall by surface impacts.

Table 2.3 lists the resulting debris sources, and their contributions to the MASTER-2009 population at the reference epoch of May 2009, for the applicable size regime larger than 1  $\mu\text{m}$ .

Diameter	> 1 $\mu\text{m}$	> 10 $\mu\text{m}$	> 100 $\mu\text{m}$	> 1 mm	> 1 cm	> 10 cm	> 1 m
LMRO	45,919	45,919	45,919	31,139	5,827	5,814	4,174
Explosion	5.62e+09	4.12e+09	3.84e+08	1.53e+07	433,466	14,719	432
Collision	3.58e+09	1.13e+09	1.17e+08	4.46e+06	92,677	2,927	63
MLI	22,241	22,241	22,241	22,241	15,790	5,750	773
NaK	30,162	30,162	30,162	30,162	18,410	—	—
SRM slag	4.98e+12	4.98e+12	2.33e+12	1.39e+08	177,914	—	—
SRM dust	6.07e+14	1.18e+13	—	—	—	—	—
Paint	1.97e+12	1.62e+12	2.28e+11	—	—	—	—
Ejecta	8.62e+13	2.70e+13	1.08e+12	8.00e+06	—	—	—
Total	7.00e+14	4.53e+13	3.64e+12	1.67e+08	744,084	29,210	5,442

Table 2.3: Sources and their contributions to ESA's MASTER 2009 space debris model in different size regimes for May 1<sup>st</sup> 2009 [2.7].

LMRO = Launch and Mission Related Objects

MLI = Multi-Layer Insulation

SRM = Solid Rocket Motor

At sub-catalog sizes residues from solid rocket motor (SRM) firings become important. The number of on-orbit solid rocket motor firings up to 2013 was on the order of 1,100 with peak rates of up to 47 events per year, and a mean annual rate of 23.5. The injection orbits where SRMs were applied are to 80% associated with upper stage missions.

The size of the solid motors, in terms of propellant capacity, covers a wide range. The most frequently used SRMs are the Star 37 motors, with a propellant mass of 1,067 kg, used for instance as final stage of Delta launchers to deploy *GPS/Navstar* payloads, the *Payload Assist Module PAM-D*, with 2,011 kg propellant, also used as *Delta* final stage for instance for GTO injections, and the *Inertial Upper Stage (IUS)*, deployed from *Titan IV* or *Space Shuttle*, for instance to inject payloads into GTO using a first stage with 9,709 kg propellant, and subsequently deliver the payload into a circular GEO by a second stage of 2,722 kg. Another powerful SRM engine, *FG-46* with 4,267 kg propellant, is used by *Long March LM-2E* launchers for GTO payload injections.

SRM combustion residues are mainly composed of aluminum oxide and residues of motor liner material. Aluminum powder is added to most solid fuels, typically with a mass fraction of 18%, to stabilize the combustion process and improve the motor performance. It is assumed that about 99% thereof is continuously ejected with the exhaust stream during the main thrust phase in the form of  $\text{Al}_2\text{O}_3$  dust of diameters largely within  $1 \mu\text{m} \leq d \leq 50 \mu\text{m}$ . At the end of the burn phase slag particles are ejected.

They have sizes of typically  $0.1 \text{ mm} \leq d \leq 30 \text{ mm}$ . It can be assumed that during more than 1,100 SRM firings more than 1,000 tons of propellant was released into space of which approximately 320 tons were  $\text{Al}_2\text{O}_3$  dust particles, and 4 tons were slag particles formed of  $\text{Al}_2\text{O}_3$ , metallic aluminum, and motor liner material. At sizes of  $1 \mu\text{m} \leq d \leq 1 \text{ cm}$  SRM combustion residues dominate the space debris environment (see Table 2.3).

Apart from intact objects, fragmentation debris, and SRM residues, there are other contributors to the space debris population:

- Approximately 128 kg of sodium-potassium alloy eutectic (NaK) escaped from the primary coolant systems of the 16 Russian *BES-5 (Buk)* reactors during ejection their cores into disposal orbit in the 1980s,
- Multi-layer insulation (MLI) material that is unintentionally released by spacecraft or rocket stages,
- Ejecta material that is released by small-particle impacts on surfaces of spacecraft and orbital stages,
- Degradation products that are released by aging surfaces of spacecraft and orbital stages.

The debris mass contribution from these sources is much less than 1% of the overall on orbit mass, and they are either too small in numbers (NaK, MLI), or too small in size (surface ejecta and degradation products) to constitute a significant risk for space missions.

From the risk point of view, the more than 160 million particles larger than 1 mm, at typical LEO collision velocities of 10 to 14 km/s, can disable sensitive satellite sub-systems, the more than 740,000 particles larger than 1 cm can render a spacecraft dysfunctional, and the 29,200 objects larger than 10 cm are likely to cause a catastrophic break-up of a satellite or orbital stage.

Figure 2.6 shows the altitude distribution of MASTER-2009 objects larger than 10 cm in terms of resulting spatial densities (in objects / km<sup>3</sup>). The contributing debris sources at these sizes are explosion and collision fragments, intact objects, and light-weight sheets of MLI. Highest concentrations are in the LEO regime, between 750 km and 900 km, with almost equal contributions from explosion fragments, collision fragments, and intact objects.

In general, however, explosion fragments dominate the LEO and GEO regions, with GEO object concentrations about three orders of magnitude below the LEO maximum. When going to a 1 cm size threshold additional source terms come in, including NaK droplets and solid rocket motor slag, while launch and mission-related objects start playing a minor role.

Figure 2.7 shows the individual contributions as a function of altitude. With the decrease of the debris sizes from 10 cm to 1 cm the enveloping curve of spatial densities tends to flatten, due to an increasing share of particles on eccentric orbits with a wider distribution over altitudes.

One cause of the increase of orbit eccentricities with decreasing object sizes lies in the area-to-mass ratio that drives solar radiation pressure and air drag forces and is inversely proportional to the object diameter. This effect leads to a rapid decay of orbits followed by atmospheric re-entry of small-size objects that have extended dwell times at altitudes within the denser parts of the upper Earth atmosphere.

Another important cause is how these particles are generated. Breakups generally impart higher Delta-V to smaller particles, so their orbits become more eccentric.



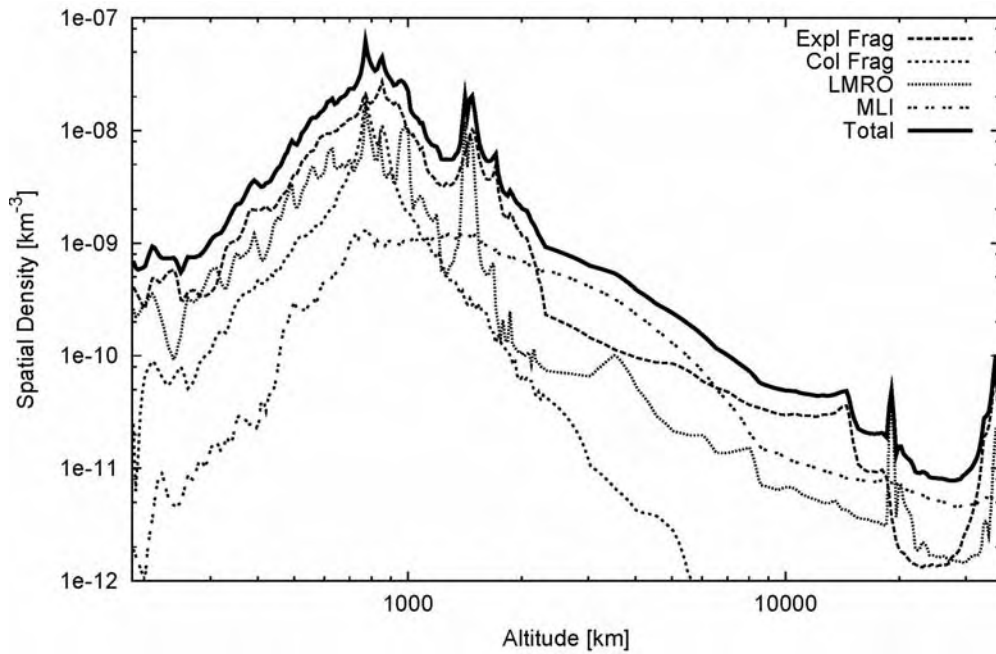


Figure 2.6: Spatial density distribution of MASTER-2009 objects of  $d > 10$  cm, in LEO to GEO altitudes, discriminated by sources [2.7].

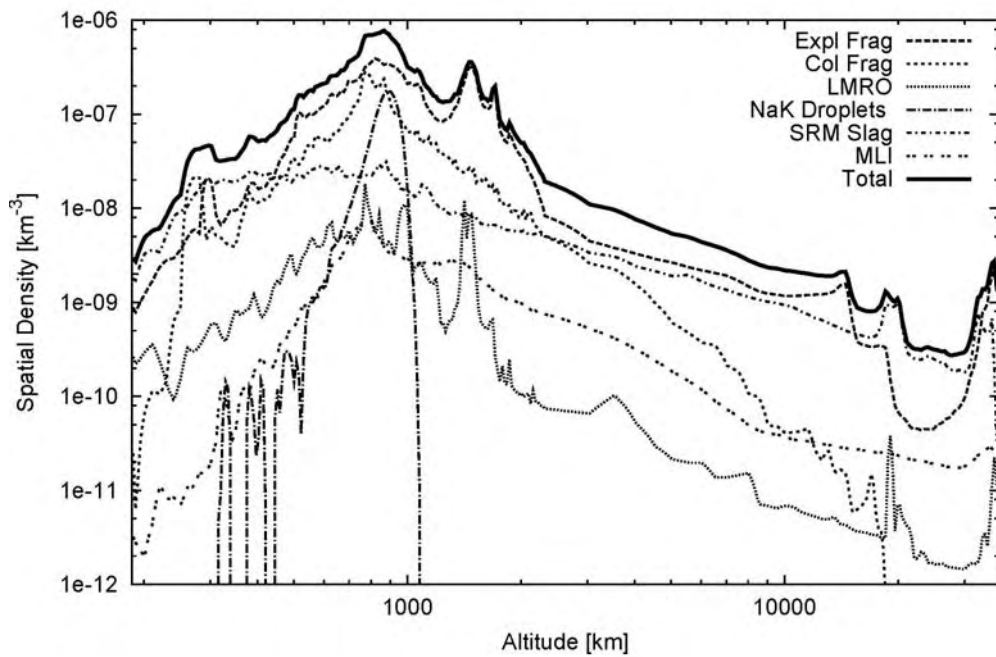


Figure 2.7: Spatial density distribution of MASTER-2009 objects of  $d > 1$  cm, in LEO to GEO altitudes, discriminated by sources [2.7].

## 2.5. Debris collision risk assessments

Spatial object densities are an essential input to debris collision risk assessments. The statistical behavior of the orbital debris population can be well represented by the laws of kinetic gas theory. Hence, the number of collisions encountered by an object is proportional to its collision cross-section, the particle density of the ambient debris environment, the relative velocity of the target, and its total time of exposure.

Since near-circular orbits are dominant for debris of critical sizes, their maximum relative velocity can be twice the orbit velocity, for an approach from the flight direction, and the minimum relative velocity can be close to zero, for an approach from 0 or 180°. Impacts from the rear quadrants can only occur for impactors that travel on eccentric orbits, during their perigee passes.

Likewise, impacts from 0° can only occur, if the impactor has an orbit with a “complementary inclination” of 180° minus the inclination of the target object. Only in that case can both objects be in the same orbit plane, on counter-rotating orbits, if their ascending orbit nodes are separated by 180°.

For typical target orbits defined in Table 2.4 the mean times between impacts by orbital debris of different sizes are listed in Table 2.5 for a common reference cross-section of 1 m<sup>2</sup>, assuming a spherical target object.

	H <sub>p</sub> [km]	H <sub>a</sub> [km]	i [deg]	a [km]	e [-]	ω [deg]
ISS	356	364.1	51.6	6738	0.000601	0
ERS-2	774	789	98.6	7159	0.001096	90
Globalstar	1399	1401	52	7778	0.0001	0
GPS	19997	20003	55	26378	0.0001	0
GTO	560	35786	7	24551	0.717405	178
GEO	35782	35790	0.1	42164	0.0001	0

Table 2.4: Sample orbits for analyzing space debris collision flux [2.7].  
H<sub>p</sub> = Altitude of Perigee, H<sub>a</sub> = Altitude of Apogee, i = inclination; a = semi-major-axis,  
e = eccentricity, ω = Argument of Perigee

Diameter	> 0.1 mm	> 1 mm	> 1 cm	> 10 cm
ISS	9.0 d	636 y	41,102 y	942,507 y
ERS	0.7 d	42.5 y	1,252 y	43,783 y
Globalstar	1.7 d	102 y	9,208 y	126,550 y
GPS	244.8 d	10,794 y	1.1e+7 y	7.2e+8 y
GTO	36.8 d	2,627 y	241,546 y	4.4e+6 y
GEO	676.3 d	18,674 y	6.5e+6 y	1.4e+8 y

Table 2.5: Mean time between impacts of a given debris size for a spherical target of 1 m<sup>2</sup> cross-section, on orbits as defined in Table 2.4 [2.7].

There are different ways to mitigate the risk and/or consequences of a collision of an operational spacecraft with a space debris object. For large-size catalog objects the concept of conjunction event analysis and collision avoidance can be pursued. For sub-catalog debris that cannot be tracked, passive protection measures can be taken.

In 2013, the orbit environment consisted of almost 12,200 cataloged LEO objects, larger than 10 cm, of a total mass of almost 2,500 metric tons. The corresponding rate of collisions among catalogued objects was 0.19 per year, resulting in one such event every 5 to 6 years.

About 45% of these collisions would have a rocket body, while 55% would have a spacecraft as their main object. As many as 22% of all collisions among catalogued objects will be attributed to a single 2° × 50 km bin at 86.5 ± 0.5° inclination and 780 km altitude, covering 72 large, intact objects, most of which are spent upper stages (*Tsyklon* 3<sup>rd</sup> stages, each with 1.4 tons and 6.2 m<sup>2</sup>; *Vostok* 3<sup>rd</sup> stages, each with 1.4 tons and 10 m<sup>2</sup>; and *Delta II* 2<sup>nd</sup> stages, each with 0.9 tons and 12 m<sup>2</sup>) [2.2].

These 72 objects are facing fragments from the *Iridium 33/Cosmos 2251* collision and from the Chinese *Feng Yun 1C* ASAT test as the main causes of their 10 cm collision flux. A secondary maximum of catastrophic collision rates at 11% is due to a cluster of Cosmos satellites at 82° inclination and 920 km altitude.

The long-term risk from resident debris mass to the environment can be expressed by the product (collision flux) x (colliding mass) x (orbit lifetime of fragments). As a simplifying conservative assumption the same orbital lifetimes shall be considered for the target object and its resulting fragments. The resulting aggregate of the individual products of collision rate, target mass, and target orbit lifetime, over all intact LEO objects, leads to a long-term debris environment risk indicator that is governed to 72% by rocket bodies, and to 28% by spacecraft. Approximately 42% of the overall long-term risk is due to objects stemming from a single bin of 2° x 50 km, centered at  $71 \pm 0.5^\circ$  inclination and  $825 \pm 20$  km altitude. Most of the related mass is due to Russian *Zenit 2* 2<sup>nd</sup> stages with an empty weight of 8.2 metric tons each, with a cross-section of 33 m<sup>2</sup>, and with orbit lifetimes on the order of 700 years.

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### 3. Measurements

This chapter addresses measurement techniques of space objects in general. It covers both, the “classical” space surveillance observations aimed at the establishment and maintenance of orbit catalogues of artificial space objects. Today this is often referred to as the surveillance and tracking observations within the context of “Space Situational Awareness”, as well as the observation and physical characterization of space debris of all sizes and types. Particular emphasis is put on the observation of the space debris population, including its statistical characterization. The operational aspects of space surveillance observations, including the observation of active objects, are described in Chapter 4.

#### 3.1. High level requirements

Regular observations of space debris residing in Earth orbit are necessary for obtaining objective and up-to-date information in order to address the following key tasks, both, at the international and national levels:

- To maintain as complete and comprehensive as possible, a database of space debris objects (as defined in this report) in the near-Earth space to provide sufficient information for analysis of conjunction events, long-term evolution of individual objects, physical characterization of non-operational space objects (including objects containing hazardous materials);
- To elaborate and improve the models that describe the current state of human-made debris objects in the near-Earth space and the dynamics of changes of this environment enabling quantitative assessments of risks related to the constantly changing number of space debris objects in different regions of near-Earth space;
- To elaborate substantiated engineering solutions for the protection of spacecraft from possible collisions with small-sized space debris fragments that cannot be traced individually;
- To formulate scientifically substantiated recommendations regarding measures aimed at reducing the amount of space debris in the near-Earth space (including through providing sufficient information to assess necessary improvements in order to comply with requirements of national and international standards and guidelines on space debris mitigation in near-Earth space).

Regular monitoring of qualitative and quantitative changes that the space debris population undergoes can be achieved solely through routine measurements, the provision of information on orbital and physical properties of space debris and the comparison of the results obtained at various time periods.

In the given context, this helps to fulfill a number of dedicated tasks, including the following ones:

- To obtain a reliable estimation of the amount of debris objects, including inter alia small-sized (from fractions of a millimeter to centimeters in cross section), of their orbital and physical properties, and to build, based on the data obtained, statistical functions representing the distribution of the values of the relevant parameters;
- To identify the potential sources of debris objects and to classify them;



- To assess the effect of each type of space debris source on the changes in the space debris population in short-, mid- and long-term perspective;
- To identify events that generate new space debris (including fragmentations due to explosion and collision);
- To design and regularly verify models describing the physics of the generation and orbital evolution of the observed debris objects in a short-, mid- and long-term perspective;
- To carry out statistical risk analysis with respect to particular near-Earth space regions for a given time interval;
- To identify the areas in near-Earth space environment with the highest space debris spatial density;
- To maintain a regularly updated database on orbital properties (with certain precision level) of the tracked objects in order to facilitate the identification and analysis of dangerous conjunctions, and to enable the use of special measurement devices (sensors) to study the physical properties of space debris.

The accomplishment of the above tasks contributes to improved understanding of space debris population in the near-Earth space environment and of the present and future effects of space debris on the safety of on-orbit space activities.

In particular, the information obtained (after its necessary processing and integration into the models developed) can be used by spacecraft designers to account for the required characteristics and design features of spacecraft protection elements, including the identification of spacecraft construction elements most exposed to small-sized human-made objects during the spacecraft's estimated lifetime in the target orbit.

In addition, objective information on the sources of small-sized debris particles and their generation processes is necessary in order to obtain qualitative and quantitative estimates related to the practicability and cost-effectiveness of the proposed space debris mitigation measures designed to prevent the generation of new debris objects.

Maintenance of the accurate orbital database for space debris objects helps to avoid unnecessary evasive maneuvers of operational spacecraft in case of predicted conjunctions.

### **3.2. Existing technologies and technical means for space debris observation**

Currently, ground-based radars as well as electro-optical sensors placed both on Earth and on board of spacecraft are used to acquire information on space debris objects larger than 0.5 - 1 cm, whereby orbital data is obtained for objects typically larger than 10 cm.

The small-size space debris population (objects less than 1 mm in size) is best measured *in situ* by using special detectors on board of spacecraft and by analyzing impact features and residues on spacecraft surfaces returned from space. Moreover, laboratory experiments can help modeling some stages of the orbital debris generation and allow studying physical properties of materials exposed to the space environment in order to better understand changes in physical properties of materials (e.g. reflectivity characteristics) as well as the processes of their deterioration and subsequent destruction.

The amount of information that can be obtained on certain space debris objects largely depends on the physical properties of the observed objects (in particular, the reflectivity characteristics of objects in the spectrum ranges used for radar and optical observations), and the orbital parameters in conjunction with the measuring instruments and the methods of observation.

Observations carried out by radar and optical sensors can be based on different methodological approaches and be aimed at both, deterministic study of individual objects, and the acquisition of statistical data about the total population of space debris objects in certain regions of space.

The results of deterministic observations can be used to estimate the following characteristics of each particular object:

- Parameters of center of mass motion and their evolution over time;
- Parameters of attitude and their evolution over time;
- Reflectivity and spectral properties (for example, the change in the intensity of the reflected signal in different regions of the electromagnetic spectrum and under different viewing conditions which allows estimating the average value of the effective area of the reflecting surface which in turn can be used to estimate the geometric dimensions);
- Effective area-to-mass ratio.

Thus, using radar and electro-optical sensors it is possible to obtain trajectory information; direction and velocity of the observed object in space relative to the observation facility; information about the reflectivity characteristics of the object in optical and/or radar bands; and their changes throughout the observation.

With enough trajectory information, it is possible to estimate the parameters of the orbital motion of each particular object with a certain degree of accuracy, as well as the ratio of the effective surface area of the object to its mass (for example, the ratio of the area normal to the vector of acceleration due to atmosphere drag or the area normal to the vector of acceleration due to solar radiation pressure to the mass of the object).

In order to support conjunction analysis and decision making on the need of avoidance maneuver, the distribution of measurements over the orbit determination interval, the geometry of the observations (number of sensors and their geographical distribution), and the accuracy of individual measurements are critical.

The results of statistical surveys can be used to assess the following characteristics:

- Object flux (per unit of observed space and per unit of time);
- Spatial density of objects;
- Estimations for basic parameters of the orbit for each individual object which has been observed during the survey based on the simplified assumption on orbital motion (e.g., on the assumption of having ideal circular orbits for all objects in the flow);
- Reflectivity characteristics of each individual object which has been observed during the survey and, therefore, the average value of the effective area of the reflecting surface permitting to infer geometric dimensions.

Periodic statistical measurements can detect changes in the distribution of space debris fragments in a particular area of the near-Earth space, which may be caused by an orbital event not yet identified at the time of the measurements (e.g., the fragmentation of an orbiting object that was not detected by means of deterministic research).

### **3.3. Existing and currently developed techniques for space debris observations**

Given the large number of potentially dangerous space debris and the complex evolution of both, individual objects, and their population as a whole, as well as the vast volume of the near-Earth space where the objects are scattered, regular observations of space debris objects in the near-Earth space is extremely challenging and requires significant financial, technical and human resources.

#### **3.3.1. Optical sensors**

So-called optical sensors operate either in the visible or the near infra-red range of the electromagnetic spectrum. In the visible range the sensors record sunlight reflected from the objects while the infra-red radiation emitted by space objects is thermal emission and does not require an illuminating source during the observation. As a consequence, the classical ground-based optical observation techniques in the visible require the object to be in sunlight while the sensor is in the dark, which constitutes a severe constraint for objects in low Earth orbits.

Optical sensors detect space debris or artificial objects in space by recording them on images where they may be discriminated as moving objects in front of the stellar background. The brightness of the objects depends on:

- The size of the object (cross section area seen by the observer),
- The surface properties of the object (the so-called albedo),
- The illumination conditions (e.g. the Sun-object-observer geometry, also characterized by the so-called phase angle), and
- The distance of the object from the observer.

In particular the brightness falls off with  $1 / \text{distance}^2$ , which is an advantage for large distances when compared with active techniques like radar or laser ranging (see below).

The ability of the sensor to detect faint objects, on the other hand, is proportional to its light collecting area (square of the sensor aperture) and furthermore depends on the angular velocity of the object with respect to the line of sight of the sensor. A fast-moving object will result in a streak in the image plane and the signal from the source will be spread over a large area on the detector making it difficult to discriminate the signal from the sky background.

In order to maximize the detection performance, the sensors must thus track the objects of interest. This is obvious in the cases where the object's trajectory is known. When searching for unknown objects, the detection performance may be optimized by blindly tracking with the expected average angular motion (rate and direction of motion) of the population of interest. In cases where the latter is unknown, a so-called sidereal tracking may be applied such that the stars will appear point-like thereby minimizing the image area "contaminated" by background clutter. Figure 3.1 shows typical limiting object sizes for ground-based optical sensors as a function of sensor aperture and object altitude [3.1].

These figures are valid for a dark site, optimum illumination and best atmospheric conditions, and assuming a perfect tracking of the objects. In reality the minimum sizes may easily be a factor of 2 to 3 larger even under considerable good conditions.

Typical angular velocities of objects with respect to the stellar background as observed by a ground-based sensor are given in Table 3.1.

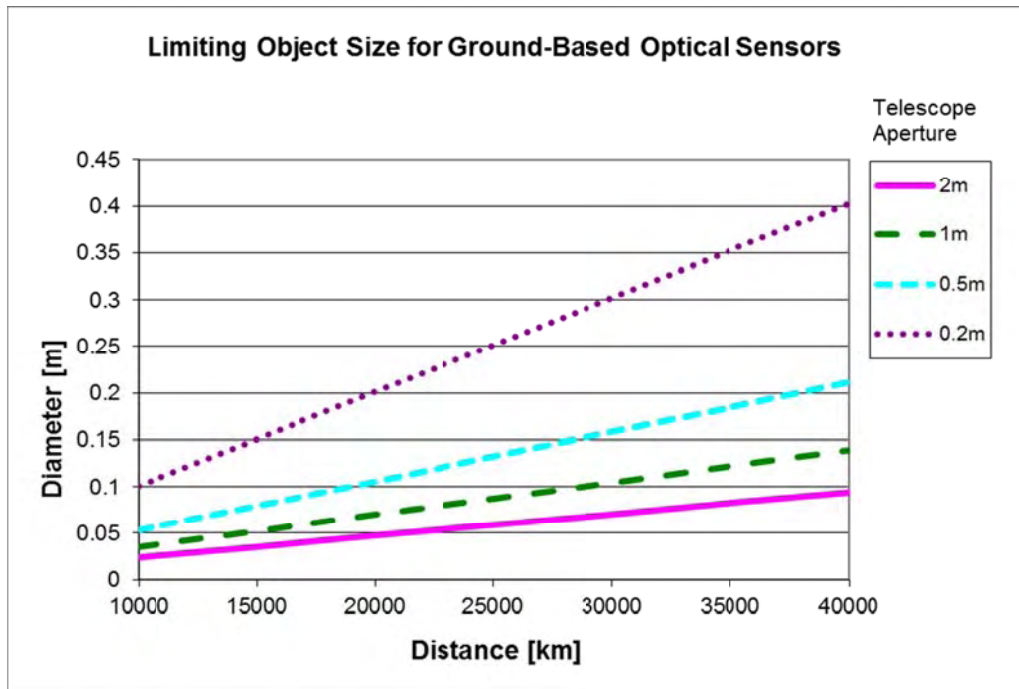


Figure 3.1: Limiting object size for ground-based optical sensors as a function of sensor aperture and object altitude (assuming a Bond albedo of 0.2, a dark site, optimum illumination, and atmospheric conditions) [3.1].

Altitude	Angular Velocity [arc seconds/second]
LEO (< 2000 km)	1000 – 2000
MEO (20,000 km)	30
GEO (36,000 km)	15

Table 3.1: Typical angular velocities of objects with respect to the stellar background as observed by a ground-based sensor [3.1].

## Survey sensors

The survey sensors are used to perform searches for objects which are unknown or for which the trajectories are unknown. Typical cases are the build-up phase of an orbital catalogue, the search for “lost” objects, or statistical space debris surveys. Orbital catalogues may also be maintained by scanning the orbital region of interest with survey sensors instead of performing tasked follow-up observations of individual catalogued objects.

Survey sensors should have a large Field of View (FoV) in order to efficiently scan an area of interest, preferentially several times per day. The Geostationary Earth Orbit (GEO) region including inclinations from 0° to 15°, to give an example, corresponds to an area of more than 10,000 square degrees. Unfortunately, wide-field optical designs are very challenging and always a tradeoff between the FoV and the aperture size. For small-size,

wide-field telescopes with apertures in the range of 0.2 to 0.4 m, a FoV of 10 square degrees is typical and optical designs with 20 to 30 square degrees are feasible. Astronomical telescopes with apertures of 1 m or larger traditionally have a FoV of less than one square degree. Recently some innovative optical designs allowed building large aperture wide field telescopes like the 1.8 m *Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)* with a FoV of about 7 square degrees (Figure 3.2), or the 3.5 m Space Surveillance Telescope of the US Defense Advanced Research Projects Agency (DARPA) with a FoV of about 10 degrees squared.

The maintenance of the orbits of GEO objects larger than about 1 m in diameter requires observations which may be provided by telescopes of rather small aperture. Figure 3.3 shows an example of a small wide-field survey telescope used for GEO catalogue maintenance.

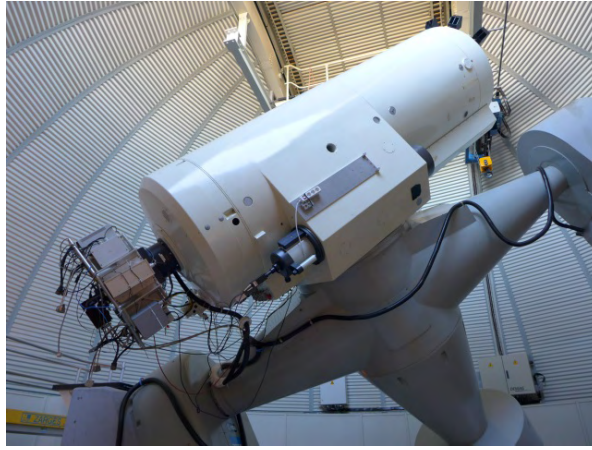


Figure 3.2: The 1.8 m PanSTARRS telescope on Mount Haleakala, Maui.



Figure 3.3: The Zimmewald Small Aperture Robotic Telescope ZimSMART with 0.2 m aperture and 10 degree squared FoV.

Several space agencies are performing deep surveys to better understand the small-size debris population using rather traditional astronomical telescopes. For this purpose ESA is using its 1 m telescope at the Optical Ground Station in Tenerife, Canary Islands (Figure 3.4), and NASA performed surveys with the 0.6 m *Michigan Orbital DEbris Survey Telescope (MODEST)* at the Cerro Tololo Inter-American Observatory (CTIO) in Chile (Figure 3.5).



*Figure 3.4: ESA 1-meter space debris telescope at the Optical Ground Station in Tenerife.*



*Figure 3.5: 0.6 m Michigan Orbital DEbris Survey Telescope (MODEST) at the Cerro Tololo Inter-American Observatory (CTIO) in Chile*

Ground-based optical survey for objects in LEO have been proposed and partially tested by several groups (ISON, [3.2]).

The challenges are the requirement that the objects need to be illuminated by the Sun while the sensor is in the dark, which means that observations are only possible during dusk and dawn periods, and, secondly, the high angular velocities of the objects. The latter results in long faint streaks for the object images which in turn allows detection of relatively bright objects only.

### **Tracking sensors**

So-called tracking sensors are used in cases where the object's trajectory is known. Examples are follow-up observations of known objects to improve or maintain their orbits or to determine physical characteristics of individual objects.

Physical characteristics like object size, shape, material, etc., are important information to determine the nature of the objects and the possible sources (e.g. of small-size fragments) eventually allowing for the design of efficient mitigation measures.



Tracking sensors do not necessarily require a large FoV and classical medium- to large-size telescopes may thus be used, provided that their mounts allow for a precise tracking of the moving targets (this is not the case for the majority of the telescopes used in astronomy).

A series of observation techniques may be use for physical characterization:

- *Imaging* will provide the object position and brightness;
- *Color photometry* and *spectroscopy* providing information on surface material properties [3.3], [3.4];
- *Infra-red* observations providing information on surface material properties, and allowing to assess the albedo trough the object temperature [3.5];
- *Time resolved photometry*, so-called light curves, allowing to determine the shape and attitude motion of objects [3.6].

### **Space-based optical sensors**

An optical sensor in space has several advantages for the observation of space debris. First of all it allows for uninterrupted observing while a ground-based sensor can only operate during nighttime and under good weather conditions. Furthermore the sky background brightness is reduced and there is no attenuation of the object signal due to the atmosphere.

A major advantage, however, is the possibility to reduce the distance between the sensor and the objects such that the small size debris population in the vicinity of the sensor can be studied. In particular, the critical object size region between 1 to 10 cm, where currently only very limited information is available, would be accessible. Several concepts were studied by space agencies [3.7], [3.8].

Several space-based optical surveillance sensors have actually flown. Examples are the US Space Based Surveillance System (SBSS), and the small Canadian satellite “*Sapphire*”. Their main mission, however, is to support the maintenance of the orbit catalogues of comparatively large object and not the study of the small-size debris population.

### **Active optical ranging**

Laser ranging to objects with retro-reflector arrays is a well-established technique providing range measurements with millimeter accuracies.

Experiments were undertaken by several groups to apply the techniques to space debris objects. These objects reflect the laser not into the direction of the incoming beam, as for retro-reflectors, but the light is scattered in a diffuse way.

As a result, the method requires high-power lasers and is currently limited to meter-size objects in LEO [3.9], [3.10]. Obviously laser ranging requires good weather conditions and either a rather precise prediction of the object’s trajectory or a passive optical sensor for the object acquisition due to the narrow laser beam (a beam width of a few arc seconds). The passive optical sensors in turn will require the object to be sunlit. Active optical ranging does not have a surveillance capability.

### 3.3.2. Radars

Radar sensors have been and are the working horses to build up and maintain orbit catalogues of space objects in LEO.

Thanks to their measuring principle, which consists of emitting microwaves and receiving radiation reflected by the objects, they are highly independent of weather conditions and may operate continuously in a 24 h per day, 7 day per week mode (with periodic down time for maintenance).

An important difference with respect to passive techniques is that the returned signals decrease proportionally to the distance to the power of 4, while the signal of passive optical techniques is reduced by the distance to the power of 2 only. This is the main reason that radars are to a great extent limited to the LEO region and less efficient than optical system at higher altitude.

LEO orbit catalogues are predominantly based on data from surveillance radars which have a large FoV, often in the form of so-called fences with up to 180° in width. These radars are mainly large, so-called synthetic aperture radars. Examples may be found in Chapter 4. Currently these radars may detect objects with a minimum size of about 10 centimeters in LEO. This limit shall be reduced to about 5 centimeters with next generation systems.

Tracking radars, on the other hand, have a narrow FoV, often much smaller than one square degree, and are used to track individual objects. Similarly to tracking telescopes, their main application is the refinement of orbits and the physical characterization of objects. The latter includes the study of temporal variation of the returned signal for the determination of the attitude motion and imaging.

Large tracking radars are instrumental to acquire statistical information on the LEO debris population in the size range of a few millimeters to a decimeter. This size range is particularly critical as these objects are not contained in today's orbit catalogues but may nevertheless produce lethal collisions with robotic and manned spacecraft.

The measurement technique consists of staring with large dish radars into a relatively small volume of space for a long-time interval, e.g. 24 hours, and to count objects crossing the beam. Such observations result in object fluxes as a function of the object size (radar cross-section), orbit altitude and inclination (assuming circular orbits).

ESA and NASA regularly perform so-called 24 hour beam-park measurement campaigns under the umbrella of the Inter-Agency Space Debris Coordination Committee (IADC) using mainly the German 34-meter diameter *TIRA* system, and the US 34-meter *Haystack* antenna.

### 3.3.3. *In situ* measurements

Information on the population of millimeter and sub millimeter sized particles, which are too small to be detected by ground-based optical telescopes and radars, is best obtained from *in situ* measurements.

These consist either in the analysis of surfaces exposed to the debris and micrometeorite environment, or in the observation of impacts on active detectors flown in space. The former surfaces may be available either on retrieved spacecraft or parts thereof or in the form of dedicated passive dust detectors brought back to Earth.

Passive detectors usually contain surfaces which are designed to record impacts of small particles. Some detectors may also catch the impactors for further analysis of their composition.

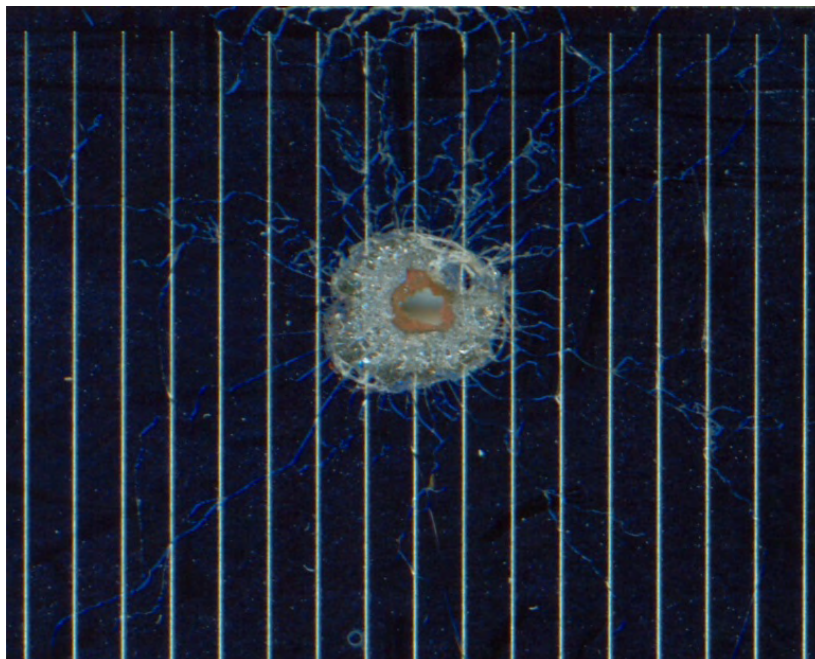
Surfaces retrieved from space are usually covered with a large number of impact craters.

The most prominent example of a large, dedicated detector to record impacts from micro-particles is the *Long Duration Exposure Facility (LDEF)* which was retrieved in January 1990 by a space shuttle after having been exposed for 5.6 years to the space environment (Figure 3.6). The setup of the experiment and the corresponding analysis of the impact craters allowed determining particle fluxes as a function of the object size for the altitude *LDEF* was orbiting. From the analysis of impactor residues in some of the craters it was also possible to separate the micrometeoroid population from the space debris micro particles.



*Figure 3.6: Long Duration Exposure Facility (LDEF) during the retrieval by the US Space Shuttle.*

Similar data could be obtained from solar arrays retrieved from the Hubble space telescope in the course of servicing missions. Figure 3.7 shows an impact feature of several millimeters in diameter on a retrieved *HST* solar array.



*Figure 3.7: impact feature of several millimeters in diameter on a retrieved HST solar array generated by a millimeter size particle [Credit: Thomas Schildknecht].*

Another good example is the European *EuReCa*:

The *European Retrievable Carrier (EuReCa)* was launched July 31<sup>st</sup> 1992 by the *Space Shuttle Atlantis*, and put into an orbit at an altitude of 508 km. It began its scientific mission on August 7<sup>th</sup> 1992. *EuReCa* was retrieved on July 1<sup>st</sup> 1993 by the *Space Shuttle Endeavor* and returned to Earth. The satellite carried a number of experiments for micro-gravity studies, solar observations, and material technology investigations.

The evaluation of the *EuReCa* impact data revealed a high sensitivity limit of the *EuReCa* solar array front top. Therefore, the large-size contribution of the solid rocket motor dust exhaust products is visible as a slight increment to the total flux distribution below a conchoidal fracture diameter of 60 micron.



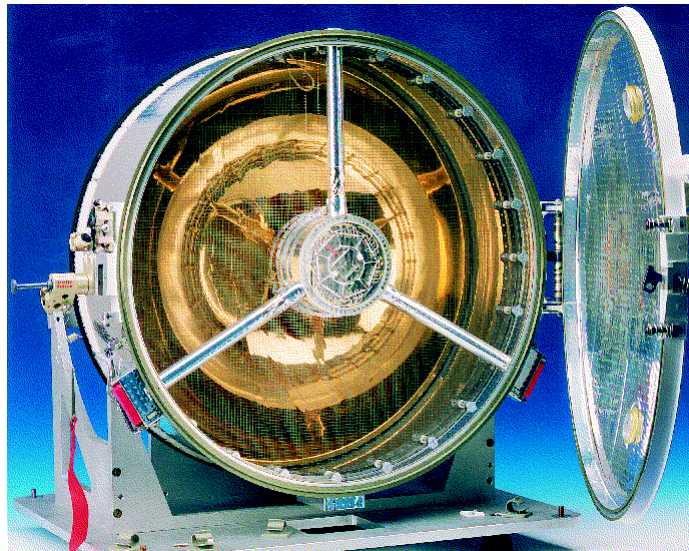
Figure 3.8: The European Retrievable Carrier [NASA].

Active impact detectors record impacts of micro-particles in real-time and need not to be retrieved from space.

The planned Navy-NASA detector *Space Debris Sensor (SDS)* is an example of a large-size (1 m<sup>2</sup>) impact sensor to be deployed at the International Space Station. *SDS* combines three particle impact detection concepts (impactor size, impact timing, and impact location) allowing determining the size of the impactor and the impact direction and speed.

The ESA *Geostationary Orbit Impact Detector (GORID)* which was operated from 1996 to 2001 as hosted payload on board of a geostationary spacecraft provided the first information on the micro-particle environment in the geostationary ring (Figure 3.9; [3.11]).





*Figure 3.9: GORID impact detector flown on a Russian GEO EXPRESS spacecraft [3.11].*

### **3.4. Existing practices for international cooperation in the field of space debris measurements**

Meanwhile, the emergence and development of new technologies makes it possible to engage an increasing number of researchers from different countries in monitoring the near-Earth space.

No single state in the world is currently able to provide a complete and constantly updated picture of the situation in orbit on its own. Thus, there is an objective need to combine capabilities in this area. The tools and technologies of optical observations of objects in the near-Earth space are no longer financially costly and are available to all interested states, which make it quite feasible to ensure the widest possible participation to study the human-made debris in the near-Earth space, especially in the high orbits (geostationary and highly elliptical orbits).

Examples of existing international practices in the areas of joint measurements, monitoring, and determination of orbital and physical characteristics of debris objects in the near-Earth space and the provision for public use and dissemination of derived products and methodologies for their use include:

- Dedicated test measurement campaigns (beam-park radar experiments and dedicated optical campaigns) for statistical studies of the population of small space debris in various regions of the near-Earth space under the auspices of the Inter-Agency Space Debris Coordination Committee (IADC), which brings together experts from 13 major space agencies of the world;
- Regular monitoring of high orbit debris within the international research project entitled International Scientific Optical Network (ISON), which brings together researchers from 15 countries;
- Bilateral space debris monitoring activities.

The monitoring data cannot be correctly interpreted and used without understanding the methodology supporting them. It is obvious that this fact must be taken into account during planning, sharing, and collaborative use of data.

Therefore, a key aspect of international cooperation in the investigation of the human-made space debris environment in near-Earth space (besides the data exchange) is the development and harmonization of common approaches to evaluate the quality of the data, to interpret them, and to assess their potential use for specific tasks; these recommended improvements are among the Terms of Reference of the IADC.

### 3.5. Existing gaps and multidisciplinary issues

Different kinds of failures and anomalies may occur during the operation of the on-board systems of spacecraft in orbit. In some cases, these failures and anomalies can indeed be caused by collisions with small-sized space debris. Nevertheless, these failures are often due to other causes – the effects of space weather, failure of electronic and mechanical components of the on-board equipment and impacts of natural objects (meteoroids and micrometeoroids), etc.

For a better understanding of the true causes of such incidents, especially in the event of failure of a spacecraft and the inability to obtain the necessary telemetry data to analyze the situation, one needs the fullest possible picture of the real state of the space environment outside the spacecraft at the time of its failure. To this end, the study of the near-Earth space environment where spacecraft operate should be comprehensive and evaluate the possible effect of each component of this environment on the spacecraft.

Furthermore, in the aftermath of an onboard anomaly after which telemetry is still available, additional information is required in order to fully explain the event. To identify debris or micro meteoroids as root cause for an anomaly, such as a sudden attitude/orbit change, information on the impact location is required. This will also allow assessing the damage and computing the full momentum vector, which provides important data on the environment and spacecraft vulnerability. On-board micro cameras are a perfect means to achieve this. Space qualified cameras in miniaturized version have been already used to monitor, e.g. the deployment of solar arrays.

They were also used to inspect the damage after a major anomaly onboard of *Sentinel-1A* as seen on Figure 3.10. With the help of the image, it was possible to understand the amount of lost power, and to discriminate man-made debris of about 1 cm size as the impactor. The more general use of such cameras on-board of spacecraft, observing large areas such as solar arrays is recommended

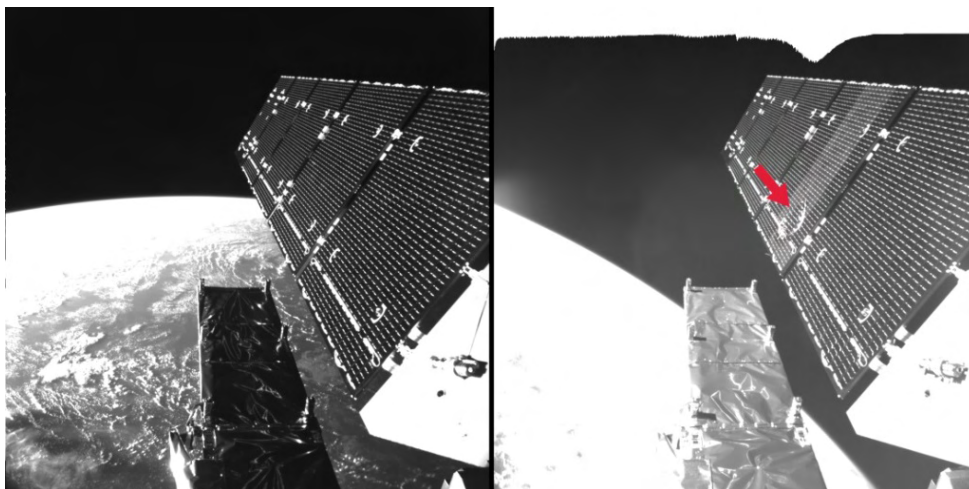


Figure 3.10: SENTINEL-1A before impact (left) and after (right) [ESA].



The existing approaches to the study of the near-Earth space debris suffer from a number of gaps. These gaps make it difficult to obtain a comprehensive understanding of the phenomenon of space debris and limit the participation of many countries in the analysis and solution of this complex and multifaceted issue.

The most serious gaps are briefly described below.

- Currently, only a few states carry out regular observation of space debris in near-Earth space. The development of common mutually agreed upon approaches to verify the information received from other parties and to fuse data from different sources in a qualified way has been and remains a relevant issue. This fact inevitably limits practical capabilities and efficiency of collaboration.

Furthermore, there is no international mechanism for exchanging verified information that, using the same methodological approach, might be used by different countries which do not carry out observation themselves, but have qualified scientific personnel, including specialists in physics, mathematics, and material engineering.

- Another aspect of the problem which is equally important in the studies of the space debris environment in near-Earth space, is the lack of standard approaches to represent measurement data (which is primary in nature), as well as to represent derived products on space debris which includes orbital information (center-of-mass motion parameters), estimation of mass, size, attitude motion parameters relative to the center of mass, as well as optical and radar reflection characteristics.

Despite the large amount of work carried out by different states at national and international levels, there are no scientifically and practically well-funded common formats that would define the structure and content of various types of information, the models for obtaining and processing information, as well as the methods of correct interpretation and practical use of information, which have yet to be agreed upon.

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## 4. Space situational awareness systems

### 4.1. Introduction

Space Situational Awareness (SSA) includes perceiving orbital anomalies or threats, maintaining an inventory of objects as completely as possible, and developing and providing timely information for collision avoidance and safe operation.

This inventory (catalogue) should provide information about the origin of the objects (name, launch country / entity) and their trajectory (orbital parameters, time history or ephemeris), allowing them to be located at any time.

To fulfill this objective, different types of sensors must be used, as seen in Chapter 3.

- First, detection systems with a wide field of view to see passing objects above a certain size and roughly calculate their orbit to locate them later.
- Then, tracking systems with a narrow field of view are used to follow a specific object, in order to take measurements and improve knowledge of its trajectory.

Basically, these detection and tracking systems are combinations of radars for low-orbiting objects or telescopes for objects in higher orbits. It is best to have geographically distributed systems that observe in different ways to overcome the limitations of each. The observation systems can be located either on the ground or in orbit.

How small an object can be seen depends on the resolution of the instrument if the observation is passive, relying on emissions or reflection from the object of interest. When the objects can be illuminated actively, very small objects can be perceived and tracked if enough illumination energy is devoted to them.

Generally, this is not operationally feasible among all of the required SSA tasks. It is important to notice that the observables (i.e., behavior of resident space objects detectable by radar and optical measurement devices) may not reveal the size or extent of an object. For example, large, thin objects aligned along the line of sight appear small.

There are also other ways to perceive and discriminate objects based on their motion, the periodicity of their signatures, their natural electromagnetic emissions, and the temporal and wavelength spectra of their signatures.

The population of smaller debris below the discernable size limit (e.g., 10 cm in LEO and 80 cm in GEO) is estimated in a statistical and empirical manner using models such as ORDEM (NASA) or MASTER (ESA).

Some authors consider that space surveillance also includes functions relating to space weather and the monitoring of near-Earth asteroids whose trajectories could threaten Earth. In the rest of this chapter, we will only be considering the functions related to space traffic, that is to say detecting and tracking artificial objects, identifying threatening debris in orbit around the Earth.

The main source of orbit data is the United States Space Surveillance Network (SSN). The SSN includes both radars and telescopes, including a space based optical capability.

Orbits determined by the SSN are publicly-available as Two-Line Element Sets (TLE), for unclassified objects.

The Joint Space Operations Center (JSpOC) processes the observations from the SSN and produces a variety of products through open user accounts on the Space Track website<sup>8</sup>. The TLE does not include a quantification of the uncertainties in orbit parameters.

Russia has a similar system with different coverage and products not so widely distributed. In addition, State Space Corporation ROSCOSMOS (former Russian Space Agency) put into operation a dedicated system for monitoring potential hazards for operational spacecraft - Automated Warning System on Hazardous Situations in Outer Space (ASPOS OKP). The International Scientific Observation Network (ISON) of telescopes provides a detailed catalogue of objects in geostationary orbit.

France has limited capability in LEO with the *GRAVES* system (*Grand Radar Adapté à la Veille Spatiale*) and in GEO with *TAROT* Telescopes. Some other devoted or collateral tracking radars (e.g. *SATAM*, *ARMOR 1 & 2* and *NORMANDIE*) are used to provide added-value services.

Germany employs the *TIRA* sensor (Tracking and Imaging Radar) for the observation of space objects as well as for the characterization of the small particle debris environment in low Earth orbit.

AGI's Commercial Space Operations Center (ComSpOC<sup>®</sup>) fuses observations from diverse sensor types to generate commercially-available orbit data products and relevant services.

There are also networks of collaborating civilian observers and emerging private observation networks such as that developed by the Astronomical Institute of the University of Bern (AIUB).

In Europe, the "*Decision of the European Parliament and the Council Establishing a Space Surveillance and Tracking Support Framework*" n°541/2014/EU was adopted on April 16<sup>th</sup> 2014. The objective is "*to contribute to ensuring the long-term availability of European and national space infrastructure, facilities and services*", providing support to the "*actions aimed to establish a SST capability at European level and with an appropriate level of European autonomy*".

The specific objectives are:

1. Assessing and reducing the risks to in-orbit operations of European spacecraft from collisions, thus enabling spacecraft operators to plan and carry out mitigation measures more efficiently;
2. Reducing the risks relating to the launch of European spacecraft;
3. Surveying uncontrolled re-entries of spacecraft or space debris into the Earth's atmosphere and providing more accurate and efficient early warning with the aim of reducing the potential risks to the safety of Union citizens and mitigating potential damage to terrestrial infrastructure;
4. Seeking to prevent the proliferation of space debris.

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<sup>8</sup> <https://www.space-track.org>

To attain these objectives, the European program shall establish a Space Surveillance and Tracking (SST) capability at a European Level, with the aim of providing SST Services to the EU user community.

This capability will include the following:

- The establishment and operation of a sensor function consisting of a network of member state ground-based and/or space-based sensors to survey and track space objects and to produce a database thereof;
- The establishment and operation of a processing function to process and analyze the SST data at national level to produce SST information and services;
- The setting up of a function to provide SST services.

In the following sections, a list of representative assets at worldwide level is presented.

## **4.2. USA space surveillance network**

The US Space Surveillance Network (SSN) is a combination of optical and radar sensors [4.3], [4.4]. It supports the United States Joint Space Operations Center's (JSpOC) mission to detect, track, identify, and catalog manmade objects orbiting the Earth. The JSpOC, located at the Vandenberg Air Force Base, tasks sensors based on need.

The sensors are maintained and operated by the US Air Force Space Command, which also develops, maintains, and executes algorithms and processes for determining orbits from observations.

The United States network carries out the following functions to the best of its ability:

- Detects new human-made objects in space;
- Produces a running catalogue of human-made space objects;
- Helps determine which country is responsible for an orbiting or re-entering space object;
- Charts the present position of space objects and extrapolates their anticipated trajectories;
- Provides estimates of the reentry epoch for space objects predicted to decay within 60 days. For some objects, and beginning four days prior to selected decay, the Tracking and Impact Prediction (TIP) message is also distributed.

The SSN sensors are divided into three categories: dedicated, collateral, and contributing (Figure 4.1):

- A dedicated sensor is one dedicated completely to space surveillance.
- A collateral sensor is primarily for other purposes such as ballistic missile warning.
- Contributing sensors are those owned and operated by other agencies that provide space surveillance support.

Primary and collateral sensors are owned and operated by the United States Air Force and subject to tasking and operational control of United States Strategic Command.

Operationally, the SSN perceives objects whose isotropic UHF radar cross sections are 10 cm in diameter in low orbit. Smaller objects may be perceived if they return sufficient



energy. Since the intensity of radar emissions diminishes with distance, the minimum operationally detectable object in geostationary orbit is about one meter in diameter.

The threshold of perception depends on how radar energy is allocated to each potential target simultaneously.

Combined, these types of sensors make up to 100,000 satellite observations each day. This enormous amount of data comes from SSN sites such as Maui, Hawaii; Eglin, Florida (Figure 4.2); Thule, Greenland (Figure 4.3); and Diego Garcia, Indian Ocean (Figure 4.4).

The data is transmitted directly to JSpOC via satellite, ground wire, microwave and phone. Every available means of communications is used to ensure a backup is readily available if necessary. However, the quality of orbit estimates does not depend as much on the number of observations; it is more important that observations be well distributed in time and location.



Figure 4.1: Configuration of the US SSN 2014

To set up and manage the catalogue, the SSN uses three different orbit estimation and propagation models: a model called General Perturbations (GP), a semi-analytical model, and a Special Perturbations model (SP) based on numerical integration.

GP and SP are not US Air Force unique terms. They evolved from Brouwer's seminal paper [4.5] on semi-analytic models and are compact, efficient, lower-fidelity approximation for perturbed orbits (orbits with non-conservative forces).



*Figure 4.2: Eglin radar*



*Figure 4.3: Thule radar*



*Figure 4.4: Diego Garcia Electro-Optical Deep Space Surveillance System*

The United States Air Force (USAF) version of GP only includes perturbations up to J4 in the geoid.

Special perturbations SP are numerical integration of the complete equations, but still with approximations to the geoid, drag, and other non-conservative forces. The degree of geoid approximation in the USAF SP is at least J4 and probably higher, but documentation is not generally available. Source code and scholarly expositions that enable user understanding in depth are also restricted. Only less precise information produced with the GP model is available on the Space Track website.

This information is given in the Two-Line Element (TLE) format: the SSN and COSPAR number of the object, average orbital elements and other parameters on 2 lines<sup>9</sup>.

The TLE provides knowledge of the orbit, whereby the uncertainties can reach hundreds of meters in LEO and several kilometers in GEO.

<sup>9</sup> see detail and format on the Space Track website, at <https://www.space-track.org/documentation#/tle>

This information is not precise enough to carry out a reliable collision risk prediction. Nevertheless, since 2010, the JSpOC has been setting up agreements with operators wishing to be provided with collision warnings based on precise data (SP) and international standard messages called Conjunction Data Messages (CDMs) are sent to the operators.

CDMs contain accurate information on dangerously close objects and the associated uncertainties, which makes it possible to calculate the collision probability. The threshold of danger is the satellite owner's prerogative, but USAF CDMs are generally issued for approaches estimated within 1 km of cataloged satellites in LEO and 5 km in GEO.

### 4.3. Russia

#### 4.3.1. Space surveillance system

According to the information provided for the public, Russian space surveillance system is operated by the 821<sup>st</sup> Main Center for Intelligence Space Situation (MCISS, former Space Surveillance Center), which was formed on December 1<sup>st</sup> 2009, and since December 2011 has been part of the Space Command of the Russian Aerospace Defense Forces [4.14].

As in the case of the US SSN, sensors forming the Russian SSN are divided into three categories: dedicated, collateral, and contributing:

- Dedicated sensors are operationally controlled by the MCISS with a primary mission of space surveillance support.
- Collateral sensors are operationally controlled by the Space Command of the Russian Aerospace Defense Forces with a primary mission other than space surveillance, usually ballistic missile warning.
- Contributing sensors are those owned and operated by other agencies (Roscosmos, Russian Academy of Sciences, and others) that provide space surveillance support upon request from the MCISS.

To monitor objects on low Earth orbits and determine parameters of their orbits, the system uses the ballistic missile early-warning radar network [4.16]. The components of this network have changed quite dramatically during recent years.

At present, it includes a few old *Dnepr* ((Figure 4.10) Olenegorsk, Mishelevka and Balkhash facilities; station in Sevastopol is to be modernized and returned to operational status in 2016) and *Daryal* ((Figure 4.9) Pechora facility) radars operating in the VHF range.

It also includes a number of radars of different types put into operation during the last decade or currently being built: *Volga* (the UHF range; *Hantzavichy/Baranavichy* facility, commissioned in 2003), *Voronezh-M* ((Figure 4.5) VHF; *Lekhtusi* facility – operational since 2009, commissioned in 2012; Orsk facility – under construction since Aug 2013), *Voronezh-DM* ((Figure 4.6) UHF; *Armavir* – operational since Feb 2009, commissioned in Jun 2013, *Pionersky/Kaliningrad* – operational since Nov 2011, commissioned in Dec 2014; *Barnaul* and *Yeniseysk* – initial operations since Dec 2014, commissioned in 2015), *Voronezh-VP* (VHF; Mishelevka – operational since 2012, commissioned in Dec 2014; *Vorkuta* – under construction since 2014; claimed to start construction: *Olenegorsk* – in 2017).



In addition to the dedicated early-warning radars, the *Don-2N* (Figure 4.7) radar of the Moscow missile defense system (centimeter band; Sofrino facility) and the *Dunay-3U* radar ((Figure 4.8) UHF; *Chekhov* facility) are also used for space surveillance. Depending on the radar type, the maximal range of detection of space objects is varying between 3,700 and 7,200 km.

Owing to geographical limitations of distribution of the described radar facilities, only LEO objects at orbits with inclinations between  $34.5^\circ$  and  $145.5^\circ$  can be tracked by the Russian SSN.



Figure 4.5: Voronezh-M radar



Figure 4.6: Voronezh-DM radar



Figure 4.7: Don-2N radar



Figure 4.8: Dunay-3U radar



Figure 4.9: Daryal radar



Figure 4.10: Dnepr radar



Figure 4.11: Krona system (radar facility)

The Russian space surveillance system uses the *Krona* system at Zelenchukskaya in the North Caucasus, which includes dedicated space surveillance radars and optical instruments.

The Krona radar works in both the UHF and SHF bands (Figure 4.11). The UHF antenna is 20 m x 20 m and the SHF one consists of five rotating parabolic antennas, which uses interferometry technique [4.17]. According to available public information, the UHF radar first discovers an object and discerns its orbit and characteristics. Then further detail and precise coordinates are obtained using the SHF radar. The laser station then targets the object and the reflected light is picked up by the telescope. The *Krona* system is used for radar and optical imaging of space objects.

To monitor objects on high-altitude orbits, the space surveillance system uses optical observations. The main optical observation complex called *Okno* [4.18] is located in Nurek, Tajikistan (Figure 4.12).

The complex consists of several telescopes in 10 domes. Telescopes allow detection of objects at altitudes of up to 40,000 km or even higher (depending of the visual magnitude). The complex began operations in 1999 and was commissioned in 2004.

It is reported that a new ground complex for 'identification of space objects' deployed in the Altai region has passed tests in 2014 [4.15].

In addition, it is announced that more than 10 laser-optical and passive radiofrequency surveillance complexes of new generation are planned to be deployed in the coming years.

This combined network generates more than 60,000 observations daily to maintain a catalogue of more than 13,000 objects, with declared capabilities of the processing facility to expand the catalogue up to 50,000 objects.

According to Russian military officials, it is expected that after all new radar, optical and RF surveillance sensors will be put into operation, it will significantly improve the information capabilities of the Russian SSN, will expand the range of controlled orbits and will reduce by 2-3 times the minimal size of tracked space objects.



*Figure 4.12: Okno optical complex*

To set up and manage the catalogue, the Russian SSN uses several different models (analytical, semi-analytical, and numerical).

#### **4.3.2. Automated Warning System on Hazardous Situations in Outer Space (ASPOS OKP, Roscosmos)**

In 2012, the Russian Space Agency (Roscosmos, now the State Space Corporation ROSCOSMOS) has started operation of the Automated Warning System on Hazardous Situations in Outer Space (ASPOS OKP) [4.19].

The system includes the Main information and analytical center located in the Mission Control Center (MCC) near Moscow, a detachment at the Keldysh Institute of Applied Mathematics (KIAM) of the Russian Academy of Sciences (responsible for monitoring hazardous situations at high Earth orbits), a detachment at the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) of the Russian Academy of Sciences (responsible for space weather monitoring and forecasts) and the network of optical facilities (Figure 4.13) operated by Astronomical Scientific Center Ltd.

The system is aimed at collecting (using dedicated, collateral and contributing electro-optical and passive radio-frequency sensors), processing and analyzing information on objects at LEO, MEO, HEO and GEO required for provision of safety of operations of spacecraft under control of Roscosmos, Russian Satellite Communication Company and non-governmental Russian satellite operators.





Figure 4.13: Some of ASPOS OKP optical facilities and instruments

The Federal Space Program 2016-2025 (FKP-2025) approved by the Russian government early in 2016 envisages further development of ASPOS OKP including deployment of new monitoring stations. One of such stations will be located in Brazil [4.20].

### 4.3.3. International Scientific Optical Network (ISON)

Since it started in 2005, the ISON project [4.6] has grown considerably: as of the mid of 2016 it brings together nearly 40 observation facilities located in 14 countries (Australia, Bolivia, Georgia, Kazakhstan, Mexico, Moldova, Mongolia, Russia, South Africa, Spain, Switzerland, Ukraine, United States and Uzbekistan). It makes use of more than 90 telescopes with aperture diameters between 0.2 and 2.6 m. The Keldysh Institute of Applied Mathematics (KIAM) of the Russian Academy of Sciences provides overall coordination of the network.

The ISON network is a civilian non-governmental network capable of providing space surveillance information on high altitude orbits (Figure 4.14). The system covers the whole of the area around the geostationary orbit (GEO) and is able to detect and track objects in this area as well as on eccentric orbits of high altitude (HEO – High Elliptical Orbits, including GTO – Geostationary Transfer Orbits and Molniya-type orbits).

Hundreds of hitherto unknown objects have been discovered in GEO and HEO thanks to ISON. ISON was responsible for finding and tracking Comet ISON. This network allows every object over 1 m and around 90% of objects over 50 cm located in the vicinity of the geostationary orbit to be constantly and independently monitored.

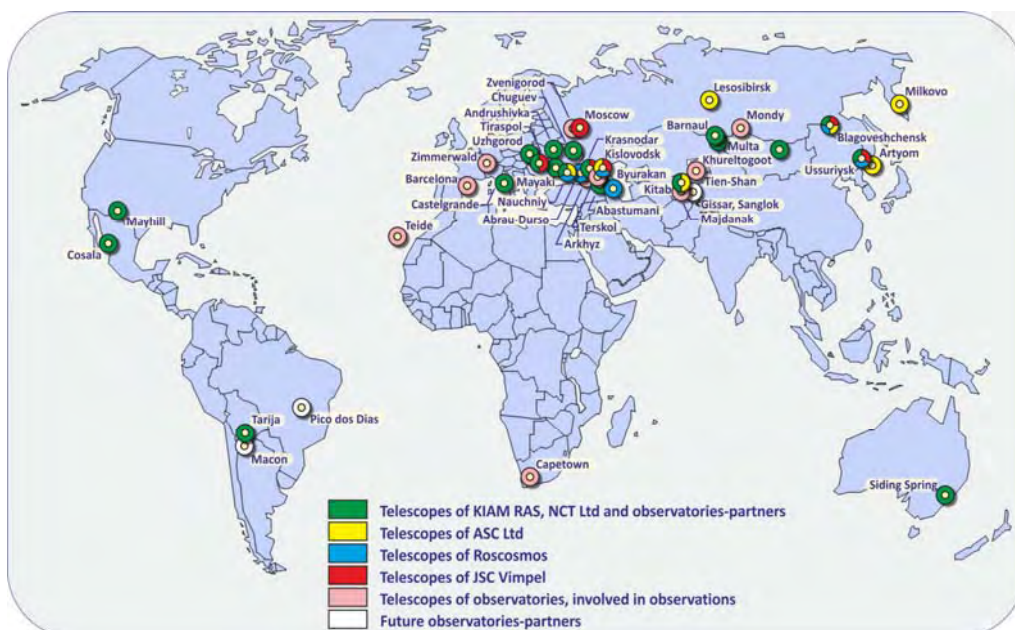


Figure 4.14: The telescopes of the ISON network

#### 4.4. France surveillance capabilities

Since 2005, France has had a limited low-orbit space surveillance capability using the *GRAVES* system (*Grand Réseau Adapté à la Veille Spatiale*, Figure 4.15), designed by ONERA, the French aerospace lab.

The system consists of a single bi-static radar associated with significant calculation systems and a secure transmission network.

The transmitter site is located near Dijon: it consists of 4 transmission antennas, each covering a sector of  $45^\circ$  in azimuth and  $20^\circ$  in elevation: the total cover in azimuth is  $180^\circ$ . The radar continuously transmits in VHF. The receiving site, located near Apt, consists of 100 antennas distributed over a metallic disc. Each antenna is linked up to an individual receiver and the detection beam is then digitized.



Figure 4.15: Emitting and receiving antennas of the Graves system

Two French operational centers are connected together through a classified link: COSMOS (Centre Opérationnel de Surveillance Militaire des Objets Spatiaux) from the French Air Force and COO (Centre Opérationnel d'Orbitographie) from CNES. The system is operated by the French Air Force. It enables a catalogue of around 2,500 objects located below 1,000 km in altitude to be independently compiled and maintained. Every object is seen at least once every 24 hours and the orbital parameters are determined using a single passage.

Transmitting antennas emit a continuous low-frequency signal towards a given angular section of space. The receiving site, located nearly 400 km away, houses a large number of omnidirectional antennas. Based on the elementary signals picked up by these antennas, a narrow-lobe beam is produced. The direction of this lobe provides an angular measurement of the object detected, while the frequency shift between the emitted signals and the received signals measures its radial velocity.

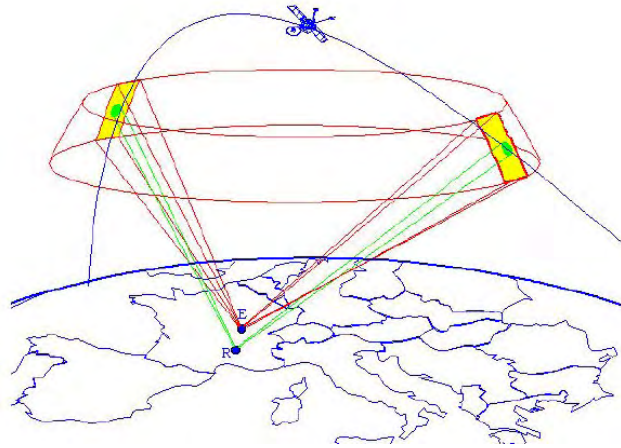


Figure 4.16: Principle of the Graves radar with 360° coverage

Based on this brand-new concept, the *GRAVES* radar provides angular and radial velocity measurements. These are fed into the orbital processing algorithms developed by ONERA to calculate the orbital parameters of the detected satellites.

Associated with the *GRAVES* surveillance radar, France uses 3 *SATAM* (*Système d'Acquisition et de Trajectographie des Armes et des Munitions*) radars to track specific objects, to refine data on the secondary object in collision risk assessment or to improve object re-entry location estimation. They are located on French territory.

France uses three *TAROT* (*Rapid Action Telescopes for Optical Transients*) telescopes located at the Calern Observatory, Observatoire de la Côte d'Azur, France, in La Réunion Island in the Indian Ocean and at the European Southern Observatory (ESO) La Silla Chili with a Field of View  $1.86^\circ \times 1.86^\circ$ . They are used to produce and maintain a database in GEO.

#### 4.5. Germany surveillance capabilities

The *TIRA* system (*Tracking and Imaging Radar*) is operated by the Fraunhofer Institute for High Frequency Physics and Radar Techniques and is located South of Bonn in North Rhine-Westphalia, Germany (Figure 4.17). It has a mechanically steerable parabolic dish antenna with a diameter of 34 m which is housed in a protective dome.

The system comprises two pulsed radars, a high power L-band radar and a Ku-band radar. The narrowband L-band radar is mainly used for the tracking of space objects while the wideband, fully-polarimetric Ku-band radar provides the raw data for the processing of high-resolution ISAR images (Inverse Synthetic Aperture Radar).

*TIRA* primarily serves the development and investigation of radar techniques for the detection, tracking and image based analysis of objects in space. The tracking radar's high sensitivity is exploited in the frame of beam-park experiments which are conducted to characterize the small size debris population in low Earth orbits.

Besides its tasks as an experimental radar sensor, *TIRA* also provides:

- Support of the launch and early operations phase of spacecraft;
- High-precision tracking data to assess and avert potential in orbit collisions;
- Image-based technical analysis of damaged or unknown satellites; and
- Real-time tracking and attitude information of risk objects during reentry.





*Figure 4.17: Tracking and Imaging Radar "TIRA" operated by the Fraunhofer Institute for High Frequency Physics and Radar Techniques*

The German Space Situational Awareness Center (GSSAC) is an interagency organization, formed by DLR Space Administration and Air Force entities. Until 2014, GSSAC activities were focused on the development of prototype SSA services and products, data processing workflows and procedures. The GSSAC is now in a transition phase to routine operations from 2015 on to incrementally achieve Full Operational Capability by 2020.

An object catalog is the backbone of SSA operations. The development of an end-to-end capability to generate, process, analyze, populate, update, and maintain an SST database requires a coordinated program of work, covering many different aspects. Such a program was set up by the DLR Space Administration, beginning with the commissioning of the *GESTRA* (*German Experimental Space Surveillance and Tracking Radar*) in 2015.

#### **4.6. ESA**

In 2008, the ESA Member States decided to set up a space surveillance program (SSA Space Situational Awareness), which aims to equip Europe with independent systems. In the field of space surveillance, services cover the detection and tracking of objects over a given size and the establishment of a catalogue of these objects, the launch of collision risk warnings, the recommendation of avoidance maneuvers, as well as the detection of explosions in orbit. Services will also cover the prediction of high-risk re-entries.

In the field of space weather, services involve monitoring the Sun, solar wind, radiation belts, the magnetosphere and the ionosphere. Furthermore, preliminary activities concerning near-Earth objects and establishing a catalogue of these objects will be carried out.

## 4.7. Japan

Japan has two observation facilities which are dedicated to the SSA activity (Figure 4.22). Both of them are owned and operated by Japan Space Forum (JSF) with technical support from Japan Space Guard Association (JSGA).

Bisei Space Guard Center (BSGC, Figure 4.18) which is located at Bisei, Okayama is specialized in the GEO observation and equipped with three unique optical telescopes, a 1 m aperture Cassegrain type telescope with 3 degree FoV (Figure 4.19), and a 0.5 m aperture Cassegrain type telescope with 2 degree FoV (Figure 4.20).

On the other hand, Kamisaibara Space Guard Center (KSGC) at Kamisaibara, Okayama for the LEO observation is equipped with a 3 m x 3 m aperture Phased Array Radar System operated in the frequency of 3.1-3.4 GHz, which can detect 1 m or larger debris at 600 km in altitude and can track ten objects simultaneously (Figure 4.21).

BSGC started its operation in 2002 and KSGC in 2004. Japan Aerospace Exploration Agency (JAXA) is maintaining its own catalogue with several hundred space objects around the Earth and is providing JSpOC with observation data based on the SSA Data Sharing Agreement between Japan and US which was concluded in 2013.



Figure 4.18: Bisei Space Guard Center BSCG

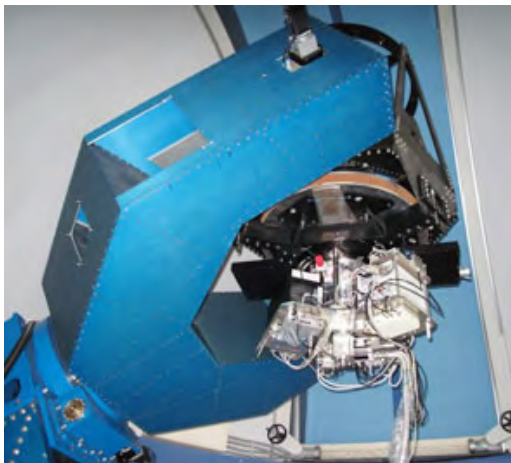


Figure 4.19: BSCG 1 m telescope



Figure 4.20: BSCG 0.5 m telescope



Figure 4.21: Kamasaibara Space Guard Center KSGC



Figure 4.22: Location of Japan Space observation

JAXA is also carrying out research and development on optical observation technologies pursuing a more efficient SSA system. An optical observation facility which consists of a 35 cm-, a 25 cm- and a 18 cm telescopes is used to take the data of GEO and LEO objects (Figure 4.23).

A FPGA board which analyzes numerous large CCD and CMOS frames taken with optical observation equipment was developed to detect faint space objects (Figure 4.24).



Figure 4.23: The optical observation facility of JAXA. Three small telescopes (35 cm, 25 cm and 18 cm) are installed in the facility [JAXA].



Figure 4.24: FPGA board for numerous large CCD frames. This enables the detection of faint moving objects within realistic analysis time [JAXA].



#### 4.8. Commercial Space Operations Center (ComSpOC®)

Major aerospace entities now recognize commercial potential in filling space track coverage and data gaps and are developing, prototyping and deploying both ground- and space-based observation systems that will greatly enhance space safety.

An example of this is the Commercial Space Operations Center (ComSpOC®), a space situational awareness facility that fuses satellite-tracking measurements from diverse partnering sensor organizations and sensor types with a complete SSA Software Suite (SSASS) [4.7, 4.8]. The ComSpOC® sensor network is shown in Figure 4.25.



Figure 4.25: Sensors in the ComSpOC® Observing Network [4.7, 4.8]

The ComSpOC uses a global collection of geographically diverse sensors comprised of optical, passive RF, and radar sensors.

As of May 2015, this network included 2 MW radars (Figure 4.26) and over 60 optical telescopes worldwide (Figure 4.27), and passive RF sensors (short-baseline array shown in Figure 4.28). Such sensors contribute observations to the ComSpOC, where those observations are fused to detect, characterize and incorporate maneuvers, produce authoritative historical ephemerides and generate predictive trajectories. Sensors in the southern hemisphere offer important observations of high inclination orbits near perigee that are not otherwise available.



Figure 4.26: 2-MW AMISR radar



Figure 4.27: Optical Large Field-of-View Telescopes



As technology has improved, it becomes easier for newcomers to develop, deploy and operate a Space Situational Awareness (SSA) tracking network. In particular, telescopes are relatively inexpensive, and improvements in CCD and optics technology offer enhanced optical tracking capabilities.



*Figure 4.28: Passive RF sensors (Allen Telescope Array w/42 short-baseline dishes)*

#### **4.9. Other sources of orbit data and conjunction services**

Additional civil and commercial sources of orbit data exist for situational awareness that either synthesize trajectories from known sources or combine observations with precise trajectories determined and planned by those who own or operate satellites.

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## 5. Collision avoidance

### 5.1. In-orbit collision avoidance

The number of objects in space has steadily increased over the past several years, so predicting collision risk in orbit has become one of the main tasks for control centers in charge of monitoring and handling satellites.

The risk of losing a satellite during a collision is no longer negligible, as presented in Figure 5.1 which shows that over a typical five-day period there are 11 approaches each with a different object and within 5 km spacing between osculating mean orbits based on Two-Line Element Sets.

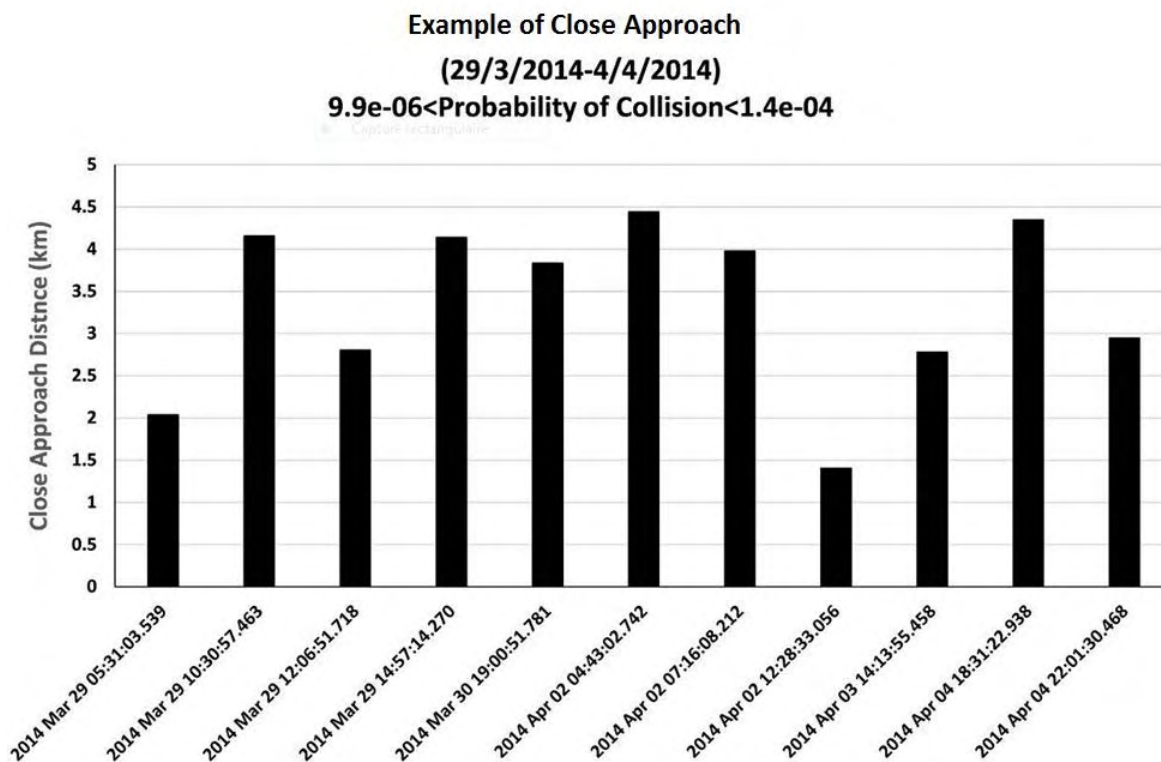


Figure 5.1: Typical Collision Risk – Example of Close Approach

It should be noted that a collision could result in the destruction of both objects and the creation of a large amount of debris. For example, in the case of the collision between the *Iridium 33* and *Cosmos 2251* satellites, two clouds of debris were created: 628 debris catalogued (with 344 still in orbit) from the *Iridium 33* satellite and 1,668 debris catalogued (with 1,102 still in orbit) from *Cosmos 2251* (situation in March 2017).

Operators manage this risk using the available space surveillance data, their own knowledge of the state of motion of their satellites, and interaction with those who operate the potential collision partners (if they are also active satellites).

This information enables them to estimate when objects will get close to each other several days in advance, calculate the risk and carry out a collision avoidance maneuver if necessary, which alters the satellite's trajectory. Every operator knows best where his satellite is, but almost none know where other satellites are other than through space surveillance data.

Flight dynamists employ a variety of methods and metrics to identify and characterize the severity of an impending collision. These include miss distance, radial separation, Mahalanobis distance, a wide variety of collision probability metrics, and others.

Probability of collision ( $P_c$ ) is becoming more popular as a tool to assess conjunction threats. Unlike other singular methods such as miss distance or touching covariance ellipsoids, many operators prefer  $P_c$ -based action thresholds because  $P_c$  incorporates miss distance, covariance size and orientation and the sizes of the conjuncting objects in a mathematically rigorous fashion. Additionally, collision probability metrics can be compared on an equal footing with other failure scenario probabilities such as the probability that a thruster would “stick open.”

A variety of  $P_c$  estimation techniques can be used, to include:

1. Short (or “linear”) encounters;
2. Low-velocity “non-linear” encounters;
3. Asymmetric object collision probability;
4. Maximum probability.

These techniques require knowledge of:

1. Object size/shape/orientation;
2. Uncertainty size/shape/orientation;
3. Nominal miss distance geometry and magnitude.

These collision metrics may change as the predicted Time of Closest Approach (TCA) approaches, and more observations can be collected and incorporated. The need for a collision avoidance maneuver often depends on whether the probability increases or decreases and whether the close approach distance grows or diminishes.

Operators must decide when or whether to perform a maneuver, balancing quality of available data and the time required to maneuver. Generally, this decision can and must be made no more than about 48 hours in advance of the estimated TCA. There is no guarantee that a maneuver will prevent a collision. We can only lower the probability that there might be a collision.

The monitoring procedure is difficult and labor intensive because of the imprecision of the available data: it generally consists of a basic level of automatic monitoring, which detects potential risks, and which then have to be analyzed in more detail by experts in orbit and trajectory estimation models.

If the risk appears to be serious, trajectography measurements are requested from the available radar systems (generally military systems): a better knowledge of the trajectory of the dangerous object can be obtained from these measurements and then the decision to carry out a collision avoidance maneuver can be taken if necessary. The whole prediction procedure takes several days (usually 3).

Finally, it should be noted that the collision avoidance maneuver alters the trajectory of the monitored satellite and generally makes it necessary to interrupt the satellite mission, which can be a serious constraint in the case of an observation satellite. A return maneuver into the nominal orbit will then be necessary before resuming the mission.

All of this, therefore, mobilizes important resources: experts, controllers, radars, calculation systems, TM/TC stations, etc. and also results in propellant being consumed, which accordingly reduces the lifespan of the satellite. To reduce the impact of these maneuvers, it is sometimes possible to anticipate a scheduled maneuver (a station-keeping maneuver, for example) by performing earlier than planned a maneuver, which it would have been necessary to do in any case, thereby reducing the cost of propellant. The general concept of collision avoidance is described in [5.6].

Depending on their size and experience, operators analyze collision warnings messages called Conjunction Data Messages (CDMs) directly to assess collision risk and decide on the necessity to perform mitigation maneuvers or use a “*Middle Man*” service. This “*Middle Man*” receives the CDMs, assesses the conjunction, analyzes the risk and provides the operator with recommendations on mitigation maneuver size and timing in case of risk level higher than the defined criteria, which reduces drastically the workload on the operator. *CARA* (*Conjunction Assessment Risk Analysis*) by NASA and *CAESAR* (*Conjunction Analysis and Evaluation Service: Alerts and Recommendations*) by CNES are examples of “*Middle Man*” service providers.

*CAESAR*, operational since 2012 as a French public service, uses data from the French assets and any CDM available (coming mainly from JSpOC). As an example in 2016, for 15 LEO and 8 GEO satellites monitored by *CAESAR*, around 1,500,000 Conjunction Data Messages were handled leading to 65 high level collision risks with alert to operators, 19 tracking support requests and finally 17 collision avoidance maneuvers.

## **5.2. Satellite owner/operator collaborative collision avoidance**

While a relatively high percentage of the orbital population is comprised of space debris, the only portion of the orbital catalog that we can readily influence to prevent collisions is the active satellite population.

Since non-cooperative tracking techniques such as radar, optical and passive RF are only able to observe what’s already occurred (i.e., historical tracking), and they are often not a reliable source of predicting future motion for active satellites.

Unknown maneuvers drag configuration changes, momentum dumps and other un-modeled forces, such non-cooperative techniques often degrade or invalidate SSA products, preventing the production of timely and actionable SSA data that can serve as the basis for valid collision avoidance processes and procedures.

In recognition of these shortcomings, three space operators (Inmarsat, Intelsat and SES) formed the Space Data Association (SDA) in 2009. The SDA is a consortium of 33 satellite operators (Figure 5.2) spanning all orbit regimes, whose charter is to seek and facilitate improvements in the safety and integrity of satellite operations through wider and improved coordination among satellite operators and to facilitate improved management of the shared resources of the space environment and the RF spectrum.

The SDA holds three key mission areas:

1. Collision avoidance monitoring (Conjunction Assessment) / Maneuver Planning Validation / Flight Safety
2. Radio Frequency Interference (RFI) mitigation / Geolocation support

### 3. Contact information (operations center) for participating satellites

The SDA maintains a secure Space Data Center (SDC) which aggregates and analyzes actionable predictive satellite ephemerides produced by all participating operators to monitor all SDA subscribers' space assets for potential collision risks and RFI incidents.

For any immediate collision risks with an operator's satellite(s), the subscribers are notified of the upcoming close approach so that the subscriber can take mitigation actions when necessary.



Figure 5.2: SDA Membership, 2017

The SDC performs continual comparisons of both positional and close approach metrics produced by disparate entities as shown in Figure 5.3.

Conjunction for SAT 1		[+] and SAT 2	
CDM min range at TCA (2015-01-12 12:09:37.109 UTC; 2.45 days out) = 5.157 km			
Ephemeris vs. CDM/TLE Comparison			
Primary	CDM Range at TCA: 10.404 km	TLE Range at TCA: 13.875 km	
Primary ephemeris epoch: 2015-01-09 00:00:00.000 UTC (1.06 days old)			
CDM vs. TLE Comparisons			
Primary Range at TCA: 18.847 km		Secondary Range at TCA: 7.745 km	
CDM Conjunction Comparisons			
CDM vs. CDM	TCA: 2015-01-12 12:09:37.109 UTC, 5.158 km		
Ephemeris vs. CDM	TCA: 2015-01-12 12:09:36.074 UTC, 6.509 km		
Ephemeris vs. TLE	TCA: 2015-01-12 12:09:37.266 UTC, 12.962 km		
Ephemeris vs. Ephemeris	N/A		
Complete AGI Viewer Scenario			
Notes:			
• Valid ephemeris for primary			
• No ephemeris available for secondary			

Figure 5.3: Example comparisons of conjunction predictions from disparate organizations



### 5.3. Collision risk mitigation in mission design and disposal

In typical satellite operations, collision risk formulations ingest relative orbit geometries, object sizes and errors in the positional knowledge as a function of time to estimate collision probability. In contrast, minimization of long-term collision risk for spacecraft mission design, debris characterizations and post-mission disposal cannot be based on positional error uncertainty volumes or in-track positions, since those inputs cannot be anticipated.

Recently, new methods [5.4] have been devised to help mission design and flight dynamics experts identify orbital regimes with reduced collision risk. While these methods cannot guarantee that a collision will not occur, they can at least identify mission and disposal orbits which have lower average collision rates.

### 5.4. Collision avoidance at launch

During the launch phase and the initial orbits, the upper stage of the launcher and the satellites put into orbit will cross the orbits used by other operators: this is particularly true in the case of a geostationary transfer orbit whose perigee is in low orbit and whose apogee borders on 36,000 km in altitude.

These newly injected objects will not be listed in the catalogues until some hours later (generally 48 to 72 hours), which means that other space users have no means of monitoring the collision risks between these new objects and their satellites. This is particularly important in the case of vehicles with a crew on board (*ISS* for example) whose control center cannot monitor the risk posed by these objects.

The launch operator alone has access to the information on the planned trajectory: he can therefore carry out the collision risk prediction. This prediction must be made for any launch date within the launch window, while taking account all the objects put into orbit (launcher stage, satellites, structural elements) over a period of around 48 hours (see Figure 5.4).

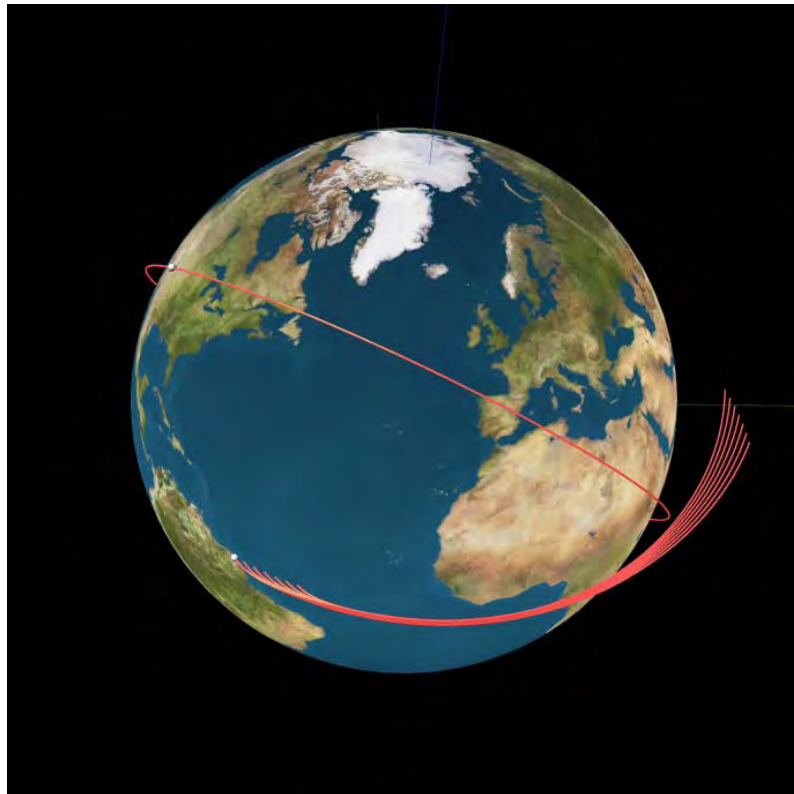
If there is a risk, shifting the launch time slightly should lead to a safe distance between objects. Once 48 hours have passed, it can be assumed that the new objects have been catalogued and that each operator is able to perform his own monitoring. However, the identity and states of motion of several small satellites deployed from the same launch vehicle have sometimes not been determined for weeks, even never. Launch of the *POPACS* cluster is in this category. Deployment of the *Planet Labs Flock* from the *ISS* suffered the same problem.

The main difficulty in predicting collision risk comes from including the dispersions of the different objects on the orbital parameters at injection: the propagation of these dispersions over 48 hours leads to relatively large volumes of error around each object and could lead to total closure of the launch window if all the catalogued objects were considered in the analysis. It is for this reason that collision risk prediction at launch is generally limited to manned vehicles or some satellites of special interest.

Figure 5.4 displays an example of the relative positions of the *ISS* orbit and ascent trajectories of a launcher from Guiana Space Center (CSG), each ascending curve corresponding to a different launch time, taking into account Earth rotation [5.9].



This kind of analysis, performed for every launch, enables to remove any collision risk during the launch phase.



*Figure 5.4: Risk collision between the ISS and a launch trajectory from Kourou: each launch time corresponds to a different trajectory because of the Earth's rotation [5.9].*

## 5.5. International standards and best practices

The International Standards Organization (ISO) and other international standards bodies (CCSDS, ANSI, ECSS) have established international standards which codify recognized orbital debris mitigation best practices and norms of behavior [5.6].

Operators are encouraged to consult these standards as well as UN COPUOS orbital debris mitigation guidelines to enhance flight safety and collaboration with other space operators.

## References

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## 6. Hypervelocity impact effects and protection

### 6.1. Introduction

The historical practice of abandoning spacecraft and upper stages at the end of mission life has allowed more than 7.5 million kilograms of debris to accumulate in orbit.

These debris particles, with sizes ranging from micrometers to meters, pose a significant threat to current and future space missions. The trajectories of debris particles with sizes in the range of a few centimeters and above can be determined through radar or optical telescope observations, and hence, collision risks with large spacecraft can be predicted to some accuracy. Smaller debris particles, with sizes of 1-2 centimeters and below, cannot be observed from Earth.

Collision risks from these small size debris particles must be calculated from statistical flux models on a probabilistic basis. Also, micrometeoroids contribute to collision probability. According to current flux models, in low Earth orbits the ratio of impacts of meteoroids to debris is about one to ten, while in GEO this ratio nears one.

The incident velocities between space debris and spacecraft in low Earth orbits range up to 15.6 kilometers per second (km/s), which corresponds to head-on collisions in low altitude circular orbits. In geostationary orbit, debris impacts on spacecraft occur at lower velocities, ranging from a few hundred meters per second to a few kilometers per second. Micrometeoroids can have much higher impact velocities, depending on their origin.

Due to the very high impact velocities involved, even tiny particles possess considerable kinetic energy and corresponding destructive power: for example, even particles with a size of two to three millimeters can penetrate spacecraft structure walls and severely damage or destroy spacecraft components.

It is the purpose of this chapter to give an overview of hypervelocity impact effects and corresponding experimental methods in the laboratory, to summarize current experimental work in the field of impact tests on spacecraft components and protection shields, to give an overview of risk assessment methodologies for spacecraft, and to provide some current examples of on-orbit impacts.

### 6.2. Hypervelocity impact effects on spacecraft

Particles impacting at hypervelocity can damage spacecraft components in various ways:

- Micron-sized particles degrade sensitive spacecraft surfaces and equipment, like solar cells, optics, and mirrors.
- Particles in the size range of tens to hundreds of microns are capable of generating impact craters that are visible to the eye, and may perforate thin components like solar cells, thermal blankets, coatings, and space suit protective fabrics.
- Such damages have been observed on the windshield panels, thermal coatings, and other surfaces of the U.S. Space Shuttle [6.1] as well as on satellites and satellite parts returned to Earth, such as the outer panels of the *Long Duration Exposure Facility (LDEF)*, the solar arrays of the *Hubble Space Telescope (HST)*, and the *European Retrievable Carrier (EuReCa)* [6.2].

- Millimeter-sized particles can perforate structure walls of satellites and manned spacecraft. To reduce the destructive effects of impacts, all modules of the *International Space Station (ISS)* have protection shields to defeat particles in the size range of several millimeters up to about one centimeter. Components of satellite propulsion systems, including pressurized tanks and lines, are vulnerable to particles of this size, since even small perforation holes may lead to leakage or induce catastrophic fracture of the component. As an example, the coolant flow tubes within ISS radiator panels have been hardened to reduce the risk from impact induced leaks. Impacts of millimeter-sized particles may also induce considerable changes in the satellite's attitude through transfer of momentum.
- The impact of particles larger than one centimeter will lead to destruction of spacecraft components and may breakup spacecraft.

Hypervelocity impacts also generate impact plasmas that may induce discharges on solar panels and other spacecraft components. For example, the European Space Agencies' *OLYMPUS* communication satellite is believed to have failed in 1993 from hypervelocity impact induced discharges [6.3].

### **6.3. Experimental studies to investigate the effects of impacts on satellite components**

Experimental studies were conducted by space agencies to investigate the damages and the failure modes that result from impacts of space debris and micrometeoroids on satellite components.

The tested satellite components consisted of, among other things, fuel and heat pipes, pressure vessels, electronics boxes, harness, and batteries. For the test setup, the satellite components were placed behind an aluminum honeycomb sandwich panel representative of a typical satellite structure wall. During the impact test, the equipment was operated in its regular operational mode. Tests were performed using two-stage light-gas gun accelerators.

In the following sections, some results of impact tests on operating harness and computers placed behind typical satellite structure walls are provided and discussed. The tests were performed as part of an ESA project [6.4, 6.5].

#### **Investigation of data transmission degradation within electrical harness**

Electrical harnesses can claim large areas of the interior surface of satellite structure walls. The total weight of the harnesses can amount to several percent of the overall spacecraft weight. Harnesses are vulnerable because only thin insulation layers protect the wires. Furthermore, harnesses are often located just behind the satellite structure walls. An impacting particle that penetrates the spacecraft structure is shattered into many small fragments that are dispersed over a large area. These fragments may hit and damage electrical harnesses.

The harness tested in [6.4, 6.5] consisted of power cables, Raychem Spec 44, 18 AWG, twisted-pair data cables, Raychem Spec 44, 20 AWG, and one radiofrequency (RF) cable specification Sucoflex 103 from Huber & Suhner, transmitting a 9.35 GHz signal. The

cables were bound together and routed in loops to increase the probability of fragment impact on the cables, as shown in Figure 6.1. They were spaced approx. 10 mm from a 1.5 mm thick Al 7075 witness plate.

The harness was placed at a stand-off  $S_1$  of 10 and 100 mm behind an aluminum honeycomb sandwich panel with multi-layer insulation. The sandwich panel consisted of 0.41 mm thick Al 2024 T3 face-sheets and a 35 mm thick Al honeycomb core (specification 2.0-3/16-07P-5056-MIL-C-7438G). Multi-Layer-Insulation (MLI) with an areal density of 0.447 kg/m<sup>2</sup> was placed on top of the sandwich panel (i.e., space-facing).

Each of the three power cable pairs was connected to a 30 VDC power supply on one side and a 200  $\Omega$  resistor on the other side (simulating the electrical load). Voltage drop at both the power supply and the resistor was measured individually for all cable pairs.

For the data cables a pseudo-random bit stream was generated, and differential data transmission technique was used. For power and data cables, the nominal input voltage and the output voltage were monitored to quantify the impact effect.

The RF cable was connected to a 9.35 GHz oscillator with a power output of approx. + 20 dBm on one side and a crystal detector on the other side. The voltage drop at the crystal detector provides a means of detection of the degradation of the RF cable.

Table 6.1 summarizes a series of experiments published in [6.5].

Exp.	$S_1$ (mm)	$v_0$ (km/s)	$d_p$ (mm)	Power Cables		Data Cables		RF Cable	
				Mech.	Electr.	Mech.	Electr.	Mech.	Electr.
4728	10	6.42	2.0	none	None	none	none	craters	none
4732	10	6.55	2.5	insul.	dist'd	severed	failure	craters	dist'd
4731	100	6.53	2.5	insul.	Error	craters	error	craters	dist'd
4727	100	6.77	3.0	insul.	dist'd	insul.	failure	craters	dist'd
4736	100	6.78	4.0	insul.	Error	insul.	failure	insul.	e.+deg.
4738	100	7.70	2.0	none	None	craters	none	craters	none
4734	100	7.59	2.5	craters	None	insul.	error	craters	dist'd
4733	100	7.68	3.0	insul.	error	craters	dist'd	insul.	error

Table 6.1 Summary of HVI experiments on harness and results (aluminium projectiles, perpendicular impact)

$S_1$  – stand-off between rear side of structure wall and cable,  $v_0$  – impact velocity,  $d_p$  – projectile diameter  
Mech. – mechanical damage ('none' = no damage to cable insulation, dust deposits possible; 'craters' = one or more craters in insulation (insulation may or may not be perforated);

'insul.' = insulation partially removed from cable (the conductor is visible); 'severed' = cable (partially) severed with at least one conductor completely cut.)

Electr. - electrical performance ('none' = signal distortion less than 1 % of nominal value; 'dist'd' = signal distortion, but no transmission error;

'error' = signal transmission error encountered, but no degradation;

'e.+deg.' = signal transmission error encountered and cable degraded;

'failure' = cable no longer working due to either a short circuit or a destroyed conductor.

A power cable transmission error was assumed if the signal rose or dropped above or below 20 % of its nominal value with at least a 1  $\mu$ s duration. A data cable transmission error was assumed if a data transmission error was encountered with at least a 1  $\mu$ s duration. An RF cable transmission error was assumed if the signal rose or dropped above or below 20 % of its nominal value with at least 10  $\mu$ s duration.)

Figure 6.1 shows an example of the recorded data during an impact test on a data cable transmitting data using the differential transmission method. Up to several tens of microseconds after the impact, temporary data transmission errors are observable, followed by nominal operation of the cables afterwards.



More severe impact damages up to permanent failure of the cable (e.g. from severing or short-circuit) are obtained when larger or faster projectiles are used. It was found that increasing the stand-off distance between structure wall and harness reduces the probability of cable failure.

Therefore, harnesses should be moved away from structure walls or alternatively, protective fabrics such as Nextel<sup>TM10</sup> or Kevlar<sup>TM</sup>, should be wrapped around the harness, as was done by NASA for ISS harnesses routed outside the manned modules. Impact conditions are described in [6.6].

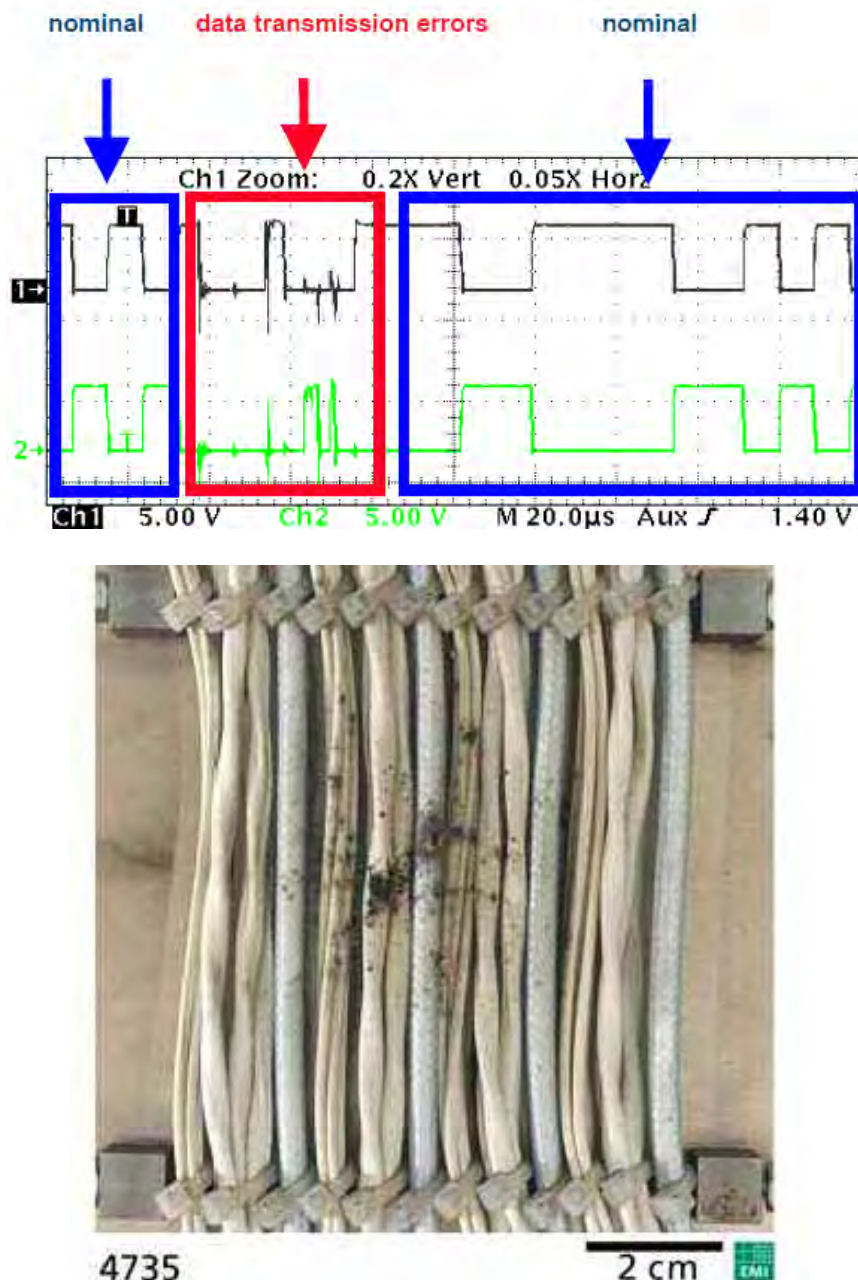


Figure 6.1: Impact test on operating harness placed behind satellite structure wall (H/C SP = Honeycomb Sandwich panel). Top: Differential signal recorded during impact. "T" denotes the projectile impact on the honeycomb sandwich panel. Bottom: Impact damages on harness [6.6].

<sup>10</sup> Nextel is a trademark of 3M Company, and Kevlar is a trademark of E. I. du Pont de Nemours and Company.

## Investigation of electronics box failure from hypervelocity impacts

Electronics boxes (E-Box) are computers or, more generally, assemblies of printed circuit boards enclosed in an aluminum box that are widely used in all satellite subsystems including the payload.

Typically, a share of 20% to 40% of a satellite bus volume consists of electronics boxes. The casing of an E-Box is typically made of milled aluminum with a thickness of between 1 to 3 mm. If the casing of an E-box is perforated during an impact, fragments penetrate its interior and may damage or destroy the electronic components, leading to potentially catastrophic consequences for a mission if this system is not redundant.

For the laboratory hypervelocity impact tests, simplified electronics boxes representative of onboard computers were designed.

The onboard computer consisted of a Printed Circuit Board (PCB) with FPGA, clock, integrated circuits, memory units, interfaces etc., located inside an aluminum box, at a stand-off  $S_2$  of 28 mm behind the box lid. In the experiments the AI-box was placed behind an Aluminum Honeycomb Sandwich Panel (Al H/C SP) with MLI, same specification as above.

Three different stand-offs between sandwich panel and front wall of the electronics box,  $S_1$ , were selected: 0, 100 and 300 mm. The lid thickness of the electronics casing was varied between 1 and 3 mm.

In the laboratory hypervelocity impact tests, the computer-boxes were in an operational mode, performing basic read- and write-operations. The observed failure modes induced by the impact were temporary failure and permanent failure:

- The temporary failures caused interruptions in the operation of the processor, followed by nominal operation a few milliseconds later. The reason for temporary failures is assumed to be related to conductive dust, which caused transient shorts. Any temporary failure i.e., temporary loss of operational performance of electronic components may manifest itself to the system operator as an in-flight anomaly. Such in-flight anomalies, including faulty data transmission and 'ghost commands', have been reported and hence, may be explained by hypervelocity impacts.
- The permanent failures manifested as sudden loss of supply voltage or loss of nominal operation of the computer.

Table 6.2 summarizes some a series of experiments published in [6.5].

In Figure 6.2, a PCB with severe impact damages (memory chip, resistors and capacitances removed, deposits of metallic spray in various locations) and the corresponding CPU signals are shown.

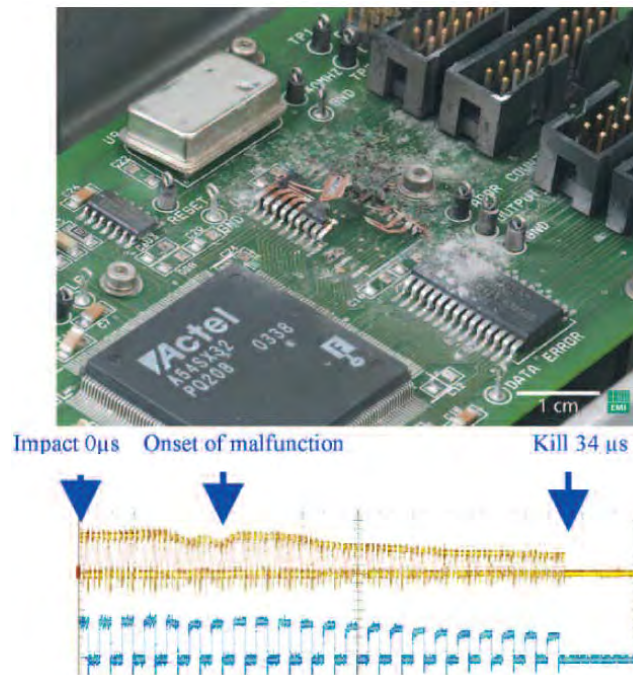


Figure 6.2: Degradation of computer performance followed by cease of operation shortly after incident of the hypervelocity particle.

Exp.	$S_1$	$t_L$	$v_0$	$d_p$	$\alpha$	E-Box Test Results	
	[mm]	[mm]	[km/s]	[mm]	[°]	Damage to Lid Mechanical Damage	E-Box failure type
4699	0	1.5	6.41	2.3	0	perforation	destroyed
4708	0	1.5	6.08	2.3	0	perforation	temporary error
4718	0	1.5	6.59	2.8	0	perforation	destroyed
4703	0	2.0	6.56	2.3	0	perforation	no malfunction
4701	0	3.0	6.17	3.2	0	perforation	destroyed
4702	0	3.0	6.65	2.5	0	no perforation	no malfunction
4721	0	2.0	6.75	3.5	45	perforation	no malfunction
4722	0	2.0	3.34	2.8	45	no perforation	no malfunction
4723	0	2.0	3.39	3.5	45	no perforation	no malfunction
4714	100	1.5	3.66	2.5	0	no perforation	no malfunction
4715	100	1.5	3.52	3.2	0	no perforation	no malfunction
4716	100	1.5	3.81	4.0	0	perforation	destroyed
4712	100	1.5	4.7	2.5	0	perforation	no malfunction
4704	100	1.5	6.56	4.0	0	detached spall	no malfunction
4706	100	1.5	6.17	4.5	0	perforation	temporary error
4719	100	1.5	6.55	4.5	45	no perforation	no malfunction
4720	100	1.5	6.60	5.5	45	no perforation	no malfunction
4711	300	1.0	5.8	3.2	0	perforation	no malfunction
4710	300	1.0	5.44	4.0	0	perforation	destroyed
4700	300	1.5	6.76	5.0	0	detached spall	temporary error
4709	300	1.5	5.66	5.5	0	perforation	destroyed

Table 6.2 Test results matrix from HVI tests on E-Boxes

$S_1$  – stand-off between rear side of structure wall and E-Box front lid,  $t_L$  – thickness of E-Box cover lid,  $v_0$  – impact velocity,  $d_p$  – projectile diameter,  $\alpha$  impact angle ( $0^\circ$  corresponds to perpendicular impact direction) [6.5]

#### 6.4. Light-gas gun accelerators: workhorses for experimental impact testing

Experimental impact testing is necessary for understanding the effects occurring at hypervelocity impact and for qualifying shielding systems against design criteria.

Two-stage light-gas gun accelerators are best suited for such investigations because they are capable of accelerating projectiles of relevant sizes (order of millimeters) to relevant impact velocities (order of 10 km/s). These types of gun accelerators have been operated since the end of the 1940s.

Figure 6.3 illustrates the basic components of a two-stage light gas-gun.

Overviews of working principles and specific setups are given, for example, by [6.7] and [6.8]. During the operation of a two-stage light-gas gun, gas pressures in excess of 1 GPa (10,000 bar) are generated temporarily, exerting enormous loads onto the gun components. Safe control of such tremendous pressures is very demanding, with regard to both engineering design as well as operational procedures.

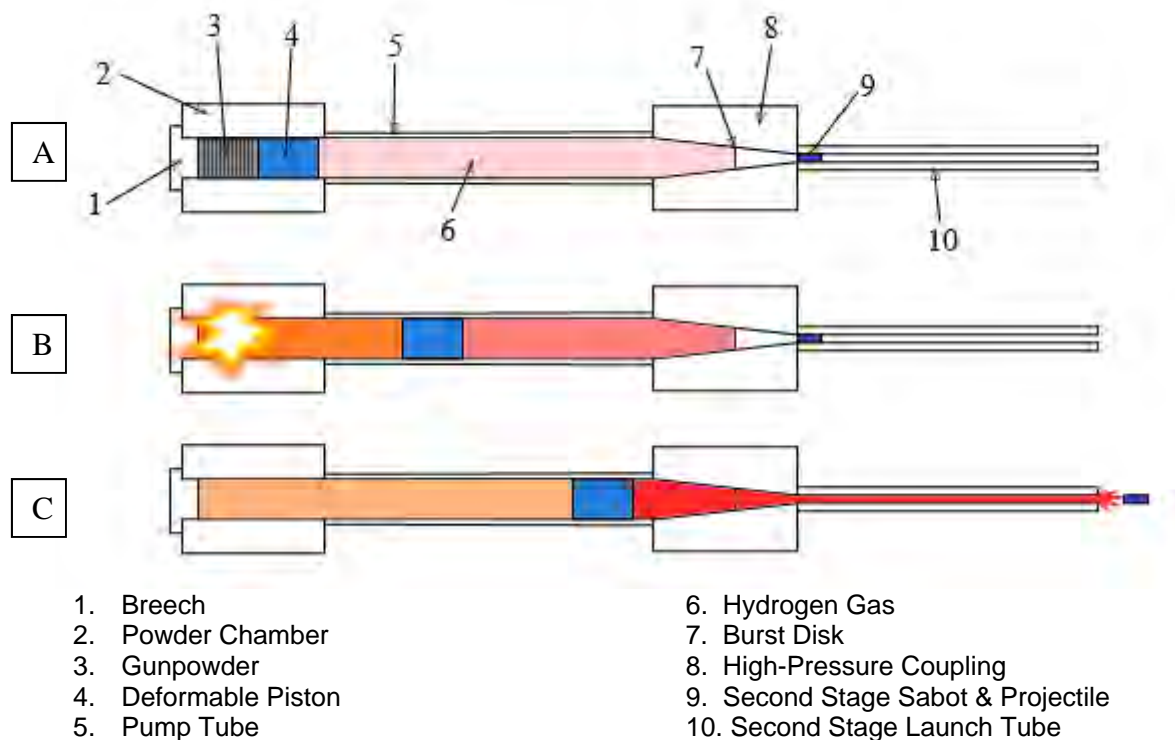


Figure 6.3: Two-Stage Light-Gas Gun Launcher [Johan Fredriksson]

Diagram (A) shows launcher before firing.

Diagram (B) depicts launcher after first stage gunpowder has ignited and the piston is traveling down pump tube, but before the burst disk has ruptured.

Diagram (C) is after the burst disk has ruptured due to high pressure in the hydrogen gas, causing the second stage sabot and projectile to be released down the second stage launch tube. Note that typically the deformable piston can be located further into the high pressure coupling at this point in the launch cycle.

At increasing projectile kinetic energy, the most heavily loaded parts of the light-gas guns experience considerable wear and erosion (e.g. [6.9]), causing experiments at high kinetic energies to be very expensive or even impossible. Thus, the main factor limiting the performance of such guns is of technological nature and related to handling the required high pressures. For this reason, the highest muzzle velocity ever achieved by a two-stage light-gas gun, which amounted to 11.3 km/s, obtained at NASA Ames facility [6.10], was never attained again.

Three-stage light-gas guns provide an interesting alternative to two-stage gun technology. A three-stage setup, [6.11], has been able to accelerate masses of 0.154 g to velocities of 8.65 km/s with only limited damage to the launcher components. The corresponding UDRI facility is currently achieving velocities of nearly 10 km/s [6.12].

Table 6.1 (cf. [6.13]) summarizes the performance of the largest and fastest light-gas gun accelerators worldwide by listing the facility parameters and selected reported experimental results.

The geometries of all facilities vary considerably: 1.8 to 30.5 m pump tube length, 40 to 355.6 mm pump tube diameter, 1.5 to 58.5 m launch tube length, 5.6 to 203.2 mm launch tube diameter.

Only three facilities (EMI SLGG, NASA Ames, UDRI) exist worldwide that have reported test results above 9 km/s within the last twenty years, and only two facilities, AEDC and EMI XLLGG, are able to accelerate projectile masses of 100 g or above to velocities in excess of 5 km/s.

Institute	EMI SLGG	UDRI	NASA AMES	NASA AMES	EMI XLLGG	AEDC 3.3"	AEDC 8"
Pump tube length (m)	1.8		15.18	15.18	14	30.5	30.5
Pump tube diameter (mm)	40		-	64.4	150	355.6	355.6
Launch tube length (m)	1.5		-	3.9	12	30.5	58.5
Launch tube diameter (mm)	8.5		5.6	12.7	50	83.8	203.2
Projectile mass (g)	0.0048*	0.0041*	0.0453*	0.94	100	500	6000
Projectile velocity (km/s)	9.1	9.89	11.3	9.54	7.4	7	5

Table 6.1 Acceleration performances of the world's most powerful two- and three-stage light-gas guns [6.13]  
EMI SLGG: EMI's Space Light Gas Gun, Freiburg, Germany.  
UDRI University of Dayton Research Institute Three Stage Launcher.  
NASA AMES: Ames Research Center, CA, USA.  
XLLGG: EMI's Very Large Light Gas Gun, Efringen-Kirchen, Germany.  
AEDC: Arnold Engineering Development Center, Tennessee, USA.  
\*projectile mass excluding sabot.

## 6.5. Shielding investigations for spacecraft

A simple dual-wall shield is called a "*Whipple shield*" after Fred Whipple who proposed in the 1940s a meteoroid shield for spacecraft consisting of a thin, sacrificial bumper followed at a distance by a rear wall [6.14]. The *Whipple shield* is shown in Figure 6.4.

The function of the first sheet or "*bumper*" is to break up the projectile into a cloud of material containing both projectile and bumper debris. This cloud expands while moving across the standoff, resulting in the impactor momentum being distributed over a wide area of the rear wall. The back sheet must be thick enough to withstand the blast loading from the debris cloud and any solid fragments that remain. For most conditions, a Whipple shield results in a significant weight reduction over a single plate, which must contend with deposition of the projectile kinetic energy in a localized area.

*Whipple shields* have been used since the early days of space flight. They typically provide protection from 1-6 mm diameter aluminum projectiles at light-gas gun velocities, and are used on *ISS* where few micrometeoroids and space debris impacts are expected (i.e., in well shadowed areas of the spacecraft where less shielding protection is needed).



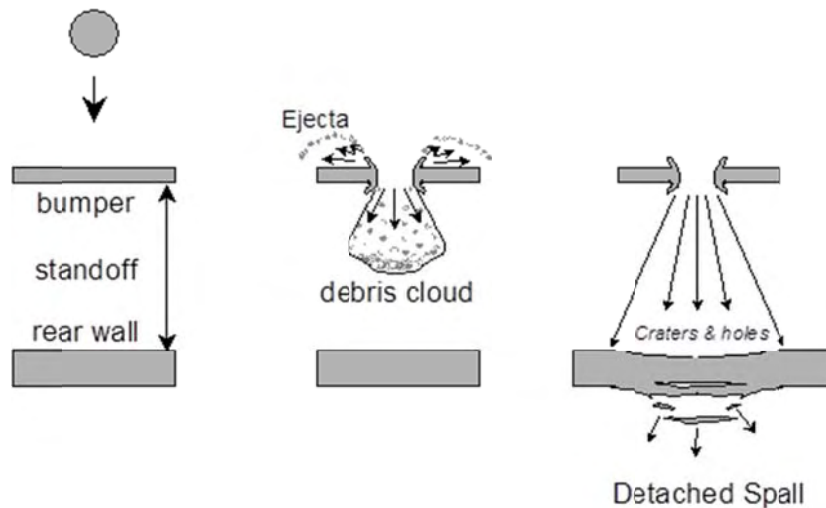


Figure 6.4: Whipple Shield

Left: Whipple shields consist of a bumper, standoff (gap or spacing), and rear wall.

Middle: Hypervelocity impacts will generate a cloud of bumper and projectile debris that can contain solid fragments, liquid, and vapor particles.

Right: The rear wall must survive the fragments and debris cloud impulsive loading. It could fail by perforation from solid fragments, spall, or tear and petal from the impulsive loading.

Incorporating more efficient, multi-bumper shielding concepts can provide significant mass savings. Typically, 50% or more mass savings are possible using multiwall shields (2 to 4 bumpers and a rear wall) compared to dual-wall shields.

To illustrate the potential, consider four shielding concepts that are sized to stop a 1-cm-diameter aluminum projectile at 7 km/s, 0° impact angle (normal to the shield) illustrated in Figure 6.5.

These shields include a conventional aluminum *Whipple shield* with a 10.2 cm standoff  $S$ ; a Nextel™/Kevlar™ stuffed *Whipple shield* with the same standoff; a *Whipple shield* with a 30 cm standoff  $S$ ; and a Nextel™ multi-shock shield concept.

The stuffed *Whipple shield* is used extensively on *ISS* to provide protection in areas that are expected to be impacted to greatest degree by micrometeoroids and space debris [6.15]. The stuffed *Whipple shield* incorporates a blanket between the outer aluminum bumper and inner pressure wall that combines two materials: Nextel™ ceramic fabric and Kevlar™ high strength fabric.

The shielding mass estimates are made assuming the shielding encloses a cylinder, with 4.2 m inside diameter by 8.5 m long using shield design equations described in more detail in [6.16]. But it is clear for this example, that there are significant mass savings by using advanced shielding concepts (i.e., up to 50% reduction). It is possible to obtain both lower mass and more effective micrometeoroid and space debris protection capability using Nextel™/Kevlar™ stuffed *Whipple* and Multi-Shock shields compared to conventional *Whipple shields*.

Detailed performances of a large variety of such shields can be found in the IADC Protection Manual [6.17].

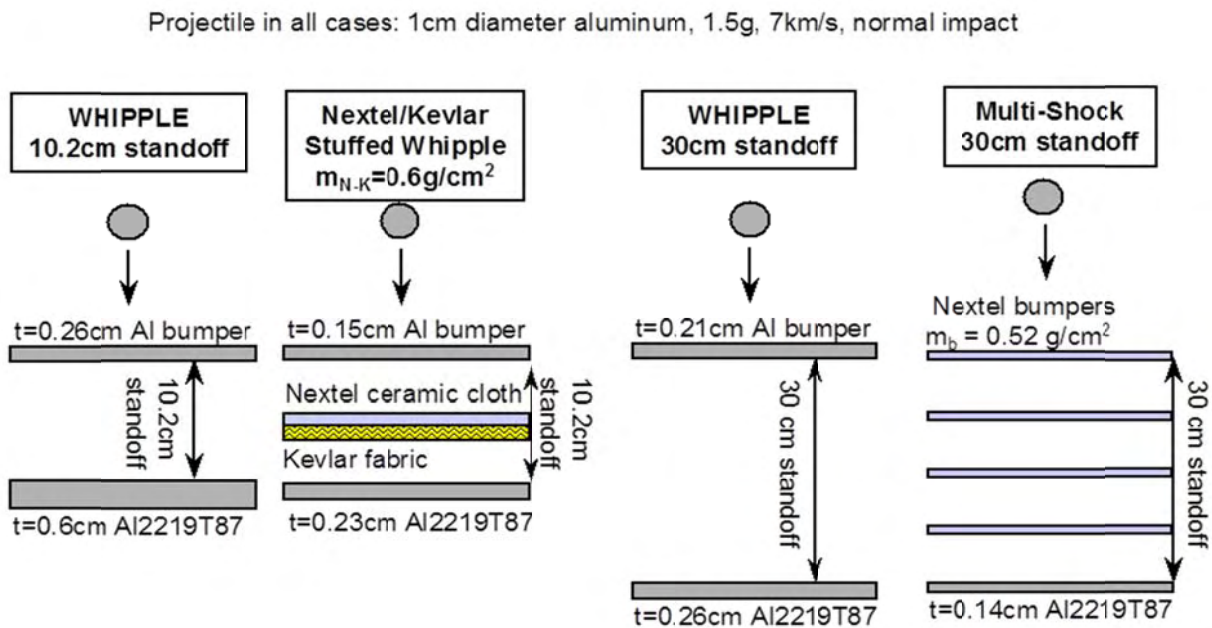


## 6.6. Risk assessment methodology for spacecraft

From the early years of space exploration, spacecraft designers have used probabilistic approaches to design for protection from micrometeoroid and space debris impacts [6.18].

Generally, mission success, reliability, and functionality are requirements applied to all types of spacecraft. Micrometeoroid and space debris protection for human exploration spacecraft is also designed to reduce the damage that would endanger the survivability of the crew.

Requirements are met when the micrometeoroid and space debris protection system and operational techniques for the spacecraft meet or exceed the required minimum acceptable risk for Loss-Of-Mission (LOM) and/or Loss-Of-Crew (LOC).



	Whipple S=10 cm	Stuffed Whipple S=10 cm	Whipple S=30 cm	Multi-Shock S=30 cm
Bumper (kg/m <sup>2</sup> ):	7.0	10.6	5.6	5.2
Rear wall (kg/m <sup>2</sup> ):	17.2	6.6	7.5	3.8
Total (kg/m <sup>2</sup> ):	24.2	17.3	13.1	9.0
Surface Area (m <sup>2</sup> )				
Bumper:	152	152	175	175
Rear wall:	141	141	141	141
Mass (kg) including support mass assumed at 30% bumper				
Bumper:	1060	1620	980	910
Support:	320	490	300	270
Rear wall:	2420	940	1060	540
Total:	3800	3050	2340	1720

Figure 6.5: Multi-wall shield comparison to Whipple shield

Spacecraft flight rules have been implemented to operate in orientations that reduce impact risks to the maximum extent possible.

Some programs have a requirement to monitor the effects of impacts with on-board sensors. Other spacecraft programs, particularly atmospheric return vehicles, have requirements to detect damage to particularly sensitive or high-risk areas of the vehicles for micrometeoroid and space debris damage, and in the case of crewed vehicles, to carry repair kits to provide a means to patch critical impact damages to thermal protection system materials and/or pressure shell.

The following general vehicle design standards for micrometeoroid and space debris protection require the following from the micrometeoroid and space debris protection system [6.19]:

1. Micrometeoroids and Orbital Debris (MMOD) risks for loss-of-mission and/or loss-of-crew shall be established.
2. MMOD protection design shall be verified by hypervelocity impact tests and analysis.
3. MMOD risk assessments shall be updated as the MMOD environment definitions change.
4. Actual damage from MMOD impacts shall be identified and compared to predictions to track and trend MMOD effects on the spacecraft.

In order to understand the dangers and effects of micrometeoroids and space debris, environmental debris models such as ESA's MASTER 2009 or NASA's ORDEM 3.0 have been developed. These provide debris flux information such as size, impact direction and debris velocity with respect to a spacecraft surface, with which information debris shielding and/or component redundancy can be applied and developed as a means of passive protection of the spacecraft.

Ballistic Limit Equations (BLEs) have been developed exploiting the results from impact tests and hydrocode analyses (numerical simulations) to predict the particle sizes causing failure of various spacecraft components as a function of impact speed, impact angle, particle density and target parameters (thickness, materials of construction, etc.).

Existing risk analysis tools such ESABASE, PIRAT and BUMPER codes apply the above-mentioned debris models in order to estimate satellite structure penetration rates.

Figure 6.6 illustrates the approach to evaluate and design micrometeoroid and space debris shielding to meet protection requirements. This analysis approach provides the means to accurately assess spacecraft risks from hypervelocity impacts, identify zones and areas of the spacecraft that are the "risk drivers" that control the impact risk, and evaluate options to reduce risk and meet micrometeoroid and space debris protection requirements.

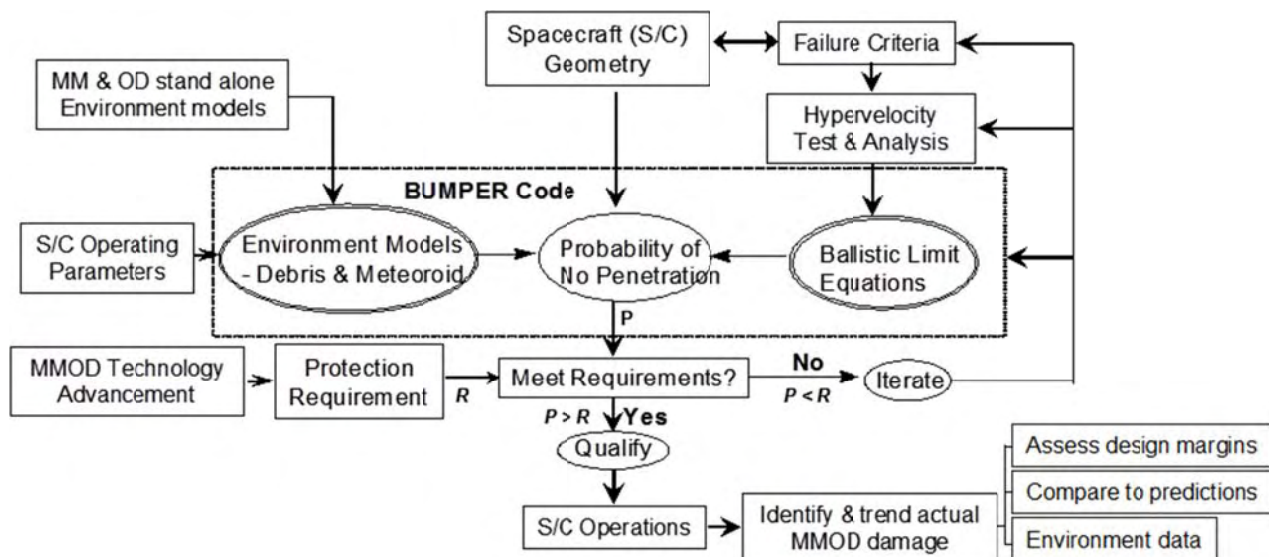


Figure 6.6: Process to evaluate and design micrometeoroid and space debris protection

An additional step in the evaluation of impact protection for *ISS* is to determine the consequences of a penetration into the crew modules and external pressure vessels.

Penetrations into the pressurized modules will lead to a depress event, as well as internal effects such as high-speed fragment release into the interior of the crew modules, light-flash, heat and possibility of fire and release of gases/liquids depending on the internal equipment that is damaged. MSCSurv code was developed to perform assessments on the consequences of penetrations into *ISS* crew modules and pressure shells.

The consequence of penetrations can be broadly categorized into:

- Penetrations that lead to loss-of-crew due to fatal injury to one or more crew;
- Penetrations that lead to crew evacuation, but not LOC;
- Penetrations that are isolated, and lead to neither LOC nor crew evacuation. MSCSurv determines if LOC or evacuation occurs due to a penetration.

The Probability of No Penetration (PNP) for the crew modules is particularly relevant to the analysis of manned-missions, such as the *ISS*. Penetration in the case of unmanned missions, however, does not automatically constitute failure of the satellite, nor does it automatically constitute the failure of any specific component.

The Christiansen-Whipple and Cour-Palais BLEs, as well as the existing software tools, are sufficient to assess penetrations through single and double wall shields [6.20].

To assess effects on hardware within the interior of typical satellite structure, the Schäfer-Ryan-Lambert (SRL) BLE was developed during an ESA study [6.4, 6.5]. The SRL ballistic limit equation computes the critical diameter necessary to produce a component failure (via penetration or detached spall from the inner side of the component cover plate) based on the material characteristics and spacing of the structure panel and the equipment cover plate, as well as the characteristics of the impacting particle.

The Particle and Impact Risk and vulnerability Assessment Tool PIRAT [6.21] uses the debris fluxes from models such as MASTER 2009 or ORDEM 3.0 to predict the localized

particle fluxes encountered by the spacecraft. Afterwards, the effects of the individual particle fluxes are evaluated deterministically.

The areas of components that are susceptible to particle impacts are determined using a geometric projected area approach. In this way, the exposed areas of components are calculated based on the relative impact trajectories of individual debris particles with respect to the S/C orientation, considering shadowing effects of internal S/C equipment.

The SRL equation (and other BLEs) is used to assess physical damage effects and the aggregate time-dependent vulnerability of each component is determined using Poisson statistics. Using a Boolean logic model of the S/C functional architecture, the associated functional degradation resulting from component failures can be determined.

As an example, [6.22], in Figure 6.7, the incident flux on external components and structure panels is shown on a face-by-face basis on a satellite on a linear scale (left and center). The failure probability for each of the analyzed satellite equipment during the mission duration is shown on the right image.

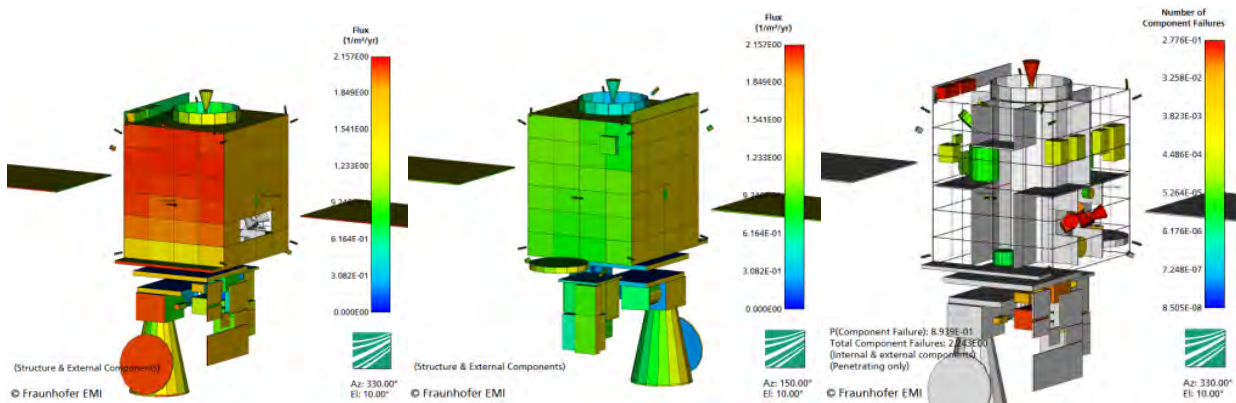


Figure 6.7: Risk and vulnerability assessment of a generic LEO satellite computed with Master 2009

Left and center: Incident flux on the satellite (in units  $1/m^2/yr$ ) from the left-leading (left image) and right-trailing (center image) perspectives. Right: Color-coded probability of failure for each of the analyzed satellite equipment, during the mission duration [6.22].

## 6.7. On-orbit impacts and analysis of returned spacecraft surfaces

While not always possible, an important aspect of ensuring proper spacecraft impact protection design is to observe and document its performance in the actual operational environment.

During *Space Shuttle* operations in the late 1990s, NASA determined that impact damage observed to the *Space Shuttle* radiators after each flight up to that point in time had been high enough to warrant upgrades to the protection of radiator flow tubes. The *Space Shuttle* Program decided to bond aluminum strips to the face sheet of the radiator panel over the flow tubes, which effectively tripled the thickness of material protecting the flow tubes. This change significantly reduced the risk of meteoroid and space debris penetration of the flow tubes, and was proven in later flights to have effectively mitigated the possibility of an early mission abort due to coolant leak from impact damage to the flow tubes.



Analysis of returned spacecraft hardware for meteoroid and space debris impact damage is also useful in updating meteoroid and space debris environment models. Impact damage to *ISS* and *Space Shuttle* has been observed on numerous occasions as shown in Figures 6.8 to 6.11.

Significant *ISS* impact damage has occurred on:

1. One of the guide-wires in an *ISS* P6 solar array was partially severed, which lead to a 3-foot-long tear in the solar array when the guide-wire snagged during a retraction and deployment cycle on *Space Transportation System STS-120* [6.23]. The guide wire was removed and “cuff-links” added by ExtraVehicular Activity (EVA) to stabilize the array.
2. Numerous outer panes of *ISS* windows have been damaged by MMOD, and in one case an *ISS* window has been covered internally using an aluminum pressure cover to maintain redundancy of the window system.
3. Near perforations have occurred to radiator coolant lines. For example, Figures 6.8 and 6.9 illustrate several impact damages on *ISS* module and US radiator coolant flow tubes.
4. EVA handholds and tools have been damaged by impacts. One EVA tool called the D-handle needed to be repaired prior to use (Figure 6.10). Other craters on handholds have been noted and are believed to be the cause of tears to EVA gloves (Figure 6.11). One EVA to *ISS* on *STS-118* was ended early due to a glove tear that exceeded safety limits.



Figure 6.8: Impacts on an *ISS* module radiator.



Figure 6.9: Impacts on a *ISS* US radiator panel (iss036e012965)



Figure 6.10: Impact crater (5 mm diameter) found on D-handle EVA tool and subsequently repaired.

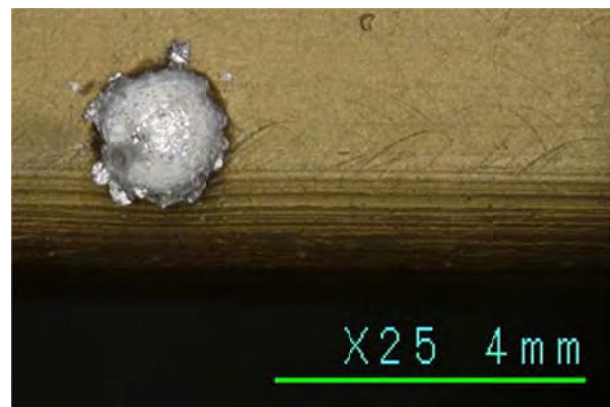


Figure 6.11: A 1.85 mm diameter crater found on an *ISS* handrail which was located on returned hardware (pump module returned on *STS-135*).



## 6.8. Concluding remarks

Spacecraft meteoroid and space debris impact protection design is based on the results from technical studies on the effects of hypervelocity impact on spacecraft systems, numerous hypervelocity impact tests, numerical simulations, and application of risk assessment tools.

Vulnerability studies have been performed to determine failure thresholds for relatively unprotected spacecraft hardware, and to assess concepts to improve impact protection. Progress has been made in researching materials and configurations that reduce the mass of meteoroid and space debris shielding.

Future efforts in impact protection are focused on developing multi-functional shielding (providing thermal and radiation protection as well as impact protection), integrating impact location and damage detection sensors, and investigating self-healing materials to seal penetrations into fluid storage tanks and pressure shells.

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## 7. Reentering space objects

### 7.1. Background

Since the first days of spaceflight about 24,000 objects from the USSTRATCOM catalogue have entered into the Earth's atmosphere [7.15]. Up to July 2016, the corresponding entering mass cumulated to around 32,000 tons. This compares with a current on-orbit population of only 7,500 tons distributed over roughly 17,900 large objects in Earth-bound orbits (March 2017).

Re-entries of catalogued objects occur daily. However, this high rate is largely driven by fragments without any on-ground risk. The re-entry rate of larger intact structure (e.g. defunct satellites) is roughly one per week.

The ratio of the cumulative number of re-entered objects vs the cumulative number of objects that have been placed in orbit has been gradually decreasing over time (from ca. 67% in 2002 to 57.5% in 2015) showing a clear trend toward a more rapid accumulation of objects in orbit.

When analyzing re-entry events, it is important to distinguish between so-called controlled and uncontrolled re-entry events.

The following definition is offered here:

- Uncontrolled re-entries occur when no orbit maneuver has been performed influencing the re-entry angle at around 120 km. The re-entry angle is defined as the angle between the velocity vector and the horizontal plane. For uncontrolled re-entries it is the natural angle the spacecraft assume due to pure atmospheric decay (which is fairly small). In uncontrolled re-entries, no target area on Earth is aimed at. The re-entry location and epoch cannot be pre-determined.
- Controlled re-entries are entry events following a de-orbit maneuver. This will increase the re-entry angle at 120 km in such a way that a target point on ground is hit by an assumed object with constant area/mass ratio. This allows control of the fall-out zone of the re-entry break-up debris. For initially circular orbits, re-entry angles of  $-1.5^\circ$  are typical to achieve a controlled re-entry (for instance the controlled reentry of ATV). With the right selection of the target area, the re-entry risk associated with controlled re-entries is virtually zero.

A subgroup of uncontrolled re-entries is "semi-controlled" re-entries. Semi-controlled re-entries occur when the re-entry epoch is not primarily driven by the decelerating effects of the atmosphere, but by 3<sup>rd</sup> body perturbations induced by the Moon and the Sun. This is relevant for highly eccentric orbits ( $e > \text{ca. } 0.7$ ), where Sun and Moon trigger a periodic lowering of the perigee altitude, leading to a re-entry as soon as the perigee is dragged in low enough (typically  $< 50$  km suffice for atmospheric capture). The re-entry location will be close to the perigee location and, therefore, the latitude of the entry will be predictable to a good degree even when no maneuver influences the trajectory.

Among the 24,000 historical re-entry events, controlled re-entries are rare. They, however, comprise ca 47% of the re-entered mass. This is due to the fact that controlled re-entry measures are typically limited to extremely large structures like space stations and space ships and supply vehicles.

The following Table 7.1 gives an overview over past top-ranked re-entries by mass [7.1].

Object	Mass kg	Re-entry Epoch	Re-entry Type
<i>Mir</i>	135,000	March 23 <sup>rd</sup> 2001	Controlled
<b>Columbia (STS-107)</b>	82,000	February 1 <sup>st</sup> 2003	Controlled <sup>11</sup>
<i>Skylab</i>	74,000	July 11 <sup>th</sup> 1979	Uncontrolled
<i>Salyut 7</i>	40,000	February 7 <sup>th</sup> 1991	Uncontrolled
<i>Salyut 6</i>	34,000	July 29 <sup>th</sup> 1982	Uncontrolled

*Table 7.1: Past top-ranked re-entries by mass*

There are two primary components of reentry analysis, determining the location/time of the reentry and identifying the surviving parts of the reentering object. These two types of analysis use somewhat different tools and input data. They may be performed separately or combined to determine expected ground casualty estimates.

The location/time of reentry for cataloged objects is predicted and published by several organizations including the US Joint Space Operations Center (JSpOC). The information can often be correlated with sightings from individuals on the ground if the reentry occurs over land. The most comprehensive to the date publicly available updating summary of information on re-entry sightings correlated to re-entries of specific orbital objects have started to be published a few years ago at the web-site of hobbyists performing visual satellite observations [7.17]

Determination of surviving components from a reentry and the corresponding ground impact energies is frequently combined with a location/time analysis to produce an expected ground casualty estimate, or the likelihood that someone on the ground could be impacted by a piece of surviving debris having a dangerous amount of kinetic energy. Both classes of analysis will be discussed further in the following sections.

## **7.2. Reentry location/time determination**

Unlike controlled reentries where the atmospheric reentry location is chosen based on mission needs, the probable reentry locations of both uncontrolled and semi-controlled reentries must be calculated based on characteristics of the reentering object and the forces, especially atmospheric drag and possibly Sun-Moon third body perturbations.

The majority of reentries are primarily driven by the effects of atmospheric drag reducing the energy of the orbit. The consequence of this is that orbits tend to circularize and then spiral to progressively lower altitudes (Figure 7.1). Eventually an altitude is reached where there is sufficient atmospheric density to cause the object to fall out of orbit and impact the Earth.

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<sup>11</sup> “controlled/accidental breakup”, debris associated to the accident

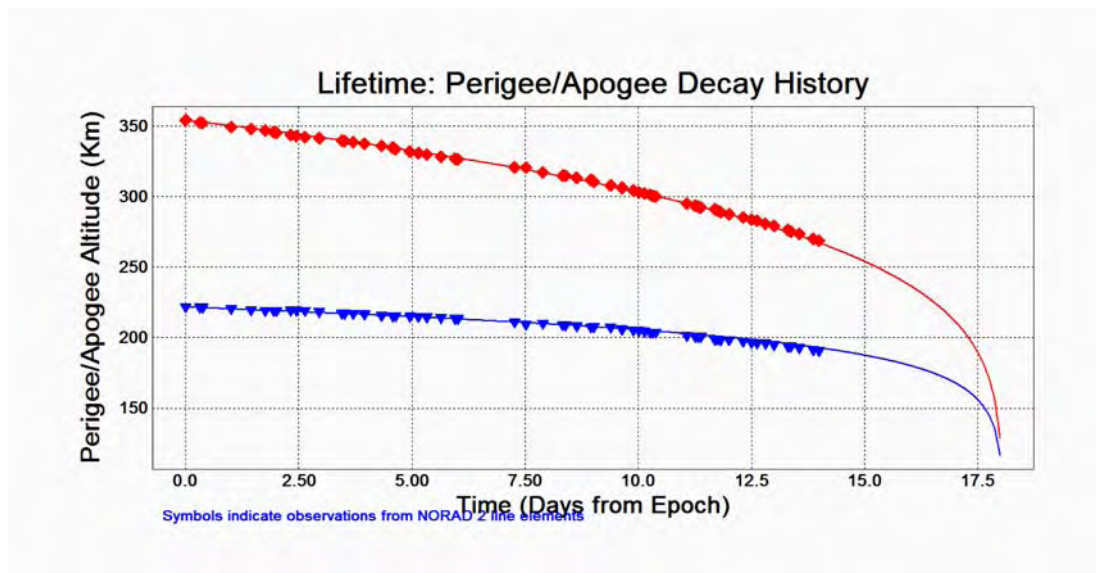


Figure 7.1: Sample Apogee - Perigee Decay History for Reentering Object

### 7.2.1. Modeling methods

Reentry times and locations are predicted by propagating an object's orbit forward in time until the forces on it cause it to impact the Earth's surface.

When predicting the time of an object's reentry, estimates are usually made on the scale of weeks to days before the expected event. Longer predictions, on the order of years, are generally used only to provide an estimate of the object's approximate time in orbit rather than for predicting actual reentry locations.

The highest fidelity propagation approach is to use a numeric integrator to integrate the equations of motion. This integration typically includes a number of orbital perturbations such as atmospheric drag, a detailed Earth gravity model, solar and lunar gravity, solar radiation pressure, as well as a model of the object's ballistic coefficient. While this approach models many of the forces in great detail, it also requires significantly more time and computational power to generate results than other approaches.

Another method uses mean orbital elements and averaged equations of motion. This approach can include representations of orbital perturbations including drag, solar and lunar gravity, and some of the Earth's gravity harmonics. Orbital elements can be propagated semi-analytically rather than requiring fully numeric integration. This method, while not including all of the details of numeric integration, is much less computationally intensive.

### 7.2.2. Uncertainties

The time and location of a reentry from orbit are linked through the flight path of the decaying object.

For most of the decay the reentering object is moving at orbital or near-orbital velocities, more than 7.5 km/s, so small uncertainties in the time of the reentry can translate into large uncertainties in the location of the reentry over the surface of the Earth, particularly for atmospheric drag driven reentries.



The reentry and Earth impact, if any, will occur along the ground track of the object, but the uncertainties can result in a wide distribution of possible reentry and Earth impact points along the ground track.

Even though the prevailing uncertainty is along-track, this along-track certainty will also trigger a cross-track uncertainty with respect to the ground (i.e., the rotating Earth). A few days before re-entry the projected ground-tracks can see a longitude shift corresponding to hundred km due to poorly predicted orbit revolution times. This is quite relevant from a civil protection point of view.

Reentry times are predicted by propagating the orbit of the object under the influence of atmospheric drag. For highly eccentric orbits the third body Sun and Moon perturbations are also of importance as they may drive the lowering of perigee and final reentry.

Except for the third body driven reentries, an object that is approaching reentry will be in a very low, near-circular orbit, making predictions of it especially sensitive to small changes in atmospheric drag effects:

- The strength of the atmospheric drag force on a reentering object is a function of the density of the atmosphere through which the object is traveling and the area that the object projects perpendicular to its direction of motion. Unpredicted variations in solar activity can result in expansion or contraction of the atmosphere producing unpredicted changes in the density of the atmosphere.
- Changes in the reentering object's attitude alter the area that it presents to the oncoming atmosphere, again changing the force of drag.

Both of these effects can introduce uncertainties into the reentry predictions.

Many objects of interest that are nearing reentry have been in orbit many years so the object's attitude may not be known.

One method to provide an estimate of the object's unknown ballistic coefficient is to use a recent series of orbit estimates from tracking information to perform differential correction. This process uses the changes seen in the series of orbit estimates to determine the most likely ballistic coefficient that would result in the observed changes. This approach enables the estimation of a current ballistic coefficient for the object of interest that can be used for better results in the reentry time estimation analysis.

During the final stages of the orbital reentry process the atmospheric forces significantly increase, inducing torques on the reentering object causing it to change orientation relative to its direction of motion. This can lead to a substantial change in its cross sectional area resulting in a sudden change in the drag force. These changes in orientation can be very difficult to predict and will introduce errors into the reentry time predictions.

Another area introducing uncertainty into reentry predictions is the level of solar activity. The drag imposed by the atmosphere largely depends on the extreme ultraviolet radiation of the Sun and the geomagnetic activity (induced by the interaction of the plasma of solar origin with the magnetosphere of the Earth).

Parameters such as these are used by atmospheric models to estimate the density of the atmosphere that will be encountered by an object as its orbit decays for reentry. Errors in the atmospheric models introduce one set of uncertainties into the orbit decay predictions. The other is that it can be difficult to predict the levels of solar activity leading to

inaccuracies in density predictions even in the absence of any error in the models. In the orbital altitude regime of 350 km and lower (where the orbital lifetimes of intact objects typically range around a few months), the solar activity can alter the orbital lifetime by one order of magnitude.

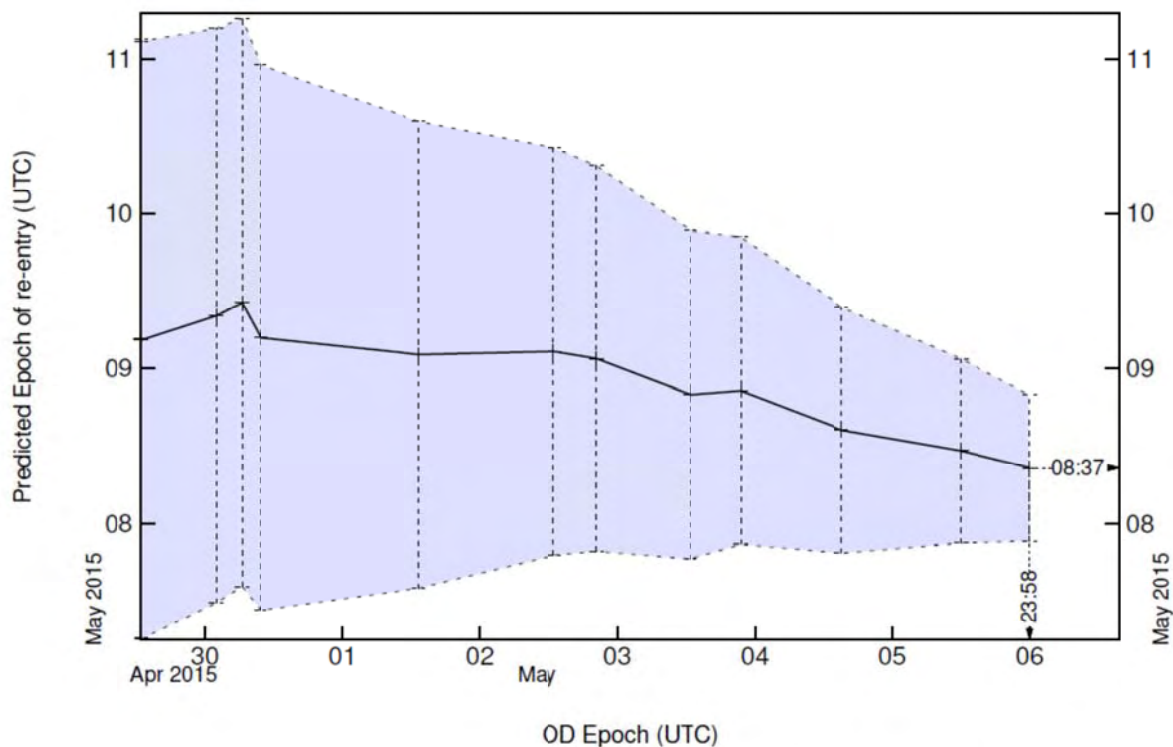


Figure 7.2: Uncertainty window associated with the ESA predictions of the uncontrolled re-entry of Progress-M-27M (OD epoch = Orbit Determination epoch) [ESA]

When comparing reentry time predictions to the actual observed events, the errors in prediction time are typically within 20% or less of the total time until reentry.

As an example, for a reentry that is predicted to occur within 10 days, the actual reentry will likely occur within 2 days of the predicted time. This uncertainty is highly dependent on the factors discussed above. At times when there is low solar activity the level of variability tends to be reduced and prediction errors can approach 10% or less. Reducing errors below these levels can be difficult.

Techniques have been developed to use the observed orbit decreases in calibration satellites to better estimate the actual atmospheric densities to reduce drag uncertainties. High fidelity six degree-of-freedom models have been used to attempt to predict the attitude of reentering objects to reduce the uncertainties in ballistic coefficients, but these predictions are also affected by the atmospheric uncertainties.

### 7.2.3. Re-entry risk

The risk on-ground due to re-entering space hardware is driven by the mass and impact velocity of the surviving objects, the number of these objects and the population density underneath.

The survivability of re-entering mass depends on the re-entry process and trajectory, and the material. Typically, 10% to 40% of the space object's dry mass tends to survive for

objects with mass greater than  $\cong 1,000$  kg [7.1]. Injuries (or casualties) could then result from the kinetic energy at impact.

Most national<sup>12</sup> mitigation standards have requirements that control the on-ground casualty risk. Whenever the on-ground casualty expectancy exceeds a value of  $10^{-4}$  per event, the standards request counter-measures such as a controlled re-entry or a change of the design (design-for-demise).

The survivability of spacecraft components during a re-entry depends on:

- The initial state (orbit state, attitude state and thermal state) of the spacecraft before the re-entry. This initial orbit state (and the associated re-entry angle, which differs between controlled and uncontrolled re-entries) determines the altitude at which major break-ups are expected. The attitude and attitude motion together with the re-entry trajectory determine the aerodynamic and aerothermal loads acting on the different parts of the spacecraft and therefore the break-up sequence.
- The spacecraft structure. The geometry, moments of inertia and internal arrangement of instruments, payloads, antennas and solar arrays drive the spacecraft dynamics during re-entry and thus the history of motion. Changes to the geometry, due to loss of components, such as solar arrays, can have a significant impact on trajectory and attitude motion and will therefore influence the further break-up sequence.
- Material used. The characteristics of the material used (melting point, heat capacity, etc.) will determine the point of time at which certain structures fail and release fragments. Also, the further evolution of the fragment properties (namely the area/mass ratio) strongly depends on the material characteristics.

In order to go from the characterization of on-ground fragments to an on-ground casualty expectation, a number of steps have to be performed. The NASA Safety Standard NSS 1740.14 provides a very well established procedure for this [7.2].

According to this, the on-ground casualty expectation depends on:

1. The average geometric cross-section of a human body;
2. The kinetic energy at impact, where only objects with impact energy higher than 15 J are considered relevant for casualties;
3. The fragment cross-section on ground, together with the average geometric cross-section of a human body, determines the casualty cross-section. This “casualty area”  $A_c$  formalizes the combined cross section of a human  $A_h$  and the fragment  $A_i$  (with  $A_h = 0.36$  m<sup>2</sup>).

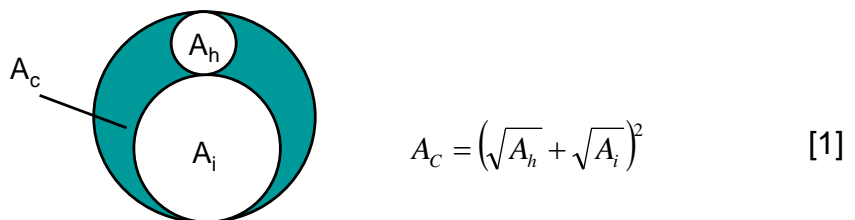


Figure 7.3: Calculation of the casualty area

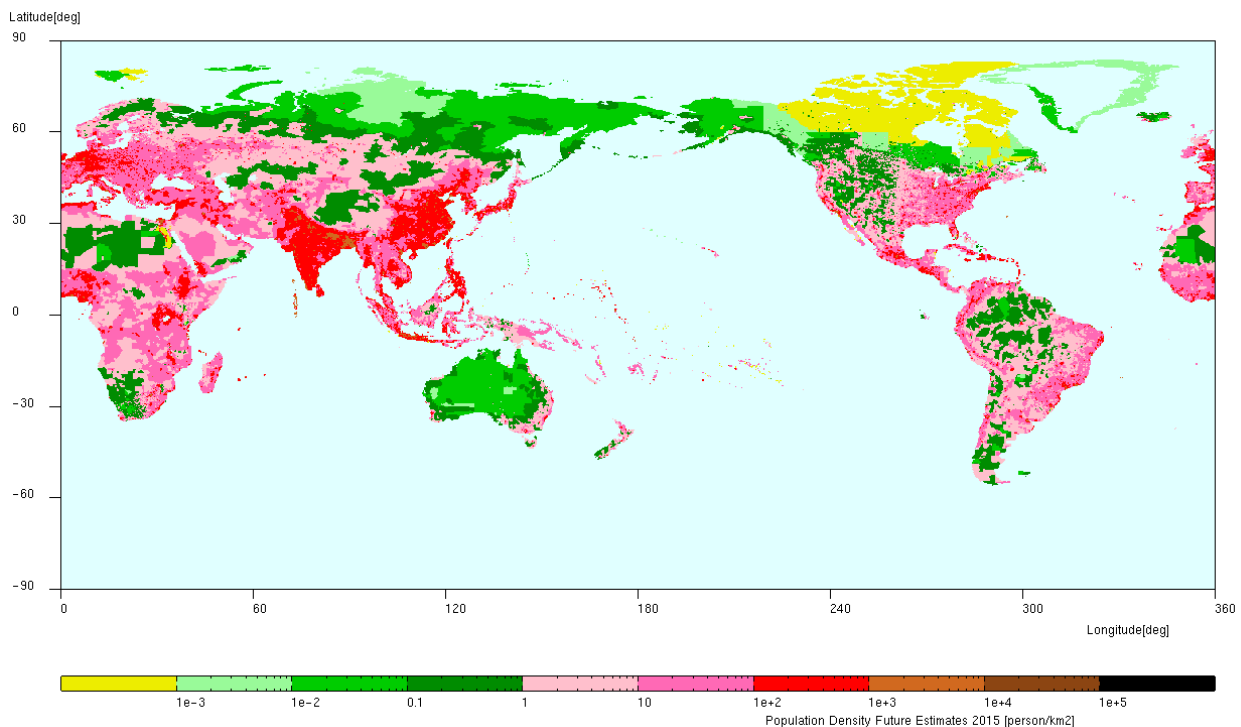
<sup>12</sup> For the definition of Nation in this context, the reader is invited to refer to §11

Since it is unknown how the fragment will hit the Earth – i.e., which side of the fragment will face to Earth, an averaging approach is used. For this, the average of all cross-sectional projections of the fragment across all aspect angles is used.

With the number and characteristics of fragments on ground being determined, the last analysis step to be performed is the multiplication of casualty cross section and population density.

The population density to be used is a critical parameter. Population density is typically reported as gridded data in terms of longitude and latitude. Different population models exist with different geospatial resolutions and different reference epochs. Once a model is selected, even for landmasses, the population density can vary by orders of magnitude from one longitude/latitude bin to the next.

Often, the Gridded Population of the World v3 (GPW) has been used as baseline [7.3]. This model is also the population model used for this purpose by most members of the Inter-Agency Space Debris Coordination Committee (IADC). It is available for 3 different epochs: 1990, 1995, 2000.



*Figure 7.4: GPW v3 data for the longitude/latitude population density distribution*

Information on country-wide population predictions can be obtained from the UN [7.4] and used to estimate future populations. Folding this information with the GPW model and the geographic location of countries, one can provide latitude dependent population densities. Such information is useful to compute the casualty expectancy for semi-controlled re-entries from highly eccentric orbits, which occur in distinctive latitude bands.

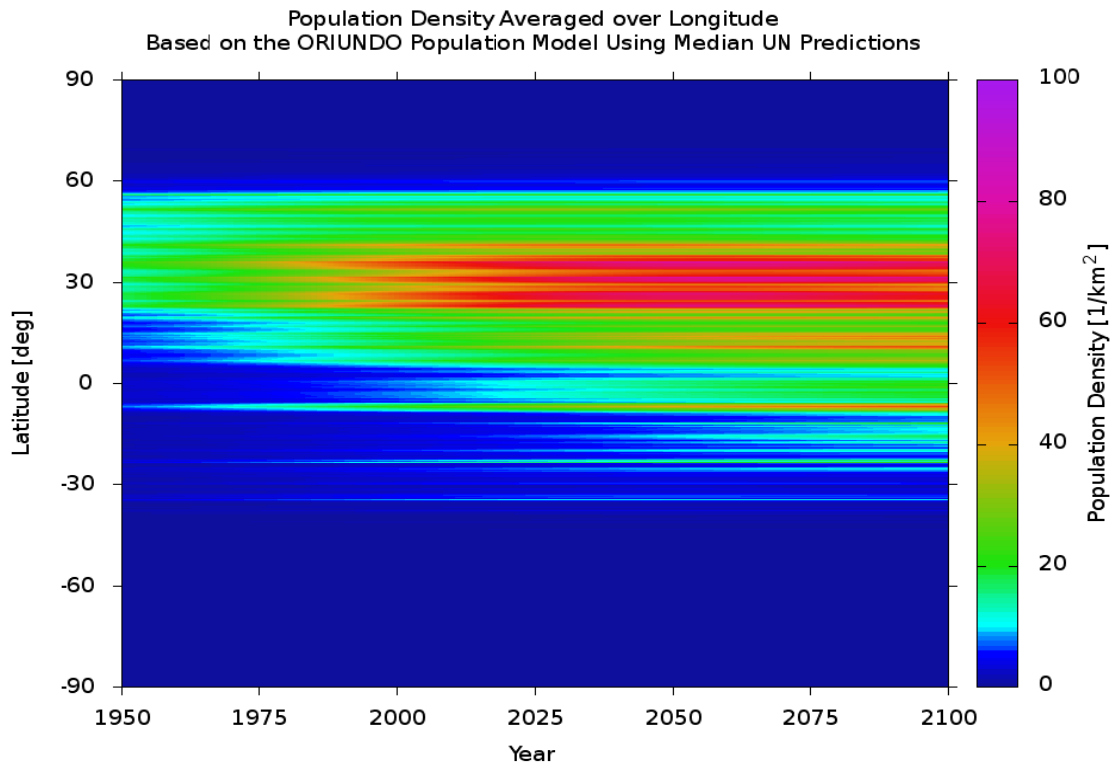


Figure 7.5: Latitude dependent (averaged over all longitudes) population density evolution (ORIUNDO result based on GWP v3 and UN population projections [7.7])

Should the orbit of the spacecraft circularize before re-entry, the situation will be different. In this case, the inclination of the re-entry object bounds the Southern-most and Northern-most latitudes that is reachable. Since, due to the sinusoidal shape of the ground-track, the space object's residence probability grows towards the bounding latitude bands, the impact probability is largest at these latitudes

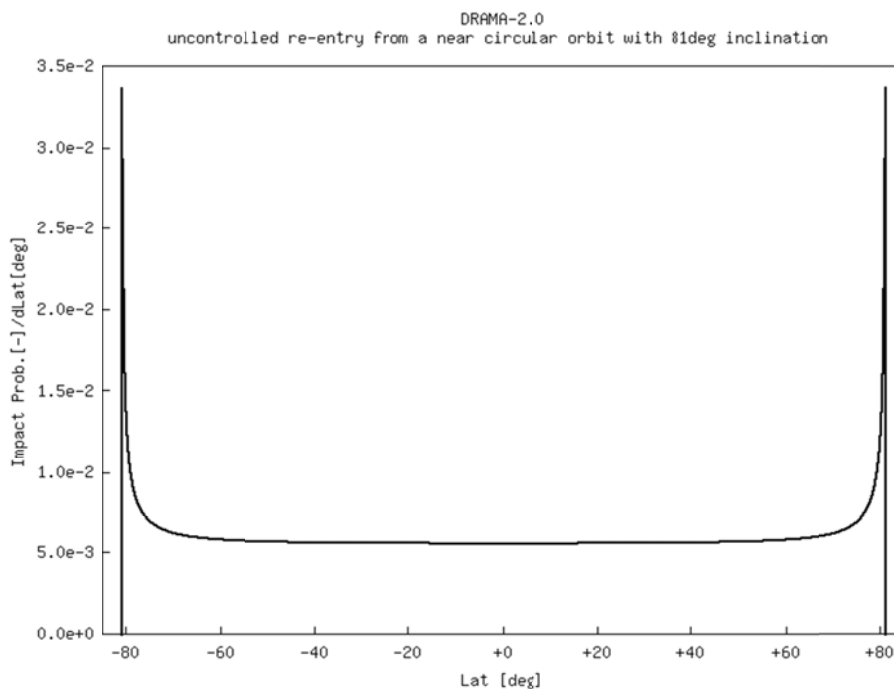


Figure 7.6: Latitude dependent global impact probability for the uncontrolled re-entry from circular orbits



Folding this with the latitude dependent population growth map gives the following result (see Figure 7.7). In this case, instead of showing the population density directly, the casualty cross section threshold is shown. This threshold corresponds to the casualty cross-section that may re-enter in an uncontrolled way without violating the commonly adopted threshold of  $10^{-4}$  for the casualty expectation. In other words, it corresponds to  $10^{-4}$  density.

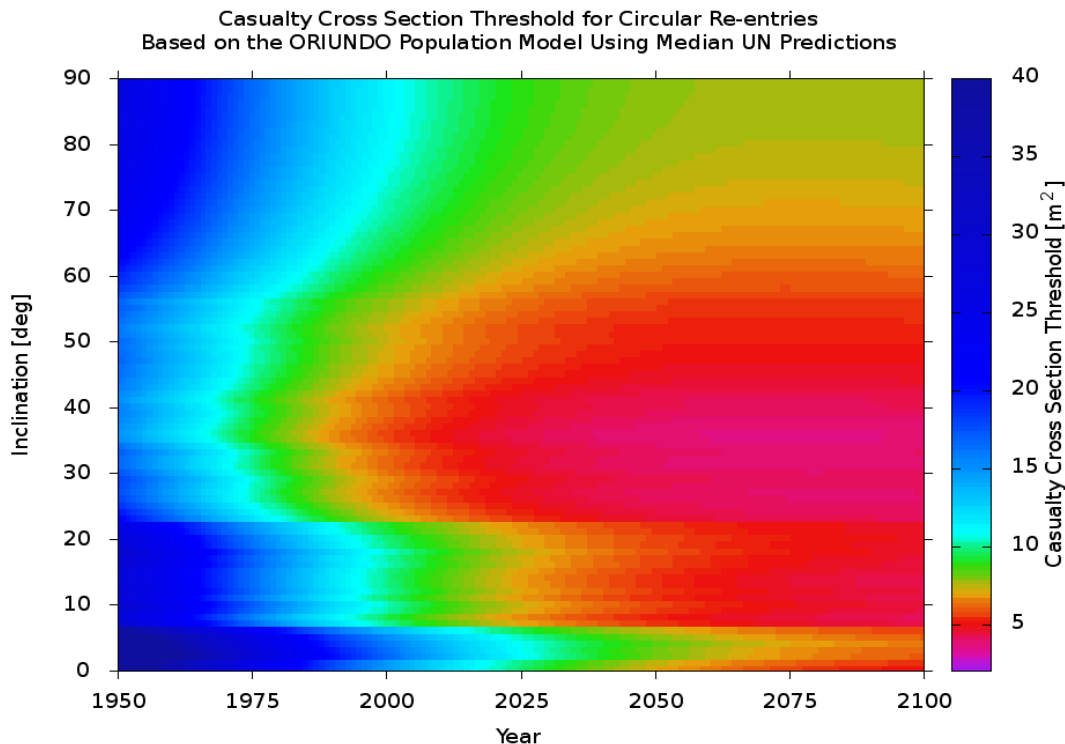


Figure 7.7: Inclination dependent allowed casualty cross-section (to comply with the casualty expectation threshold of  $10^{-4}$ ) for the uncontrolled re-entry from circular orbits [7.7]

The debris fall-out footprint, however, does not fall into a single latitude bin. The along-track dispersion can reach on the order of 800 km and will therefore span a few degrees in latitude depending on the orientation of the velocity vector.

### 7.3. Hazardous objects

Hazards can be generated by any surviving object due to its kinetic energy. Some onboard material, however, can also generate chemical risk due to toxicity. One example for this is hydrazine.

Being poisonous, hydrazine can increase the casualty area compared to the classical (kinetic) definition by factors if it survives re-entry. The survival of hydrazine is, however, rare, since mostly all fuel is spent at the end of the mission and remaining fuel is expected to burn up during re-entry as soon as exposed to the atmosphere with sufficient partial pressure and temperature of the ambient oxygen in the atmosphere.

In rare events, such as *USA-193*, hydrazine can be frozen onboard in large amounts (due to mission loss right after orbit injection). In the case of *USA-193*, which was expected to re-enter in an uncontrolled way during March 2008 with large amounts of frozen hydrazine onboard, it was decided to prevent the uncontrolled re-entry by intercepting the object with a ground-based missile [7.8].



Figure 7.8: Telescope view of the USA-193 interception shortly after impact [youtube]<sup>13</sup>

In addition to chemical risk, risks due to radioactive material also exist. Since 1959 two different types of nuclear energy generation have been used onboard of spacecraft:

- Radio-isotope Thermo-electric Generators (RTGs), based on the energy gained from natural decay of radiating material;
- Actual nuclear reactors based on the nuclear fission process.

Two historical re-entry events involved reactors using U-235.

- A Russian Radar Ocean Reconnaissance satellite (Cosmos-954) (RORSAT) re-entered over Canada after loss of control and polluted the surroundings in 1978.
- Similarly, Cosmos-1402 re-entered over the Indian Ocean in 1983 [7.9].

As a consequence of the first incident, the *RORSAT* operations scheme was changed. After the end of the mission, or in case of problems, the reactor was separated from the spacecraft and injected into a disposal orbit at about 950 km. Nevertheless, the orbital decay time is still significantly shorter than the half-life of U-235. RTGs, however, usually employ materials with shorter half-life. Since the 1960s, the RTG design considers this risk by sheltering it in a way that no material is exposed during reentry and after impact. For the case of impact on water, it should sink and shelter the material over a very long time.

The IADC conducts an annual reentry prediction test campaign in preparation for the reentry of hazardous objects.

The hazard may be due to the object's large size and likelihood of surviving fragments causing significant damage or that the reentry event may cause radioactive contamination. The annual tests provide the IADC members the opportunity to practice coordinating the

<sup>13</sup> <https://www.youtube.com/watch?v=lvXV2QEdA34>

exchange of tracking information and reentry predictions for an object chosen as the target of opportunity. The tests prepare the IADC members to respond and cooperate if the reentry of a potentially dangerous object is foreseen.

#### 7.4. Statistics on reentries

The number of uncontrolled re-entries saw an all-time high in the decades between 1970 and 1990, when the space race had led to launch rates above 100 per year. Due to the short orbital lifetime of many of these objects, the number and mass of objects in uncontrolled re-entries in these years was unusually high (up to 400 tons compared to 80 tons today) [7.5].

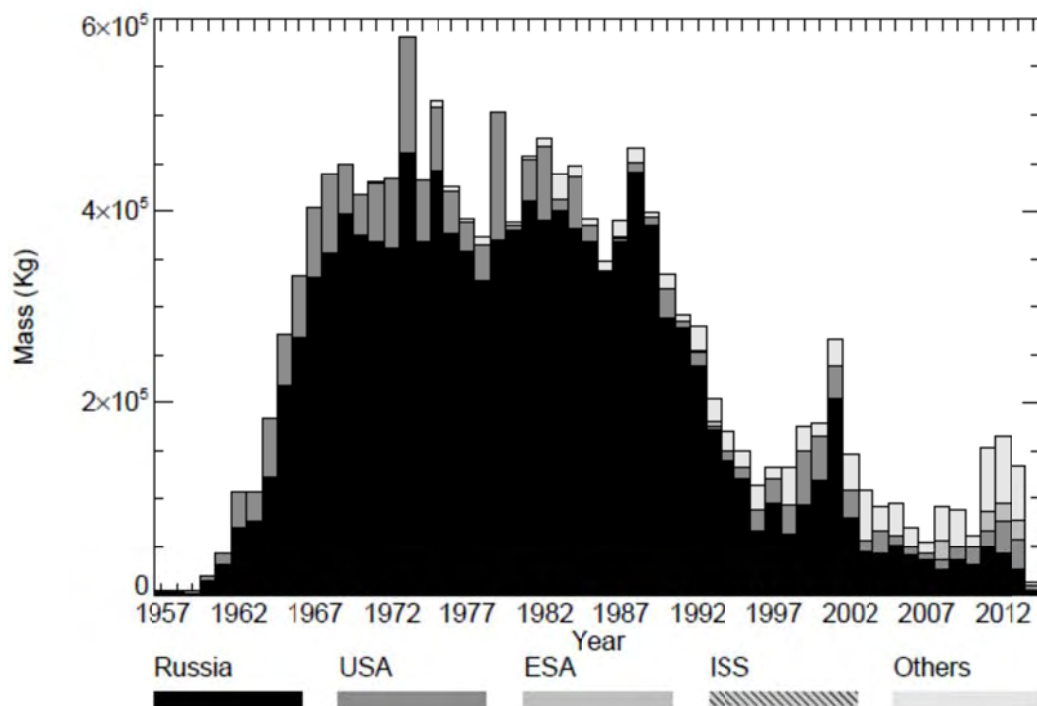


Figure 7.9: Mass of objects decayed or returned from orbit per year and nation (excluded reusable launch systems and return capsules)

An approximate method generated from data obtained during high-fidelity re-entry break-up analysis and taking into account the inclination and the population density distribution at re-entry epoch allows a derivation of a rough-order-of-magnitude on-ground casualty estimate for the history of re-entries.

The NASA definition of the casualty cross-section has been used for this purpose (see §7.2.3).

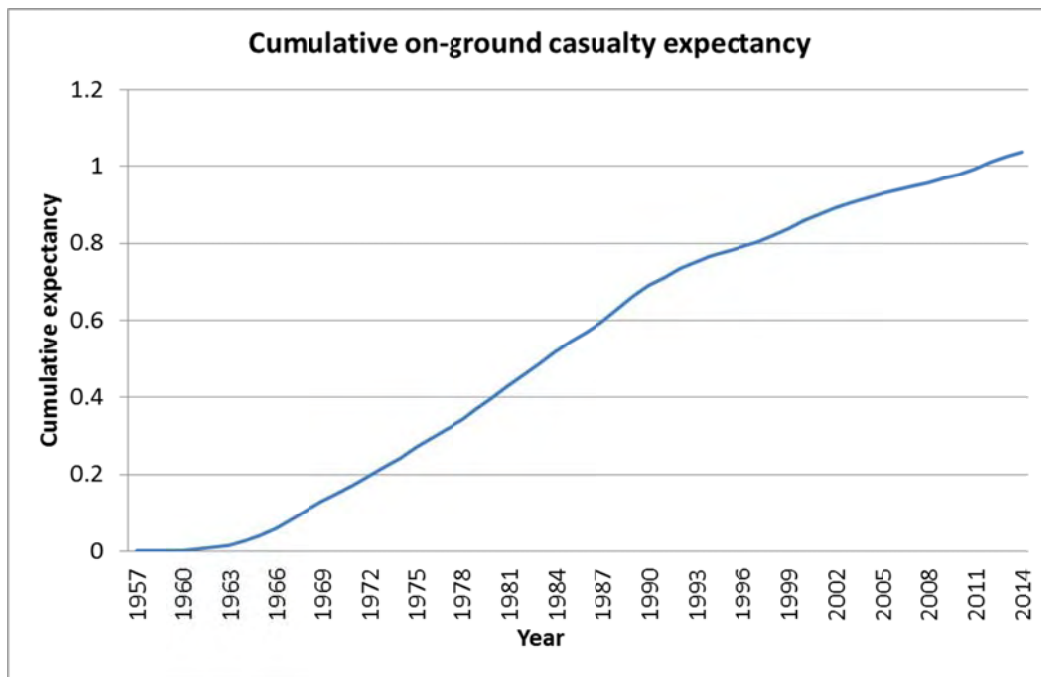


Figure 7.10: Cumulative on-ground casualty expectancy [7.6]

According to these results, the expected number of casualties to have occurred since the beginning of spaceflight should be roughly 1.

Figure 7.11 shows that the majority of the casualty expectancy is generated by objects with casualty expectancy above  $10^{-4}$ . This is important, because it implies that the current guidelines, which apply this threshold level, would enforce significant risk reduction.

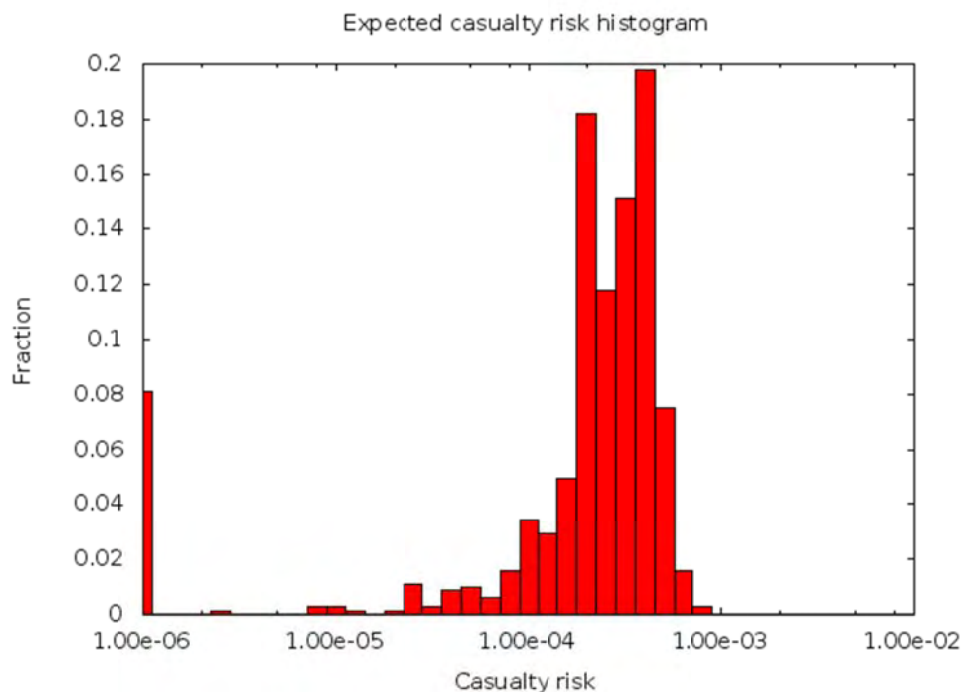


Figure 7.11: Expected casualty risk histogram [7.6]

Further analysis reveals that the risk reduction would have reached up to 90% in nearly all analyzed periods using this criterion.

## 7.5. Reentry survivability analyses

Two different approaches are used to perform re-entry survivability analyses.

- The first more simple and much faster method is named “object oriented”. Most existing programs are part of this group. Representatives of this category are NASA’s ORSAT [7.11] and Debris Assessment Software (DAS) [7.12], the SARA module which is part of ESA’s DRAMA software [7.6a], or the DEBRISK tool used by CNES in the frame of the French Space Act [7.13].
- The second group uses a so-called “spacecraft oriented” approach. The only representatives of this category are ESA’s SCARAB [7.10] and CNES PAMPERO [7.16].

### 7.5.1. Object oriented approaches

So-called object-oriented re-entry survivability analysis tools are used to compute the casualty area and impact location of surviving fragments with the use of some simplifying assumptions:

- The major spacecraft break-up altitude is pre-determined and leads to the release of all components (or alternatively to the release of compounds with their own pre-determined release conditions for sub-components);
- All released components are pre-determined and have simplified shapes (typically spheres, plates, cylinders, boxes);
- All released components are considered randomly tumbling and melt from the outside layer-by-layer, hence maintaining their shape type;
- The trajectory analysis of all fragments considers translational motion only (three degrees of freedom).

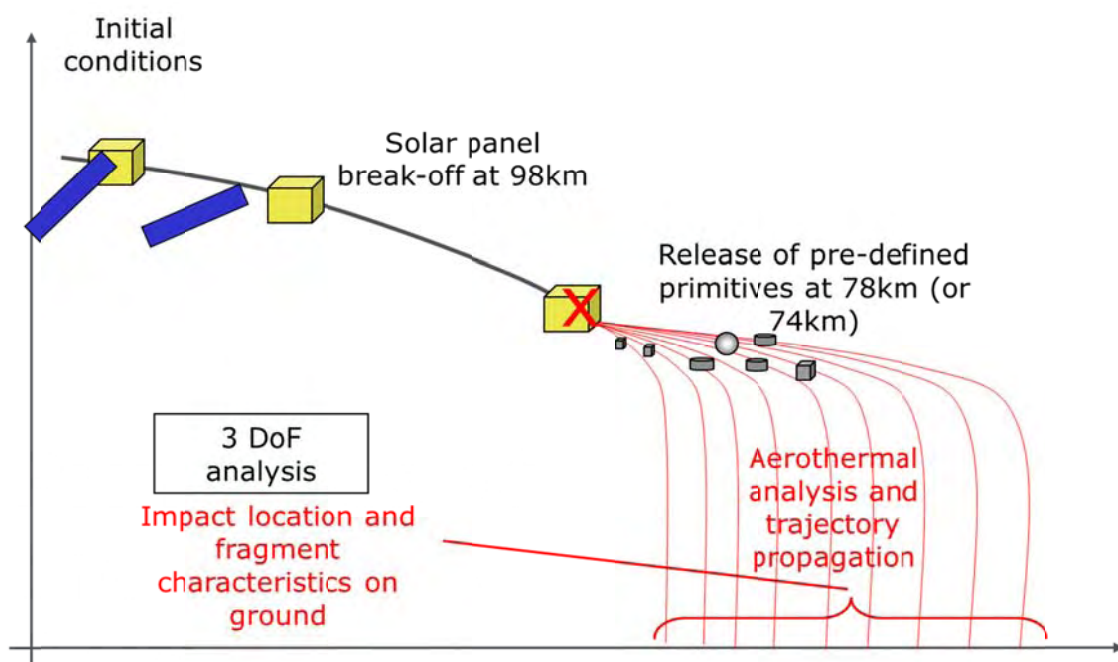


Figure 7.12: Working Principle of the Object-oriented tool ESA-DRAMA [7.6a]

### 7.5.2. Spacecraft oriented approaches

Spacecraft-oriented tools take into account the spacecraft geometry and moments of inertia in a full-force and torque six degree of freedom analysis. A highly detailed model of the spacecraft is broken down into discrete volume panels to form the starting point of the analysis.

In the subsequent simulation, aerothermal loads and heat transmission by convection, conduction and radiation, as well as aerodynamic and dynamic forces and structural loads are considered for each volume panel. Changes to the geometry due to the failure of a panel, and the consequences on the attitude and further demise and destruction process are considered.

This highly deterministic approach makes spacecraft oriented codes adequate and relevant tools to study the influence of spacecraft design changes on the on-ground casualty providing insight into the break-up sequences and expected fragment geometries. This process of incorporating re-entry survivability considerations into spacecraft design to limit surviving debris is known as “*design for demise*” and will play an important role for missions, which have chosen an uncontrolled re-entry as part of their disposal.

These tools are also suited to clarify critical issues like the probability for explosive break-ups, detailed footprint analysis for controlled re-entries or the effect of critical components on the re-entry (pyrotechnics, coupled structures, large external components).

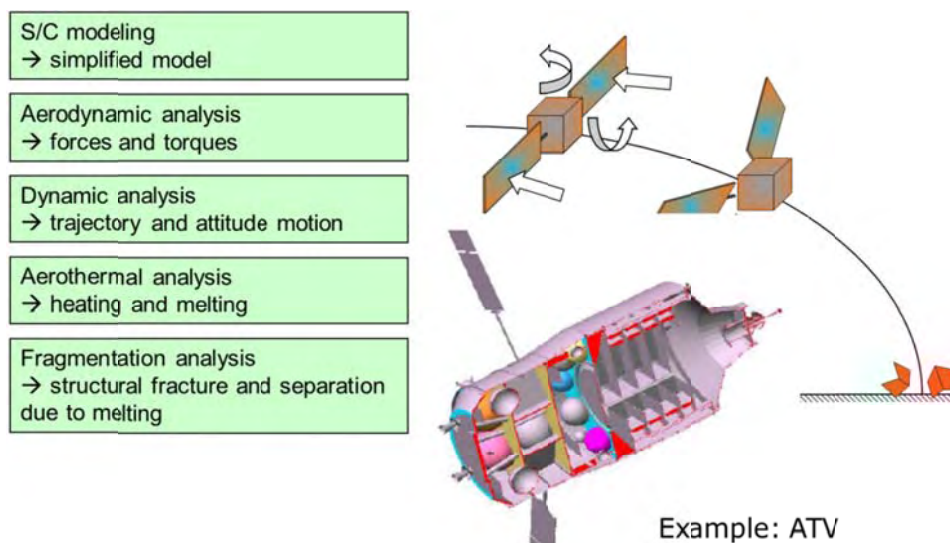


Figure 7.13: Working Principle of the spacecraft-oriented tool SCARAB [7.10] and sample for the level of detail required as modelling input (ATV-1)

### 7.5.3. Issues with the prediction

Atmospheric re-entry and break-up analyses are normally deterministic. A single set of assumptions on the initial conditions and the process is used and the outcome represents one possible outcome. To reflect the fact that a number of parameters in this process are actually uncertain, a parameter range would have to be taken into account. This will lead to a probabilistic assessment e.g. in a Monte Carlo approach. The result is an expectation value together with an uncertainty interval.



In addition to the uncertainties that affect reentry time and location determination, re-entry break-up analyses of uncontrolled re-entries have additional parameters that are relevant and can impact the results of the on-ground risk:

- Atmospheric density dispersion;
- Break-up/explosion altitude dispersion;
- Initial attitude of the object (for 6 degree-of-freedom spacecraft oriented software);
- Modelling depth of the object (moment of inertia, detail on internal components, knowledge on material properties, center of gravity).

## **7.6. Policy issues**

A few legal issues arise in terms of the ownership of reentered objects and responsibility for damage caused by debris that survives to the Earth's surface. These will be discussed in chapter 11.

An additional policy issue is the potential conflict between reentry and orbital debris mitigation rules:

- For large objects it is best, from the standpoint of orbital debris, to cause the objects to reenter at end of mission life or within 25 years.
- From the standpoint of reentry safety, if large objects will result in an unacceptably large debris footprint on the ground, the consequence of rules may push for the objects to remain in orbit.

Both deorbiting and not deorbiting may cause unacceptable results.

## **7.7. Solutions**

### **7.7.1. Controlled re-entry**

Controlled re-entries require the modification of the satellite or upper stage's orbit through a maneuver that changes the orbit significantly in a short time.

This puts constraining requirements on the propulsion system, since the perigee needs to be lowered (for LEO, typically within 30 minutes) from orbital altitudes to altitudes where atmospheric capture is guaranteed.

Besides pure atmospheric capture, it needs to make sure that all the fragments are contained in a predictable area (i.e., the so-called debris fall-out footprint). This footprint is typically determined by the along-track components which can stretch from a few hundred kilometers to a few thousand kilometers depending on the re-entry angle.

Very often, the South Pacific Ocean Uninhabited Area (SPOUA) is used for controlled re-entries, which is the largest unpopulated ocean space on the globe.

For controlled re-entries, dispersion parameters are usually considered to determine the break-up debris fall-out zone. This helps when rendering the necessary margins and contributes to the associated risk assessment.

The following uncertainties are often considered:

- De-orbit boost delta-V realization dispersion ;
- Atmospheric density dispersion;
- State vector dispersion at 120 km geodetic altitude;
- Break-up/explosion altitude and magnitude dispersion.

It is common practice to pre-announce the re-entry to the relevant authorities of the concerned air- and sea space well in advance (roughly two days' notice to airspace and 6 days' notice to sea space authorities). These authorities will then issue warning messages for the Flight Information Region (NOTAM = Notice to Airmen) and (NAVAREA = Navigational Area), respectively.

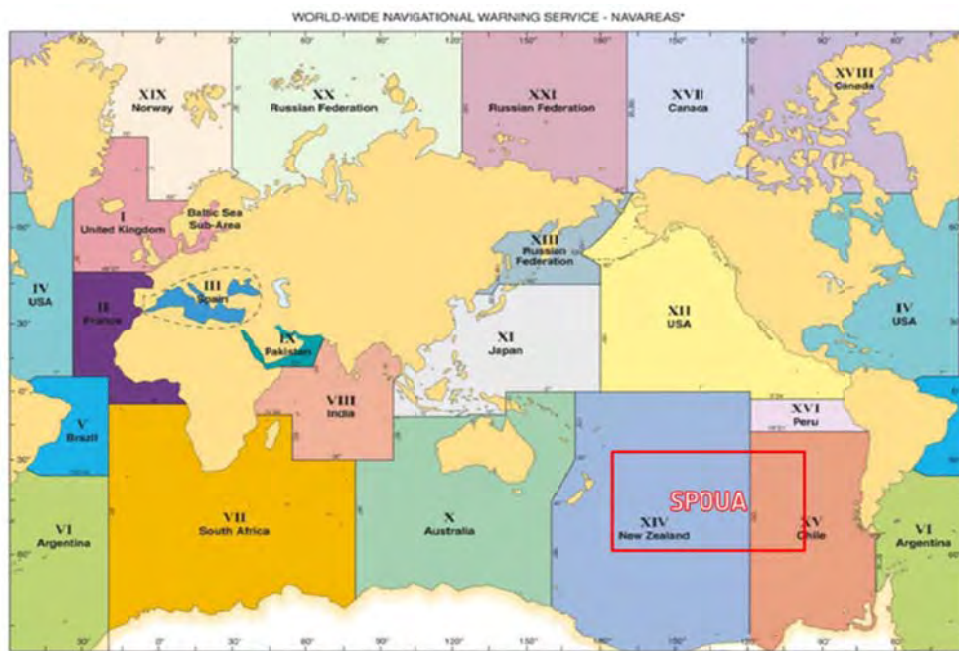


Figure 7.14: South Pacific Ocean Uninhabited Area (SPOUA) mapped over the NAVAREAS

### 7.7.2. Design for demise

A potential approach for reducing the ground reentry hazard for larger objects is a technique called Design for Demise, or D4D [7.14].

This approach is based on designing space vehicles so that they and their components will not survive reentry with a sufficiently large debris reentry footprint to be considered hazardous.

Several approaches can be used including eliminating materials with high melting points, designing the space vehicle's structure to come apart early in the reentry process and arranging components to reduce shielding effects. For the approach to be effective it requires careful consideration of reentry survivability in the vehicle design phase.

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## 8. Future environment

### 8.1. Historical orbital debris environment

Nearly six decades after the launch of *Sputnik-1*, in 1957, the number of tracked human-made objects in Earth orbit has steadily increased due to launches (over 5,250 to the present day) and to on-orbit breakup events.

It is the uncontrolled breakup fragments that dominate the environment.

Kessler and Cour-Palais [8.1] reasoned in 1978 that the amount of space debris in Earth's orbit would reach a tipping point in which the future space debris population would be dominated by fragments produced by the mutual collisions between the objects already present in the population.

Many of the present-day orbital debris modeling programs began after that work. The mechanisms behind the current space debris environment and the risk posed to our space-assets, both current and future, is the subject of those programs. The basic impetus behind these efforts is that Earth orbit will continue to be a unique asset for commercial communications, Earth observations, and military tasking among other uses.

Basic requirements of the orbital debris future environment investigations begin with modeling of the past and current environments. Databases such as the Joint Space Operations Center (JSpOC) two-line element sets (TLEs) and the European Space Agency (ESA) DISCOS provide information such as satellite launch times, orbital elements over time, mass, size, collisional and non-collisional fragmentation events. They can be considered as having a reasonable accuracy for unclassified human-made objects larger than about 10 cm in LEO according to Xu, et. al. [8.2].

Figures 8.1 and 8.2 illustrate common metric charts used by orbital debris investigators in those two regions. Spatial density within 50 km concentric shells vs the altitude range of those shells is presented on May 1<sup>st</sup> 2009. The ESA MASTER-2009 model is used with the ESA DISCOS database for both figures.

Figure 8.1 includes spacecraft, spent rocket bodies, and fragmentation debris throughout LEO.

The large population ranging from about 600 km to 1,000 km and peaking at about 800 km includes spacecraft, spent rocket bodies, and mission related debris, but is dominated by debris fragments from over 200 energetic breakup events that inhabit or cross the region (including fragments of the *Fengyun-1C* due to the antisatellite test and the *Iridium 33/Cosmos 2251* due to accidental collision).

The smaller peak at about 1,500 km is dominated by three accidental explosions of *Delta 2<sup>nd</sup>* stage rocket bodies that occurred in the mid-1970s. Atmospheric drag is too inefficient at that altitude to significantly lower the altitude of those fragments (cf. Figure 8.3).

In Figure 8.2 it is notable that the spatial density in GEO is around two orders of magnitude lower than in LEO. The large peak at about 35,800 km includes active and abandoned

geostationary satellite population. The majority of the off-peak objects are fragmentation debris (There are two acknowledged explosive breakups in GEO).

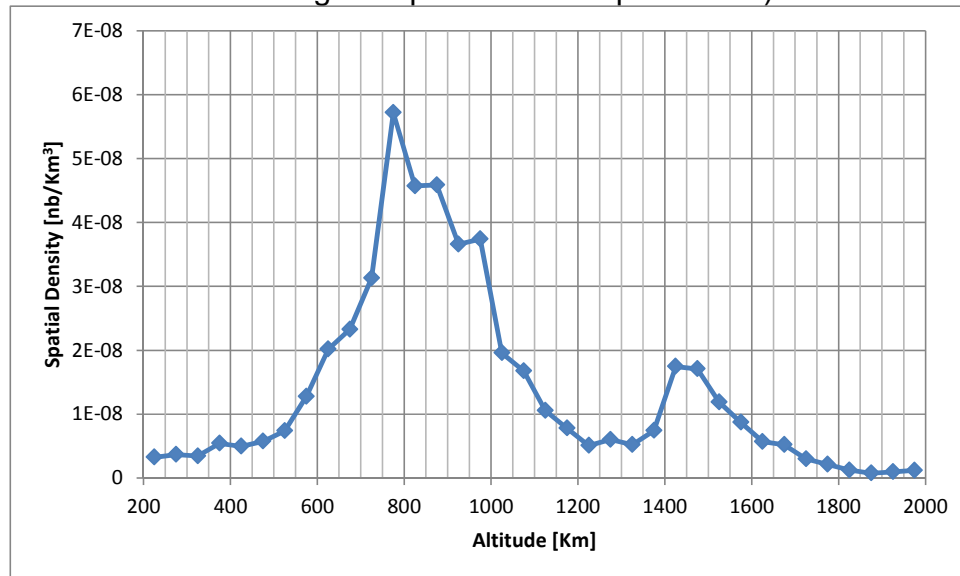


Figure 8.1: Spatial density vs altitude of 10 cm and larger objects in the LEO debris environment on May 1<sup>st</sup> 2009 [8.18]

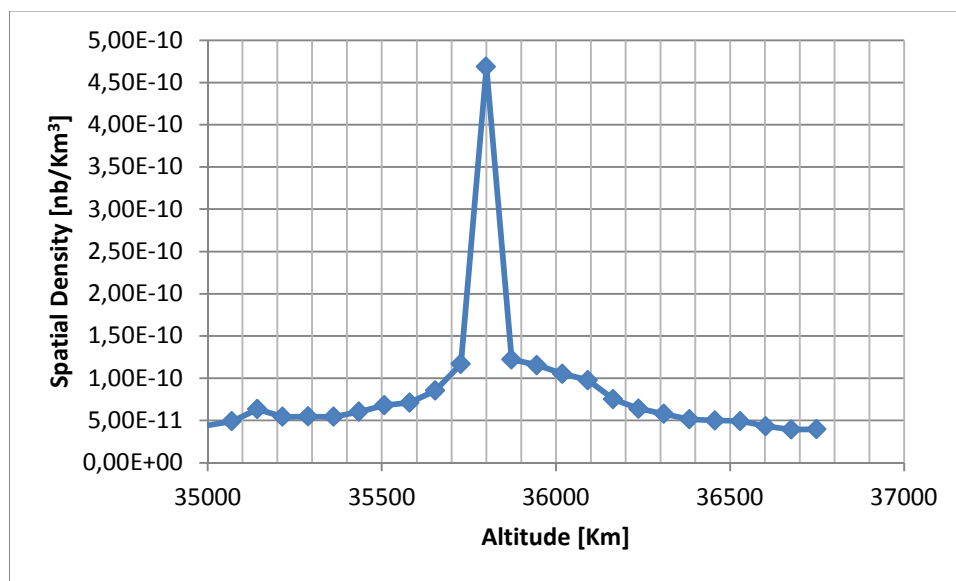


Figure 8.2: Spatial density vs altitude of 10 cm and larger objects in the GEO debris environment on May 1<sup>st</sup> 2009 [8.18]

The historical model mimics known launch traffic and breakup events by depositing spacecraft, rocket bodies, and fragments at known orbital positions and times and propagating them forward with the applied forces that correctly predict their known orbital positions over time (e.g., historical solar flux, Sun/Moon positions, Earth gravity, and others).

The fragmentation model must include size or mass, delta-v, and area-to-mass, for each fragment in a breakup event, (down to some specified minimum size or mass). In this way, historical launches and breakups are handled deterministically as we are interested on modeling the past and current environment.



Though orbital debris studies do extend to GEO orbits as we have shown in Figure 8.2, the increase on the number of human-made objects through the years has been considerably larger in the LEO region (i.e., 200 – 2,000 km) than in any other orbital regime. This is true for launches and breakup events. The region also has the most reliable remote sensors for debris and intact cataloging (10 cm and larger). Finally, it is the region of crewed spacecraft. For these reasons, all further discussion in this chapter applies to LEO only.

The objects displayed in Figure 8.3 are intact (spacecraft and spent rocket bodies) that have reached End of Life (EOL) between 2000 and 2013 [8.7]. Orbital decay lifetimes are color-coded. Of course, the lower the initial insertion perigees and apogees, the shorter the lifetimes.

A comparison with Figure 8.1 must lead the reader to the conclusion that the objects on the 600-1,000 km peak are leaving orbit faster than objects at higher altitudes, but they are being replenished by launches and , more so, by fragmentations within that low altitude peak.

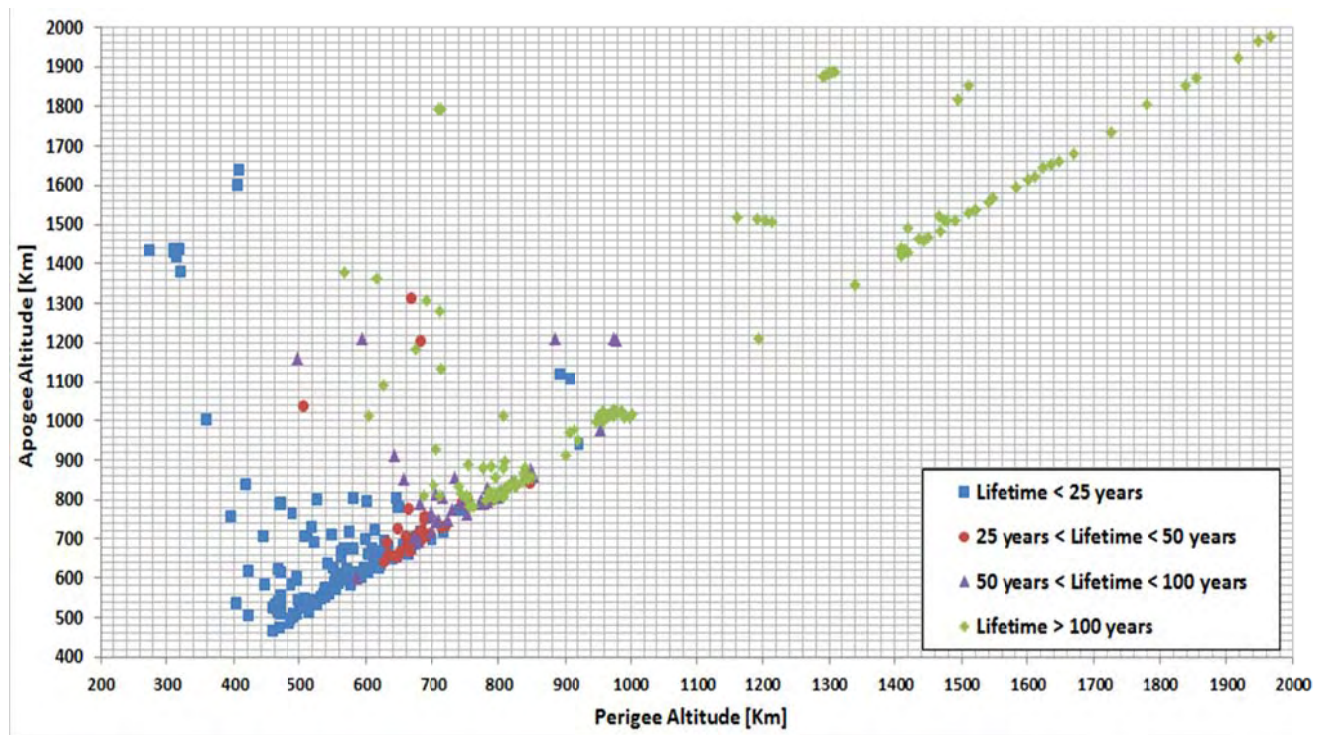


Figure 8.3: Apogee altitude vs Perigee altitude with lifetimes for LEO satellites and spent rocket bodies [8.7]

In addition to the spatial density, which is directly related with the probability of collision, if one is interested on the consequences for the environment of a given collision, a parameter of paramount importance is the mass of the colliding objects.

This is explicitly shown in Eq. 2, where  $N(L_c)$  represents the number of collision fragments of a given characteristic length  $L_c$  (in meters), or larger, and  $M$  is the mass parameter (in kg) that is defined differently in the case of a catastrophic and of a non-catastrophic collision [8.19].

$$N(L_c) = 0.1M^{0.75}L_c^{-1.71} \quad [2]$$

Figure 8.4 presents on the same chart the spatial density and the mass as a function of the altitude for 10 cm and larger objects in the LEO environment on May 1<sup>st</sup> 2009, using the ESA-MASTER 2009 Model [8.18].

It is clear that the spatial density peak at about 800 km is correlated with the significant concentrations in the mass distribution. The mass distribution is dominated by intact objects (spacecraft and rocket bodies) which represent 95% of the total mass in orbit. Such correlation is of paramount importance, as it shows that a collision on the densest regions of LEO orbit will have extremely important consequences for the environment.

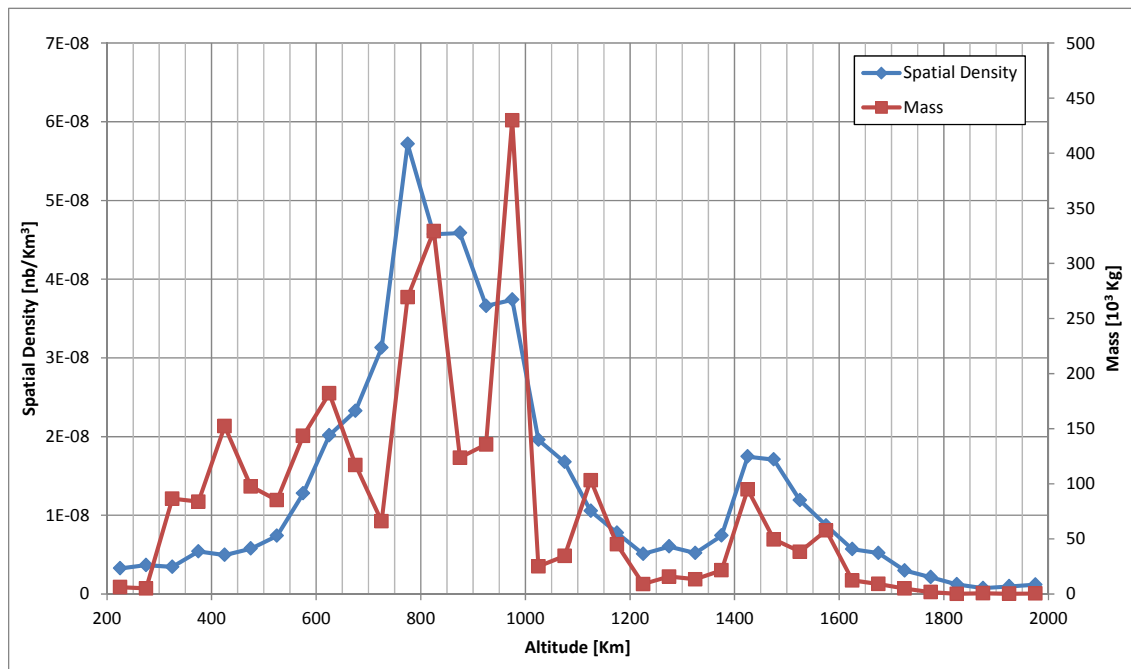


Fig. 8.4: Spatial density and mass vs altitude for the 10 cm and larger objects in the LEO debris environment on May 1<sup>st</sup> 2009 [8.18].

## 8.2. Future orbital debris environment

### 8.2.1. Predicting the long term evolution of the environment

Starting from a reference population computed at a given epoch (e.g.  $\geq 10$  cm population on May 1<sup>st</sup> 2009), future environment modeling must include assumptions on anthropogenic variables such as future launch traffic cycle modeling, Post-Mission Disposal (PMD) of used spacecraft and rocket bodies compliance rates, spacecraft and rocket body passivation success rates.

Exogenic variables such as the long term evolution of solar activity or the accidental spacecraft and rocket body collision rates as well as endogenic variables as the number, size, mass, area and delta velocity of the fragments generated after a fragmentation must be also modeled.

The goal of future environment modeling is not to derive the real population at a future epoch but to test the effectiveness of various mitigating and remediation practices for a given number of possible futures.

Given the uncertainty of any particular scenario, all environment models apply a Monte Carlo (MC) approach to take into account the uncertainty linked with variables such as the

number of collision events or the fragment distribution in such an event. The number of MC samples required in the statistical study of the future debris environment has been shown to be about 30 in Liou 2008 [8.8].

The typical time-span for future propagation is 100 years, though longer periods such as 200 years have been tested, with 200 MC samples, to study phenomena like the critical density condition (i.e., Kessler Syndrome) in specific LEO altitude regions [8.9].

Concerning the modeling assumptions, which are used to constrain one of the many possible futures, a common baseline scenario that has been applied to launch traffic is Business-As-Usual (BAU). This normally corresponds to a case where current day operational practices remain unchanged. Here the latest 7 to 10 years of the yearly traffic files are simply repeated into the future for as long as the projection is required. In a BAU scenario no special mitigation is practiced. That is no PMD criterion is applied, and there is no spacecraft or rocket body passivation, so these may explode randomly at a rate inferred from the past non-collisional fragmentation events. It is the worst-case scenario.

As mitigation practices have evolved, current usage of BAU has come to include an 8-year traffic cycle and some percentage of PMD (i.e., the application of the 25-year Rule) which was adopted internationally about 10 years ago) [8.11]. Also spacecraft and rocket bodies are passivated by some percentage, reducing the future non-collisional fragmentation rate.

Figures 8.5 and 8.6 presents the results obtained with NASA-LEGEND long term evolutionary model.

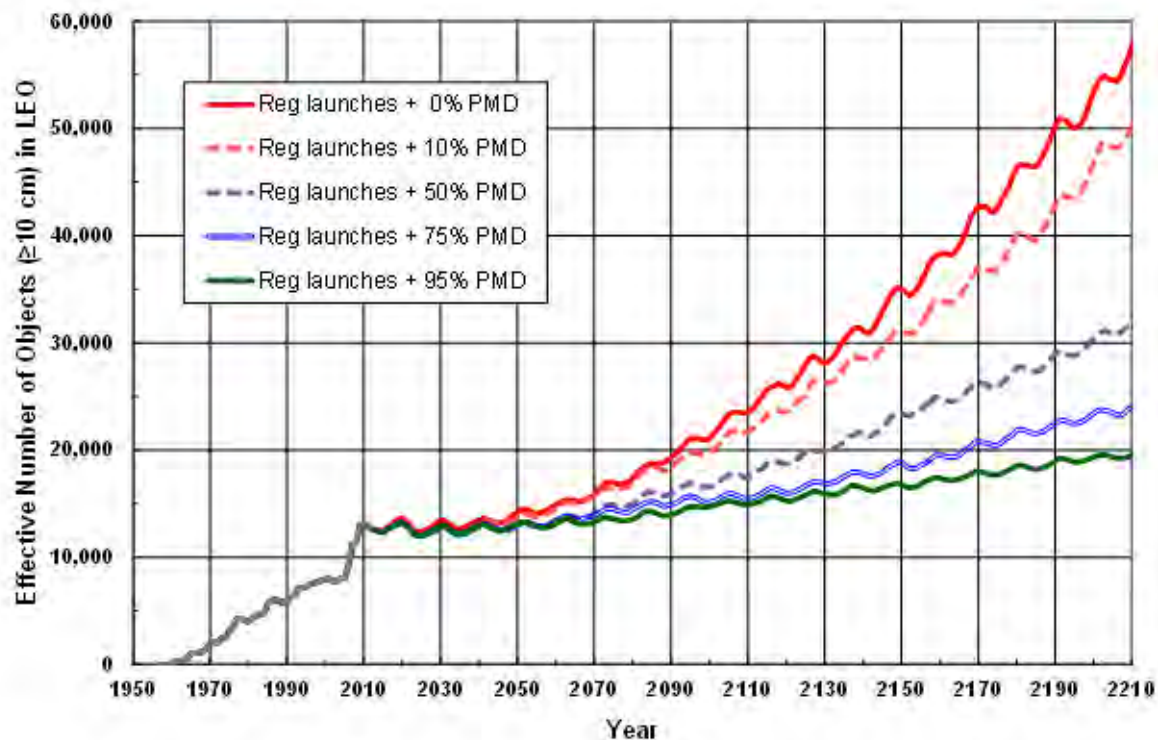


Figure 8.5: Effective Number of Objects  $\geq 10$  cm in LEO vs year (NASA LEGEND model simulations average of 100 Monte Carlo runs per scenario). The periodic variations on the projection region are due to the solar cycle [8.3].

N.B.: The effective number of objects refers to human-made objects spending a fraction or its entire orbital period on LEO regime (i.e., 200 – 2,000 km). For clarification, an object, with apogee's altitude below 2,000 km will be considered as one effective LEO object

while an object with perigee altitude equals to 800 km and apogees altitude equals to 3,000 km will be considered as a 0.49 effective LEO object.

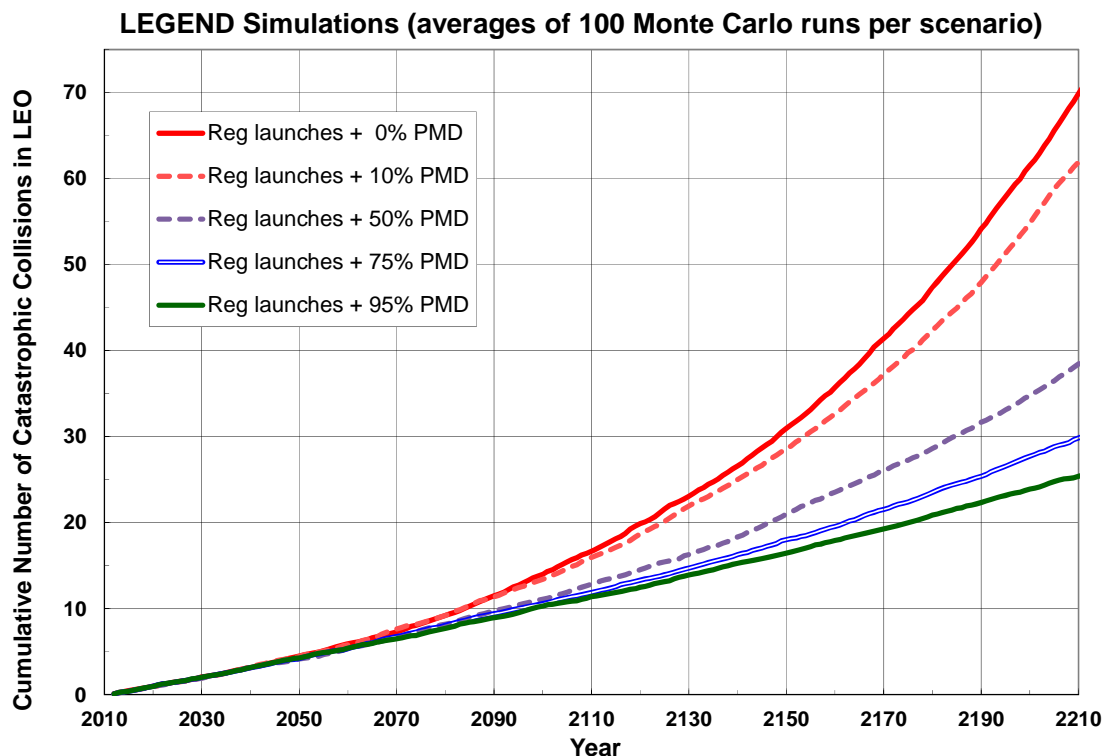


Figure 8.6: Cumulative number of catastrophic collisions ( $E > 40$  J/gr) as a function of time (NASA LEGEND model simulations averaged of 100 Monte Carlo runs per scenario). [8.3].

On these figures ‘Reg launches’ implies the 8-year cycle and the percentage of PMD implies the percentage of spent intact human-made objects moved into 25-yr lifetime orbits. Future vehicle passivation rates are set at 100%. PMD appears to be very effective at limiting future debris, but under the modeling assumptions, it is notable that even PMD at 95% does not stop the growth. Catastrophic collisions occur when the impact energy-target mass ratio exceeds 35-45 J/g for any 2 objects larger than 10 cm in size colliding on orbit [8.18]. It represents a total disruption of both objects.

Modeling studies like this one with LEGEND have contributed to the mitigation policies of national and international technical groups. Bolstered by earlier studies NASA was the first space agency to issue a comprehensive set of orbital debris mitigation guidelines in 1995 [8.12].

Other countries and organizations followed with their own modeling programs, including Japan, France, Russia, and the European Space Agency (ESA), and adopted their own orbital debris mitigation guidelines [8.13].

In 2002, after a multi-year effort, the Inter-Agency Space Debris Coordination Committee (IADC)<sup>14</sup>, comprised of the space agencies of 10 countries, at the time, as well as ESA, adopted a consensus set of guidelines designed to mitigate the growth of the orbital debris population [8.11].

<sup>14</sup> See section 12.1.2

In February 2007, the Scientific and Technical Subcommittee (STSC) of the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS)<sup>15</sup> completed a multi-year work plan with the adoption of a consensus set of space debris mitigation guidelines very similar to the IADC guidelines. The guidelines were accepted by the COPUOS in June 2007 and endorsed by the United Nations in January 2008 [8.16].

The development and testing of different future environment models was accelerated with the support of the IADC. With now 13 member agencies organized into 4 working groups and a steering committee, the IADC primary purpose remains *“to exchange information on space debris research activities between member space agencies, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperative activities and to identify debris mitigation options”*.

In the frame of IADC, a cooperative study was defined to analyze the Stability of the Future LEO Environment, under optimistic assumptions. Six member agencies participated to this study where the main objective was to investigate if more aggressive measures than PMD and EOL passivation, as the active debris removal (ADR) of human-made objects from the environment, may be needed to guarantee the long-term sustainability of space activities.

Each group used its most advanced model for the task. The models are independent save for some collaborative feedback. The only concession made by the group was to agree to use the ESA MASTER-2009 model population of May 1<sup>st</sup> 2009 shown in Figures 8.1 and 8.4 as a baseline for the start of the future scenarios including the 8-year traffic cycle. All models have independently implemented the NASA Breakup Model of 2000 [8.19].

Agency	ASI	ESA	ISRO	JAXA	NASA	UKSA
Model	SDM	DELTA	KSPROP	LEODEEM	LEGEND	DAMAGE
MC Runs	275	100	40	60	150	100

*Table 8.1: Number of Monte Carlo (MC) simulations performed by participating models. (Taken from IADC Working Group 2 Action Item 27.1 final report [8.6]).*

The agencies, models, and number of Monte Carlo runs are listed in Table 8.1. Each simulation was carried out for 200 years. Commonly-accepted mitigation measures were implemented. A compliance of 90% PMD within 25 years was assumed (i.e., 90% of spacecraft and rocket bodies were moved into 25-yr orbits at EOL) as well as 100% success in the passivation of spacecraft and rocket bodies, leading to an optimistic simulation (cf. 8.7 and 8.20 for statistics concerning real compliancy to mitigation guidelines). Collision avoidance was not considered.

It is important to remark that the baseline scenario considered for the IADC Action Item 27.1 study, allows investigating the evolution of the space debris population on six of the many possible futures. The results and conclusions from this study are quite robust but remains conditioned to the modelling assumptions.

Figures 8.7 and 8.8 display the projection period growth based on the mitigation measures applied by all groups, most notably the 90% PMD rule.

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<sup>15</sup> See section 12.3.2



The figures can be compared to the NASA LEGEND Figures 8.4 and 8.5 with the 90% PMD option. Figure 8.5 in particular displays an increase in the number of objects in LEO by about 30% over the 200-year projection period across all agency calculations.

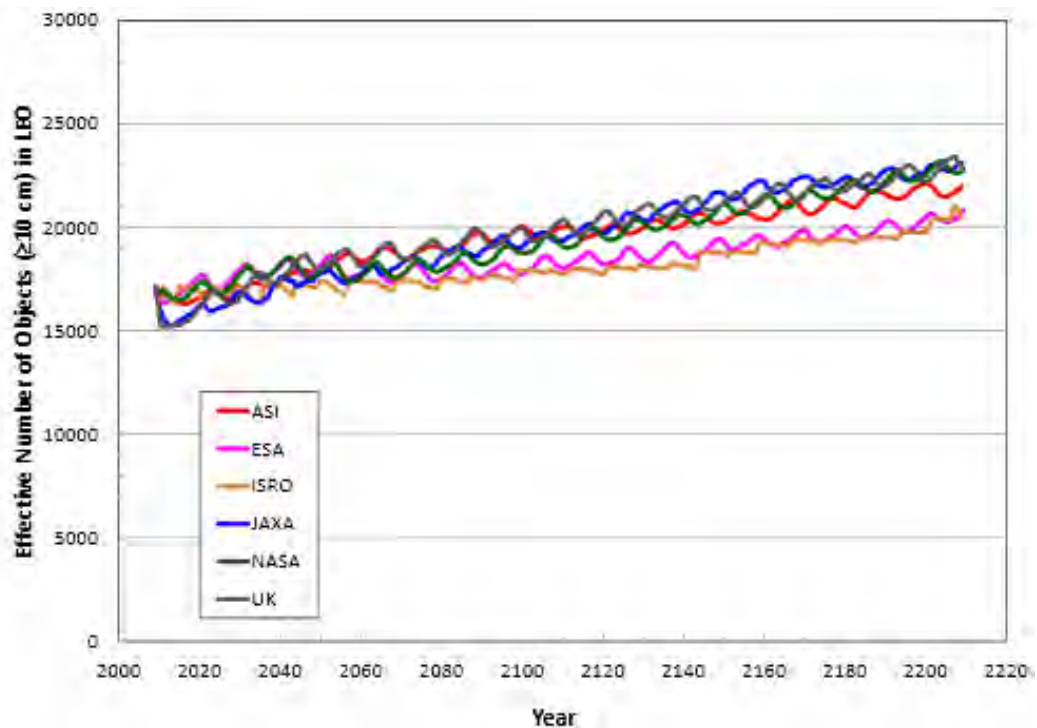


Figure 8.7: Effective number of objects 10 cm and larger in LEO from the 'Stability of the Future Environment' cooperative IADC study [8.6].

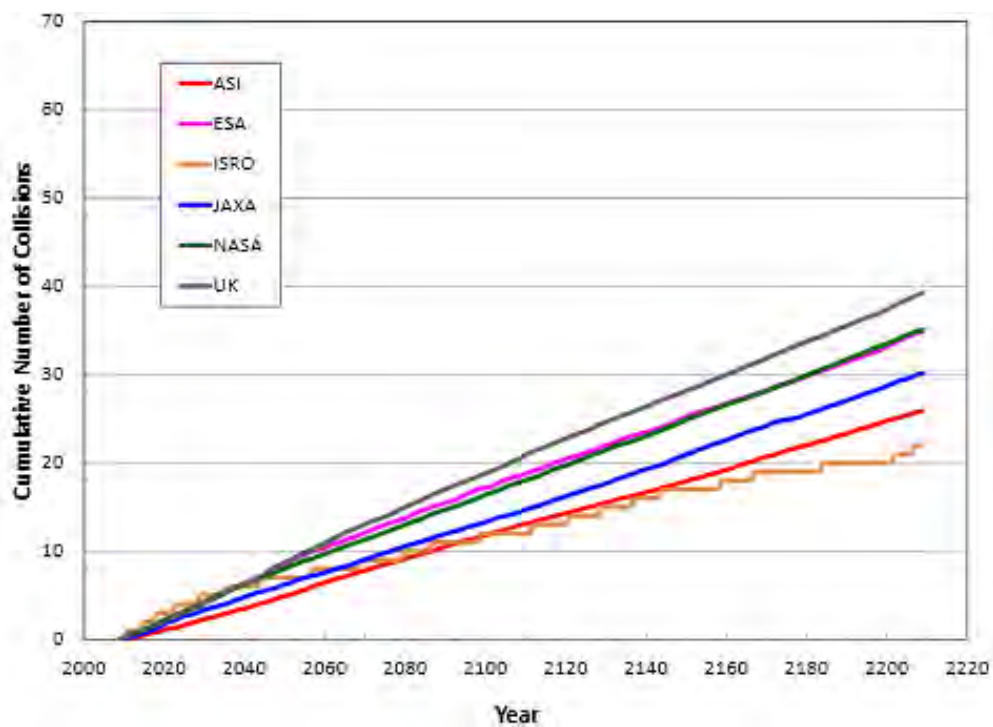


Figure 8.8: Cumulative number of catastrophic collisions from the 'Stability of the Future Environment' cooperative IADC study [8.6].



In reference to the specific cause of that increase, Figure 8.9 displays the ASI results, which is the agency that performed the highest number of Monte Carlo runs (275). The top curve in each figure is the orbital population increase overlaid with the 1-sigma standard deviation. The bottom three curves illustrate the growth or decay of intacts and fragments. The growth of the overall LEO intact and orbital debris environment is dominated by collision fragments in the future (all agency results agree).

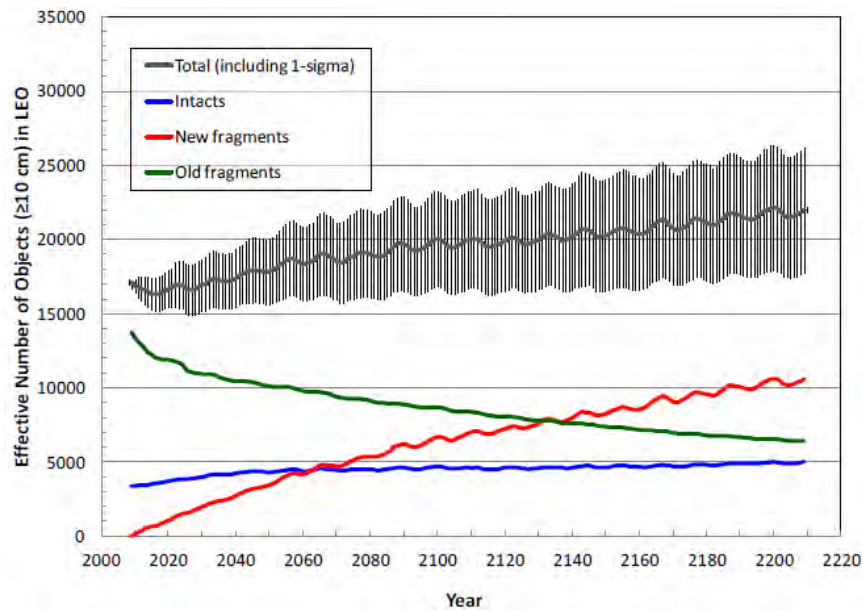


Figure 8.9: ASI (Italian Space Agency) 275 Monte Carlo runs from the 'Stability of the Future Environment' cooperative IADC study [8.6].

### 8.2.2. Uncertainty sources and possible futures

As previously stated, long term evolution of the space debris population is conditioned to a great number of uncertain variables, which will lead to a great number of possible future scenarios. To fully analyze the need or the robustness of mitigation and remediation measures, the investigation of the long-term evolution of the space debris population and the effectiveness of mitigation and remediation measures for all those possible futures will be of paramount importance.

Several national and international studies, for example in the frame of the IADC, are being done now to perform such complete analysis. Among the variables taken into account to derive a representative number of possible futures we can list:

- Initial debris environment;
- Atmospheric density models;
- Long term Trajectory propagation;
- Collision probability estimation;
- Collision energetic threshold for catastrophic break-up;
- Collision geometry leading to catastrophic break-up;
- Collision class leading to catastrophic break-up (debris vs debris, debris vs intact, intact vs intact);

- Break-up models (fragment number, area, mass and velocity distributions);
- Target ranking for active debris removal;
- Future launch traffic and space technology evolution;
- Quality of mitigation measures adopted and overall levels of compliance;
- Viable technological options for remediation measures with active removal;
- Future deliberate actions endangering the environment (e.g. ASAT tests);
- Evolution of solar and geomagnetic activity;
- Evolution of the upper atmosphere of the Earth at satellite altitudes.

Figure 8.10 gives an example of how one of these uncertain variables (e.g. solar activity proxy F10.7) will impact on the possible futures. Baseline scenario used for Figure 8.10 future projections is the same one described on [IADC-12.08]. Details on the solar activity used to build Figure 8.10 long term projections can be found on [8.17].

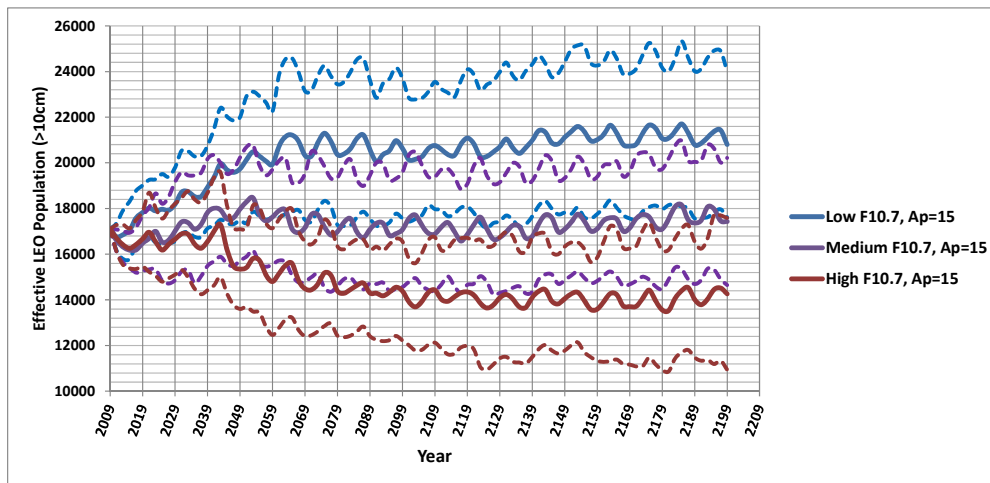


Figure 8.10: MEDEE (CNES) simulated LEO debris population (objects 10 cm and larger) as a function of solar Flux 10.7. The thick curves are the arithmetic means from 40 MC projections. The dotted curves represent the 1- $\sigma$  standard deviation. [8.6].

As stated before, another very important uncertain variable that will impact the long-term evolution of the space debris evolution is the future launch traffic and technology evolution.

- Since the beginning of the 21st century we have observed a dramatic increase on the number of nano / micro satellites launched into orbit. Projections based on announcements and future plans of developers and programs indicate nearly 2,400 nano / microsatellites to be launched from 2017 to 2023 [8.21]. Today, technical challenges and limited launch limited availability constraints near-term growth, despite a continuing backlog of satellites awaiting launch. The risk posed by nano / micro satellites to the space environment highly depends on the number and on the orbit on which these satellites are deployed. The nano / micro satellites non-compliant with mitigation guidelines will dominate the build-up of the long term debris [8.22].
- In addition to nano / microsatellites, another source that would have a major impact on the long term evolution of the space debris environment are new space missions as the internet constellations. Such large constellations, though addressing the lack of basic internet coverage in some world regions, are expected to launch hundreds

or even thousands of satellites in the Low Earth Orbit region. Reference [8.23] describes the effect that such large constellations may have on the long term evolution of the space debris environment and the most important parameters driving such evolution.

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## 9. Space debris mitigation

Recognizing that most of the human-made objects currently in orbit are space debris, several space agencies and international organizations have been striving to generate less debris by applying debris mitigation measures since the early 1990s. However, there will be little net benefit if only few space faring nations introduce preventative measures.

Space is a public domain. And if it is to be protected so that all can continue to exploit its unique attributes, there must be concerted and cooperative action among all space faring nations. In part, this is necessary to make economic competition equitable, but it is also necessary to keep valuable operational regions technically and economically viable for the future.

The most distressing aspect of the space debris problem is that it is getting worse in those regions most extensively used and could grow at some altitudes and inclinations such that collisions among larger objects could become a significant debris growth factor.

Because of the time and cost necessary to modify designs and operations practices, the debris problem has a significant time lag between the recognition of the issues and the effect of changes. It has been shown that as of today about half of satellites reaching their end-of-life are compliant with the 25-year rule in LEO (see below).

For this reason it is prudent that further action is taken as soon as practical.

The uncertainty involved in many of the present analyses highlights the need for technological developments to depict more accurately the hazard from space debris, prevent its creation, and provide protection from its impact.

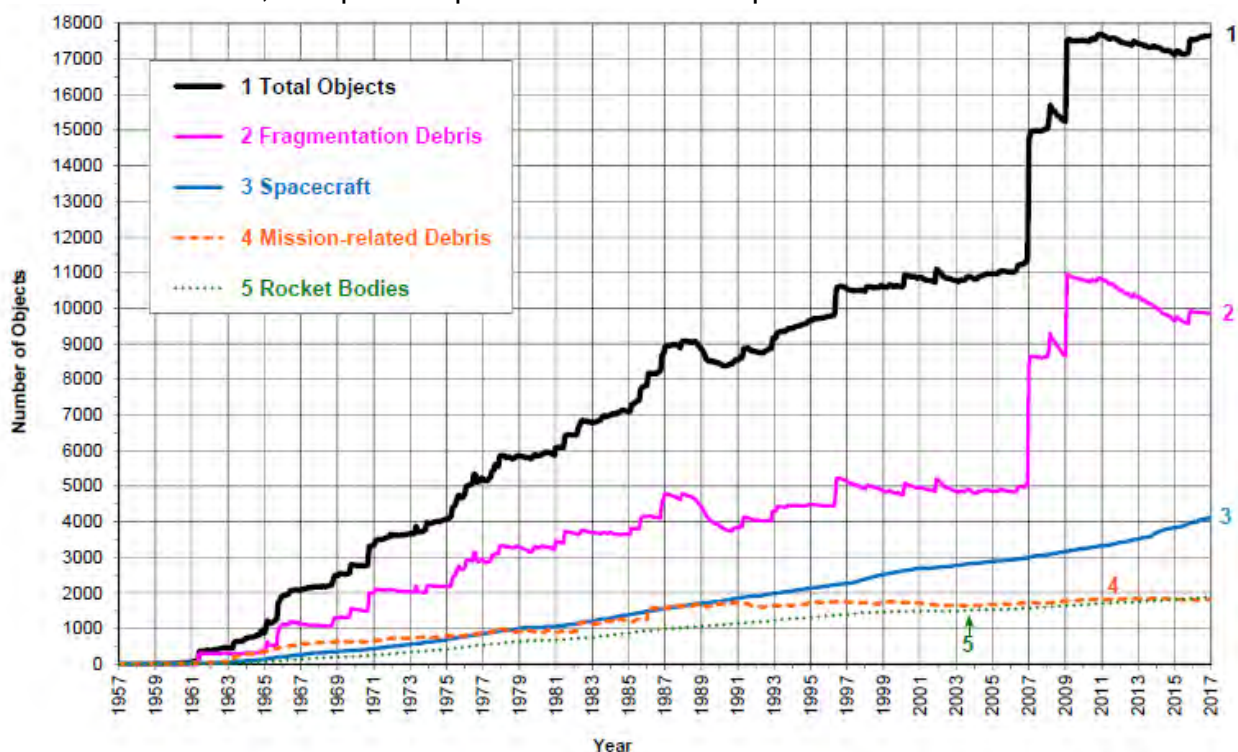


Figure 9.1: Monthly Number of Catalogued Objects in Earth Orbit by Object Type [9.9].

Figure 9.1 shows the monthly number of objects catalogued by the US SSN divided into different classes of objects (see also Figures 2.1 and 2.6 in Chapter 2).



It can be seen that right from the beginning of space flight, the environment is dominated in numbers by fragmentation objects. As of April 2016 fragments contribute about 56% of the cataloged population.

Typical sources of these fragmentation objects are on-orbit explosions due to propulsion system failures or on-orbit collisions, either intentional or unintentional. According to a database provided by the NASA Orbital Debris Program Office, as of January 1<sup>st</sup> 2016 more than 300 orbital fragmentations (excluding aerodynamic break-ups) have occurred. Thus minimizing the potential for on-orbit break-ups and preventing on-orbit collisions are important measures to avoid the future generation of new fragmentation debris.

The second most common origin of all trackable objects are spacecraft and rocket bodies. This includes non-operational and operational spacecraft, the latter number being today roughly 1,300. Spacecraft together with rocket bodies are the most important potential sources of future new fragmentation debris. The proper disposal at end-of-life and release of energy that could lead to a rupture is of utmost importance. Fortunately, natural forces, especially atmospheric drag, work to clean space debris and satellites from LEO region, but this mainly affects objects below about 700 km altitude. Spacecraft and rocket bodies above this altitude regime could have lifetimes in orbit for several hundreds of years and are thus potential sources for break-ups – especially collisional induced – for a long time.

Finally, mission-related debris are objects left in orbit either by design (e.g., covers or objects released for experiments). Mission related objects have been a source of debris in the past but are becoming less significant today.

The curves in Figure 9.1 also show that the number distribution is heavily influenced by major breakup events and solar activity levels.

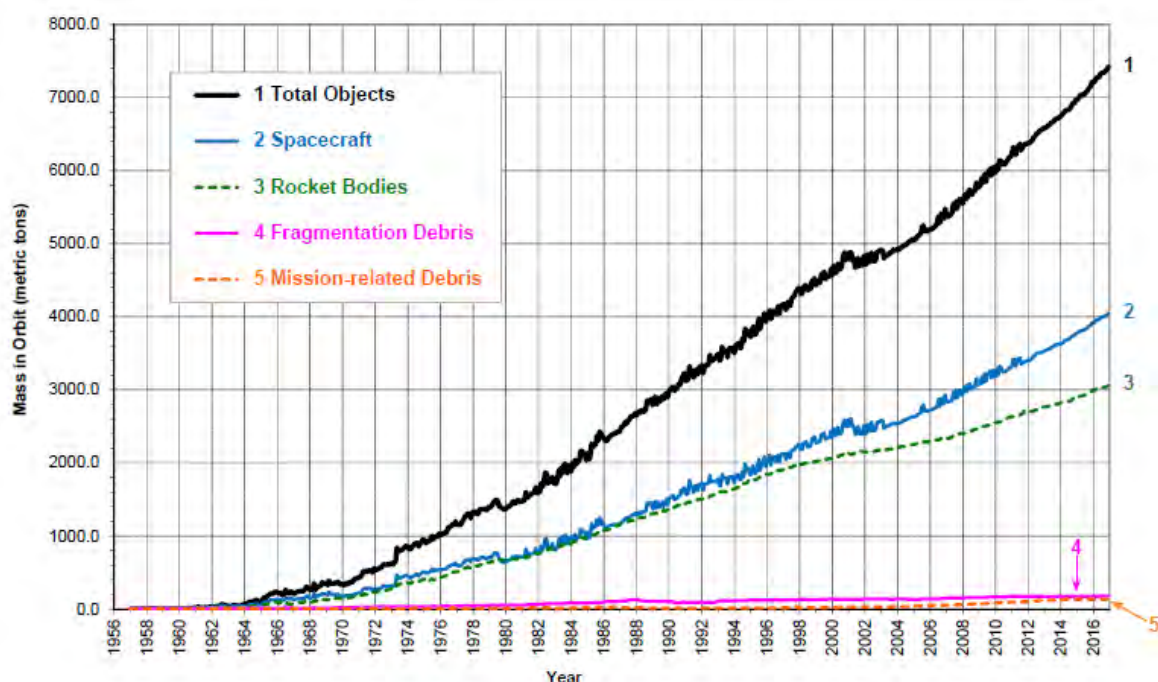


Figure 9.2: Mass increase in Earth Orbit by Region [9.9]

The mass distribution is dominated by spacecraft and rocket bodies. Fragment debris only account for less than 5% of the total mass in space. The total amount of material in space shows a steady increase over time. There is no sign of slowing down. When the mass distribution is analyzed for different orbital regimes, LEO, MEO, and GEO, there is a similar pattern of increase in all of them (Figure 9.2). If the amount of material continues to increase in the future, more accidental collisions are expected to occur, which in turns will significantly increase the number of fragments in space.



The IADC defines space debris mitigation measures as “consist[ing] of all efforts to reduce the generation of space debris through measures associated with the design, manufacture, operation, and disposal phases of a space mission.” The ultimate goal of the mitigation effort is to address both the number and the mass increases as shown in the two figures above.

In the following sections, the most important mitigation measures are explained.

### **9.1. General objective of space debris mitigation guidelines**

The objectives and fundamental principles of space debris mitigation activities, issued and applied by several national and international organizations of space faring nations, are to take measures to:

- Limit the number of objects released during normal operations,
- Minimize the potential for on-orbit break-ups,
- Prevent on-orbit collisions, and to
- Dispose of spacecraft and orbital stages that have reached their end-of-life.

Very often in the same context the aspect of limiting the risk to people on ground from re-entry of space structure is also addressed in the frame of debris mitigation.

In general, space debris mitigation guidelines define what should be accomplished, rather than describing how to organize and perform the necessary work to achieve the objectives.

However, mitigation measures can only be efficiently implemented if they are considered right from the beginning, starting from the mission definition and planning phase of a space project. This will allow the mission office to identify any potential non-compliance issues early and develop a plan to address the issues in a cost-effective and timely manner. Therefore the setup of a proper space debris mitigation plan prior to the preliminary design review of a mission is recommended [9.1], [9.5].

### **9.2. Protected regions**

Two regions of Earth’s orbit –LEO and GEO – are recognized to be of unique use for space activities. Any activity taking place in these regions of outer space should be performed while recognizing the very unique nature of those regions to ensure their safe and sustainable use.

These regions have been singled out with regard to the generation of space debris and are designated as LEO and GEO protected regions. An illustration of these zones is given in Figure 9.3.

*“The LEO protected region is defined as the spherical region that extends from the Earth’s surface up to an altitude of 2,000 km”.*

The LEO protected region is the region of Earth’s orbit where most of the Earth observations and remote sensing satellites reside, including several major telecommunication constellations.

Human space flight also takes place in this region, which deserves special attention to protect astronauts from possible threats due to space debris impacts.

The low Earth orbit protected region is also the one with the highest density of space debris at about 800 km altitude (c.f. Chapter 2, Figure 2.6) and the highest risk of collision-induced catastrophic fragmentations.

*“The GEO protected region is a segment of a spherical shell that extends from 200 km below the geostationary altitude (35,786 km) to 200 km above the geostationary altitude, and whose latitude is between  $-15^\circ$  and  $+15^\circ$ ”.*

The GEO region is heavily populated mainly with communication satellites and thus also of great interest for the commercial market.

Although the debris population in this region is relative low compared with that in LEO and the average encounter velocity between a piece of debris and an operational spacecraft is typically less than 1 km/sec, there is no atmospheric drag to remove objects from the environment. Most of the debris generated in GEO will remain in GEO permanently. Therefore, protection of the GEO environment is critical for the long-term sustainability of outer space activities.

The GEO protected region is selected to ensure that sufficient space is reserved for operational spacecraft and a corridor for re-positioning maneuvers of operational spacecraft.

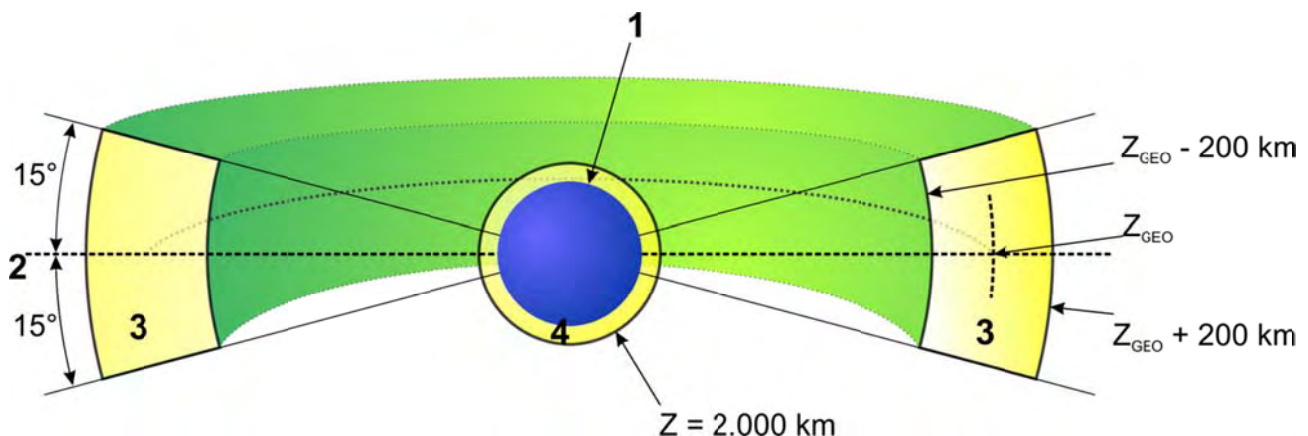


Figure 9.3: Definition of LEO and GEO protected regions (1 – Earth, 2 – equator, 3 – GEO protected region, 4 – LEO protected region). [M. Metz – DLR]

### 9.3. Mitigation measures

- Limiting Debris during normal operations

In all operational orbit regimes, spacecraft and orbital stages should be designed not to release debris during normal operations. Where this is not feasible, any release of debris should be minimized in number, area and orbital lifetime.

As can be seen from Figure 9.1, the generation of mission-related debris has slowed down over the past 15 years. The effort to further limit the release of mission-related debris is not cost-prohibitive and needs to be encouraged.

- Minimizing the potential for on-orbit break-ups

This mitigation measure encompasses several elements – accidental explosions during and after mission, and intentional destructions:

1. The potential for break-ups during mission should be minimized

2. All space systems should be designed and operated to prevent accidental explosions and ruptures at end-of-mission
3. Intentional destructions, which will generate long-lived orbital debris, should not be planned or conducted.

Before the Chinese *FengYun 1C* ASAT test in 2007, almost all fragmentation debris were generated by accidental explosions. Therefore, it is critical to minimize the potential for on-orbit explosions during mission operations and after end of mission.

The objective to reduce accidental explosions during mission operation is also shared by the satellite builders and operators for mission safety and assurance. There is extra incentive to achieve this objective by all involved.

Minimizing the potential for on-orbit explosions after the end of mission, however, faces more challenges. Many currently used subsystems containing energy sources are not designed for end-of-mission passivation. For examples, fuel cannot be vented, batteries cannot be drained or disconnected, and components cannot be depressurized. There is a cost associated with changing the hardware designs or adding new capabilities in the process to meet the objective which is not related to mission success, but is of interest only to the complete space community.

An intentional destruction at a high altitude can lead to serious consequences to pollute the environment for decades or longer. This negative effect was illustrated by the Chinese *FengYun 1C* ASAT test in 2007. The global community needs to reach a consensus to avoid similar events in the future.

#### 9.4. Post mission disposal measures

The mitigation measures described above aim to limit the growth of the orbital debris populations by numbers (c.f., Figure 9.1). The post mission disposal measures described in this Section are developed to address the mass buildup in the environment in the future (c.f., Figure 9.2). Ideally, the most effective means to avoid adding mass to the environment is by direct retrieval or designed deorbit of the rocket bodies and spacecraft at the end of mission. Unfortunately, the long-term benefit to the environment does not justify the high costs associated with this approach, and the cost for doing so significantly increases with altitudes based on the current technologies. Therefore, different measures are developed for different orbital regimes to balance the cost with benefit.

For spacecraft operating in GEO, the post mission disposal measure requires the spacecraft to be maneuvered to a graveyard orbit far enough away from GEO so that its orbit will not interfere with operational spacecraft in the GEO protected region ( $35,786 \pm 200$  km). The same measure is applied to propulsion system that needs to be separated from the spacecraft.

The disposal maneuver should place the spacecraft in an orbit that remains above the GEO protected region. The IADC and other studies have found that fulfilling the two following conditions at the end of the disposal phase would give an orbit that remains above the GEO protected region:

1. A minimum increase in perigee altitude of :

$$235 \text{ km} + (1000 \cdot C_R \cdot A/m), \quad [3]$$

where  $C_R$  is the solar radiation pressure coefficient,  $A/m$  is the aspect area to dry mass ratio ( $\text{m}^2/\text{kg}$ ), 235 km is the sum of the upper altitude of the GEO protected region (200 km) and the maximum descent of a re-orbited spacecraft due to luni-solar & geopotential perturbations (35 km).

## 2. An eccentricity less than or equal to 0.003.

The intent of the graveyard orbit is to separate retired spacecraft and propulsion systems from the GEO protection zone.

This is, of course, not a permanent solution. The buildup of material in the graveyard zone will eventually lead to accidental collisions among the disposed objects and generate fragments not only in the graveyard zone but also potentially entering the GEO protected zone. A more permanent solution will need to be developed in the future.

Rocket bodies and spacecraft passing through the LEO region should be de-orbited (controlled re-entry is the preferred option) or where appropriate maneuvered into an orbit with a reduced lifetime. It is recommended that the remaining orbital lifetime be reduced to less than 25 years at the end of mission.

Natural forces, especially drag, work to clean space debris from the LEO region, although this is efficient primarily for satellites below 700 km. For a typical satellite equipped with big solar panels of a few square meters a 25-year lifetime after end of mission can be achieved by decay due to natural forces at approximately 600 – 650 km circular orbit. This is only an approximate value, as the exact remaining orbital lifetime depends on the solar activity, which itself has a large uncertainty in the prediction.

Spacecraft equipped with a propulsion system can actively reduce their remaining orbital lifetime before being passivated. For a given amount of propellant, lowering perigee will be sufficient to minimize the remaining orbital lifetime, compared with lowering both apogee and perigee to a new, lower circular orbit. Satellites without de-orbiting capability should not be launched to the orbits within the LEO protected region if their post-mission lifetime is greater than 25 years.

While removal of mission-terminated spacecraft from LEO protected region is an effective mitigation measure to reduce the mass in orbit, the ground casualties that might be caused by fragments surviving uncontrolled atmospheric re-entry should be carefully considered in mission planning, particularly for large spacecraft and rocket bodies.

To assess the human casualty risk of impact by objects that survive re-entry, reliable analysis tools for survivability and acceptable analysis conditions should be used. A criterion of 1 in 10,000 human casualty risk from random-reentry debris is consistent with the risk accepted by Range operations, and has been adopted by several major space-faring countries.

## **9.5. Prevention of on-orbit collision**

The objective of this measure is to limit the generation of debris from accidental collisions involving operational spacecraft and other objects in the environment. Collisions with objects larger than about 10 cm in diameter are likely to result in the catastrophic destruction of the spacecraft and lead to the generation of a significant amount of space debris. Fortunately, the U.S. Joint Space Operations Center (JSpOC) is capable of tracking these larger objects and is conducting conjunction assessments for all operational spacecraft and provides warnings to the owners or operators of the spacecraft involved.

To better ensure mission safety and prevent the generation of new debris, the spacecraft owners and operators are encouraged to conduct collision avoidance maneuvers for high risk conjunctions.

## 9.6. Global implementation of mitigation measures

Space debris mitigation measures are implemented by national space agencies and international organizations using various implementation mechanisms. Details can be found in Chapter 11 and the “*Compendium of space debris mitigation standards adopted by States and international organizations*” [9.8]

Some ten years after the IADC Space Debris Mitigation Guidelines were issued and presented to the UN, and some 5 years after the issuing of the UN Space Debris Mitigation Guidelines, statistical analyses show that the level of compliance with the 25-year rule has been low, as demonstrated by [9.6] and displayed in Figure 9.4.

This discouraging trend will lead to a high population growth in the future.

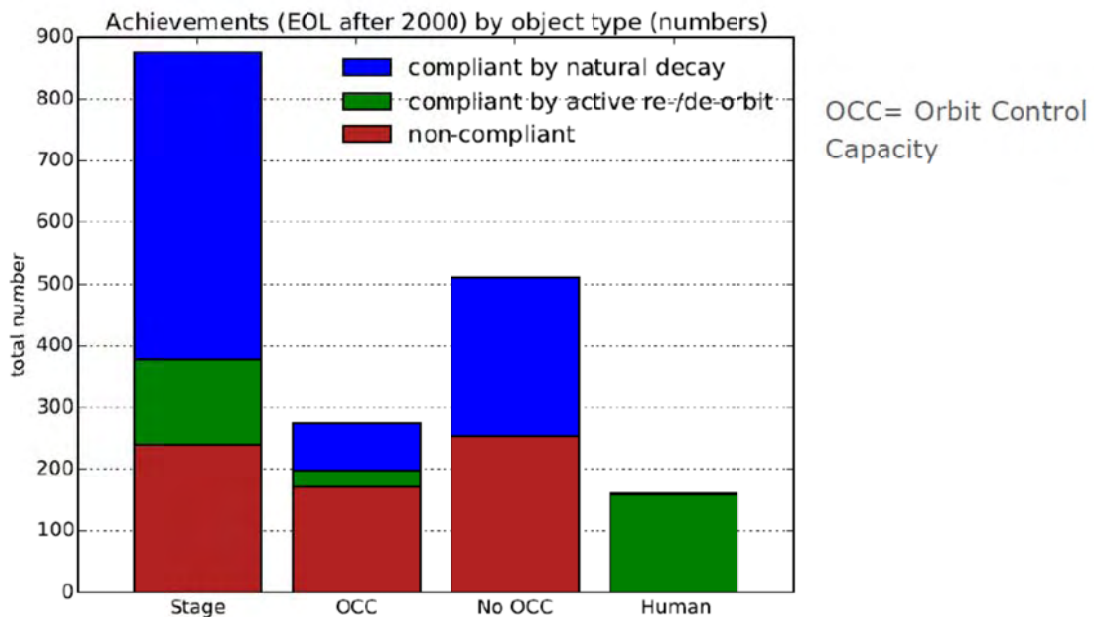


Figure 9.4: Summary of post mission disposals for rocket bodies and spacecraft which ended their missions after 2000 [9.6].

The effectiveness of using the 25-year rule to control the population increase in LEO has been analyzed by many groups over the past 20 years.

A recent example is provided in Figure 9.5, elaborated under various assumptions of Post Mission Disposal (PMD) compliances. The differences between a high-compliance projection and a low-compliance one could be a factor of two or three. A higher population growth will increase the risk to operational spacecraft and, more seriously, increase the cost for any remediation efforts that may become necessary in the future. A good compliance with the existing mitigation measures is the best first line of defense against future population growth in LEO and should be treated as a priority by the global space community.

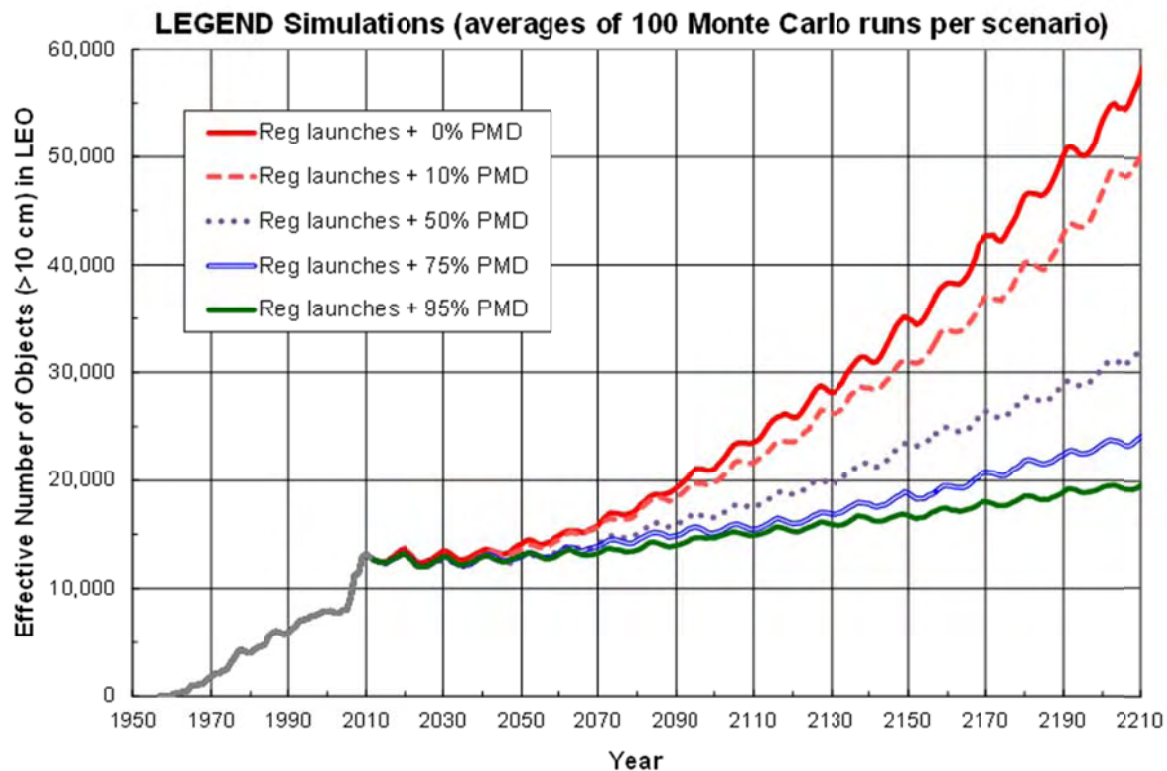


Figure 9.5: Projected space debris population increase in LEO for different levels of compliance with the 25-year rule [9.10].

In GEO, the situation is somewhat different. Overall, the level of compliance is much better than that in LEO. As shown in Figure 9.6, the level of compliance has increased to more than 60% in recent years (even though it dropped back to 40% in 2016).

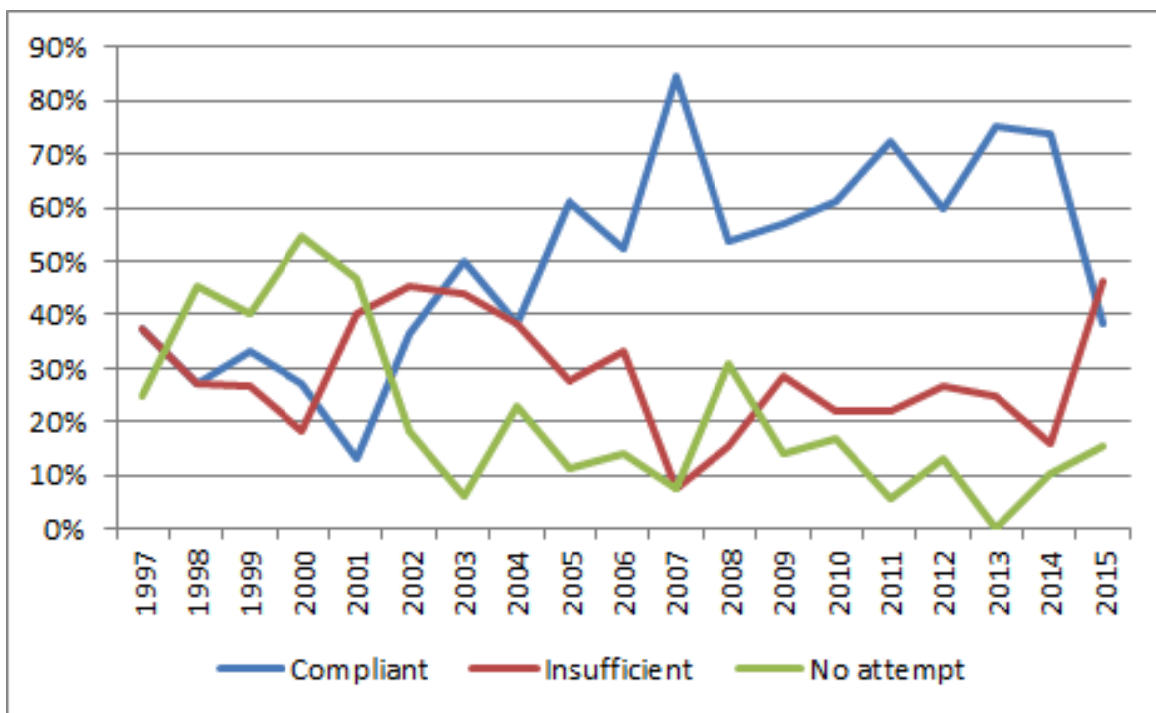


Figure 9.6: Compliances of post mission disposal in GEO since 1997.



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## 10. Debris remediation

### 10.1. Introduction

Most of the larger cataloged fragments and all intact derelict objects may cause catastrophic fragmentation upon impacting other objects in LEO<sup>16</sup>.

While there has been a variety of effective debris mitigation guidelines developed, and applied internationally to reduce the deposition of new orbital debris, these mechanisms will not be sufficient to control the future growth of the population. This is because there is already sufficient number of, and mass of derelict debris in Earth orbit to produce a collisional hazard great enough to spawn collisional breakups in the future, even without any new objects being placed into orbit [10.1]. The process of removing artificial space debris from orbit that has already been abandoned is termed space debris remediation.

This chapter examines removal of any debris but the focus will be on prevention of collisions of massive objects since such encounters could produce tens of thousands of fragments capable of disrupting or terminating a satellite's mission.

There are three distinct categories of space debris that must be considered for potential remediation: Lethal NonTrackable (LNT) debris, Catalogued Fragments (CF), and Intact Derelict Objects (IDO).

The roughly 1,300 operational payloads, though not debris, can still be part of future collisional events as *Iridium-33* was in 2009. However, these objects will not be considered as subjects of debris remediation. Table 10.1 depicts characteristics of each family of derelict objects for LEO and GEO only [10.2]

The key metric for all future debris control measures, both mitigation and remediation, is to act in such a way as to permit all satellites to continue to function without a reduction in operational capacity due to debris impact.

As a result, we must strive to eliminate production of LNT and CF which is best done by preventing large derelicts (i.e., IDOs) from colliding.

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<sup>16</sup> A catastrophic breakup will occur from an impact when the ratio of the kinetic energy of the collision to the mass of the target exceeds 35-45 J/g and the impact velocity exceeds 6 km/s. [10.49]

Characteristic	LNT – Lethal Nontrackable Debris		CF – Cataloged Fragments		IDO – Intact Derelict Objects (R/Bs and Nonoperational P/Ls)	
	LEO	GEO	LEO	GEO	LEO	GEO
Mass Range	1 gm – 500 gm	500 gm - 10 kg	500 gm - 10 kg	10 – 15 kg	>10 kg	>100 kg
Size Range	5 mm – 10 cm	10 cm - 1m	10 cm – 1 m	1 m - 2 m	>1 m	>2 m
Total Number	~600,000	~2,000	~8,100	~1,000	~2,500	~620
Total Mass	~100 kg	~1,000 kg	~100,000kg	~10,000 kg	~2,000,000 kg	~1,000,000 kg
Average Relative Impact Velocity	10 km/s	200 m/s	10 km/s	200 m/s	10 km/s	200 m/s
Effect of Impact on Large Object	Mission-degrading or mission-terminating		Mission-terminating and debris production		Significant debris production	
LNT Produced	N/A		~10 /kg	~2 /kg	~50 /kg	~10 /kg
CF Produced			N/A		~10 /kg	~2 /kg
Characterization Issues	Cannot detect or track regularly from the ground		Mass, shape, and density difficult to determine from size		Tumble rate is unclear but dry mass is well known	
Distribution In Orbit	Assume to be distributed in altitude and inclination similarly to CF and IDO		Contours follow previous breakup events and quantified by the satellite catalog		Contours follow popular orbits	
	Affected significantly by drag	Affected significantly by solar radiation pressure	Below 950 km debris is very populous	Some fragments will migrate to gravitational wells	Depends on deployment process – several major clusters of concern	Most derelicts will oscillate about gravitational wells
Removal Issues	Requires large surface area collector with a robust structure capable of maneuver		Requires large surface area collector that is durable and capable of maneuver		May be tumbling, hard to grapple, and require system to move; LEO to deorbit but for GEO move to graveyard orbit	

Table 10.1: The three families of debris targeted for remediation span from mm-sized chips to massive defunct payloads and rocket bodies.

## 10.2. Methods for Lethal Non Trackable (LNT) debris and Catalogued Fragments (CF)

Many previous analyses have shown that sweeping out LNT or CF with a collection device once they have been deposited in Earth orbit is neither a technically feasible nor cost-effective approach to reducing the hazard from orbital debris ([10.2] to [10.5]).

LNT cannot be seen from the ground reliably and any sweeping device that statistically would capture a significant number of LNT would simultaneously have an unacceptably high probability of being struck by CF and IDOs. This complicates any sweeper design requiring exceptionally robust capture media and/or avoidance maneuver capability.

In the end, the resultant design cost, size, and complexity are not deemed viable at this time, so the focus has remained on preventing IDOs from colliding with each other and Active Debris Removal (ADR) is seen as the primary means to reduce this hazard.

### 10.3. Intact Derelict Objects (IDO).

Figure 10.1 represents possible means to mitigate and remediate debris.

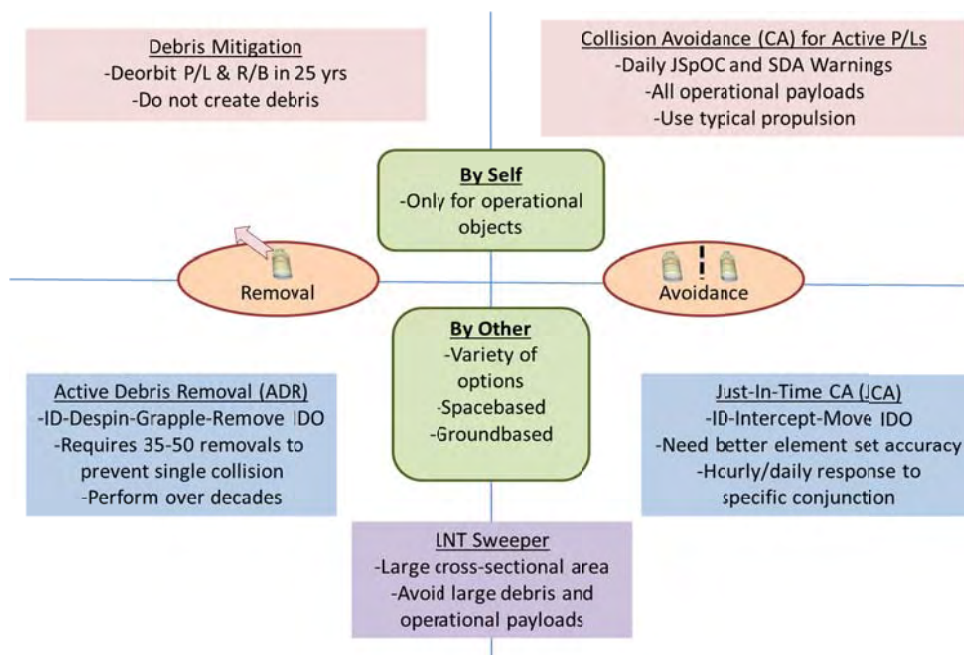


Figure 10.1: Remediation options are the potential actions in the lower half of the figure. [10.6]

- The upper left quadrant includes the debris mitigation measures that each space user performs for themselves while still in control of their satellite to remove (or never deposit) hardware in orbit.

This includes a variety of mechanisms to reduce the orbital lifetime after operational use such as propulsive maneuvers, orbital selection, or activation of drag-enhancement devices and electrodynamics tethers.

- The upper right quadrant is the active Collision Avoidance (CA) process where the US's Joint Space Operations Center (JSpOC) issues thousands of Conjunction Summary Messages (CSM) globally each year.

Many of these result in satellite operators executing collision avoidance maneuvers. However, due to the imprecise nature of conjunction calculations, the majority of the CSMs are not acted upon. Sometimes this is because the satellite operator uses system ephemeris to show the conjunction was unlikely to occur or the system did not have the operational imperative or capability to make the maneuver.<sup>17</sup>

- However, once the hardware has been abandoned, the only real options are removal by some intervening mission shown in the lower half of the Figure 10.1. ADR and JCA primarily act on IDOs while passive sweepers target the removal of LNTs. None of these modes of debris management have been proven or executed systematically to date.

<sup>17</sup> If this figure were to cover the removal of small debris then the lower left hand quadrant would include sweeper systems. However, this figure focuses on the prevention of collisions between large debris objects sufficient to create large numbers of lethal fragments.

### 10.3.1 Active Debris Removal – ADR (Remove Derelicts)

ADR is the act of not only removing derelict objects abandoned in orbit but also moving operational satellites from their operational orbits at the end of their life. This may mean that the object is moved to insure an eventual reentry or just to a different orbit where other satellites do not operate (e.g., graveyard orbit above GEO).

ADR requires three steps:

1. Rendezvous,
2. Grapple/detumble (as necessary),
3. Movement to a lower altitude to reduce remaining orbital lifetime.<sup>18</sup>

Grappling/detumbling is whatever is needed to permit the object to be prepared for it to be acted upon by the deorbit device.

There are several approaches under consideration – all of which become more difficult the more massive and dynamic the object being captured is. Therefore, a database of debris angular motion via light curve and imaging radar observation would be useful for a more detailed and specific operational discussion; an action at IADC level is currently ongoing on this topic.

Grappling approaches include hooks, harpoons, nets, glue, foam, tentacles, and tailored connectors. It will not be cost-effective to create unique interfaces for each class of objects individually yet it will also be difficult to make generic capture devices that will work reliably. As a result, there will likely need to be a coupling between target selection grappling mechanism. Groups of the same type of derelict hardware might be selected to avoid this difficulty.

When examining ADR options there are several metrics that should be considered:

- Design maturity: Technology Readiness Level (TRL) provides a measure of programmatic risk and potential investment needed to make a solution operational;
- Efficiency: cost per object removed and cost per collision prevented determine financial efficacy of approaches being considered;
- Rendezvous trajectory: an orbital intervention creates potential risk to generate more orbital debris;
- Orbit application: solutions that can be used for multiple orbital regions (e.g. LEO, GTO, and/or GEO) might be preferable;
- Propellant: amount of propellant needed to rendezvous and remove objects adds cost and weight; and
- Reentry: the ability to control deorbiting to minimize risk to people on the ground is preferred.

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<sup>18</sup> For geosynchronous orbit (GEO) and even high LEO objects, the hardware may be moved to a higher, less-used orbital altitude. This may create a short-term solution for the cluttered altitude but does not obviate all orbital collision risk; it just moves it.



ADR involves the removal of large derelict objects in a number of ways listed below. The majority of these will require a rendezvous, grapple, and stabilization of tumbling objects in order to initiate the ADR mechanism. This is not a trivial process.

Objects slated for removal may be selected based upon their mass, cross-sectional area, probability of collision with other large debris, and orbital lifetime of debris generated (i.e., based largely on orbital altitude).

Objects routinely identified as likely choices for removal are the many massive depleted rocket bodies and some defunct payloads in LEO and GEO.

ADR methods currently being considered include:

- Propulsive tug is a fairly low risk approach from an engineering perspective but still requires rendezvous and grapple [10.8], [10.27], [10.28], [10.31] to [10.35].
- Inflatable drag devices may be effective and reliable at lower altitudes but would lose effectiveness and require much larger areas as the target altitude went above 650-800 km [10.7], [10.9].
- The electrodynamic tether has been studied extensively and has shown good potential capability but the engineering challenges are significant and it loses some effectiveness at higher inclinations (and many derelict objects are in high inclination orbits) [10.22], [10.23], [10.25], [10.26].
- The momentum tether is not discussed as often as the electromagnetic tether; however, it has been shown to be viable for derelict removal [10.51].
- A solar sail is simple and reliable but its size scales with the mass of the object being moved so may become unwieldy for moving/removing very massive objects. In addition, solar sails have the requirement to be oriented correctly with respect to the Sun so may preclude its use in some orbits [10.10], [10.12].
- The Ion Beam Shepherd concept is technically feasible and the large power requirements and the need to maintain a precise location relative to the derelict make its deployment unlikely [10.24].
- The Geosynchronous Large Debris Deorbiter (GLiDeR) is very similar to the ion beam shepherd but uses electrostatic forces for moving the derelict. While potentially viable it can only be used in GEO and has some of the same issues as the Ion Beam Shepherd [10.39].
- Ground-Based Lasers (GBL) hold the promise of moving/removing debris without having to out any additional mass in orbit. However, laser technology needs to progress to provide sufficient energy on the orbiting derelict objects and will be more effective on smaller objects that can be tracked reliably. GBLs also have some imposed constraints of being stationary on the ground within a thick atmosphere that makes the energy propagation to orbital debris challenging [10.8], [10.16] to [10.20].
- Space-based lasers eliminate many of the issues of ground-based lasers such as atmospheric attenuation, range, and geometry issues. However, orbiting a high power laser has its own engineering, operational, and policy hurdles that will need to be addressed [10.8], [10.20].

There are many viable ADR approaches under review and it may be years before it is clear which one (or ones) will be the most likely to be fielded operationally.

Figure 10.2 shows eight of the widely discussed ADR core technologies (small sample among numerous other concepts).

Starting in the top line we see on the left a grapple arm aimed at linking rigidly the chaser and the debris<sup>19</sup>; on the right an Electro Dynamic Tether (EDT) is attached on the debris by a smaller chaser, using its motion through Earth's magnetic field to generate thrust that can move a derelict object into a reentry trajectory<sup>20</sup>.

In the middle line, left, a net is thrown by the chaser to capture the debris before pulling it with a tether<sup>21</sup>; in the middle, as semi-rigid deployable structure enables the chaser to capture the debris<sup>22</sup>; on the right a solar sail uses sunlight as the propulsive force to move a debris object into a reentry trajectory in order to increase its descent rate<sup>23</sup>.

Last, on the bottom line on the left, a tethered grapple captures a debris before pulling it and releasing it on an atmospheric reentry path<sup>24</sup>; in the middle, tentacles surround the debris, creating a rigid link with the chaser<sup>25</sup>; the scheme on the right depicts the concept of contact-less grapple that may be possible in geosynchronous orbit to capture an abandoned object<sup>26</sup>.

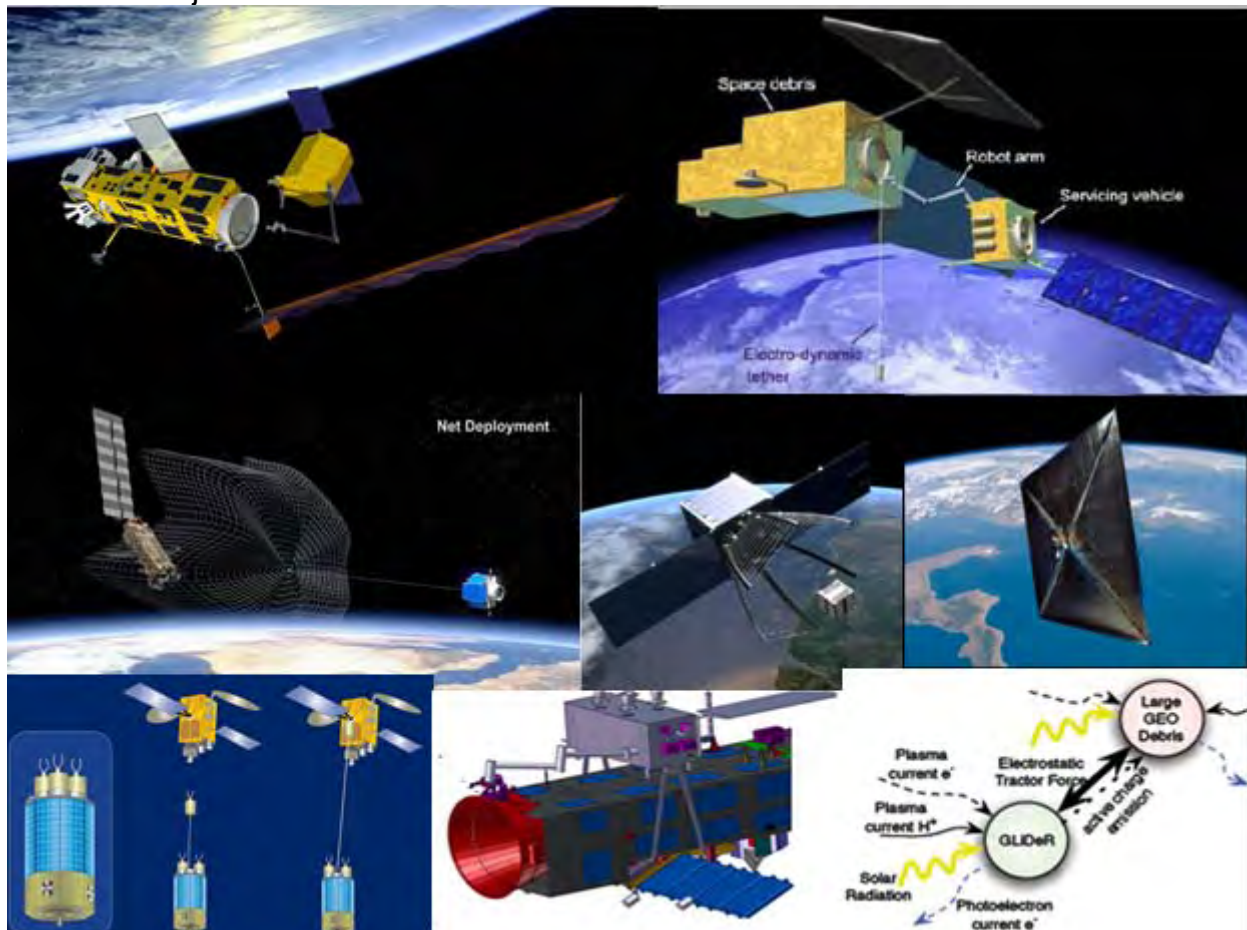


Figure 10.2: Some typical ADR technologies

<sup>19</sup> Credit MacDonald, Dettwiler and Associates Ltd (MDA)

<sup>20</sup> Credit Kawamoto JAXA

<sup>21</sup> Credit Airbus Defence and Space

<sup>22</sup> Credit Jamani Caillet EPFL

<sup>23</sup> Credit University of Surrey

<sup>24</sup> Credit Starke Airbus Defence and Space

<sup>25</sup> Credit Biesbroek ESA

<sup>26</sup> Credit Schaub University of Colorado Boulder

The number of lethal objects in orbit determines the current debris hazard while the mass of objects in orbit will drive the future hazard. This is because when two large objects collide there will be thousands of destructive objects (i.e., Cataloged Fragments, CF) liberated which can in turn destroy satellites or terminate/disrupt satellite operations.

ADR is likely to be applied first in the regions where there is a large reservoir of massive derelicts and high probability of catastrophic collision where drag is has minimal influence.

Figure 10.3 shows the spatial density of trackable objects as the blue line (i.e., likely to fragment an IDO upon impact) and the mass of IDOs in 20 km altitude ranges in LEO as the purple bars. ADR is likely to be applied first in regions where there are significant mass, a high probability of collision, and minor drag effects such as around 780 km and 860 km [10.6].

A considerable amount of research aims at establishing a priority list of objects which should be removed first. It is impossible to predict which specific objects will collide or break up in the next few years. If this would be known, it would be easy to pick the next removal targets based on the impact their collisions will have on the future debris situation. What is known today are the characteristics of the debris objects (mass, cross section area, orbit) and also which orbital regions are more likely to have collisions.

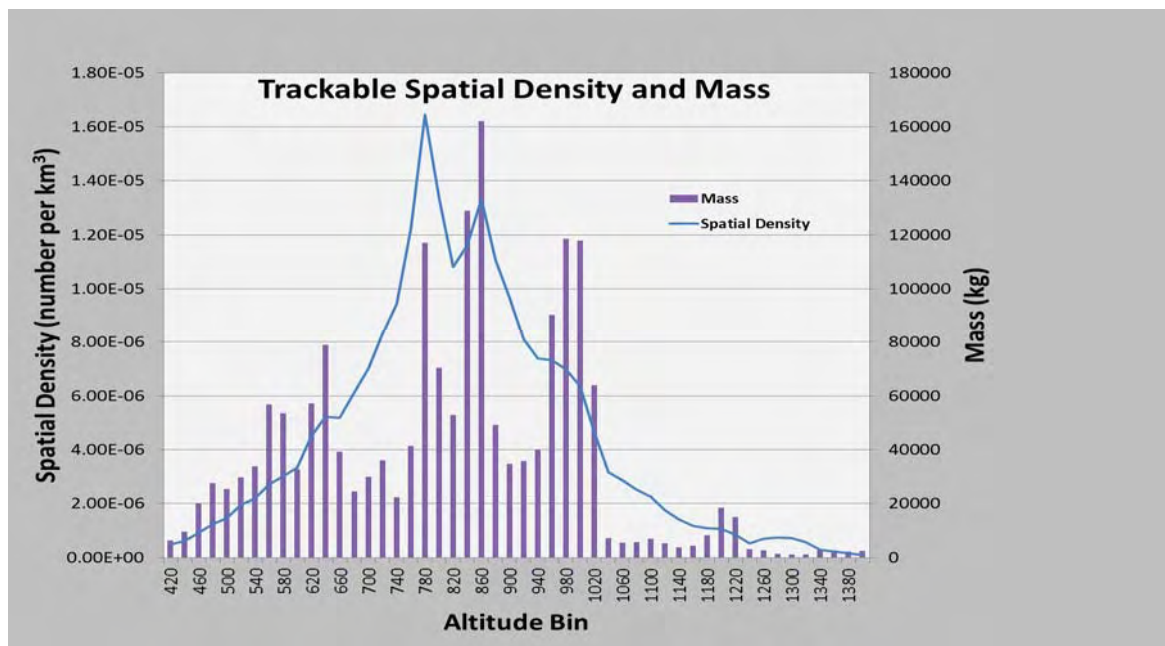


Figure 10.3: Trackable objects spatial density and mass [10.6]

In Figure 10.4, the LEO orbital region is visualized using altitude and inclination, based on the JSpOC catalog as accessible from Spacetrack.org<sup>27</sup>. Perigee and apogee altitudes are plotted over their corresponding orbital inclinations. 10 dominant inclination bands are discernable (63°, 65°, 70°, 71°, 74°, 81°, 83°, 87°, 90°, SSO band starting at 97°). This observation highlights densely populated regions in LEO. ADR missions should target these regions since it will be possible to conduct multi-target missions because the maneuvers required to reach successive targets are small.

One commonly used metric to rank objects for removal priority is multiplying the mass by the catastrophic collision probability associated with that object orbit. This metric focuses

<sup>27</sup> [www.space-track.org](http://www.space-track.org)

on the effect of collision (i.e., number of debris generated), to the debris environment. Applying this metric one by one to resident space objects produces a list of 500 top priority objects. In each group, the highest priority objects are annotated next to the group.

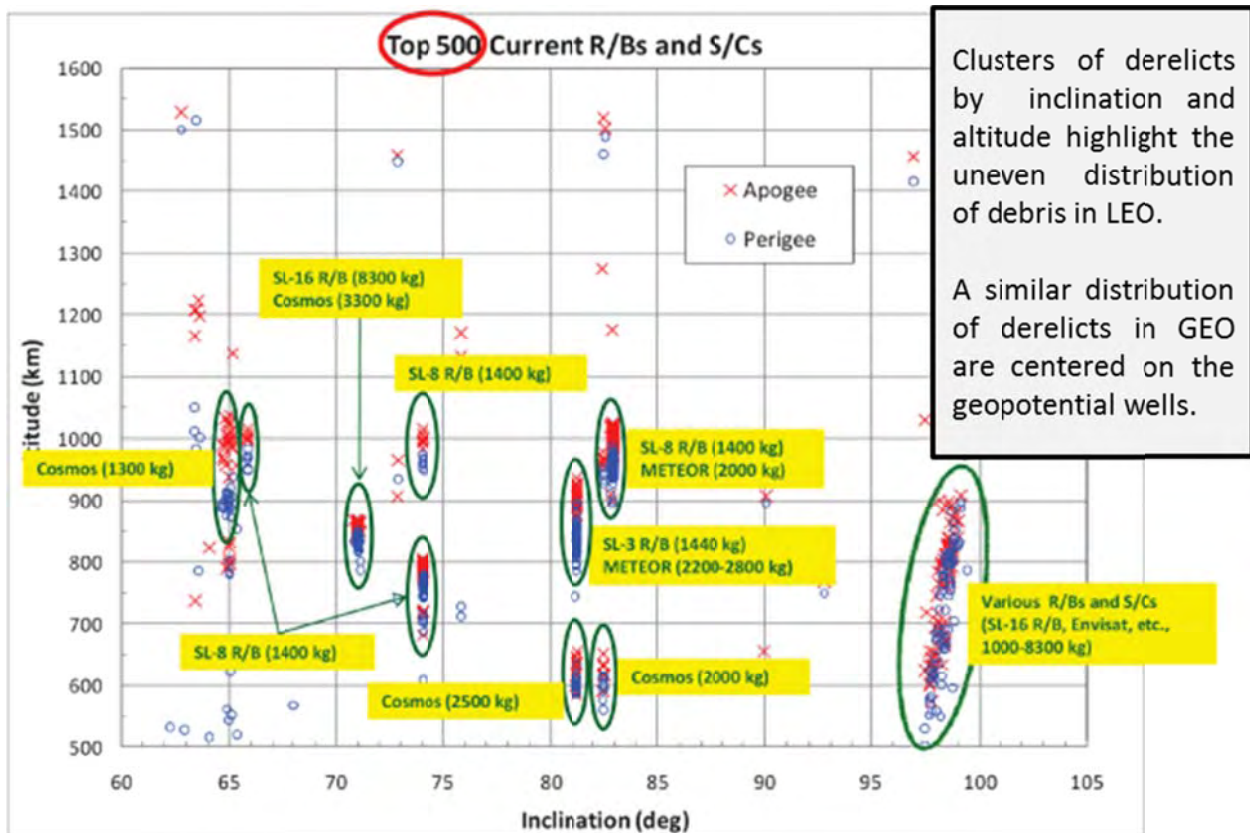


Figure 10.4: Clusters of hardware deposited in LEO show the large amount of mass in the proximity of key orbits. [10.3]

For the ADR mission, objects are selected that have the greatest mass and greatest likelihood of colliding with a trackable object and are then removed years to decades in advance of a potential collision. Clumps of these derelict objects have been identified in LEO by a variety of authors ([10.1], [10.3], [10.6], [10.33]). There is a significant energy requirement for the propulsion and guidance to rendezvous with a non-cooperative object and for the removal/reentry maneuver.

For example, the altitude around 780 km altitude has the current greatest collision hazard; however, altitudes around 860 km and just below 1,000 km will grow in number more rapidly because of the larger number of fragments produced with each collision between two massive derelict objects (typically used rocket stages). The lower atmospheric density at these higher altitudes also means that any generated debris will remain in orbit longer. Consequently, these are the regions that should have first priority for ADR operations. Inclination distributions are important when considering rendezvous and grapple since inclination changes are so energy intensive, thus objects in similar inclinations can be more efficiently removed.

The seminal work on ADR operations, done with optimistic assumptions, suggests a removal rate of 5 objects per year would prevent the LEO debris environment from becoming unstable [10.1]. A total operations time of 100 years is used in this analysis showing that ADR operations will prevent fourteen of 40 collisions predicted to occur over the next 100 years. This equates to about 35 objects (i.e., 500 removals will prevent 14



collisions,  $500 / 14 = 35$ ) having to be removed for each collision prevented. This produces a cost per collision prevented using ADR to vary between \$100 Ms to \$1 Bs with current technology [10.6]. These totals are small relative to many satellite replacement costs, however, the means of allocating these costs to past, current, and future operators has not yet been resolved.

A subset of ADR, though it is not strictly “debris removal”, is the process of moving retiring GEO satellites to a super-synchronous graveyard orbit. The amount an object is moved above the geostationary orbit is a function of the objects final area-to-mass ratio and results in graveyard orbits between 245 - 435 km above GEO [10.44]. Current guidelines call for GEO satellites to be moved to super-synchronous orbits to reduce cluttering in GEO.

However, there is evidence that this reservoir of large, aging payloads and rocket bodies may be producing High Area-to-Mass Ratio (HAMR) objects that may be perturbed into the path of operational geostationary satellites by solar radiation pressure [10.45], [10.47]. Early observations suggest that these objects have been spawned by satellites after only a couple of decades. This process is being studied carefully as it may create a significant problem as the number of objects in the graveyard orbit continues to grow of the next few decades. This operational sequence to dispose of dead GEO payloads will be refined and improved over time.

### 10.3.2 Just-in-time Collision Avoidance (JCA)

ADR is a statistical process, acting years to decades in advance of the collisional event it is hoping to prevent. Conversely, JCA is a deterministic process [10.6]. It will be executed only when an impending collision is predicted. JCA execution requires a mechanism for nudging a derelict object from an inevitable (or at least one with a high probability) collision such as the introduction of a gaseous cloud into the flight path of one of the two objects predicted to collide.

Figure 10.5 depicts a notional JCA operational process.

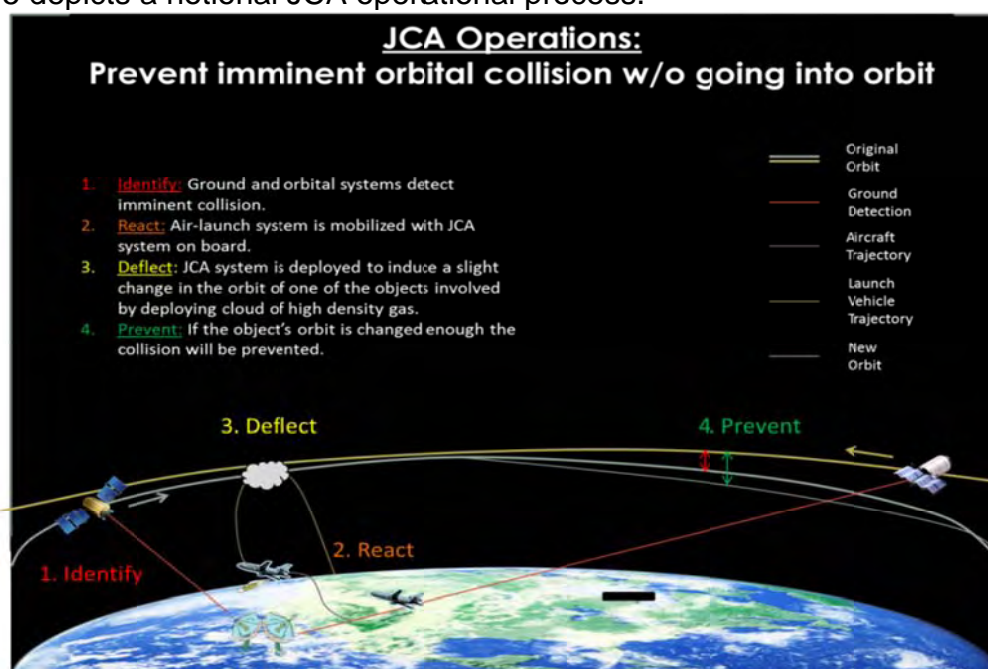


Figure 10.5: Just-in-time collision avoidance will require a system of responsive launch vehicles (possibly a sounding rocket) and low impact deflection devices to prevent imminent collisions of derelict objects. Note that this artist's depiction shows the collision being avoided one that is very near the “deflect” stage but in reality the derelict will be nudged about half of an orbit before the predicted collision [10.6].

Other concepts considering the use of space based lasers have been published [10.52].

The higher the area-to-mass ratio of the object, the greater the change in the orbit from the impulse will be. A full analysis of the technical viability of JCA and the likely cost per collision prevented was recently completed [10.6].

JCA has the potential to contribute tactically to debris remediation but it depends heavily on three challenging requirements: 10 m positional placement uncertainty (currently 100 m – 1 km in LEO), a device to nudge (but not break apart) a derelict object, and a ~\$300 k-\$500 k small payload launch cost (currently \$1M US for a sounding rocket with 150 kg payload to 1,200 km). However, one over-arching observation is that JCA may be best for rocket bodies (due to higher area-to-mass ratio and no need to de-tumble) and ADR may be best for payloads (easier to grapple, safer to handle, and denser object).

More research and a series of technology demonstrations are required before the final determination of the optimum mix of sweepers, ADR, and JCA can be determined.

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## **11. Legal aspects of space debris**

### **11.1. Introduction**

Space debris is becoming a serious threat but its legal ramifications are as yet unclear. In the past, states launched objects into outer space without much consideration for environmental effects or collision risks. At the end of their useful life, objects remain in space; larger objects may re-enter the Earth's atmosphere sooner or later, depending on the size of the object and the height of the orbit. Re-entering objects can cause damage on Earth or to aircraft. In addition, non-maneuverable debris can collide with active satellites while in space and cause damage to objects and astronauts, and the ever-growing population of non-functional objects pollutes the outer space environment.

Questions of ownership, responsibility, and liability for damage caused by debris need to be addressed, and there is a growing awareness that outer space must be kept clean and safe for future use. Technical standards and guidelines concerning debris mitigation are in place, but there are no internationally binding legal rules for debris mitigation and remediation.

Nevertheless, standards and guidelines can be transposed into national law and thus become binding in the national legal order. In previous IAA studies on space debris, legal issues have been addressed to some extent.<sup>28</sup> The fact that the present "IAA Situation Report on Space Debris" includes a section on legal issues illustrates the increasing awareness that these aspects cannot be neglected and can be helpful in setting rules and standards to address the problem. This chapter analyses the current status of the law and indicates future trends.

### **11.2. The UN space treaties and space debris**

The drafting of outer space law was initiated immediately after the launch of the first object into outer space, as states were from the start convinced that regulation of man's activities in outer space was necessary in order to ensure that outer space would be used for peaceful purposes and in an orderly manner.

The basis for the spaceflight regulatory environment is derived from Treaties and Principles developed by the United Nations. Since 1958/1959, issues relating to the use of outer space have been dealt with through the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). The Scientific and Technical Subcommittee of COPUOS addresses related technical issues, whereas the Legal Subcommittee deals with legal matters.

Five UN treaties were adopted between 1967 and 1979, which set the scene for the activities of man in outer space.<sup>29</sup>

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<sup>28</sup> For instance the 2013 study on "*Space Debris Environment Remediation*" contains a chapter (chapter 5) on legal aspects of debris remediation. The initial *IAA Position Paper on Orbital Debris* of 1993, updated in 2001, has a section (5.4) that mentions legal approaches to implement debris control methods. Its Annex 5 gives a timeline of discussions in the UN. The study on Space Debris Mitigation of 2006 contains a page about the structure of mitigation rules (international, national and industry standards).

<sup>29</sup> All texts, official titles and sources of the five UN space treaties can be consulted on the website of the Office for Outer Space Affairs in Vienna, the UN office supporting the work of the UN Committee on the Peaceful Uses of Outer

They are:

1. *The “Treaty on principles governing the activities of states in the exploration and use of Outer Space, including the Moon and other celestial bodies” of 1967 (Outer Space Treaty);*
2. *The “Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects launched into Outer Space” of 1968;*
3. *The “Convention on international liability for damage caused by space objects” of 1972;*
4. *The “Convention on Registration of Objects launched into Outer Space” of 1976; and*
5. *The “Agreement Governing the Activities of States on the Moon and Other Celestial Bodies” of 1979.*

The first three treaties were ratified by around ninety states (more than 100 for the Outer Space Treaty, which can be said to have reached the status of customary international law, binding even on states that have not ratified it), the fourth by around fifty and the last by only fifteen states so far.

Major space powers such as the USA, Russia, China, India, Japan, France, the UK, Canada and Germany have all ratified the first four treaties. None of these has ratified the Moon Agreement. Several international intergovernmental organizations (such as ESA, EUMETSAT and EUTELSAT) have declared their acceptance of the rights and obligations under some of the treaties (this is possible for all but the Outer Space Treaty). Many countries have reflected their obligations under the treaties through the enactment of national legislation.

For the time being, there is no internationally agreed definition of space debris and the term is not even mentioned in any of the treaties. But several provisions of the 1967 Outer Space Treaty and subsequent treaties are of direct or indirect relevance to the issue of space debris.

The first, and most important, principle is contained in Article I. It states that the exploration and use of outer space must be carried out for the benefit and in the interests of all countries and are the province of all humankind. Outer space is free for exploration and use without discrimination, on a basis of equality and in accordance with international law. The concepts are not clearly defined and can be subject to varying interpretations – but the general idea is clear: the use of space should somehow benefit humankind. The freedom to use space is, of course, not absolute, but subject to respect for the freedom of other users.

Article III states that activities must be carried out in accordance with international law, including the UN Charter, in the interest of maintaining international peace and security and promoting international co-operation and understanding. This includes Articles 2.4 and 51 of the UN Charter, prohibiting the threat or use of force on the one hand, and recognizing the individual and collective right of self-defense on the other. Furthermore,

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Space (UN COPUOS). See <http://www.oosa.unvienna.org>, especially under ‘Space law’. In addition to the treaties, a number of other important principles have been produced by the United Nations and are embodied in UN Resolutions.



international cooperation is an obligation under the UN Charter, which *ipso facto* also applies to space activities. Article III also implies that general international law, including international environmental law, applies to activities in outer space.

The Treaty also contains important rules concerning responsibility and liability (Articles VI and VII, further elaborated in the Liability Convention). A state is internationally responsible for 'national activities' in space, and a launching state is liable for damage caused by its space object to another state or its natural or juridical persons, whether that damage occurs in space, in the air or on the ground. A unique characteristic of space law is that it only has a system of state liability, i.e., a private entity or a natural person cannot present a claim based on the Treaty against another state directly under the Treaties, but must be represented by its state; nor can a private entity be held directly liable. An important question is whether a state might be held responsible under Article VI for creating space debris or for not cleaning up space debris. If damage occurs, a state could be held liable to compensate that damage in accordance with Article VII. So far these articles have never been put to the test before an international tribunal.

Article VIII of the Treaty provides that the state of registry "retains" jurisdiction and control over an object launched into outer space, and provides that ownership of objects launched into outer space and of their component parts is not affected by their presence in outer space or by their return to Earth. This suggests that the state of registry remains the owner of a space object even after its useful lifetime, whether it remains in space or returns to Earth.

Article IX stipulates that states are to explore outer space, the Moon and other celestial bodies "so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter". States must conduct their activities in outer space with "due regard" to the corresponding interests of other states parties. If a state believes that an activity planned by it, or its nationals, would cause potentially harmful interference with activities of other states, it must undertake international consultations before proceeding with it. In addition, if a state party believes that an activity of another state could cause potentially harmful interference, it may request such consultation. Thus, if potentially harmful interference is expected, international consultations are required.

The Moon Agreement amplifies this provision by stating that "*in exploring and using the Moon, States Parties shall take measures to prevent the disruption of the existing balance of its environment whether by introducing adverse changes in that environment, by its harmful contamination through the introduction of extra-environmental matter or otherwise. States Parties shall also take measures to avoid harmfully affecting the environment of the Earth through the introduction of extra-terrestrial matter or otherwise.*"

The 1972 Liability Convention expands on Article VII of the Outer Space Treaty. The Convention has never been invoked in a court case, and hence its provisions, some of which are rather vague, have never had the benefit of being interpreted or clarified by case law.

Some accidents could have led to claims under the Convention, for instance, part of the cost incurred for cleaning up nuclear waste caused by the 1978 crash of *Cosmos 954* on Canadian territory was reimbursed by the then USSR, but this was not done under the

terms of the Convention (the USSR did not admit liability)<sup>30</sup>. The more recent collision between *Iridium 33* and *Cosmos 2251* in 2009 also did not lead to any liability claim under the Convention<sup>31</sup>.

The Convention has a victim-oriented approach, and identifies several states as potentially liable 'launching states'. A launching State is defined as: (i) a state which launches or procures the launching of a space object; and (ii) a state from whose territory or facility a space object is launched (Article I c and d). Only states may present a claim. Private individuals or companies have no direct cause of action under the Convention, but depend on their government to present a claim to (one of) the launching state(s).

A launching state is absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft in flight, according to Article II. Fault liability applies for damage caused by its space object to another State's space object "*elsewhere than on the surface of the Earth*" i.e., in outer space (Article III). This can be a challenge in case of a collision between a defunct and a working satellite hundreds of kilometers up in space, which perhaps explains why there is no case law.

The term "damage" is defined in Article I (a) of the Convention as "*loss of life, personal injury or other impairment of health; or loss of or damage to property of States or of persons, natural or juridical, or property of international intergovernmental organisations*". It is not clear whether this definition includes harm to the extra-terrestrial environment per se, without harm to persons or property. Environmental pollution may cause harm to persons or property; but then it would be the "secondary" damage to persons or property resulting from the "primary" damage to the environment that gives rise to compensation under the Convention. Environmental law principles also apply to outer space activities through Article III of the Outer Space activity, so their violation may give rise to a breach of an international obligation and if damage occurs, it could be compensated under general international law.

For damage to be compensable, it must be caused by a space object to a space object, persons, or property of another state. Does the term "space object" include an inactive satellite or a lost screwdriver? If space debris does not qualify as "space object" in the sense of the Liability Convention, the Convention would not apply. Article I defines a space object as including "component parts of a space object as well as its launch vehicle and parts thereof." Can a space object cease to exist? And if so, when does this happen? When its fuel is used up? When it ceases to function? When it disintegrates? Logically, an inactive satellite or even a lost screwdriver should still be regarded as (a component part of) a space object for which responsibility remains with the launching State and which can give rise to liability of the launching state, if damage occurs.

A complicating factor is that in some cases the "object" may be so small that it is practically impossible to identify it, in order to determine who is responsible for the damage it caused. This situation is likely to worsen as the debris population grows.

The 1975 Registration Convention aims to facilitate the identification of objects launched into Earth orbit or beyond. It provides that a launching State must register the space object in a national register and furnish to the United Nations, "*to the greatest extent feasible and as soon as practicable*", the following information concerning each space object that is

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<sup>30</sup> See [http://www.oosa.unvienna.org/oosa/SpaceLaw/multi\\_bi/can\\_ussr\\_001.html](http://www.oosa.unvienna.org/oosa/SpaceLaw/multi_bi/can_ussr_001.html) and [http://www.jaxa.jp/library/space\\_law/chapter\\_3/3-2-2-1\\_e.html](http://www.jaxa.jp/library/space_law/chapter_3/3-2-2-1_e.html).

<sup>31</sup> See T. Masson-Zwaan, Space law and the satellite collision of February 10<sup>th</sup> 2009, COSPAR Information Bulletin nr 174 (2009) p. 4-11, available at <https://openaccess.leidenuniv.nl/handle/1887/13924>.

launched into Earth orbit or beyond:

- Name of launching State(s);
- An appropriate designator of the space object or its registration number;
- Date and territory or location of launch;
- Basic orbital parameters, including:
  - Nodal period;
  - Inclination;
  - Apogee;
  - Perigee;
- General function of the space object.

The information that has to be provided is vague and general, and, although useful for identifying the launch of a space object, has limited operational value in determining the position of the space object once initial injection into orbit has been performed. This renders the identification of fragmented or otherwise released objects even more difficult.

Registration per se does not have any consequences for the determination of liability for damage caused by the object. The “registration state” and the “launching state” are not necessarily one and the same. There can be several “launching states”, but only one of them can be the “registration state”. Firstly, the definition of “launching state” includes the launcher, the procurer, and the state from whose territory the object is launched. Secondly, in case of a joint launch, all “launching states” shall jointly determine which one of them shall register the object. If damage occurs, the registration state will be the most easily identifiable launching state, but all states that qualify as launching state and all parties to a joint launch are jointly and severally liable. The state that paid compensation can present a claim for indemnification to the other launching states.

### 11.3. The relevance of non-legally binding instruments

The treaties do not provide clear rules on space debris, even though they contain certain obligations that are relevant in this respect. These basic rules (e.g. benefits and interests of all states, due regard for the activities of other states, state responsibility, liability for damage, ownership, jurisdiction and control, etc.) would benefit from clarification and elaboration. Although a new treaty would be the ideal solution in the long run, the prospects are not so good. The last UN space treaty dates back to 1979 and has only 16 states parties. Admittedly, it addresses the controversial issue of commercial exploitation of space resources, and consensus on a space debris mitigation treaty might be easier. Until that happens, other instruments, even though not legally binding per se, provide useful additions to the basic rules of the treaties.

In 2007, UN General Assembly Resolution 62/217 endorsed the Space Debris Mitigation Guidelines that had been adopted by UNCOPUOS<sup>32</sup>. The text explaining the background contains a definition of space debris, but it serves only for the purpose of the document: *“space debris is defined as all man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional.”*

The UN guidelines are based on earlier principles, especially those of the Inter-Agency Debris Coordination Committee, IADC. The standards are discussed in the chapter on

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<sup>32</sup> A/RES/62/217, see <http://www.oosa.unvienna.org/oosa/SpaceLaw/gares/index.html>

References and Standards, but in the context of this chapter it is important to observe that the UN set of guidelines is not a legally binding instrument, like a treaty is. However, they could evolve into international customary law with sufficient state practice and *opinio iuris* and can also become binding through incorporation into national law.

The adoption of UN General Assembly Resolution 62/101 of 17 December 2007 (*Recommendations on Enhancing the Practice of States and International Intergovernmental Organizations in Registering Space Objects*)<sup>33</sup> was aimed at increasing the efficiency of the registration process and is also useful in the context of space debris. For instance, it recommends that consideration be given to the furnishing of additional information on a change of status in operations, for instance when the space object is no longer functional, on the approximate date of decay or re-entry, and on the date and physical conditions of moving a space object to a disposal orbit.

UN General Assembly 68/75 of December 11<sup>th</sup> 2013 gives recommendations on national legislation relevant to the peaceful exploration and use of outer space<sup>34</sup>. It contains a direct reference to space debris by noting “the need to maintain the sustainable use of outer space, in particular by mitigating space debris, and to ensure the safety of space activities and minimize the potential harm to the environment”.

In addition, among the eight recommendations that states could take into account in developing their national space legislation, number 4 reads as follows: “*The conditions for authorization should be consistent with the international obligations of States, in particular under the United Nations treaties on outer space, and with other relevant instruments, and may reflect the national security and foreign policy interests of States; the conditions for authorization should help to ascertain that space activities are carried out in a safe manner and to minimize risks to persons, the environment or property and that those activities do not lead to harmful interference with other space activities; such conditions could also relate to the experience, expertise and technical qualifications of the applicant and could include safety and technical standards that are in line, in particular, with the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*”.

The expected adoption of guidelines for the Long-term Sustainability of Outer Space Activities that are being developed by Scientific and Technical Subcommittee of UN COPUOS<sup>35</sup> will make a significant contribution to the further development of rules on debris mitigation and remediation. Lastly, a Code of Conduct for Space Activities that is being developed at the initiative of the EU<sup>36</sup> could also contribute to the subject matter.”

Calculations indicate that if five large objects are removed each year, the cascading effect predicted by Kessler could be halted<sup>37</sup>.

To reverse that trend and actually reduce the debris population, ten large objects need to be removed each year. Hence, ‘active debris removal’ (‘ADR’) is one option for potential debris remediation operations, and several technical solutions are on the drawing board of public and private entities<sup>38</sup>. Commercial, legal and policy issues are manifold. Legal issues include questions of ownership, prior permission, liability, payment, security, and

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<sup>33</sup> A/RES/62/101, *ibid*.

<sup>34</sup> A/RES/68/74, *ibid*.

<sup>35</sup> See [http://www.oosa.unvienna.org/pdf/limited/c1/AC105\\_C1\\_L339E.pdf](http://www.oosa.unvienna.org/pdf/limited/c1/AC105_C1_L339E.pdf).

<sup>36</sup> See [http://eeas.europa.eu/non-proliferation-and-disarmament/outer-space-activities/index\\_en.htm](http://eeas.europa.eu/non-proliferation-and-disarmament/outer-space-activities/index_en.htm).

<sup>37</sup> See “Stability of the Future LEO Environment”, an IADC study presented to UNCOPUOS, February 2013, available at <http://unoosa.org/pdf/pres/stsc2013/tech-12E.pdf>.

<sup>38</sup> See the 2013 IAA study on “Space Debris Environment Remediation”.

insurance.

An analogy with marine law, especially the salvage and wreck removal conventions of the International Maritime Organisation<sup>39</sup>, is interesting. The quickly evolving branch of international environmental law<sup>40</sup> is also relevant in this context. A gradual emergence of a legal obligation for states to protect the environment and to remediate damage can be observed. Some landmark cases often cited in this context are the Trail Smelter arbitration of 1939<sup>41</sup> where an international obligation of states not to permit the use of their territory to the detriment of another state was laid down, and the 1996 Advisory Opinion on the legality of nuclear weapons<sup>42</sup>, where the International Court of Justice (ICJ) recognized an international obligation to protect the environment. More recently, this was confirmed in the 2010 Pulpmill case<sup>43</sup> of the ICJ, which addressed the obligation to conduct so-called Environmental Impact Assessments (EIAs).

However, it may take a major mishap, as in the Hollywood blockbuster “Gravity”, for the community of states to agree on concrete progress and strong obligations to prevent the creation of new debris and remove spent objects.

#### 11.4. National legislation

With the increasing commercialization and privatization of space activities, a growing number of countries have reflected their obligations under the Outer Space Treaties by means of national legislation<sup>44</sup>. The development of national rules on space debris may lead to harmonization and perhaps eventually to internationally binding rules.

In June 2014, a major achievement in this respect was the publication by UNCOPUOS on its website of a “Compendium of space debris mitigation standards adopted by States and international organizations”, developed by Canada, the Czech Republic and Germany<sup>45</sup>. The compendium contains information about national mechanisms (or the absence thereof) submitted by (so far) 27 states<sup>46</sup>. States with the most advanced mechanisms include France, the UK and the USA. In addition, the Compendium contains the following international mechanisms: the European Code of Conduct for Space Debris Mitigation; the ESA Space Debris Mitigation for Agency Projects; the IADC Space Debris Mitigation Guidelines; ITU Recommendation ITU-R S.1003.2, and the UNCOPUOS Space Debris Mitigation Guidelines.

#### 11.5. Conclusion

The UN space treaties lay the foundations for the orderly conduct of space activities. They

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<sup>39</sup> See <http://www.imo.org/About/Conventions/ListOfConventions/Pages/Default.aspx>.

<sup>40</sup> See [http://www.asil.org/sites/default/files/ERG\\_ENVIROMENT.pdf](http://www.asil.org/sites/default/files/ERG_ENVIROMENT.pdf) (*sic*).

<sup>41</sup> See [http://legal.un.org/riaa/cases/vol\\_III/1905-1982.pdf](http://legal.un.org/riaa/cases/vol_III/1905-1982.pdf).

<sup>42</sup> See <http://www.icj-cij.org/docket/files/95/7495.pdf>.

<sup>43</sup> See <http://www.icj-cij.org/docket/files/135/15877.pdf>.

<sup>44</sup> A database of national space legislation is maintained by UNCOPUOS, see <http://www.unoosa.org/oosa/en/SpaceLaw/national/state-index.html>. Note that states that do not have a national space law must still authorize and supervise private entities' space activities, but do so on a case-by-case basis.

<sup>45</sup> See <http://www.unoosa.org/oosa/en/COPUOS/Legal/debris/index.html>.

<sup>46</sup> The are: Algeria, Argentina, Australia, Austria, Belgium, Canada, Chile, Czech Republic, France, Germany, Italy, Japan, Mexico, the Netherlands, Nigeria, Poland, Slovakia, Spain, Switzerland, Ukraine, the UK and the USA.

contain certain provisions that are relevant in the context of space debris, even though the term as such is not used.

However, the treaties do not contain sufficiently clear terminology or obligations. These are increasingly necessary as the problem of debris becomes more pressing with space activities by states, as well as private entities, increasing. The basic principles contained in the UN treaties can be clarified and elaborated by means of non-legally binding instruments, such as guidelines, UN resolutions, or codes of conduct. Consistent state practice and *opinio iuris* in applying these mechanisms can lead to the emergence of customary international law.

In addition, an increasing number of states include mechanisms to address space debris within their national legal order. In the end, all space actors, whether they are major space players, emerging space-faring nations, international organizations, or private commercial entities, have a common interest in safe-guarding outer space for future use. Eventually this conviction, and the gradual development of rules at various levels, will hopefully lead to the adoption of a new UN treaty in this field.

## **References**

### **UN Treaties**

[11.1] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (the "Outer Space Treaty"), adopted by the General Assembly in its resolution 2222 (XXI), opened for signature on January 27<sup>th</sup> 1967, entered into force on October 10<sup>th</sup> 1967

[11.2] Convention on International Liability for Damage Caused by Space Objects (the "Liability Convention"), adopted by the General Assembly in its resolution 2777 (XXVI), opened for signature on March 29<sup>th</sup> 1972, entered into force on September 1<sup>st</sup> 1972

[11.3] Convention on Registration of Objects Launched into Outer Space (the "Registration Convention"), adopted by the General Assembly in its resolution 3235 (XXIX), opened for signature on January 14<sup>th</sup> 1975, entered into force on September 15<sup>th</sup> 1976

### **UN Resolutions and other UN documents**

[11.4] Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, Endorsed by the Committee on the Peaceful Uses of Outer Space at its fiftieth session and contained in A/62/20, annex (2007)

[11.5] Resolution 62/101 of December 17<sup>th</sup> 2007: Recommendations on enhancing the practice of States and international intergovernmental organizations in registering space objects

[11.6] Resolution 68/74 of December 11<sup>th</sup> 2013: Recommendations on national legislation relevant to the peaceful exploration and use of outer space

### **Other documents**

[11.7] Draft International Code of Conduct for Outer Space Activities, proposed by the EU, March 31<sup>st</sup> 2014 (European External Action Service)

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## **12. International aspects**

### **12.1. Towards an international recognition of the space debris issue**

Since the 1980's the awareness of the risks posed by space debris has raised beyond communities of space debris experts and the need to address this issue was progressively acknowledged and national efforts gradually evolved towards international ones.

#### **12.1.1. The growing importance given to the issue in the main international forum on space activities**

The problem of space debris appeared in the major international forum on space activities in the 1980s. In 1989, the first US interagency report on orbital debris called for international cooperation towards space debris mitigation [12.1].

The space debris experts have been very active in raising awareness through the main international space organizations such as COSPAR, IAA, IAF, and IISL. The IAA published a first position paper on space debris in 1993. Information on space debris was put before the UN COPUOS and its Subcommittees at several occasions during the 1990s and space debris was added as an official agenda item of the Scientific and Technical Subcommittee of the UN COPUOS in 1994. The ITU acknowledged the danger of collisions of spacecraft with debris during the first session of the WRC in 1985 and asked the International Consultative Committee International Radio-communications (CCIR) to prepare a report on the problem. The issue was, however, not addressed again at the second session in 1988 [12.2].

#### **12.1.2. Establishment of a dedicated international forum: the Inter-Agency Space Debris Coordination Committee (IADC)**

The Inter-Agency Space Debris Coordination Committee (IADC) is the international body of technical expertise on space debris mitigation and remediation.

It was formed in 1993 as an international governmental forum for the coordination of activities related to space debris. Its primary purposes are: to exchange information on space debris research activities between members, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperative activities, and to identify debris mitigation options. The IADC members are national or international space agencies that perform space activities and actively contribute to space debris research and include ASI, CNES, CNSA, CSA, DLR, ESA, ISRO, JAXA, KARI, NASA, ROSCOSMOS, SSAU and UKSA.

The Committee work program is governed by a Steering Group and performed in four Working Groups on measurements; environment and database; protection; and mitigation. For over 20 years the IADC has produced authoritative definitions in space debris terminology; produced mitigation guidelines and a debris protection manual; conducted re-entry test campaigns, space debris measurement campaigns in LEO, MEO and GEO; and performed comparison of debris models of simulations of the future LEO environment. [12.3]

The work of the IADC has been instrumental in raising awareness on the space debris issue. Its studies based on inputs of, and endorsed by, its member agencies provide a sound, credible basis for policy-makers.

## **12.2. Major events that raised public awareness on debris**

A few catastrophic events have contributed to a heightened public awareness on the risks of space debris [12.4], in particular the Chinese destruction of a satellite and the first accidental collision between two satellites.

In January 2007, China deliberately destroyed its inoperable *Fengyun-1C* weather satellite [12.11]. An estimated 3,433 debris (10 cm or larger) were created by this anti-satellite test. Two years later, on 10 February 2009, the first ever accidental on-orbit collision between two satellites occurred between an American communication satellite (*Iridium 33*) and a Russian military satellite (*Cosmos-2251*) [12.12]. Both spacecraft were destroyed and more than 2,296 cataloged fragments (10 cm or larger) were generated. Those two events significantly increased the number of debris in orbit and triggered further work on the debris issue.

## **12.3. Addressing the debris issue**

### **12.3.1. A collective action problem**

Space debris is a problem to which all spacefaring nations have contributed and has become a major issue for all current and future space actors. Those actors are facing a collective action problem, as all of them would benefit from limiting the number of debris but none wishes to bear the associated costs and risks. These conditions call for a cooperative approach, which would ultimately lead them to share the costs and risks. This collective action need to be taken by the numerous stakeholders, public and private ones, at national and international levels. They include States, national agencies, intergovernmental organizations, commercial operators, etc., with different interests and constraints. This number of stakeholders continues to grow.

### **12.3.2. Relevant on-going international initiatives to ensure the sustainability of the outer space activities**

Three complementary initiatives are addressing some of the policy and security issues associated with space sustainability and are, therefore, relevant to the question of space debris. Two major initiatives addressing space sustainability, safety and security were undertaken in the UN framework: the working group on Long-term Sustainability of Space Activities (LTSSA) of the Scientific and Technical Sub-Committee of the UN Committee on the Peaceful Use of Outer Space (COPUOS) and the Group of Governmental Experts (GGE) on TCBMs in Outer Space. Both initiatives are based on the work of technical and legal experts and their goal is to produce practical recommendations in relevant areas.

The topic of the long-term sustainability of outer space activities for the first time was highlighted by Gérard Brachet, as Chairman of COPUOS, in 2006. During 2008-2009 informal working groups have developed a background paper on this issue for COPUOS. In February 2010 the Scientific and Technical Subcommittee have decided to establish the

Working Group on the Long-term Sustainability of Outer Space Activities (LTSSA) with the goal to identify areas of concern for the long-term sustainability of outer space activities, propose measures that could enhance sustainability, and produce voluntary guidelines to reduce risks to the long-term sustainability of outer space activities.

In June 2011 COPUOS adopted Terms of reference and methods of work of the working group. During 2012-2014 four Expert Groups of the LTSSA Working Group have produced reports [12.15] containing first version of draft guidelines for consideration by the WG. In June 2016 COPUOS agreed to a first set of guidelines [12.16]. Work continues on a second set of guidelines which will be brought together with the preambular text and the first set of guidelines to form a full compendium of guidelines to be adopted by the Committee and referred to the General Assembly in 2018 to coincide with UNISPACE+50.

The Group of Governmental Experts (GGE) on Transparency and Confidence-Building Measures (TCBMs) in Outer Space is an initiative of the UN General Assembly First Committee, which is in charge of security and disarmament issues. This Group of 15 international experts was set up in 2011 [12.13] to prepare recommendations on TCBMs that could help ensure strategic stability in the space domain by reducing the risks of misunderstanding and miscommunication in space activities. Their final report [12.14] was presented at the UN General Assembly in October 2013.

Europe has addressed the question of space debris and space sustainability through a proposal for an International Code of Conduct for Outer Space Activities. The objective of this EU initiative is to improve security in space through a pragmatic and incremental process, based on the development of TCBMs, as a means to achieving enhanced safety and security in outer space, and to limit the creation of space debris. The first draft Code of Conduct was adopted by the EU Council in December 2008. During 2010-2014 a number of multilateral expert meetings and consultations took place that resulted in issuing of several revised versions of the proposed Code. The European External Action Service (EEAS) is leading this process. Final version of the Code produced in May 2015 supposed to be used as the basis for a multilateral negotiation phase.

The EU tried to initiate these multilateral negotiations with 109 UN Delegations and 8 inter- and non-governmental organizations in July 2015 in New York [12.5]. However, during the opening round, major concerns were articulated by several States on rules of procedure, mandate, process and / or substance of the draft Code of Conduct. The EEAS, therefore, proposed to continue deliberations in the form of consultations, revise the program of work, and propose options for a future UN process based on the comments received during the New York consultations.

These three efforts are not formally coordinated. They actually demonstrate the breadth and complexity of the space sustainability, safety and security issues. They gather people from very different communities (i.e., diplomats from the disarmament or space domains, technical experts, lawyers, etc.) in different fora.

### **12.3.3. International cooperation on space surveillance**

- Cooperation on space surveillance and exchange of data between public organizations

Several States and satellite owners-operators monitor the location of objects in

space, but only in a limited manner. The US military Space Surveillance Network has the most complete picture of the space environment and tracks 23,000 human-made objects in orbit. Space Situational Awareness (SSA) capabilities exist also in Europe, Russia, China, Japan, and India.

Several space agencies have been working on space debris for decades and are trying to better assess the associated threats and risks and their evolution. There is in fact a growing demand for information on space debris from satellite operators as well as from policy-makers. There is still a need to improve the cataloguing of debris, especially of debris of smaller sizes, and to promote information sharing to move towards a list of space objects as exhaustive as possible.

Most satellite operators depend today on space objects data from the US Space Surveillance Network available through the web site [www.space-track.org](http://www.space-track.org) run by the U.S. Joint Space Operations Center. At the level of the UN COPUOS it is proposed to consider feasibility of establishing under the auspices of the United Nations an international platform for sharing information on monitoring of space objects and events. Such a platform could effectively accumulate and provide access to information on the operational situation in the near-Earth space obtained from different sources to serve the purpose of ensuring unified record-keeping on objects and events in space and achieving consistency in interpretation and use of the information required to support safety of operations in outer space.

To ensure the operational safety and reliability of their satellites, satellite communication companies Inmarsat, Intelsat, and SES in 2010 formed a non-profit entity called the Space Data Association (SDA) to provide services to participating operators for collision warning and mitigating radio frequency interference. By 2014, both private and governmental satellite operators responsible for more than 300 operational satellites in both LEO and GEO were members. Each member satellite operator contributes information on the positions and other aspects of its satellites to the SDA, which in turn provides operators with operational data critical to safe and efficient satellite operations.

The further development of SSA capabilities around the world would increase the overall knowledge on space debris and facilitate the exchange of data. More sensors that are better distributed around the globe would contribute to more comprehensive and accurate SSA data.

- Cooperation on characterization of the space environment

In addition to the exchange of data, there is also a need to cooperate to further refine the models that predict the evolution of the debris population and the models that evaluate the risks of collisions and re-entries.

Several space agencies have developed expertise and experience in the areas of space debris and meteoroid environment and risk assessment models, analysis of debris mitigation measures and their effectiveness for long-term environmental stability, in orbit collision risk assessments, re-entry safety analyses, and space debris database. Related international work on standards and guidelines is also carried out, especially within the IADC and the Consultative Committee for Space Data Systems (CCSDS).



#### **12.3.4. International cooperation on debris mitigation**

Since the 1990s, important progress has been achieved on debris mitigation at the international level, in particular with the “*space debris mitigation guidelines*” developed by the IADC in 2002 which aim at limiting the debris released during normal space operations; minimizing the potential for on-orbit break-ups and collisions; and removing non-operational space objects from populated regions. The guidelines were updated in 2007.

Based on these inputs, the UN COPUOS adopted its “*Space Debris Mitigation Guidelines*” in 2007. Both sets of guidelines represent a major step forward, even if adherence to the guidelines remains voluntary. They have influenced many national and international guidelines, requirements and standards. In 2004, the ITU Radio-communication Sector revised its recommendation for the disposal of GEO spacecraft to be consistent with the IADC corresponding recommendation [12.6].

A number of space agencies have also already implemented those guidelines as mandatory requirements in their new programs [12.7]. These efforts have already led to a decrease of the annual growth rate of tracked debris since the 1990's.

#### **12.3.5. Towards a potential international cooperation on debris removal?**

The awareness of the space debris problem has certainly increased in the past decade, and so has the interest in debris removal [12.8].

Mitigation measures limit the increase of debris number, but long-term proliferation is still expected, even with full mitigation compliance, and even if all launch activity was halted. The population of large and massive objects seems to have reached a critical concentration in LEO.

As a consequence, the number of large and massive objects (3,300 physically intact objects) must be controlled. A limitation of the launch rate – currently about 70 to 80 objects per year into LEO – or a further reduction of the spacecraft orbital lifetime cannot by themselves prevent collisional cascading. Therefore, there is an interest in active debris removal (ADR).

Debris removal will most likely require international cooperation. The main stakeholders would need to agree on the priorities for removal. They should decide which orbit and which size of debris should be targeted first and define specific target debris.

There is, however, no consensus on which type of objects should be prioritized for removal. The choice is delicate as it might be misperceived as driven by political considerations. Specific types of debris were indeed generated by a single actor, as for instance a large number of Russian rocket upper stages. Overall about 38% of the larger catalogued debris (>10 cm) can be identified as the result of Russian/USSR space activities, 30% come from American activities, and 22% come from Chinese activities. Moreover, a large share of space debris come from spacecraft that were involved in military activities and their launching States will certainly be reluctant to allow any interference or removal with those debris.

But a clear choice of targets is all the more necessary as there is not one technical option that would be best suited to remove all types of debris.

The proposals for ADR missions should especially seek to minimize their safety and security concerns, which impede cooperation, mainly because ADR technologies and systems are of dual-use nature, as many of them could also be used to damage or destroy a spacecraft. The development of ADR technologies can be misperceived as a pursuit of offensive space operations [12.9]. These concerns must be anticipated and addressed at an international level. ADR operations conducted by one State or covertly could create misperceptions that could lead to tensions and instability [12.10].

For the same reasons, the security of ADR technologies and operations should be ensured. This requires measures to ensure the security of the ground segment that controls ADR missions (which can be subject to physical or cyber-attacks) and actions to limit the proliferation of technologies deemed critical.

ADR operations can also be a source of safety and security concerns for satellite owners and operators as proximity operations might put at risk nearby satellites but also because they enable intelligence gathering, surveillance, reconnaissance, and docking. Furthermore, the characterization of the space debris or the information that should be provided to the one performing the removal could create intellectual property issues as the knowledge gained about the spacecraft could be of economic or strategic value. Most space actors have no, or limited, means to know what is going on in orbit, and especially if and how operations are conducted and if those have consequences on their assets and on their security.

Additional specific challenges come from satellites with US components or technologies. If a decommissioned spacecraft or part of it is removed by a non-US organization, transfer of knowledge or hardware from these satellites and the removal of the satellite itself are considered as export and falls under the International Traffic in Arms Regulations (ITAR) regime. Licenses or waivers would be necessary for the non-US organization to conduct such operations.

Various policy and security issues need to be addressed at different levels, by a combination of top-down and bottom-up approaches, in order to create national and international conditions favorable to develop and conduct ADR operations.

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- [12.16] Document A/71/20 (Report of the Committee on the Peaceful Uses of Outer Space. Fifty-ninth session (June 8<sup>th</sup>-17<sup>th</sup> 2016)), Annex.



## 13. Synthesis & further references

### 13.1. Synthesis

Some people say that “the space debris situation is a real problem which will hopefully be managed in due time”... It depends how optimistic you are, and whether you see the glass as half-full or half-empty...

- On a positive note, one can remark that the mass density of all LEO debris computed in the volume ranging from ground to 1,500 km altitude is the same as that of two large bottles of soda poured in the Mediterranean Sea. The total mass in orbit is equivalent to that of the Eiffel tower, spread into a variety of pieces ranging from shrapnel to integer spacecraft and stages across LEO. The probability that a 1 m<sup>2</sup> surface will be struck each year by a cataloged object (i.e., greater than 10 cm in size) is 0.000025 or 1/40,000. In addition, no one has ever been hurt by reentering debris, despite more than 25,000 atmospheric reentries since 1957.
- A more pragmatic assessment would state that the continuous increase in both mass and number of debris since the launch of *Sputnik 1*, despite a significant reduction in the number of yearly orbital missions, and despite more than 20 years regulations at international level is problematic. The orbital population may even be in a run-up situation where collisions among objects can generate more new debris than can be cleaned naturally by atmospheric drag, or by potentially future active debris removal activities. These fragments are long-lived and travel very fast, leading to probabilities of collision which become troublesome; a standard satellite launched at 800 km SSO has typically 3 to 5% chance to be terminated during its operational lifetime due to collision of small debris (see for instance [13.31]) without proper shielding. Operators have also to devote a significant effort to avoid collision of their spacecraft. This situation may worsen in the future with the development of swarms of small satellites and mega-constellations.

### 13.2. Overall logic of works

Work on space debris has been structured these last decades following several steps: characterization, international awareness, simulations, regulation, and preparation for the future.

#### 13.2.1. Reference studies

The first reference studies on space debris appeared after the peak of space activities of the 1970's. In a visionary publication [13.1], Don Kessler and Burt Cour-Palais established in 1978 the first model describing the environment by calculating the spatial density as a function of altitude, then deriving a collision model enabling finally the prediction of the long-term evolution of the space debris population. At the time of the article, there were 3,866 large objects on orbit.

This work was refined by Don Kessler in 1991 [13.2], in which the elements of the so called “*Kessler syndrome*” were quantified. Kessler analyzed the consequences of the accumulation of orbital debris in specific regions and defines the concept of “critical

density”; critical density is achieved when a population is of the size in an orbit of sufficiently long life that the population will produce fragments from random collisions at a rate which is increasing and is greater than the removal rate due to natural processes, primarily atmospheric drag. Figure 13.1 depicts his estimate of the critical density value in relation to the spatial density of cataloged objects as of December 1989. At that time, there were 7,000 large objects on orbit, there are now over 22,000.

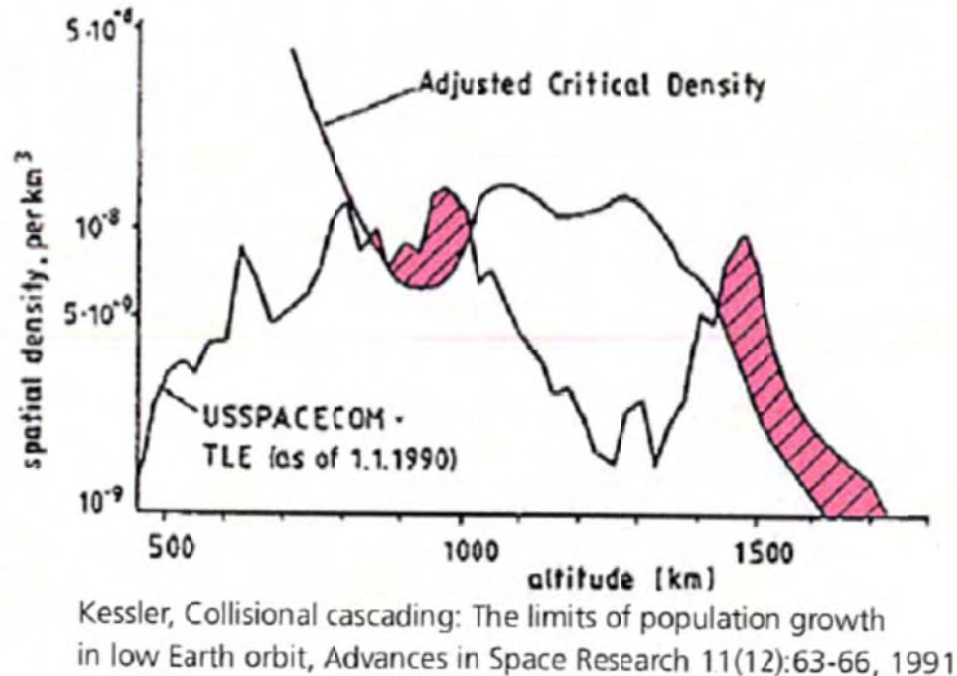


Figure 13.1: Notion of critical density [Kessler – 13.2]

A third historical reference that contributed to the community dialogue: the “SAFE” contract placed to all European industry by Walter Flury in 1987 led to a Final Report [13.3] in 1990. This study enabled an exhaustive review of the then existing information on the control of debris creation, the identification of the scenarios that lead to the production of space debris, and the generation of a set of recommendations. This study raised the consciousness of all the European actors involved in launchers, manned vehicles, GEO, HEO and Polar satellites, and greatly helped pave the way for the first reference regulatory documents that would be codified in the following years.

Numerous other studies that appeared just before 1990 led to the second phase of regulation.

### 13.2.2. Initial standards

In the USA, the first space debris standard was issued in 1995 [13.4].

More recently, the “*National Space Policy of the United States of America*” [13.5] gives numerous recommendations concerning space debris, mentioning the UN Space Debris Mitigation Guidelines as a reference, asking for adoption of international and industry standards and policies to minimize debris; asking for the development, maintenance and use of space situational awareness information; and application of the “*US Governmental Orbital Debris Mitigation Practices*” [13.6].



NASA standards were completed with a large collection of similar documents applicable to the other US agencies such as FCC, FAA, etc.

JAXA produced its own standard NASDA-STD-18 in 1996 [13.7], dealing with the contractual requirements to be applied, and all the technical topics that were to become classical: avoidance of voluntary destructions, minimization of mission-related objects, collision avoidance, and disposal at end of mission. This document has been very helpful in the preparation of international standards (this standard has been revised to JMR-003 version C, which keeps good compliance with ISO 24113: 2011).

In Europe, the first effort to regulate space debris was the PSS-01-40, September 1988 [13.8]. The PSS series of standards were then transformed by the ECSS (European Cooperation for Space Standardization) resulting in the ECSS-Q-40B in May 2002 [13.9] which contained some requirements linked to space debris.

ESA then issued two sets of standards, the second of which is now the basis for all activity by the European Agency [13.10].

CNES issued its own standard in 1999 [13.11], and this document progressively evolved to serve as the basis for the “*European Space Debris Mitigation Standard*” (EDMS), issued in February 2003 [13.12], but was never officially approved. It was transformed in June 2004 into the “*European Code of Conduct for Space Debris Mitigation*” [13.13], which was signed by ASI, BNSC, CNES, DLR, and ESA. This document eventually served as the basis for ISO 24113.

In 2008, CNES enacted the first law dealing with space debris. The Space Operations Act [13.21] covers the safety aspects of every space operation performed under the responsibility of France, to include launchers, launch sites, satellites manufactured in France, etc. This law, then unique in the world, includes all space debris mitigation options and was promulgated on December 10<sup>th</sup> 2010 and every French operator has had to comply with it.

Since this date, numerous National Standards have been issued, mainly by Russia in 2007 [13.14] and DLR in 2009 [13.15].

### **13.2.3. International cooperation**

The origin of the Inter-Agency Space Debris Coordination Committee IADC dates from the late 80s. The first international coordination meeting on the topic of space debris was held in Rolleboise (France) in October 1987. It gathered NASA and ESA representatives who presented their respective activities in the domain. The possibilities of technical coordination identified during this first meeting included exchanges of two-line element sets; predictions of reentering objects; exchanges of material and data from space missions; and exchanges of research results.

The ESA-NASA Orbital Debris Coordination Committee met again five times, before including Japan in 1992 and the Russia Space Agency in 1993. The name of this committee then changed to become the IADC while the first Terms of Reference of IADC were issued in October 1993.

Other members progressively joined IADC: BNSC (which later became UK Space Agency), CNES, CNSA and ISRO in 1996; DARA (which later became DLR) in 1997; ASI in 1998; NSAU in 2000; CSA in 2011; and last KARI in 2015.

The scope of the IADC [13.16] is to review all on-going cooperative space debris research activities between member organizations; recommend new opportunities for cooperation; serve as primary means for exchanging information and plans concerning orbital debris research activities; and to identify and evaluate options for space debris mitigation.

The members of IADC are national agencies (or supra-national as ESA) and the delegations may include experts coming from other organizations or government agencies in their delegation. IADC is organized around four specialized Working Groups and a Steering Group.

The four Working Groups are:

- WG1: Measurements
- WG2: Environment and Data Base
- WG3: Protection
- WG4: Mitigation

Throughout the years, the IADC has produced a number of significant reports, available in the public domain of the Committee website:

[13.17] is the Mitigation Guidelines, approved in 2002 unanimously by the then 11 members and revised in 2007. It was used extensively as the basis for the “*UN Space Debris Mitigation Guidelines*” finalized in 2007, then for the ISO 24113 and for some recent national standards. It is completed by the “*ISO Support to Mitigation Guidelines*” [13.18] which explains how to deal with the Guidelines and gives practical examples.

[13.19] is the “*IADC Protection Manual*”, fundamental to any spacecraft designer, assisting the design of the structures, providing tools to compute the probability of penetration upon impact, and provide practical rules on how to shield the most critical zones.

[13.20] is the IADC report “*Stability of the Future Environment in LEO*”, that started from a major effort led by a majority of IADC members, synthesizing a series of simulations under various hypotheses with projections over the upcoming 200 years. This report confirms the instability of the current LEO population and recommends full compliance to the mitigation rules approved at the international level. It also states that in order to stabilize the LEO environment, more aggressive measures, such as Active Debris Removal, should be considered.

#### **13.2.4. ISO standards**

Following a recommendation made by Japan during IADC deliberations, a set of ISO standards devoted to space debris was published. These are now widely used at the international level.

The highest level standards document is the ISO 24113 [13.22]. This relatively short set of requirements is directly derived from the IADC Guidelines. The main specifications are the definition of the two protected regions; the 25-year rule in these regions; the limitation in

number and size of mission-related objects; the avoidance of breakups in orbit; and the end of life (EOL) requirements including passivation and re-entry.

The ISO 24113 is associated to a number of “second tier” ISO standards, each detailing one of the high level requirements of the high level document.

ISO’s space debris standards are voluntary and can be adopted in a number of ways. For example, they can be included as part of a commercial contract between the customer and supplier of a space system, or they can be used by a space-faring country as the basis for developing a set of national regulations on space debris. Efforts are currently underway within ISO to consolidate the second tier standards into a smaller, more coherent set of documents.

The following Figure 13.2 shows the current structure of the collection of ISO standards related to orbital debris.

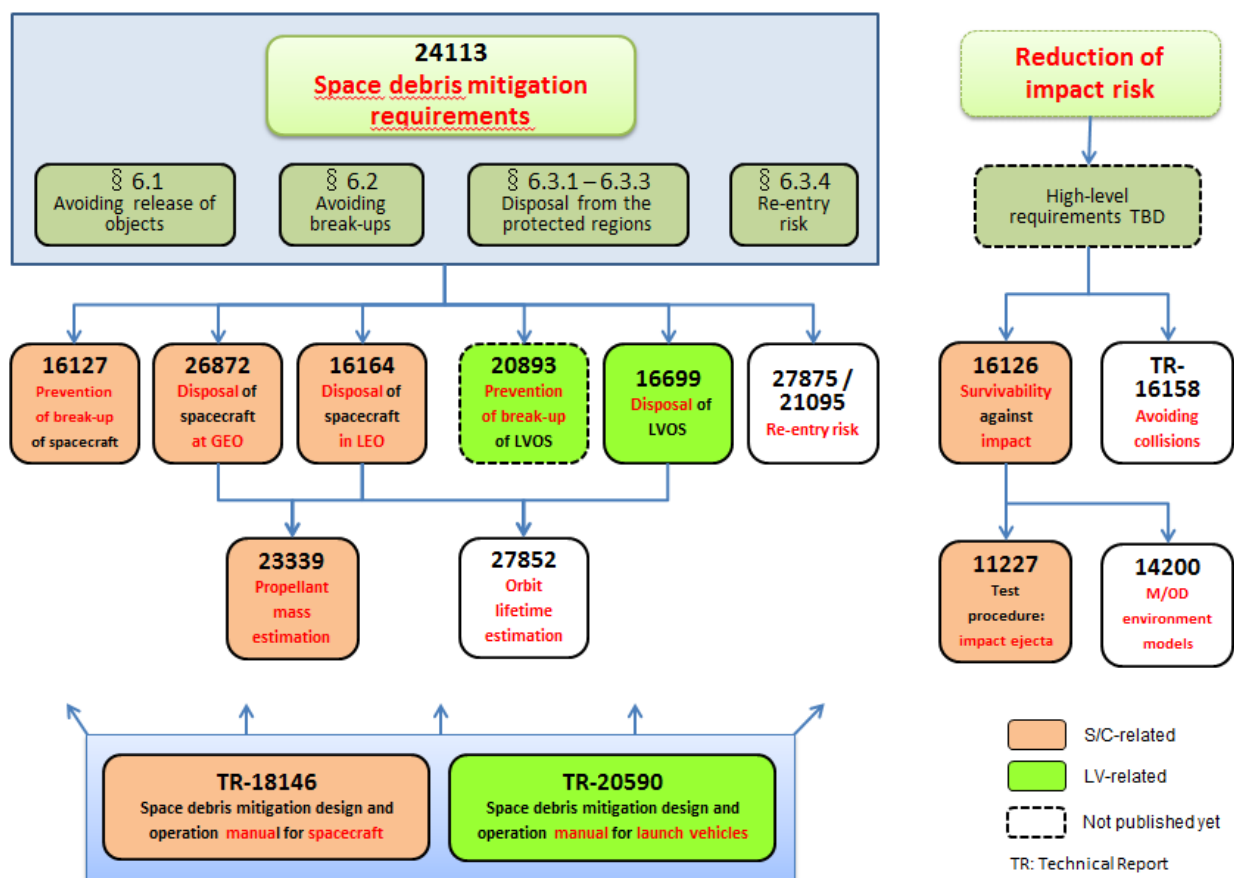


Figure 13.2: Structure of ISO Space Debris Mitigation “Core” Work Items

### 13.2.5. Future regulations

As can be seen, there are a lot of regulations, codes of conduct, guidelines, standards, and even laws, both at national and international level related to orbital debris. Unfortunately, as mentioned in Chapter 9, they are not always applied in a comprehensive way.

Which way is the best: national, international, UN, or International NGO (ex. ISO, IEC, ITU, etc.)? There is no easy answer. One can just hope that the convergence of all these

documents, basically specifying the same recommendations, will eventually be applied by every responsible space operator.

### 13.3. To know more

A wide number of space debris related events occur every year, dedicated congresses, dedicated symposia within a congress, dedicated sessions, or specialized workshops. To note just a few:

- Every year, the International Academy of Astronautics (IAA) organizes its Space Debris Symposium at the occasion of the International Astronautical Congress (IAC). There are usually 9 or 10 sessions, each including 8 to 10 papers, plus posters, covering all the aspects of the space debris domain [13.23].
- Every four years since 1993, ESA has organized a major congress dedicated to every aspect of space debris, so far at ESOC in Darmstadt, Germany. The proceedings of the conference are widely distributed [13.24].
- Some other congresses include a significant number of sessions devoted to space debris, such as the COSPAR [13.25], the IAASS [13.26], or the EUCASS conference [13.27].
- Last, some dedicated workshops are organized on an irregular basis: three CNES workshops every two years dealing with Collision Avoidance [13.28]; End of Life (EOL) operations [13.29]; Modelling and Active Debris Removal [13.30]; JAXA workshops [13.32]; and progress reviews for specific projects (e.g., ESA-CleanSpace project).

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## Appendix 1

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<sup>47</sup> <http://iaaweb.org/content/view/487/655/>

## Appendix 2

### List of acronyms and abbreviations

a	Semi-Major-Axis
ADR	Active Debris Removal
AIUB	Astronomical Institute of University of Bern
ASAT	Anti-Satellite weapon
ATV	Autonomous Transfer Vehicle
BAU	Business as Usual
BLE	Ballistic Limit Equation
CA	Collision Avoidance
CCD	Charge Coupled Device
CCIR	Consultative Committee of Radio communications
CCSDS	Consultative Committee for Space Data Systems
CDM	Conjunction Data Message
CF	Catalogued Fragment
CMOS	Complementary Metal Oxide Semi-conductor
ComSpOC®	Commercial Space Operations Center
COPUOS	UN Committee for Peaceful Use of Outer Space
COSPAR	Committee on Space Research
CPU	Central Processing Unit
CSM	Conjunction Summary Message
$\delta$	Declination
D4D	Design For Demise
e	Eccentricity
EEAS	European External Action Service
EGO	Extended Geostationary Orbit
EOL	End Of Life
ERS	European Radar Satellite
ESO	Earth Escape Orbit
EVA	Extra-Vehicular Activity
FoV	Field of View
FPGA	Field Programmable Gate Array
GEO	Geostationary Earth Orbit
GGE	Group of Governmental Experts
GP	General Perturbations
GTO	Geostationary Transfer Orbit
GPW	Gridded Population of the World
$H_A$	Altitude of Apogee
HAO	High Altitude Orbit
HCSP	Honey-Comb Sandwich Panel
HEO	Highly Elliptical Orbit
$H_p$	Altitude of Perigee
i	Inclination
IAA	International Academy of Astronautics
IAC	International Astronautical Congress
IADC	Inter-Agency Space-Debris Coordination Committee
IAF	International Astronautical Federation
ICJ	International Court of Justice
IDO	Intact Derelict Object
ISON	International Scientific Optical Network
ISS	International Space Station
ITU	International Telecommunication Union
IUS	Inertial Upper Stage
JCA	Just-in-time Collision Avoidance
JSpOC	Joint Space Operations Center
KIAM	Keldish Institute of Applied Mathematics
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit

LMRO	Launch and Mission Related Object
LNT	Lethal Non Trackable
LOC	Loss Of Crew
LOM	Loss Of Mission
LTSSA	Long-term Sustainability of Space Activities
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MC	Monte Carlo
MCISS	Main Center for Intelligence Space Situation
MEO	Medium Earth Orbit
MLI	Multi-Layer Insulation
MMOD	Micro-Meteoroid and Orbital Debris
MRO	Mission Related Object
MW	Megawatt
N/A	Not Applicable
NaK	Sodium Potassium eutectic alloy, coolant liquid for BES-5 Buk reactors
NAVAREA	Navigational Area
NGO	Non-Governmental Organization
NOTAM	Notice to Airmen
NSO	Navigation Satellites Orbits
OBDH	On-Board Data Handling
OD	Orbital Debris
ORDEM	Orbital Debris Engineering Model
Pc	Probability of Collision
PCB	Printed Circuit Board
PDF	Probability Density Function
P/L	Payload
PMD	Post Mission Disposal
PNP	Probability of No Penetration
POPACS	Polar Orbit Passive Atmospheric Calibration Sphere
R/B	Rocket Body
RF	Radio Frequency
RFI	Radio Frequency Interference
RORSAT	Radar Ocean Reconnaissance Satellite
RTG	Radio-isotope Thermo-electric Generator
S/C	Spacecraft
SDA	Space Data Association
SDC	Space Data Center
SHF	Super High Frequency (3 – 30 GHz)
SP	Special Perturbations
SPOUA	South Pacific Ocean Unhabited Area
SRL	Schäfer-Ryan-Lambert
SRM	Solid Rocket Motor
SSA	Space Situational Awareness
SSASS	Space Situational Awareness Software Suite
SSN	Space Surveillance Network
SSO	Sun Synchronous Orbit
SST	Space Surveillance & Tracking
STM	Space Traffic Management
t	Thickness
TC	Telecommand
TCA	Time of Closest Approach
TCBM	Transparency and Confidence-Building Measures
TIP	Tracking and Impact Prediction
TLE	Two-Line Elements
TM	Telemetry
TRL	Technology Readiness Level
UHF	Ultra-High Frequency (0.3 – 3 GHz)
UTC	Universal Time Coordinated
VHF	Very-High Frequency (30 – 300 MHz)
$\omega$	Argument of Perigee

## Appendix 3

### **International Academy of Astronautics (IAA)** ***A Brief Description***

#### **Founded:**

16 August 1960, Stockholm, Sweden, by Theodore Von Karman. Independent non-governmental organization recognized by the United Nations in 1996.

#### **Aims:**

Foster the development of astronautics for peaceful purposes; Recognize individuals who have distinguished themselves in space science or technology; Provide a program through which members may contribute to international endeavors; Promote international cooperation in the advancement of aerospace science.

#### **Structure:**

Regular Meeting; Board of Trustees consisting of: President; four Vice-Presidents and twenty-eight Trustees, seven from each Section: Basic Sciences, Engineering Sciences, Life Sciences and Social Sciences. Current President: Dr. Peter Jankowitsch, Past-President: Dr. Madhavan G. Nair, USA, Vice-Presidents: Dr. Francisco Mendieta-Jimenez, Mexico; Prof. Liu Jiyuan, China; Dr. Hiroki Matsuo, Japan; Prof. Anatoly Perminov, Russia, Secretary General Dr. Jean-Michel Contant, France.

#### **Activities:**

Encourage international scientific cooperation through symposia and meetings in the area of: space sciences, space life sciences, space technology & system development, space systems operations & utilization, space policy, law & economy, space & society, culture & education; Publish cosmic studies dealing with a wide variety of topics including space exploration, space debris, small satellites, space traffic management, natural disaster, climate change, etc.

#### **Cooperation with other Academies:**

Establish cooperation with Royal Swedish Academy of Sciences (1985), Austrian Academy of Sciences (1986, 1993), Academy of Sciences of France (1988, 2001), Academy of Finland (1988), Indian Academy of Sciences (1990, 2007), Royal Spanish Academy of Sciences (1989), German Academy of Sciences (1990), Kingdom of Netherlands (1990), Academies of Arts, Humanities & Sciences of Canada (1991), U.S. Academy of Sciences (1992, 2002), U.S. Academy of Engineering (1992, 2002), Israel Academy of Sciences and Humanities (1994), Norwegian Academy of Science and Letters (1995), Chinese Academy of Sciences (1996, 2013), Academy of Sciences of Turin (1997), Australian Academy of Sciences (1998), Royal Netherlands Academy of Arts and Sciences (1999), Brazilian Academy of Sciences (2000), U.S. Institute of Medicine (2002), Academy of Sciences of Ukraine (2010, 2012), Academy of Sciences of South Africa (2011), Royal Society of South Africa (2011), Pontifical Academy of Sciences (2012).

#### **Publications:**

Publish the journal of the International Academy of Astronautics ACTA ASTRONAUTICA ranked 5th in the world; Yearbook, Dictionaries and CD-ROM in 24 languages (last languages Afrikaner and Swahili); Book Series on small satellite, conference proceedings, remote sensing and history. All publications available at <https://shop.iaaweb.org>.

**Membership:**

Active members 1144 in 86 countries in four Trustee Sections; Honorary members (2)

- *Africa:* Algeria, Burkina Faso, Cameroon, Egypt, Ethiopia, Ivory Coast, Kenya, Libya, Morocco, Nigeria, Senegal, South Africa, Tunisia.
- *Americas:* Argentina, Bolivia, Brazil, Canada, Chile, Columbia, Cuba, Guatemala, Mexico, Peru, Uruguay, USA, Venezuela.
- *Asia:* Bahrain, Burma, China, India, Indonesia, Irak, Israel, Japan, Kazakhstan, Korea, Kuwait, Kyrgyz Republic, Malaysia, Mongolia, Pakistan, Saudi Arabia, Singapore, Sri Lanka, Syria, Thailand, Turkey, Vietnam.
- *Europe:* Armenia, Austria, Belarus, Belgium, Bulgaria, Croatia, Cyprus, Czech Rep., Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Macedonia, Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, Ukraine.
- *Oceania:* Australia, New Zealand.

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