A Space Debris Primer

Earth's orbital environment is becoming increasingly crowded with debris posing threats ranging from diminished capability to outright destruction of on-orbit assets.

Roger Thompson

This article originally appeared in The Aerospace Corporation's technical magazine Crosslink, Fall 2015.
Visit the Crosslink website at www.aerospace.org/publications/crosslink-magazine

The term "space debris" can be misleading to a lay reader, and potentially conceals the very real dangers and complex problems those words describe. "Debris" can conjure the image of earthbound litter, which lies on the ground and may only offend aesthetically.

In Earth orbit, however, debris is anything but motionless, and while there is quite a bit of room in the various orbits humans place satellites, that room is becoming increasingly crowded with functioning and nonfunctioning spacecraft, and the bits and pieces leftover from collisions, explosions, and slippery-fingered astronauts.

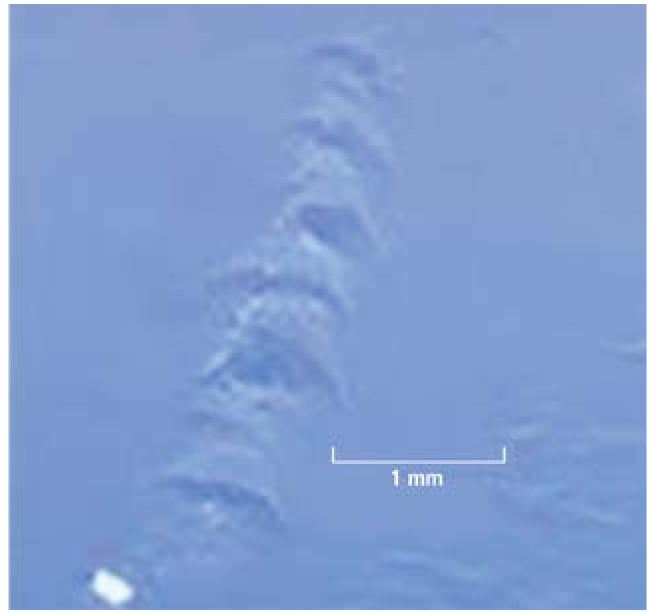
The simple definition of space debris is any human-made object in orbit that is not in active use. Debris can be obsolete or inactive spacecraft, parts of satellites or launch vehicles, or fragments of spacecraft and rockets that have been broken up in some fashion. Space debris comes in all sizes, from microscopic particles to nonoperating satellite and rocket bodies tens of meters in length.

Debris Origin

Most space debris comes from "breakup events" caused by explosions and collisions, many of them deliberate. In the 1960s several spacecraft were intentionally destroyed through self-destruct mechanisms or antisatellite tests. The two worst events in the growth of the space debris population were the deliberate destruction of the Chinese Fengyun-1C satellite on January 11, 2007, part of a Chinese antisatellite test; and the accidental collision of Iridium 33 and Cosmos 2251 on February 10, 2009. Those two events added more than 3300 and 2200 fragments, respectively, to the catalog of tracked objects, and perhaps hundreds of thousands of smaller fragments.

Of the numerous accidental explosions, residual onboard propellant is the principal cause, but it is unknown what caused that propellant to explode. Some explosions may have resulted from a collision with other space debris. On average, there are four breakup events per year. Most breakups and explosions produce a relatively small number of debris objects (compared to collisions, which are more destructive), but these add up over the years and the events account for the bulk of the catalog.

Once debris is created from a breakup event, it moves in many different orbits, which change over time. Further, while all objects that are in orbit at the same altitude are moving at approximately the same speed (for nearly circular orbits), they are not necessarily moving in the same direction. For objects in low Earth orbit (LEO), the orbital speed is approximately 7.5 kilometers per second, or 17,000 miles per hour. However, when two objects move close to each other—an event called a conjunction—their relative velocity approaching each other from the side, or even head-on, can be as high as 14 kilometers per second (more than 31,000 miles per hour). Most conjunctions converge at about a 45-degree angle, which results in a relative velocity of approximately 10 kilometers per second—ten times faster than a rifle bullet.



Courtesy of NASA

This image was captured by the orbital debris collector experiment flown on the Russian space station Mir. The experiment was delivered and retrieved by NASA space shuttles STS-76 and STS-86. The collector used an aerogel—a very low-density material sometimes called "solid smoke"—to slow and capture the particles. The space debris shown in this image is a paint flake. In 1994, a paint flake about this size created a crater almost 1/2 inch in diameter in a shuttle side hatch window.

At such velocities, the danger to satellites and space-based systems becomes obvious. The kinetic energy of even a small particle at these speeds can do tremendous damage. The potential damage imparted is proportional to the debris object's mass; therefore, space debris is divided into categories based on size and mass according to that potential damage.

Debris Size Potential Dangers

The first category includes objects that are approximately 10 centimeters in diameter (fist-sized) and larger, which can be tracked by the U.S. Space Surveillance Network (SSN), and are listed in a resident space object catalog. An impact from an object this size is the equivalent of a bomb blowing up inside the spacecraft. Because debris objects this size can be tracked, conjunctions with other bodies can be predicted, and in some cases, an at-risk satellite can be maneuvered to avoid a collision. The SSN can often track debris smaller than 10 centimeters, but that depends on the shape and composition of the object, considered in concert with the size of the debris. The lower limit for reliable tracking of an object is somewhere between 5 and 10 centimeters. There are currently more than 22,000 objects being tracked by the SSN.

The next category of space debris is objects smaller than 10 centimeters, down to 1 centimeter. An impact from a 5-centimeter object—the middle of the range—is the equivalent of being hit by a bus traveling at highway speed. Debris objects in this range cannot be tracked, but are large enough to destroy a satellite or rocket body if the debris collides with the main body of the spacecraft (collisions with solar arrays, booms, and antennas may not completely destroy a satellite).

Space debris comes in all sizes from microscopic particles to obsolete spacecraft and rocket bodies tens of meters in length. Pictured here is an Agena upper stage.

Debris size	Mass (g) aluminum sphere	Kinetic Energy (J)	Equivalent TNT (kg)	Energy similar to
1 mm	0.0014	71	0.0003	Baseball
3 mm	0.038	1910	0.008	Bullets
1 cm	1.41	70,700	0.3	Falling anvil
5 cm	176.7	8,840,000	37	Hit by bus
10 cm	1413.7	70,700,000	300	Large bomb

The average LEO impact speed of 10 kilometers per second means the high relative velocities of small fragments can be dangerous.

It is currently estimated that there are approximately 500,000 of these fragments in orbit at LEO altitudes. Every one has the potential to cause catastrophic damage to an active satellite. Space debris larger than 1 centimeter has the potential to completely fragment any object it hits. If that object is a large mass such as a satellite or rocket body, the resulting collision will add tens of thousands of new space debris fragments to the population.

Debris objects between 3 millimeters and 1 centimeter make up the next category of space debris. An impact from an object this size ranges from the equivalent of being hit by a bullet (damaging but not necessarily destroying the satellite) up to being hit by an anvil falling from a height of two stories (in which destruction of the satellite is certain). These objects also cannot be tracked, and it is estimated that there are millions of them in LEO. However, because particles near the lower limit of this category are so small, they will usually cause only localized damage. Any such damage may still end a satellite's mission if the debris hits a critical component such as a computer, sensor, or propellant tank, but the impact will usually not add a significant amount of space debris as would be the case if the debris fragment was larger.

The last category of space debris comprises objects that are smaller than 3 millimeters. An impact from a 1-millimeter aluminum particle is the equivalent of being hit by a baseball thrown by a major league pitcher. These small particles cause localized damage, particularly in configurations where the surface condition of the impacted spacecraft is important to its function, such as solar arrays and optical systems (telescopes, star trackers, cameras, etc.). Some spacecraft components can be shielded to prevent damage from debris this size, but not all of them. There are an estimated 10 million space debris objects in LEO that are smaller than 3 millimeters. They are still a risk to space-based assets, but one that can often be effectively dealt with through better designs and shielding.

Mitigating the Hazards

Although improved spacecraft design and shielding can be effective in minimizing damage from orbital debris, it is far better to prevent an impact in the first place. Collision avoidance (COLA, or CA) is a process where the time of closest approach and probability of collision are computed from orbital data (this is only possible for objects large enough to be tracked, which are 10 centimeters and larger). If the probability of collision is high and an avoidance maneuver is an option, satellite operators may choose to maneuver their satellite to reduce the risk of collision. Of course, this is only possible when one of the objects at risk is an active, maneuverable satellite; only a few hundred of the more than 1000 active satellites have this capability.

Collision avoidance is an issue that can be easy to understand in the abstract—determine the likelihood a piece of debris will strike a satellite and take measures to avoid it—but difficult to apply, or even to decide to apply. This arises because the risk of a satellite being struck by a piece of debris is very low, on the order of one in tens of thousands, even one in a million or more. At the same time, the consequences of both taking action and not taking action are extremely high. If a satellite operator decides the risk is too high and takes action to avoid a collision, valuable maneuvering fuel must be expended, shortening the useful life of the satellite. If the operator decides not to take action and an impact occurs, the satellite and its capability are lost; replacing it may take years and millions of dollars. For commercial operators, business losses could run into the billions. There is also the attendant increased risk to other satellites from the debris generated by this collision. Consequently, while there is risk in both taking COLA actions and not doing so, the implications of a satellite loss are so great that COLA thresholds—in which a satellite is maneuvered out of harm's way—may be very low, from one in 10,000 to one in a million.

The uncertainty inherent in COLA results from the physics of how debris is created and disbursed. Initially, a fragmentation event looks like an expanding, spherical volume of debris, much like what is seen in high-speed photographs of an explosion. However, each fragment is actually in a distinct orbit slightly different from the parent object, because the collision or explosion causes a small change in the velocity of each fragment. As the mechanics of orbital motion come into play over time, the cloud of fragments—the debris—spreads around the orbit close to the plane of the

Debris size	Quantity	Impact
1 mm to 3 mm	Millions	• Cannot be tracked • Localized damage
3 mm to 1 cm	Millions	• Cannot be tracked • Localized damage • Upper limit of shielding
1 cm to 5 cm	500,000 (estimated)	• Most cannot be tracked • Major damage
5 cm to 10 cm	Thousands	• Lower limit of tracking • Catastrophic damage
10 cm or larger	Hundreds to low thousands	• Tracked and cataloged by space surveillance network • Catastrophic damage

The size and quantity of debris distributed from a given event are factors affecting the impact and potential damage caused by the occurrence.

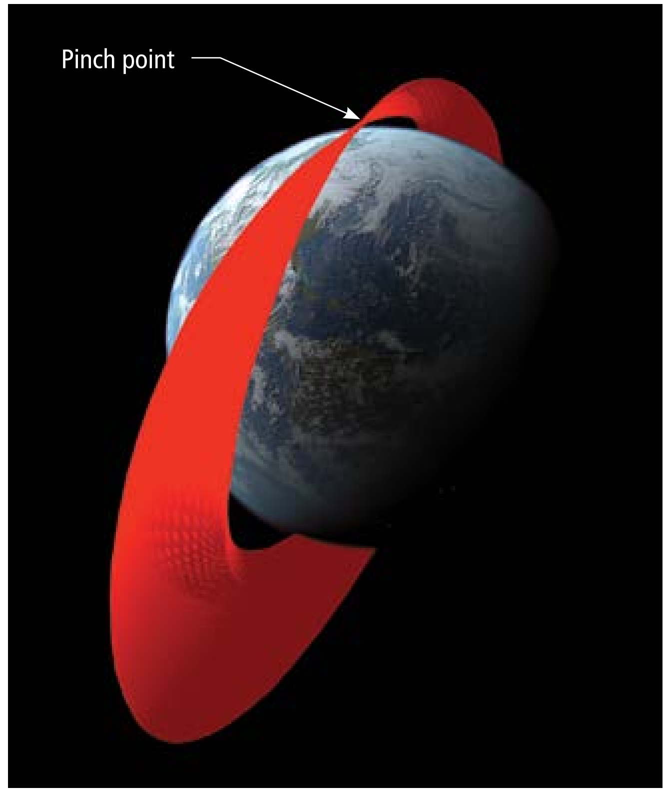
parent orbit. Eventually, however, all of the debris will return to the point of the collision, because that point is common to the orbits of all the debris created by the collision. This is called the pinch point.

Over time, orbital perturbations and the atmospheric drag characteristic of LEO will cause the debris to further expand and distribute around Earth until the cloud resembles a shell, causing it to become part of the new background flux of orbital debris. This causes a paradoxical situation in that the risk of any one piece of debris being involved in a collision becomes lower over time because the debris is spreading out; and the risk of collision in general becomes higher, as there are more pieces of debris out there and the volume they cover becomes larger.

The disparity between risk of collision and actual collision can be seen in several actual on-orbit collision events. In 1991, the debris from the Russian Cosmos 1275 navigation and communications satellite collided with Cosmos 1934. The predicted miss distance for the event was 512 meters, with a collision probability of one in 50,000; nonetheless, the collision occurred. In 1996, Cerise, an active French reconnaissance satellite, collided with debris from an Ariane 1 rocket launch. In this incident, the predicted miss distance was 882 meters and the probability of collision one in two million. The most well-known such orbital collision, the 2009 Iridium 33-Cosmos 2251 event, had a predicted miss distance of 584 meters, a collision probability of one in five hundred thousand. Each of these events had low collision probabilities and estimated miss distances in the hundreds of meters. Because of the uncertainties of predicted orbital position, those miss distances were in fact zero.

In addition to determining cause, number, and risk of orbital debris, mitigation and remediation are also important issues. Mitigation concerns itself with the policies and methods that will, in the short term, lower the growth rate of space debris populations. Remediation is the process of removing space debris to clean up the orbital environment.

Mitigation efforts have been in use for more than 20 years. These include reducing or eliminating the release of mission-related debris; end-of-life passivation (eliminating energy sources such as pressurants, propellants, and charged batteries); and postmission disposal—reentering or moving an obsolete object to a disposal orbit, or lowering its orbit



As the mechanics of orbital motion come into play, the cloud of fragments—the debris—spreads around the orbit close to the plane of the parent orbit. Eventually, all of the debris will return to the point of the collision, because that point is common to the orbits of all the debris. This is called the pinch point.

such that it will reenter within 25 years.

Remediation is a long-term solution because a cost-effective method does not currently exist. A number of concepts are in development and some technology demonstrators are expected to fly in the next few years, but it will be at least a decade before meaningful remediation can be relied upon to reduce the growth in space debris. It took decades for the problem of space debris to reach or at least approach a critical phase. Awareness and willingness to address the problem is the first step, and that has largely been accomplished through international efforts and cooperation. Solving the problem of space debris, however, has no easy answers.

About the Author

Roger C. Thompson, Senior Engineering Specialist, Mission Analysis and Operations Department, joined Aerospace in 1996. He works on a broad spectrum of space situational awareness projects, collision avoidance, orbital maneuvers, and analysis of satellite architectures. He has a B.S. in engineering science and mechanics from North Carolina State University, and an M.S. and a Ph.D. in engineering mechanics from Virginia Polytechnic Institute and State University.

AEROSPACE
www.aerospace.org