The Issue of Space Debris

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Abstract

Since 1957, human space activities have placed a great deal of objects in orbit around Earth. Debris represents a growing risk for operational satellites, in case of collision, and on the ground when it reenters the atmosphere. This situation calls for action, namely, in the following four areas: obtaining accurate knowledge of the situation, protecting satellites and populations, reducing as far as possible the creation of new debris, and cleaning up in space by removing the largest objects. The prevention measures mainly consist in post-mission management for satellites and launchers. Measures have been developed, and have met with broad consensus. However, to ensure more systematic application,

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legal mechanisms are also being established, States being liable in the event of an incident. Protection actions are also needed, but offer only partial solutions: these actions involve setting up services for preventing the risk of collision and predicting atmospheric reentries. However, due to collisions between debris objects, these actions alone will not be enough to stabilize the debris population: cleanup actions will eventually be necessary.

39.1 Introduction

Since 1957, human space activities in orbit have produced a large amount of waste, known as space debris, which has become a real problem – to the extent that there is now an urgent need for regulation, while also developing the means to one day begin cleanup.

The purpose of this chapter is to describe the situation in space and the risks associated with this debris, and then to review the various actions to be implemented in the short and medium term.

39.2 The Situation in Orbit

39.2.1 Where Space Debris Comes From

More than 5,000 spacecraft have been launched since Sputnik, resulting in a large amount of waste being put into orbit. The different types of space debris include (Rathgeber et al. 2010):

- Operational satellites and abandoned satellites which remain in orbit around Earth.
- Upper stages of the launchers used to place these satellites in orbit.
- Operational debris, objects intentionally released during space missions: covers used to protect instruments during the launch phase, systems used to attach solar panels or antennas before deploying them in orbit, separation devices and straps, etc.
- Fragmentation debris: debris produced when objects in orbit collide with space debris or meteorites, and from the accidental or voluntary explosions of spacecraft.
- Propellant residue: solid propellant motors used to carry out transfers in orbit, especially between a transfer orbit and geostationary orbit, which release small alumina particles during thrust periods. This problem is especially critical at the end of the thrust period when combustion becomes unstable, at which point slag measuring several centimeters can be ejected into space.
- Debris from the ageing of materials in space. The space environment is very harsh, with major temperature differences between shade areas and areas exposed to the Sun, atomic oxygen and ultraviolet rays, etc. The ageing process causes large amounts of debris to be produced (separation of photoelectric cells, weathering of thermal protection covers, and peeling of paint, etc.).

There are other, more anecdotal sources of debris which have also had a significant impact on the population of objects in orbit:

- In 1961 and 1963, as part of the Midas 4 and Midas 6 experiments, the US Air Force planned to release several million copper needles (West Ford Needles) into orbit at an altitude of around 3,000 km. The goal was to create a ring of dipoles around Earth to act as a passive reflector for military communications. Only the second experiment was partly successful. The needles then formed clusters, 65 of which could still be seen from the ground in 1998.
- In the 1980s, the Soviet Union used Radar Ocean Reconnaissance Satellites (RORSAT) equipped with nuclear reactors. At the end of their mission, the cores of these reactors were re-orbited at altitudes between 900 and 1,000 km to allow their radioactivity to decrease before they fell back into the atmosphere. Leaks in the cooling circuit were found on 16 of these satellites, which resulted in drops of liquid sodium potassium (measuring between 1 mm and several centimeters) being released into orbit.

39.2.2 Debris Inventory

Knowledge of the debris population is obtained using radar or optical observation means, on the ground or in orbit, and by studying the effect of debris on surfaces that have spent time in space.

The debris is generally broken down into the following categories:

- "Large" objects, measuring more than 10 cm in low orbit and 1 m in geostationary orbit: these objects are listed individually, or catalogued, by space surveillance systems (see paragraph 3.1). Around 15,000 are routinely cataloged by the US surveillance network. However, their total number is estimated at 20,000, not all of them being catalogued.
- Objects measuring between 1 and 10 cm: based on statistical observations, the total is estimated at several hundred thousand.
- Objects measuring between 1 mm and 1 cm, which are counted in tens of millions.

Figure 39.1 shows the breakdown of catalogued objects by category (source: public catalogue of the US Space Surveillance Network). It should be noted that active satellites make up only 6 % of the population of catalogued objects in space.

Figure 39.2 (Source: NASA Orbital Quarterly News, volume 16, issue 1 January 2012) shows the progression over time of the number of objects catalogued by the space surveillance network in the United States. The total number of objects is the sum of the four components shown in the graph: fragmentation debris, spacecraft, mission-related debris, and rocket bodies. Two events in particular added large amounts of waste: the voluntary destruction of the Fengyun 1C satellite in January 2007, and the collision between the active Iridium 33 satellite and the abandoned Cosmos 2251 satellite in February 2009.

Figure 39.3 (Source: NASA Orbital Quarterly News, volume 16, issue 2, April 2012) shows the progression in the total mass of artificial objects in orbit around

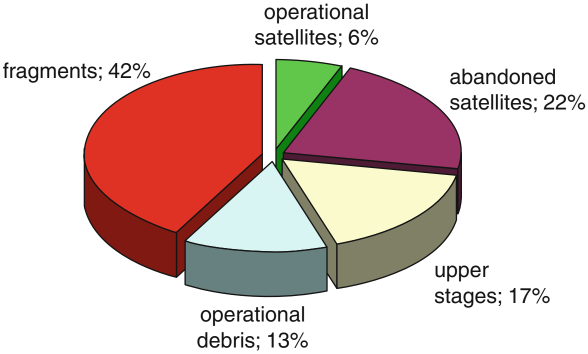

Fig. 39.1 Breakdown of catalogued objects

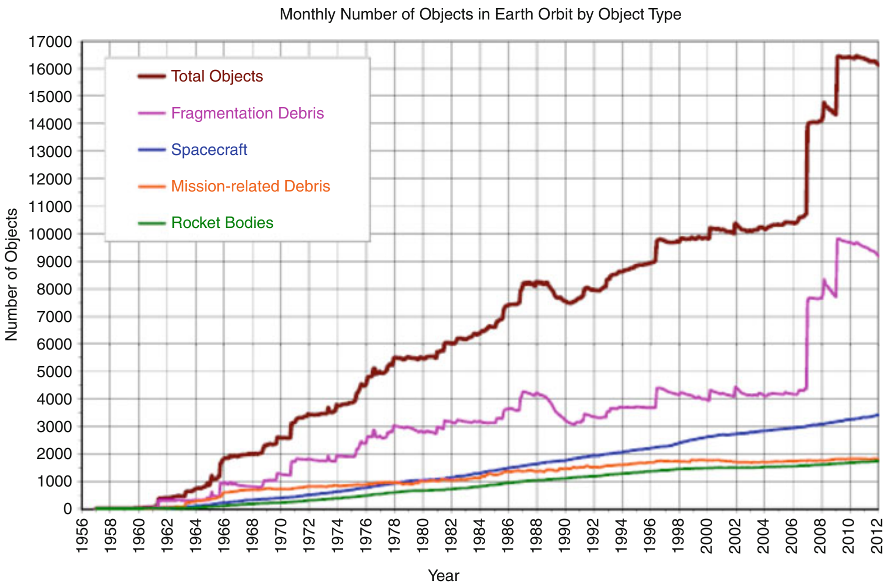

Fig. 39.2 Progression in the number of catalogued objects as a function of time

Earth, and in each of the four categories mentioned above. The progression is almost linear, climbing steadily since the 1980s. The two events mentioned above impacted the number of objects, but not the total mass.

39.2.3 Lifetime

The lifetime of objects in orbit depends on their altitude, due to the effect of atmospheric drag.

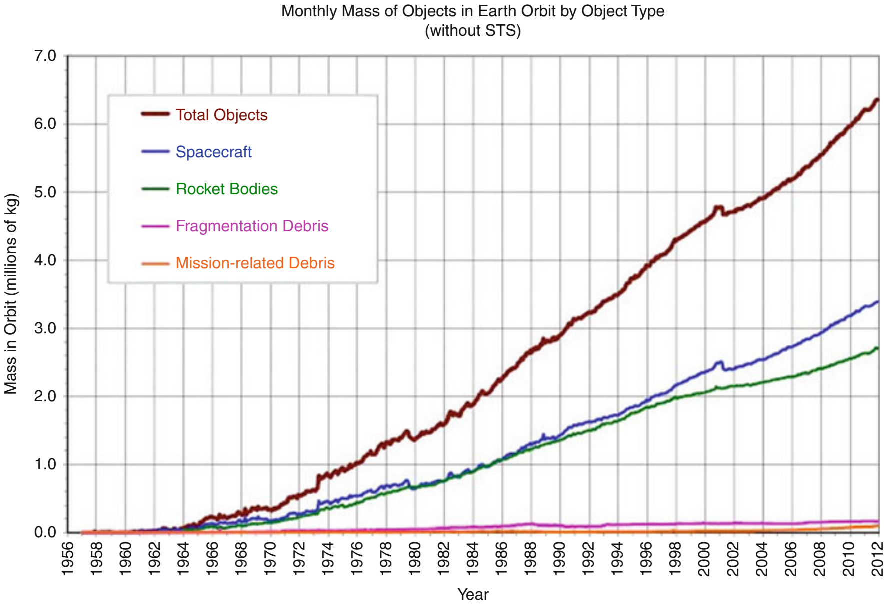

Fig. 39.3 Progression in the mass of objects in orbit

Atmospheric density decreases more or less exponentially in function of the altitude. Traces of atmosphere are still present in low orbits, and these molecules slow the passage of orbiting objects. Reducing their speed causes them to lose altitude, in which case they meet even greater resistance, since the lower the altitude, the higher the atmospheric density will be. Ultimately, as the cycle continues, the object will be captured by the atmosphere and fall into the dense layers. This phenomenon is significant in low orbit (at altitudes below 1,000 km) and nonexistent in geostationary orbit. In the case of the International Space Station (ISS) located at an altitude between 350 and 400 km, the lifetime would be between 6 months and a year without maneuvers. Altitude-boosting maneuvers are made regularly to offset this disturbance. At a higher altitude, around 800 km, the lifetime of a satellite is around 200 years and beyond; lifetime increases quickly the higher the altitude.

However large differences in orbital lifetime estimation may be observed due to the influence of solar activity. The Sun's ultra-violet radiation causes excitation of the different molecules in the atmosphere resulting in the temperature being increased and in overall dilatation of the atmosphere. Important variations of the solar activity are observed during the 11-year cycle of the Sun. For instance, at 400 km altitude, according to the NASA MSISE-90 model of the upper atmosphere, the density during high-activity periods may reach 100 times the density value during low-solar-activity periods. This explains why a large number of satellite decays are observed during periods around the maximum. In addition, shorter term variations exist and lead to large dispersions when predicting reentries.

39.3 Risks Associated with on the Ground and in Orbit

39.3.1 Risks on the Ground

When the spacecraft reenters the atmosphere, encountering the dense layers of the atmosphere at a very high speed, it is subjected to strong aerothermodynamic forces. Appendages, such as antennas and solar panels, are torn off at an altitude of around 90 km, and at around 75 km the spacecraft disintegrates. The debris is exposed to a very high heat flux: most of the materials are vaporized, but some components can survive these conditions, e.g., materials such as titanium, steel, ceramics, or components which are shielded by others (masking effect). It is generally estimated that 20–40 % of the mass in orbit reaches the ground in the form of debris. This debris is distributed along the track mainly as a function of its surface-mass (S/m) ratio. The impact zone on the ground is typically 1,000–1,500 km long (in the direction of the track) and 50–80 km wide. The random fall-back of these pieces is a risk on the ground if they fall onto inhabited areas. Although debris is regularly found on the ground, thus far, the random reentry of debris has never caused any injury or damage.

When the object that is going to fall presents a major risk due to its mass or the materials it is made of, the usual procedure is to conduct a controlled reentry. This involves one or several deceleration maneuvers in order to guide the object's fall to a chosen impact zone on the ground, as was done for the MIR station in March 2001 and the European ATV, for example.

39.3.2 Risks in Orbit

Objects in orbit travel at a very high speed (8 km/s for an object in low circular orbit). At speeds such as this, the kinetic energy of even a small piece of debris is very high: at 10 km/s, a 1 mm aluminum sphere has the same kinetic energy as a rifle bullet. So it is understandable that satellite operators worry about the risks of collisions between their precious satellites and the debris they regularly encounter. Collisions are not a figment of our imagination: their effects can be seen on spacecraft and any surfaces that have spent time in space and returned to Earth. For example, a large number of impacts, luckily small ones, have been found on space shuttles, on the solar panels of the Hubble telescope, and on the LDEF (Long Duration Exposure Facility) spacecraft. They have also been spotted on the International Space Station during extravehicular activities. Unfortunately, collisions between large objects (catalogued objects) also occur, and have major consequences in terms of producing new debris. The most recent example is the 10 February 2009 collision between the Iridium 33 satellite and an old Russian satellite (Cosmos 2251) abandoned in space. The consequence was of course the destruction of both objects, and the creation of a great deal of debris: around 1,400 new objects measuring over 10 cm have been catalogued, and the smaller pieces of debris are far more numerous.

When a collision occurs, it is generally considered that:

- Debris larger than 1 mm can cause perforations: the effect on a satellite depends on the location of the impact and can result in equipment failure.
- Debris larger than 2 cm can result in loss of the satellite (lethal collisions) due to the force of the impact, its dissipation in the structure and projection of particles inside the satellite at very high speed.
- Debris larger than 10 cm not only results in loss of the satellite, but also produces a great deal of debris (catastrophic collisions).

39.4 Actions to Be Implemented

Now that we have a clear picture of the situation and the associated risks, we will discuss the implications and identify the actions to be implemented. There are four types of solutions:

- First, having the best possible knowledge of the debris population, how it is distributed and its characteristics. This involves space surveillance activities for the largest objects and modeling activities for smaller objects (statistical models indicating the particle flux).
- Once the situation has been ascertained, the next step is protection: protection against small debris thanks to shielding and adapted architecture, protection against large objects by avoiding collisions in orbit or during launches, and protection on the ground by monitoring atmospheric reentries.
- In addition to these actions, we must also stop creating new debris which will exacerbate the problem in the medium term. Thus, we must apply these prevention measures to satellites and launcher stages and most importantly, manage their disposal when they are no longer in use.
- Finally, in the longer term, we will surely have to do clean up in space, i.e., retrieve and remove the largest objects abandoned in orbit before the prevention measures went into effect.

In the following paragraphs, these four types of actions are described in greater detail.

39.4.1 Knowing the Situation

The goal of space surveillance is to inventory the objects above a certain size which are in orbit around Earth. This inventory (catalogue) provides information on the origin of the objects (name, launching country) and their trajectory (orbit parameters) so that the object can be looked up later. To obtain this information, different types of sensors have to be used: first, detection tools with a wide field of vision allowing objects above a certain size to be seen as they pass by, and their orbit to be roughly calculated so they can be found again later, and second, tracking tools with a narrow field of vision which can follow a given object in order to take trajectography measurements and better define its trajectory. These detection and tracking tools basically consist in radars for objects in low orbit and telescopes for objects in higher orbits. They may be located on the ground or in orbit.

The main source of information is the Space Surveillance Network (SSN) set up by the United States, which provides the most complete information. Russia has a similar system for which very little information is available. There is also the ISON telescope network, which provides a detailed catalogue of the objects in geostationary orbit. Finally, France has a limited-capacity network: the Graves system.

The core of the SSN is the JSpOC (Joint Space Operations Center) located at the Vandenberg Air Force Base. The JSpOC is responsible for programming the sensors and collecting and then analyzing the data in order to compile and manage the catalogue. The SSN can follow objects measuring around 10 cm in low orbit (and potentially objects measuring around 5 cm at low altitude and in inclined orbits) and objects measuring around 1 cm in geostationary orbit.

To create and manage the catalogue, the SSN uses two different orbitography models: (1) general perturbations (GP), an analytical model based on a simplified representation of forces, and (2) special perturbations (SP), a model based on numerical integration with a more accurate representation of forces. Only the less precise information produced using the GP model is available on the Space Track website. This information is set out in TLE (Two-Line Element) form: the object's SSN and COSPAR number, and the mean orbit parameters on two lines (see details and format on the Space Track website). TLEs provide only a rough idea of the orbit: the degree of uncertainty can be up to several kilometers on creation of the TLE, and gets worse over time. This information is not accurate enough to reliably predict risks of collision.

The population of smaller debris, below the size threshold, is no longer defined deterministically, but statistically: this information is obtained from flux models such as ORDEM (NASA) or Master (ESA).

For a given date and orbit, these models provide the flux on the different surfaces of a spacecraft, according to the size or mass of the debris in question. The flux is the number of impacts per surface unit (m^2) and per time unit (year). The models also indicate the direction and speed of the impacts.

As these small particles cannot be observed from the ground, knowledge of them comes only from information provided by debris detectors (very rare), or (primarily) from examining surfaces which have spent time in space after their return to Earth: LDEF (Long Duration Exposure Facility), Eureca, Space Shuttle, Hubble solar panels, etc. These observations are only possible in very low orbits, which allow the models to be correctly "readjusted" for the corresponding altitudes. For other altitudes, the models are "extrapolated" without there being any means of verifying their accuracy: given the absence of measurements, the degree of uncertainty is surely very high.

Table 39.1 Annual probability of collision with objects >10 cm and with catalogued objects

	Objects > 10 cm	Catalogued objects
ENVISAT	0.015	0.0073
ERS2	0.0039	0.0021

39.4.2 Protection

39.4.2.1 In Orbit

With the number of objects in space steadily increasing, predicting the risk of collision in orbit has become one of the primary tasks of the control centers which monitor and manage satellites. The annual risk of losing a satellite in a collision is no longer negligible, as shown in Table 39.1 for two satellites in low orbit (Klinkrad 2006):

It must be kept in mind that a collision would result not only in the destruction of both objects but also create large quantities of debris. For example, the collision between the Iridium 33 and Cosmos 2251 satellites created two clouds of debris: the 2012 SSN catalogue listed 492 pieces of debris from the Iridium 33 satellite and 1,361 pieces of debris from Cosmos 2251.

To manage this risk, operators use the available space surveillance data. These data allow them to foresee dangerously close passes several days in advance, to calculate the risk, and to conduct an avoidance maneuver, slightly altering the satellite's trajectory in order to ensure a safety distance from the hazardous object.

The surveillance process is fairly time consuming due to the inaccuracy of the available data: it generally involves a first-level of automatic surveillance which detects potential risks, which must then be more closely analyzed by orbitography experts. If the risk appears serious, trajectography measurements are requested from available radar means (usually military means): these measurements provide better knowledge of the hazardous object's trajectory, assisting the operators in taking the decision as to whether or not an avoidance maneuver must be implemented. The entire prediction process spans several days (typically 3). It should be pointed out that the avoidance maneuver changes the monitored satellite's trajectory, which generally means that its mission must be interrupted. In the case of an observation satellite, this can be a major constraint. A maneuver will then be needed to return the satellite to the nominal orbit before resuming its mission. All of this requires significant means: experts, controllers, radars, calculation means and TM/TC stations, etc., and uses propellants, reducing the satellite's lifetime by as much. To reduce the impact of these maneuvers, a planned maneuver (such as a position maintenance maneuver) can sometimes be anticipated, i.e., a maneuver that would have been necessary in any event can be implemented ahead of schedule, which limits the use of propellants.

To allow the risk of collision to be predicted more reliably, since 2011, the JspOC has dispatched collision alerts in the form of Conjunction Summary Messages (CSM) to operators: these messages are drafted using precise information and contain the characteristics of the close pass and associated dispersions (covariance). With this information, the operators are able to calculate the probability of collision.

This process is illustrated by the following figures from risk-of-collision surveillance for 18 satellites carried out at CNES (French Space Agency) in 2010: the automatic process identified 353 risks with a probability of collision higher than 10^{-4}. In addition, 92 alerts were received from JSpOC. After analyzing these cases, 21 requests for radar measurements or support to JSpOC were issued (probability of collision higher than 10^{-3}), and in the end, 13 avoidance maneuvers were carried out.

Risk-of-collision surveillance is not limited to close passes with "large" catalogued objects whose trajectories are known. Because they are so numerous, smaller objects represent a greater risk for satellites. Moreover, they are not catalogued, which means they cannot be avoided. Shielding has been developed to protect them, but due to the increased mass this implies, this solution is reserved for several special spacecraft, such as the International Space Station. Satellites are usually not shielded, but their walls provide a certain degree of protection.

39.4.2.2 During the Launch Phase

During the launch phase and the first orbits, the launcher's last stage and the satellites placed in orbit cross orbits used by other operators: this is especially true of a geostationary transfer orbit with a perigee in a low orbit and an apogee at an altitude of around 36,000 km. These newly injected objects will not be listed on the catalogues for some hours (typically 48 h), which means that other space users have no way of monitoring the risk of collision between these new objects and their satellites. This is especially important for manned spacecraft (such as the ISS) whose control center cannot monitor the risk from these objects.

The launch operator alone has information on the planned trajectory, and can therefore predict the risks of collision. This prediction must take into account all objects placed in orbit (launcher stages, satellites, structural components) for a period of approximately 48 h. In the event of risk, postponing the launch time by several seconds ensures a safety distance between objects. After this 48-h period, it is considered that the new objects are catalogued, and that each operator can carry out their own surveillance.

The main difficulty in predicting risk of collision during a launch lies in considering the dispersions affecting the orbit parameters of various objects at injection: propagating these dispersions over 48 h results in significant amounts of error around each body, and could close the launch slot completely if all catalogued objects were considered in the analysis. This is why predicting the risk of collision during the launch is generally limited to manned spacecraft and certain satellites of particular interest.

39.4.2.3 On the Ground

As indicated in paragraph 2–1, when a spacecraft disintegrates on reentry, the resulting fragments represent a risk on the ground. Controlled reentries allow the fall-back area to be defined, thereby avoiding risk for populations. However, most reentries are uncontrolled, with no control over the fall-back area. For example, in 2011, of the 499 listed reentries, 25 were controlled and 474 were uncontrolled. The latter category included 63 satellites and launcher stages, i.e., slightly more than one uncontrolled reentry of a large object per week.

The debris fall-back area spans several hundred kilometers along the orbit path and measures a few tens of kilometers in width (typical values: length 1,000–1,500 km, width 50–80 km).

In the case of a natural (random) reentry, it is impossible to predict the exact location of the fall-back area, due to the lack of accurate information on several factors:

- The atmospheric density ρ and its variability below an altitude of 200 km
- The object's attitude (i.e. its orientation with respect to the velocity vector) which defines the drag surface S: the object can be rotating, or stabilized, or have a variable orientation, inducing a possible lift effect
- The aerodynamic coefficient C_D
- The mass m

This makes it impossible to accurately estimate the main perturbation (atmospheric drag), which is proportional to $\rho C_D S/m$.

In terms of how precisely fall-back time can be predicted, the generally accepted uncertainty margin is 10 % of the remaining time to fall-back. For example, 10 days before fall-back, the uncertainty margin is ±1 day (i.e., anywhere within the limits of the inclination), and 10 h before, the uncertainty margin is ±1 h.

This 10 % margin has been confirmed by the atmospheric reentry exercises organized each year by the Inter-Agency Space Debris Coordination Committee (IADC), in which the orbits returned by each of the agencies are pooled, and the fall-back predictions are compared.

Thus, to summarize, if the uncertainty in the fall-back time is taken to be 10 % of the remaining time to fall-back, this gives the following dispersions on the position of the exact impact area:

- 48 h prior ±4.8 h or approximately ±3 orbits
- 24 h prior ±2.4 h or approximately ±1.6 orbits
- 12 h prior ±1.2 h or approximately ±32,000 km

This uncertainty value of 10 % could be reduced to around 5 % if better knowledge of the trajectory were available thanks to more measurements more evenly distributed along the entire orbit. In the best-case scenario, several hours before reentry, the uncertainty is around 30 or 40 min, corresponding to uncertainty on the impact point of slightly less than one revolution. It should be noted, however, that the debris *cannot* fall outside this 50- to 80-km-wide strip located beneath the orbit path.

Within several hours to several days after reentry, the Space Track website indicates the position of the observed passage point at 80 km, with an accuracy value of ±1 min (±500 km). Thus, after the fact, we can delineate an area of approximately 2,000 × 100 km which is liable to have been affected by the fragments. This additional information may be useful should it be necessary to determine liability.

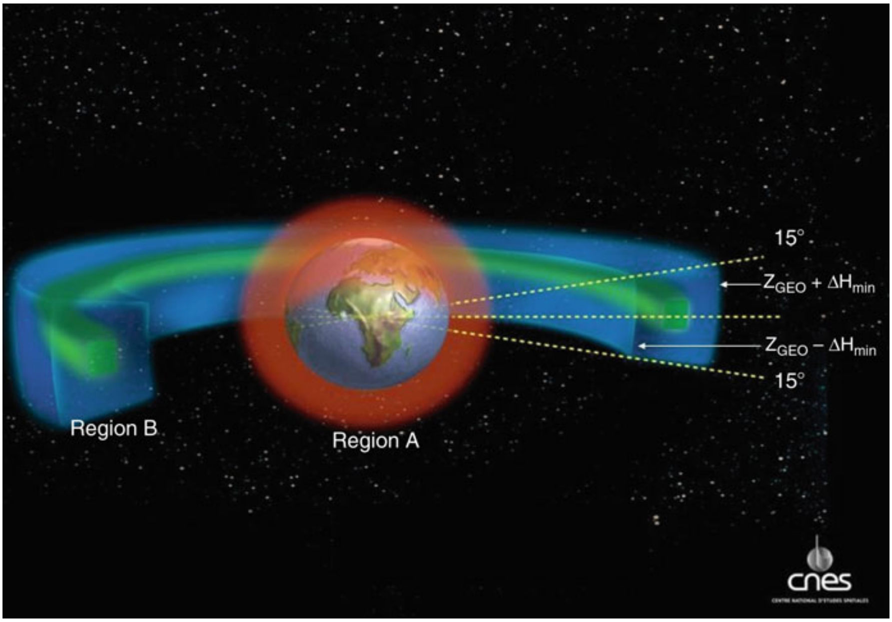

Fig. 39.4 Protected regions in space (Region *A* – Low Earth Orbit, Region *B* – Geostationary Orbit)

39.4.3 Stopping Production of Debris

The problem of space debris is mainly an issue in low orbit and geostationary orbit:

- Region A: Low Earth Orbit (LEO) is where the highest concentration of space objects is found (density curve), especially at altitudes of 700–900 km. This is the area in which two major events occurred, resulting in the creation of large quantities of debris: (1) voluntary destruction of the Fengyun 1C satellite in January 2007 and (2) the collision between the Iridium 33 satellite and Cosmos 2251 in February 2009.
- Region B: geostationary orbit is a very specific area (circular and equatorial orbit, with a period equal to the period of the Earth's rotation). In order to share this unique resource between operators, the longitudes and frequencies need to be managed. Moreover, due to the distance from Earth, the effect of atmospheric drag is null, and debris created in this area will stay there and drift, crossing paths with positions occupied by operational satellites.

39.4.3.1 Principle of Prevention Measures

The main space agencies represented within the IADC have identified two regions in space to be protected (see Fig. 39.4):

- The Low Earth Orbit (LEO)-protected region is the volume that extends from the Earth's surface up to a spherical shell of 2,000 km altitude above the equator.

Table 39.2 De-orbiting maneuver and quantity of propellant required according to altitude

Altitude (km)	300	400	500	600	700	800	900	1,000
ΔV (m/s)	89	117	145	172	198	223	248	272
Propellant mass	62	81	99	117	134	151	167	182

- The geosynchronous (GEO)-protected region is a segment of the spherical shell defined by the following: the altitude extent is bounded by the geostationary altitude ±200 km (35,786 ± 200 km above the equator) and the latitude extent is bounded by ±15 deg (centered on the equator).

The prevention measures implemented by satellite or launcher operators can be broken down into three categories:

- No longer intentionally releasing objects in space (mission-related objects): e.g., covers which protect optical systems during launch, various other covers, springs and straps, etc., which used to be released after injection into orbit. This category also includes the alumina particles ejected by solid propellant motors, used for transfers into geostationary orbit, for example. In particular, these motors can release slag measuring several centimeters at the end of combustion: ejected at a low speed, this debris stays close to the orbit being used. Pyrotechnical cutting systems are also a potential source of debris when they are activated: using "clean" systems, which trap the debris produced, should reduce the creation of this type of debris.
- Reducing the risks of explosion in orbit: this means avoiding the accidental or voluntary explosion of spacecraft during their in-orbit lifetime. This period covers not only the operational mission phase, but also their post-mission life in orbit after the withdrawal from service phase. More than 220 fragmentations in space have been listed thus far, representing the primary source of debris. Many of these fragmentations had to do with the propulsion system or batteries. After mission termination, the object is "passivated" and then abandoned in space. To passivate means to make the object inert in order to eliminate the risk of subsequent explosion due to an internal cause (such as accidental mixing of propellants or battery overcharge) or external cause (such as a debris or meteorite impact against a pressurized tank). The passivation process consists in emptying all propellants remaining on board, lowering the pressure in all tanks (e.g., pressurization gas), and discharging and isolating the batteries to prevent accidental recharging.
- Managing the end-of-life orbit: the goal is not to leave objects in space for "too long," due to the risks of collision and debris production. For satellites in low orbit, the best solution is to conduct a controlled reentry, which immediately frees up the orbit and minimizes the risks on the ground, by having the debris fall into an ocean. In practice, this operation requires a large amount of propellants, which increases rapidly with altitude. Table 39.2 indicates the amplitude of the maneuver and the amount of propellant required to go from a circular orbit at a given altitude to a reentry orbit with perigee 0 in the case of a 2-t satellite and a specific pulse of 290 s:

When controlled reentry is not possible, the accepted practice is, insofar as possible, to limit the time objects spend in orbit. The current maximum recommended period is 25 years. At the end of the operational mission, operators must maintain the ability to maneuver, in order to move the object into a lower-altitude orbit so that the wear from atmospheric drag will cause it to fall out of orbit within 25 years. Another solution consists in transferring objects above the protected region, i.e., to an altitude of over 2,000 km. Reentry into the atmosphere is no longer an option for satellites in geostationary orbit, due to the quantity of propellants this would require. Thus, this solution consists in freeing up the useful orbit by transferring objects to a "graveyard" orbit 200 km above the protected region. Once they have been transferred, the objects must then be passivated.

39.4.3.2 International Cooperation

End-of-life operations are complex and represent a considerable workload for operators. Some of the main difficulties involved are:

- The difficulty of accurately estimating the quantity of propellants remaining in the tanks on board: given the uncertainty associated with the different estimation methods, greater margins are taken to ensure that the end-of-life operations can be carried out, which reduces the mission duration accordingly.
- The need to maintain control of the satellite, especially during passivation: risk of degrading the orbit attained or losing the attitude when the tanks are emptied.
- The difficulty of deciding to stop the mission of a satellite which is still operating correctly: the operator may tend to prolong the mission a bit, at the risk of not being able to carry out the end-of-life operations.
- The fact that these operations need to be taken into account right from the satellite or launcher design phase (necessary systems), which leaves open the question of spacecraft already in orbit.

Implementing these measures represents additional costs for operators: reducing operational life, cost of operations, additional systems to be included in spacecraft designs, deoptimizing launcher trajectories, etc.

Operators are of course willing to implement the prevention measures . . . on the condition that their competitors be subject to the same requirements. Thus, the challenge is to reach a general consensus so that all actors are applying the same rules. There have been discussions on this subject at various levels:

- The United Nations provides the natural framework for discussions between States. The Scientific and Technical Subcommittee (STSC) of the Committee on Peaceful Uses of Outer Space (COPUOS) has addressed the issue of space debris. Work in this area was completed in June 2007, with the publication of the UN-COPUOS Space Debris Mitigation Guidelines (reference A/AC.105/C.1/L.284) which sets out seven high-level guidelines to apply in space. This document was then ratified by the United Nations General Assembly on 10 June 2008 (A/RES/62/217). In 2010, the STSC recalled the importance of ensuring the safe and sustainable future use of outer space and decided to establish a dedicated working group. The working group will prepare a report on the long-term sustainability of outer space activities containing a consolidated set of current practices and operating procedures, technical standards and policies associated with the long-term sustainability of outer space activities. On the basis of all the information collected, the working group will produce guidelines, which could be applied on a voluntary basis by States, either individually or collectively; international organizations; national nongovernmental organizations, and private sector entities to reduce the risks to space activities for all participants and to ensure that all countries have equitable access to outer space (United Nations 2011). The report should be submitted to the COPUOS in 2014.

- More technical discussions are undertaken by space agencies within the framework of the IADC (Inter-Agency Space Debris Coordination Committee), made up of the following 12 agencies: ASI (Agenzia Spaziale Italiana), CNES (Centre National d'Etudes Spatiales), CNSA (China National Space Administration), CSA (Canadian Space Agency), DLR (German Aerospace Center), ESA (European Space Agency), ISRO (Indian Space Research Organisation), JAXA (Japan Aerospace Exploration Agency), NASA (National Aeronautics and Space Administration), NSAU (National Space Agency of Ukraine), ROSCOSMOS (Russian Federal Space Agency) and UKSpace (UK Space Agency). In 2003, IADC published the IADC Space Debris Mitigation Guidelines, a document which describes the prevention measures in detail. This document defines the protected regions in space, e.g., and explains that 25 years is the recommended maximum period for objects to stay in low orbit after the end of their operational life.
- Finally, for the practical application of these recommendations by manufacturers and operators, norms and standards will have to be developed for use in drawing up contracts. ISO completed an important task in drafting Standard 24113 (Space Systems-Space Debris Mitigation) published in 2010, which contains all of the rules relating to space debris. This document is based on a series of implementing standards describing how to apply them and proposing verification solutions and methods. A third level of documents, the technical notes, completes the body of work with substantiating information.

Other initiatives are also ongoing such as the International Code of Conduct for Outer Space Activities proposed by the European Union. The project was launched in 2008 as a means to achieve enhanced safety and security in outer space through the development and implementation of transparency and confidence-building measures. The proposed Code would be applicable to all outer space activities conducted by States or nongovernmental entities, and would lay down the basic rules to be observed by space faring nations in both civil and defense space activities. Discussions open to the participation of all UN Member States, will begin in 2012 with a view to adopt the Code in 2013.

39.4.3.3 Application Mechanisms

The IADC recommendations were first adopted in the regulatory documents of space agencies, e.g., NASA, JAXA, and CNES standards, and the European Code of Conduct for Space Debris Mitigation (ASI, BNSC, CNES, DLR, and ESA). These documents applied to these agencies' projects, but not to the activities of private manufacturers and operators. Thus, the private sector was free of any obligation. However, the measures were generally applied by "responsible" operators.

This regulatory gap was mentioned in resolution 62/217 of the General Assembly of the United Nations dated 1 February 2008 (document A/RES/62/217), which approves the COPUOS Space Debris Mitigation Guidelines and states the need for a legal framework for States which are liable for the activity of their nationals: "...and invites Member States to implement these guidelines through relevant national mechanisms."

This need had already been stated in 1967 in the Space Treaty (Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies). Article VI stipulates that "the activities of non governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty."

Thus, the States are liable in the event of damage caused on the ground or in space as a result of their nationals' activity. In response to this situation, States are gradually creating legal instruments allowing them to monitor the space activities for which they may be held liable. The United States, e.g., has set up a licensing system managed by three organizations: the FAA (Federal Aviation Administration) for launch operations, the NOAA (National Oceanic and Atmospheric Administration) for Earth observation satellites, and the FCC (Federal Communications Commission) for radiocommunications satellites. The United Kingdom has also set up a similar licensing system. In France, the Parliament passed the Space Operations Act (*Loi sur les Opérations Spatiales*) in June 2008, which came into effect on 10 December 2010. Other countries are taking similar initiatives and setting up equivalent systems.

The goal of these legal instruments is to set up a national authorization and monitoring system for space activities carried out under the State's jurisdiction, or for which the State is internationally liable under the United Nations Treaty. These instruments apply to satellite and launch operators, and their purpose is to ensure personal safety and public health and to protect property and the environment on Earth, in the atmosphere and in orbit. In this regard, requirements relating to the safety (risks on the ground) and prevention of space debris play a key role.

Although quite different in form, these various texts are basically equivalent in their content, and particularly with regard to debris prevention, they comply with the IADC Mitigation Guidelines and ISO standard 24113.

Nevertheless, the situation is far from perfect: the satellites and launchers in operation today were designed before these regulatory texts were published. Thus, it is not always possible to apply some of these rules, such as passivating used helium tanks to pressurize propellant tanks. For this reason, the texts generally provide for a transitional period during which operators must show that they have made their best efforts considering the existing design. Down the road, another problem may arise if all countries, without exception, do not implement equivalent

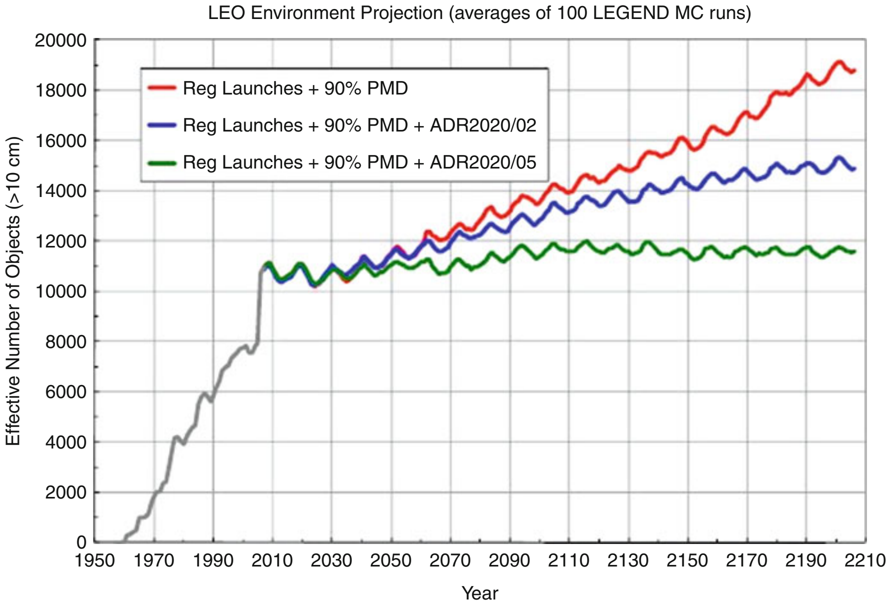

Fig. 39.5 Simulated LEO population growth as a function of time

systems. To evade the requirements, operators could decide to base themselves in countries without regulations or with much less stringent regulations. This would create a situation of unfair competition, much like that existing in maritime law with flags of convenience.

39.4.4 Removing Old Debris

Prevention measures will be effective in significantly reducing or eliminating the creation of new debris, but this will not solve the problem of "old" debris already in orbit. Various studies are being carried out to estimate long-term debris population growth. The models developed by various agencies are based on variety of assumptions on the number of future launches, mission types, satellite size and lifetime, how thoroughly prevention measures are applied, the number of accidental explosions, etc. All of these models show the situation continuing to worsen.

Indeed, collisions between objects will produce new debris, which will in turn create new collisions, and so on. This chain reaction or cascading effect (also known as the Kessler syndrome, after Don Kessler, the NASA writer who revealed this phenomenon in 1978) will mainly occur in the region between 700 and 1,000 km of altitude, where debris is densest.

Figure 39.5 (Liou 2001) shows the progression over time in the number of catalogued objects, for three assumptions:

- No active debris removal
- Active debris removal starts in 2020 and two objects are removed each year (ADR 2020/02)
- Active debris removal starts in 2020 and five objects are removed each year (ADR 2020/05)

These three simulations are based on the assumptions that (1) the number of launches will continue at the same rate as over the past 8 years and (2) post-mission disposal (PMD) measures will be effectively applied with a 90 % success rate.

If the assumptions for long-term growth prove to be true (i.e., inexorable population growth even with full application of the prevention measures), cleanup in space will be necessary: abandoned objects will have to be removed. The largest objects, which are potential sources of more debris in the event of collisions, will have to be removed first. The studies available at present show that 5–10 large objects per year would have to be removed to stabilize the debris population.

Various solutions, some more exotic than others, have been proposed by many different authors, but certain technical difficulties still need to be resolved:

- Approaching and capturing a noncooperative spacecraft, which is likely to feature a complex rotation movement: the capturing solutions involve systems of nets, harpoons, claws or robotic arms, etc.
- Attaching a de-orbiting system: solid propellant kit, electrodynamic cable, inflatable surface, sail, etc.

No-contact solutions have also been proposed: e.g., a laser (on the ground or on board) to reduce objects' speed, electrostatic attraction between the chaser and the target, "blowing" the target via an electric propulsion system installed on the chaser, etc.

The technical feasibility of these solutions has yet to be demonstrated. Once more in-depth studies have been carried out, one or several designs will have to be selected, and missions demonstrating the critical technologies will have to be carried out before the first operational mission can be planned.

In any case, the cleanup spacecraft will have to be able to move between orbits in order to reach different debris, which will be fairly complex.

Aside from these technical challenges, other difficulties of political, legal, and economical nature will also have to be considered:

- Political difficulties: active debris removal operations could be used as a cover for military activities. This confirms the need for international agreement and transparency between the various actors. Also, certain countries may feel singled out or reproached when it comes to cleaning up the objects they have abandoned in space.
- Legal difficulties: there is currently no international consensus on the definition of the term "debris": according to the United Nations Treaties, objects in space forever remain the property of their launching State, so prior authorization is needed before touching an object belonging to another State.
- Economic difficulties: these cleanup missions will probably be fairly costly. Who will pay for them, and in what form? States will probably also ask themselves why they should remove their objects from space when other States do not do the same, or worse, fail even to apply the prevention measures.

39.5 Conclusion

The space debris issue is a growing concern for all space-faring nations: the increasing population of objects orbiting the Earth represents a collision risk to operational satellite and also a risk on the ground in case of fragments surviving the reentry.

Ongoing actions aim at knowing the situation (observations, modeling) better and at protecting satellites through shielding and collision avoidance. In parallel, important actions are necessary to reduce the production of new debris through the implementation of mitigation measures such as the disposal of satellites and upper stages at the end of their operational life.

However, the problem being global, the solutions shall be agreed by all. An international consensus is therefore necessary:

- In the short term, the same rules shall be applied by all space actors. Mitigation measures have already been defined and approved at the international level. National regulation systems shall be now implemented by each country to ensure their immediate application by all operators.
- In the middle term the space community has to confirm the future instability of the space environment, even if the mitigation measures are fully applied, and to confirm the need to remove from orbit several objects per year.
- In the longer term active debris removal missions will require an increased international cooperation due to complex technical, economical, legal, and political issues.

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