

Space debris

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Space debris are all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, *that are non functional*. This widely accepted official definition was adopted by the Inter-Agency Space Debris Coordination Committee (IADC) [IADC Website \(http://www.iadc-online.org\)](http://www.iadc-online.org), an international governmental forum for the worldwide coordination of activities related to the issues of man-made and natural debris in space.

The space debris population

The first artificial satellite, Sputnik 1, was launched by the USSR on October 4, 1957. Since then about 5 000 launches have occurred, placing nearly 7 000 payloads in orbit. Most of these spacecraft eventually re-entered into the atmosphere, so that currently there are about 3 500 satellites and probes orbiting the Earth, together with about 1 800 upper stages, i.e., parts of the rockets used to bring them to space. Of all these spacecraft, only about 900 are operational. All the rest are *space debris*. This population of satellites and rocket bodies encompasses about 99% of the mass orbiting the Earth, estimated to be around 5 000 metric tons. On the other hand, in terms of number of objects, intact spacecraft are largely outnumbered by fragments, which also enter the space debris population. Fragments started to be produced when the first known break-up in orbit took place, the explosion of the *Transit 4A* rocket body that occurred on June 29, 1961. Since then about 200 in-orbit explosions, some accidental and some deliberate (about 30%), have been recorded. In recent years a new type of objects was added to the in-orbit population: collision fragments. On July 24, 1996, the first recorded accidental collision between an operational satellite and a piece of debris was recorded: the French micro-satellite *Cerise* was hit, at the relative velocity of 14.77 km/s, by a fragment, of about 10 cm², coming from the explosion of an Ariane rocket upper stage that happened ten years before. As a matter of fact only a few debris were produced by this event due to the particular geometry of the collision. But this was a clear sign that collisions in space are indeed a real threat. Then, 13 years later on Feb. 10, 2009, 16:56 UTC, the much feared first accidental collision between two large spacecraft took place. The satellite Iridium 33, part of a large multi-plane communication satellites constellation, collided against an old, non-operational Strela-2M, Russian communication satellite (codenamed Cosmos 2251) launched on September 16, 1993. The collision took place at an altitude of 789 km above the Taymyr Peninsula in Siberia. Both satellites were shattered, generating two large clouds of debris, including about 2 000 trackable fragments (see later) larger than a few centimeters. As shown in (Rossi, Valsecchi and Farinella, 1999), the complex interaction of these clouds with spacecraft in the different constellation orbital planes could highly enhance the risk of further, secondary, collisions in the future.



Figure 1: Computer generated image of the distribution of the catalogued space debris around the Earth (Courtesy: ESA Space Debris Program Office).

The most severe event ever recorded, in terms of number of fragments, was the deliberate fragmentation of the polar-orbiting Chinese weather satellite Fengyun 1C. This satellite was intercepted by a Chinese born ballistic missile on Jan. 11th 2007, to test anti-satellite weapons. This collision occurred at an altitude of 865 km, produced more than 2 500 long lasting fragments greater than 5 cm, and a huge quantity of smaller particles (the models predict about 150 000 fragments larger than 1 cm from this kind of event).

Other type of debris include so-called mission related debris (e.g., sensor caps, yo-yo masses used to slow down the spacecraft spin, etc); sodium-potassium liquid metal droplets leaked outside the Russian ocean surveillance satellites (RORSAT, where this liquid was used as a coolant for the nuclear reactor generating the power on board); the so-called *West Ford Needles*, i.e. copper dipoles, 1.77 cm long, released in space in 1961 and 1963 by the American satellites Midas 3 and Midas 6, for telecommunication experiments; fragments and foils coming from the delamination of spacecraft surfaces exposed to the space environment effects, etc.. Going down to even smaller sizes (between 10 μm and 1 cm) the population is dominated by aluminum oxide (Al_2O_3) particles coming from rocket motors with solid propellant and paint flakes.

Observation and cataloguing of space debris

All the un-classified spacecraft currently in orbit are catalogued by the United States Strategic Command (USSTRATCOM) in the Two-Line Element (TLE) catalogue [1] (<http://celestrak.com/>). In this catalogue about 16 000 objects are listed along with their current orbital parameters. The limiting size of the objects included in the catalogue (due to limitations in sensor power and in observation and data processing procedures) is about 5 to 10 cm below a few thousand kms of altitude and about 0.5 - 1 m in higher orbits (up to geostationary). Only about 6% of the objects in the TLE catalogue are operative satellites. Approximately 24% are composed of non-operative spacecraft; around 17 % by upper stages and about 13% by mission related debris . Finally, some 40% are fragments.

The orbits of the TLE catalogue objects are maintained thanks to the observations performed by the Space Surveillance Network (SSN). The network is composed by 25 sensors, both radars and optical sensors. The radars include mechanically steered dishes, one radar interferometer (the NAVSPASUR "radar fence", composed by a network of three transmitting and six receiving radar sites spanning the continental US along the 32nd–33rd parallel) and large phased-array radars capable of tracking several objects simultaneously. These last radars can track space objects in excess of 40 000 km in range and represent the largest source of information for the catalogue, especially for objects in Low and Medium Earth Orbit. The introduction of the large L-band "Cobra Dane" radar in Alaska, for example, raised the number of objects in the catalogue by about 10% pushing the network to its limits in terms of processing and archiving power.

Above several thousand kms of altitude radar power is not enough to monitor the small space debris, as the returned flux is proportional to the -4 power of the distance, so the SSN uses optical sensors for detecting high-altitude small-sized objects. The Ground-based Electro-Optical Deep Space Surveillance System (GEODSS), is composed by electro-optical devices in 6 different observing sites. This system, combining in each observing site three telescopes (two primary 1 m telescopes and one 40 cm auxiliary) achieves accurate pointing and a very good sensitivity (limiting magnitude about 16.5). Tracking and data processing is now automated and about 80 000 observations, both radar and optical, are processed daily by the SSN.

To get data on the smaller objects in Low Earth Orbit (LEO) not included in the catalogue, different sensors, or the same sensors but operated in a different manner, are needed. Radar campaigns were carried out to detect objects of 1 cm and below by putting the radar in a "beam park" mode, where the radar stares in a fixed direction and the debris randomly passing through the field of view are detected. This allows the number of objects to be counted, i.e., the recovery of the object's flux, but only a rough determination of their individual orbits.

As far as the higher orbits are concerned, and the geostationary ring in particular, dedicated, non-routine,

optical observation campaigns have been performed to characterize the environment in this vital region of the circumterrestrial space. As an example, for this purpose the European Space Agency (ESA) has installed a 1 m Schmidt telescope in the Canary Islands. The limiting detection size in GEO for this telescope is about 20 – 30 cm (Schildknecht, 2007).

These ground based observations are then supplemented by the data obtained from the analysis of the surfaces of spacecraft returned to Earth after some time spent in orbit, which mainly detect mm and sub-mm particles (e.g. the Long Duration Exposure Facility (LDEF), a satellite released and then retrieved by the Space Shuttle, the Hubble Space Telescope solar panels, the Space Shuttle external surface itself, etc.) and from impact sensors on board a few satellites.

The current estimate, derived from observations and simulated populations, is that the total number of non-trackable particles of 1 cm and greater is around 350 000, while those larger than 1 mm could be more than 5×10^8 . Man-made space debris dominates over the natural meteoroid environment down to millimeter sizes.

Spatial distribution

The spatial distribution of objects in Earth orbit can be divided into three main regions of space, as a function of altitude: Low Earth Orbit (LEO, below about 2 000 km), Medium Earth Orbit (MEO, between 2 000 km and about 30 000 km) and Geostationary Orbit (GEO, above 30 000 km).

Figure 2 shows the spatial density of objects for three different size regimes

as a function of altitude.

The Low Earth Orbit region

LEO is by far the most crowded zone in circumterrestrial space.

Fig. Figure 3 is a detail of Fig. Figure 2, for the objects larger than 10 cm, clearly showing a non-uniform density, with the highest peaks between 800 and 1 000 km. These are due to a large number of satellites and upper stages related to civil and military missions for Earth observation, surveillance and telecommunication, together with the fragments generated by a significant number of fragmentations that have taken place in those regions. As can also be seen from Fig. Figure 3, the Fengyun-1C fragmentation occurred exactly in this already critical region, contributing significantly to the density peaks.

The rapid decline of objects density below about 500 km of altitude (Fig. Figure 3) is due to the effect of air drag. Atmospheric drag is the most important perturbation in LEO, since it subtracts energy from an orbiting object causing its decay into the atmosphere. It represents, therefore, the main sink process acting against the overcrowding of circumterrestrial space. Since the atmosphere density decreases exponentially with altitude, this perturbation is efficient only up to about 800 km above the surface of the Earth (e.g., (Milani, Nobili and Farinella, 1987), (Chobotov, 2002), (Montenbruck and Gill, 2000)). Many other perturbations act

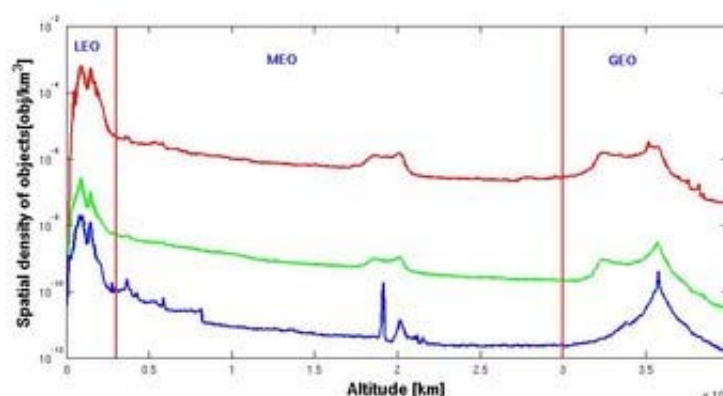


Figure 2: Spatial density of objects as a function of altitude for three different size thresholds: objects with diameter larger than 1 mm (red line), 1 cm (green line) and 10 cm (blue line).

on a satellite in LEO, but none of them causes a secular change in the semimajor axis. Gravitational perturbations, due to the non-spherical shape of the Earth, are important mainly in changing the angular arguments of the satellite orbit.

LEO is the region with the highest collision risk for orbiting objects. The two accidental collisions ever recorded happened around the high density regions in LEO as pointed out in Fig. Figure 3. The average

intrinsic collision probability per unit time (P_i) in LEO is in excess of $10^{-9} \text{ m}^{-2} \text{ year}^{-1}$ (Rossi and Farinella, 1992). The intrinsic collision probability is defined as the collision rate between two bodies (of radius r and R) for which $(r + R) = 1 \text{ m}$. This means that the number of collisions between two orbiting particles, expected during a time interval t , can be formally expressed as $P_i (R + r)^2 t$ (Rossi and Valsecchi, 2006). As an example, given the numbers quoted above, a 10 square meter structure in LEO should expect on average about a 1%

probability of impact with a centimetric particle, over one year. Note that the average collision velocity in LEO is about $V = 9.65 \pm 0.88 \text{ km/s}$ (Rossi and Farinella, 1992), meaning that the energy involved in a collision is on the order of 10^3 Joules even for a centimeter-sized projectile.

The Medium Earth Orbit region

The Medium Earth Orbit region can be defined as the zone of space lying between LEO and the geostationary ring. This orbital zone is becoming increasingly important since it is the home of navigation constellations such as the American GPS, the Russian GLONASS, the European Galileo and the Chinese Beidou. With circular inclined orbits lying between about 19 100 and 23 200 km of altitude, these satellite systems provide autonomous positioning with global coverage of the globe. Beyond the constellation related spacecraft (also including the old non-operational satellites and the upper stages), a large number of other satellites and debris cross the MEO regime. In particular it is worth mentioning spacecraft in Geostationary Transfer Orbits (GTO) and in Molnyia orbits. GTOs are near equatorial, highly elliptical orbits ($e \simeq 0.7$) used to bring satellites up to the geostationary ring, having their perigee in LEO and their apogee just below GEO, and are mainly populated by the spent upper stages used to perform transfer maneuvers. A Molnyia orbit is a highly elliptical orbit ($e \simeq 0.7$) close to the critical inclination ($i \simeq 63^\circ$), such that the precession rate of the argument of perigee is null and the orbit apogee is frozen in the northern hemisphere. This orbit is therefore populated by a large number of spacecraft and debris related to Russian telecommunication satellites (e.g., Chobotov, 2002). About 5 200 objects crossing the MEO region are included in the TLE catalogue and more than 20 000 objects larger than 1 cm are predicted by environment models to be in this region.

The dynamics of these orbits are strongly perturbed by resonances between the Earth gravity field and third body attraction (Chao, 2005), (Rossi, 2008). In the case of the high elliptic orbits (GTO and Molnyia) the interactions between third body perturbations and the atmospheric drag at perigee can strongly influence their lifetime.

The lower density of objects in MEO (see Fig. Figure 2) makes the collision probability in this region about two orders of magnitude lower than in LEO. Nonetheless, the average collision velocity at the GPS/GLONASS altitude is still about 5 km/s, making collisions, even against centimetric debris, still highly energetic events,

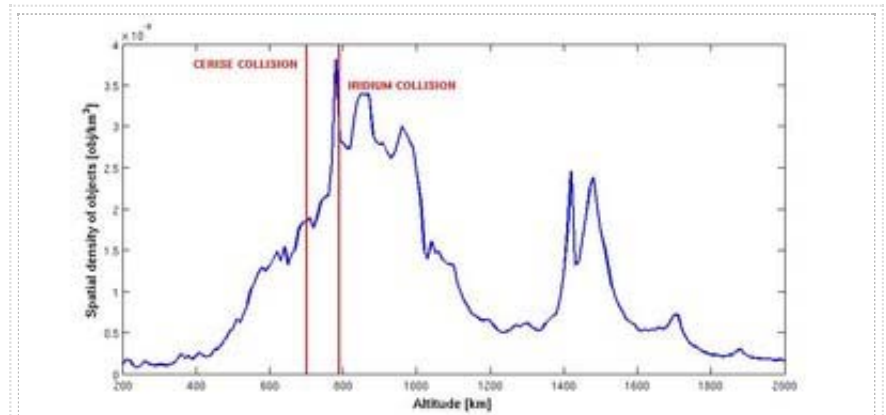


Figure 3: Spatial density of objects with diameter larger than 10 cm in LEO, as a function of altitude. The vertical lines mark the location of the Cerise and the Iridium 33 - Cosmos 2251 collisions.

prone to dangerous consequences for the orbital environment (Rossi, 2008).

The Geostationary orbit region

The rightmost region in Fig. Figure 2 is the one populated by geosynchronous objects. A *geosynchronous orbit* is an orbit around the Earth with its orbital period matching the Earth's sidereal rotation period. The ideal synchronous semimajor axis, for a spherical Earth, is $a_{sync} = 42\,164$ km, corresponding to an altitude $h_{sync} = 35\,786$ km. In the classification scheme adopted here, the GEO region includes geosynchronous orbits having $e \simeq 0$ and inclination $15^\circ \geq i \geq 0^\circ$.

A circular geosynchronous orbit having inclination $i = 0^\circ$ is called *geostationary* since a satellite placed in this kind of orbit will remain almost fixed with respect to a ground station. This is the reason why most of the telecommunication and weather satellites are placed in these kinds of orbits. In reality the dynamics of objects in GEO are perturbed by gravitational effects due to the Earth's oblateness, the ellipticity of the Earth equator, the Sun, and the Moon, to the extent that a geostationary satellite, if not controlled, will quickly leave its assigned orbital position. In particular, the above perturbations cause a libration (or circulation) of the satellite's longitude with a very long period about two stable equilibrium positions, located at the longitude of 75° East and 245.5° East (two unstable equilibrium points are located at 161.8° and 348.5° E) (Montenbruck and Gill, 2000). The Sun and Moon's attraction also cause a precessional motion of the orbital plane, inducing an oscillation of the inclination which reaches a maximum value $i_{max} \simeq 15^\circ$ and then bounces back to 0° , with a period of about 53 years. Also taking into account the typical large dimensions of the solar panels and antennas of geostationary satellites in the GEO region, solar radiation pressure perturbation becomes significant (Milani, Nobili and Farinella, 1987). The controlled satellites in GEO are almost all coplanar, with near zero eccentricity (and all rotating in the same direction) and are therefore confined in a torus-like region around geostationary altitude. This keeps the collision risk and the relative velocities very low. On the other hand, the above mentioned perturbations tend to increase the orbital eccentricity and the relative inclination of uncontrolled debris leading to dangerously high relative velocities (of several hundreds of m/s) crossing this operational torus. To minimize the collision risk between operative satellites and non-operational spacecraft, a protected zone was defined at the international level by the IADC, defined as a toroid centered on the geostationary orbit and extending 200 km above and below the geostationary altitude and $\pm 15^\circ$ in declination. Every spacecraft at end-of-life should be moved to a stable disposal orbit with perigee and apogee outside this zone.

Due to its physical distance, the population of objects in the GEO region are mostly characterized by optical telescope observations and the exact amount of smaller debris is still quite uncertain (Schildknecht, 2007). In the TLE catalogue about 1 000 objects with diameter larger than about 1 m reside in the GEO region. Dedicated optical campaigns from the ESA telescope (and from other similar American and Russian sensors) revealed a large number of non catalogued debris. Most of these are probably the result of a still undetermined number of explosions that have occurred among spacecraft and upper stages. Only two fragmentations have been confirmed near the geostationary orbit, but the models tend to indicate that a few more undetected fragmentations should have taken place in this regions in order to explain the existence of all the non catalogued objects.

Long term evolution

At the end of the '70s Donald Kessler (Kessler and Cour-Palais, 1978) first pointed out the possibility that a process of mutual collisions between objects presently in orbit could lead to the creation of a debris belt surrounding our planet and jeopardizing, if not preventing, all space activities. Mathematical models and large numerical Montecarlo codes have been developed in the last decades to simulate the interplay of all the physical processes involved in the evolution of the debris population, such as launches, explosions, collisions, orbital evolution, active de-orbiting, etc. (e.g. (Rossi et al., 2009), (Liou and Johnson, 2008)).

Although partly model dependent, results for the long term evolution of space debris show that the population in LEO is unstable. This means that, even in the absence of any future launches or explosions, collisions between objects already in space will sustain growth in the number of objects (Rossi et al., 1992), (Liou and Johnson, 2008). The models predict that, even in this *best case scenario*, within the next 100 years collision fragments will become the dominant population in LEO and will continue to grow in a more than linear trend, as shown in Fig. Figure 4.

Nowadays, the main mitigation measures adopted to curb the growth of space debris are passivation of spent upper stages and old satellites to prevent in-orbit explosions (obtained with the venting of any residual propellant and discharging of the batteries), limitations on the release of operational debris, and de-orbiting of spacecraft after the end of their operative life (IADC, 2002). Though absolutely necessary, these measures are not enough to counteract and reverse the destructive pace of space debris growth. Some kind of *space traffic management*, where routine avoidance maneuvers are undertaken whenever the collision risk between any two objects exceeds a given threshold, should be implemented. Even this might not be enough and the active removal of objects will most probably be the only effective solution to the growth of the space debris.

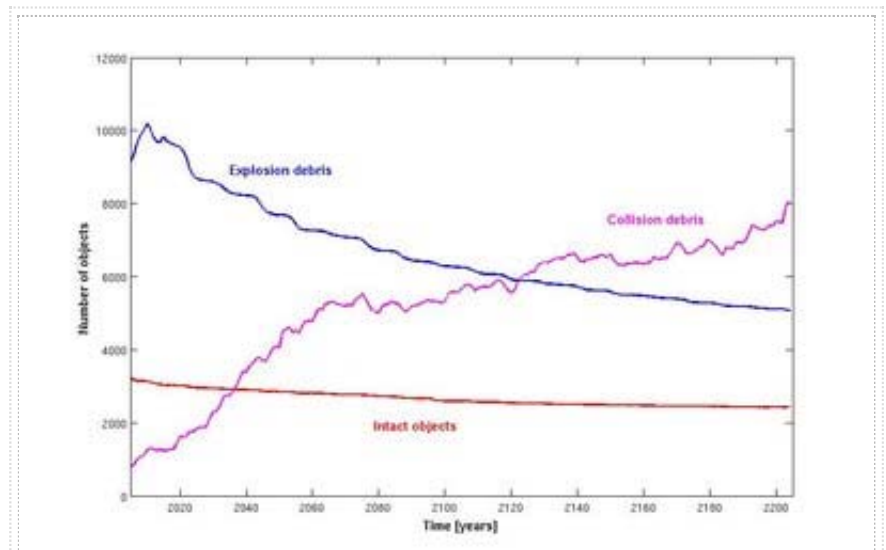


Figure 4: Breakdown of the number of LEO objects larger than 10 cm in the scenario where no future launches are simulated: intact objects (red line), explosion debris (blue line), collision debris (magenta line) (Rossi et al., 2009).

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Recommended reading

- ✦ Klinkrad, H. (2006). Space debris: models and risk analysis. Springer Praxis, Chichester, UK. ISBN 3-540-25448-X

External links

[Inter-Agency Space Debris Coordination Committee \(IADC\)Website \(http://www.iadc-online.org\)](http://www.iadc-online.org)

<http://orbitaldebris.jsc.nasa.gov/newsletter/newsletter.html>) NASA Space Debris Program Office, *Orbital Debris Quarterly News*

[ESA Space Debris Program Office \(http://www.esa.int/esaMI/Space_Debris/SEMCILO5VQF_o.html\)](http://www.esa.int/esaMI/Space_Debris/SEMCILO5VQF_o.html)

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