National Aeronautics and Space Administration

Orbital Debris Management & Risk Mitigation

APPEL | Academy of Program/Project & Engineering Leadership

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The Impact of Orbital Debris on Space Exploration

In the early years of the Space Age, the goal of spacecraft design and engineering was to build vehicles that could explore realms beyond Earth. For decades now, however, aerospace engineers have also been challenged to design spacecraft and missions that preserve the Earth orbit environment by minimizing **orbital debris**.

Liftoff of the Apollo 17 Saturn V Moon Rocket from Pad A, Launch Complex 39, Kennedy Space Center, Florida, at 12:33 a.m., December 17, 1972.

Photo Credit: NASA

Section 1.1

An Introduction to Orbital Debris

ORBITAL DEBRIS: EXPANDING THE EARTH SATELLITE POPULATION

The moon is the only natural satellite orbiting Earth. But it's no longer the only satellite near Earth. **Low Earth orbit** (LEO) is filled with manmade objects, many of which are softball-sized or larger. These objects are called orbital debris. Even debris as small as a few millimeters in diameter can have a significant impact on operational spacecraft.

Extremely small particles of debris—some even smaller than a millimeter—aren't easily detected by sensors on Earth. So how do scientists know orbital debris is a problem? Evidence of collisions with orbital debris (e.g., cracks, craters, dents, etc.) has been seen on spacecraft such as the Hubble Space Telescope, the surface of which offers ongoing details about the size and quantity of orbital debris in the LEO environment. NASA also routinely inspects the surfaces of objects that return from space, as these surfaces provide "snapshots" of the LEO environment for the time the spacecraft was operational.

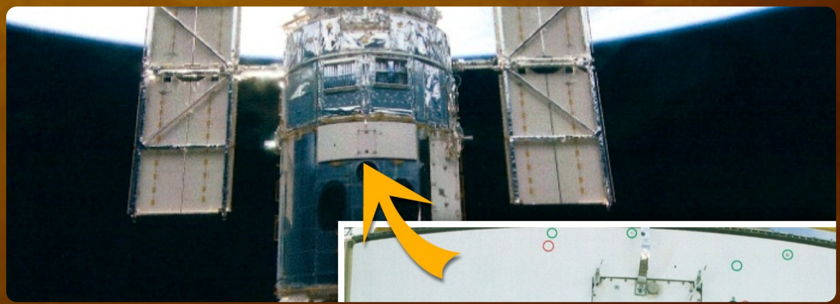


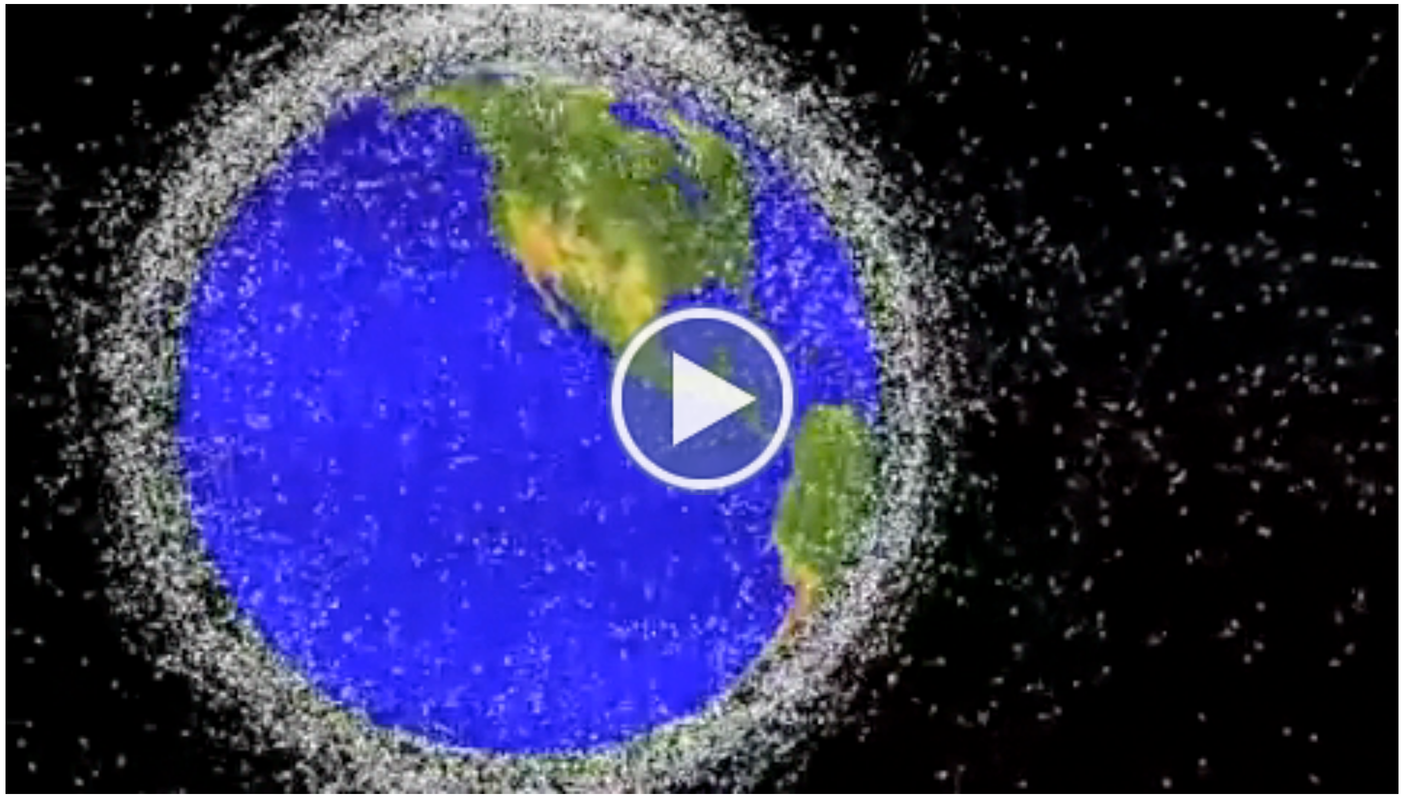
Image 1.1.1 Particle impact features on the Hubble Space Telescope.

Photos from a servicing mission in 2009 revealed numerous impact features, marked by the green circles in the photo above, that had appeared since the previous servicing mission in 2002. The red circles represent impact features from a study performed during the 2002 servicing mission. Over the course of its lifetime, microscopic examinations have revealed nearly 700 hypervelocity impact features greater than 0.3 millimeters on the Hubble Space Telescope.

Photo Credit: NASA

GROWTH OF EARTH SATELLITE POPULATION, 1965-2010

Before the launch of Sputnik 1 in 1957, there were no manmade objects in Earth orbit. But the number of satellites has steadily increased.

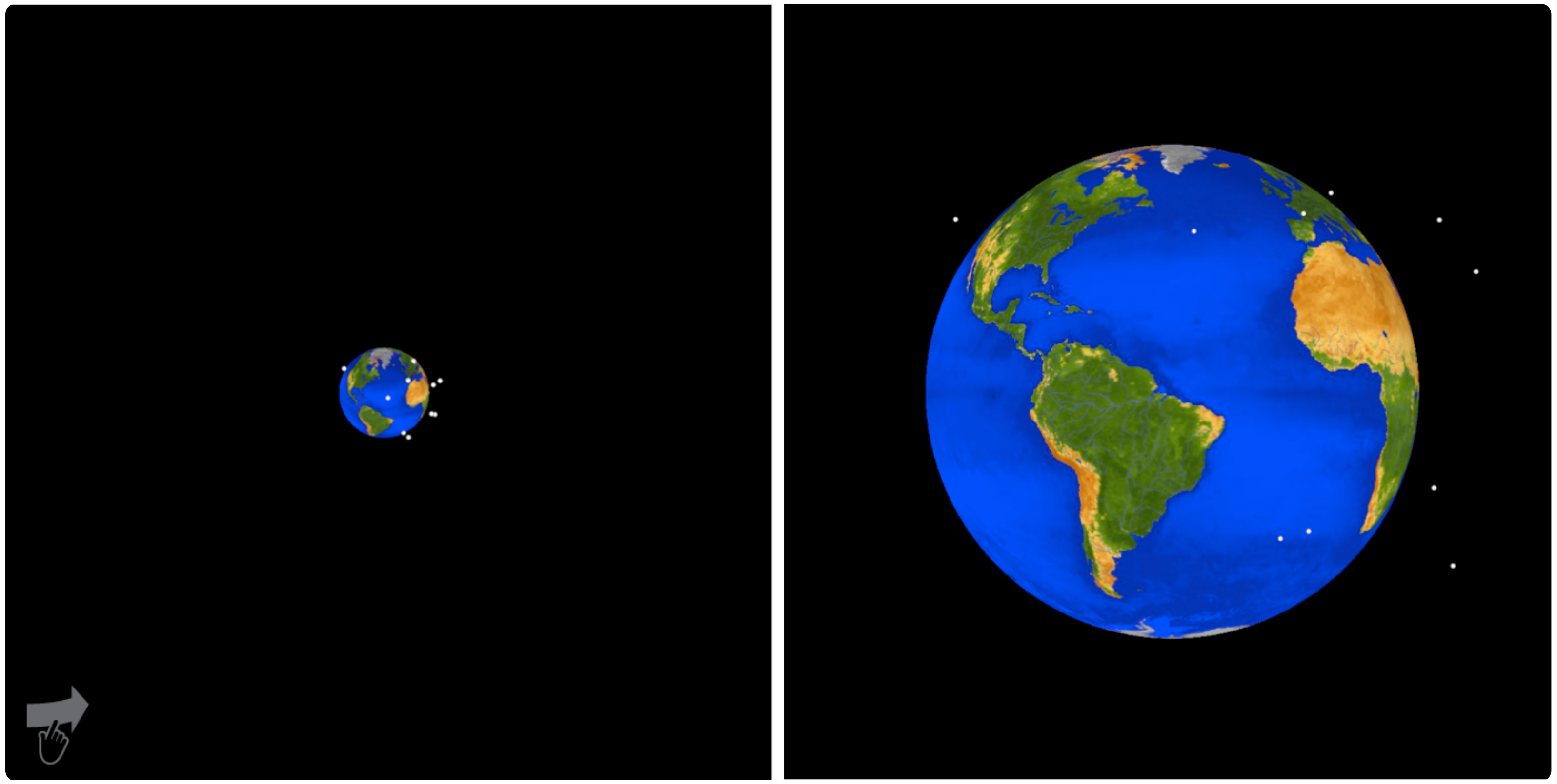


Video 1.1.1 Earth debris in motion.

All of the objects in video are tracked by the U.S. Space Surveillance Network, which is operated by the Department of Defense. The objects travel in different directions, at different altitudes, on different elliptical planes. Although this image makes LEO look more congested than it is, the congestion does get worse each year.

Video Credit: NASA

While the objects in the images shown in the below gallery are not to scale, it's evident that the amount of debris in Earth orbit increased with time. By 1975, there was a geosynchronous ring of debris, representing the **geosynchronous orbit (GEO)** in which many communications and weather satellites are placed today. By the end of 2012, the space between GEO and LEO had seen a significant increase in orbital debris. Today, a goal of NASA and other space practitioners is to manage threats posed by existing orbital debris and minimize the potential for new debris in order to protect the near-Earth environment for future generations.



Gallery 1.1.1 Geosynchronous view (left) and low Earth orbit view (right) - 1960 to 2010.

1960: *Representation of Earth and its satellites, 1960, seen up close and from afar.*

Image Credit: NASA

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Section 1.2

The NASA Orbital Debris Program

The growing quantity of debris in Earth orbit poses a danger to users of the orbital environment, such as spacecraft. It also increases the risk that humans or manmade structures could be impacted when objects reenter Earth's atmosphere. Initiatives have been put in place at both the federal and international level to mitigate orbital debris. The National Space Policy of the United States of America directs agencies and departments to implement *U.S. Government Orbital Debris Mitigation Standard Practices*. The U.S. has also endorsed the United Nations' *Space Debris Mitigation Guidelines*, introduced in 2007.

NASA established the Orbital Debris Program at Johnson Space Center in 1979 to address issues and lead research on orbital debris. The program is recognized as a world leader in environment definition and modeling as well as mitigation policy development. The program, which is closely aligned with the Department of Defense (DOD) in many areas involving space situational awareness, works in different ways to support the goal of continued space exploration with minimal orbital debris impact.

NASA ORBITAL DEBRIS PROGRAM ACTIVITIES

RESEARCH

Researches the characteristics of orbital debris to support risk assessment for NASA projects and programs.

SUPPORT

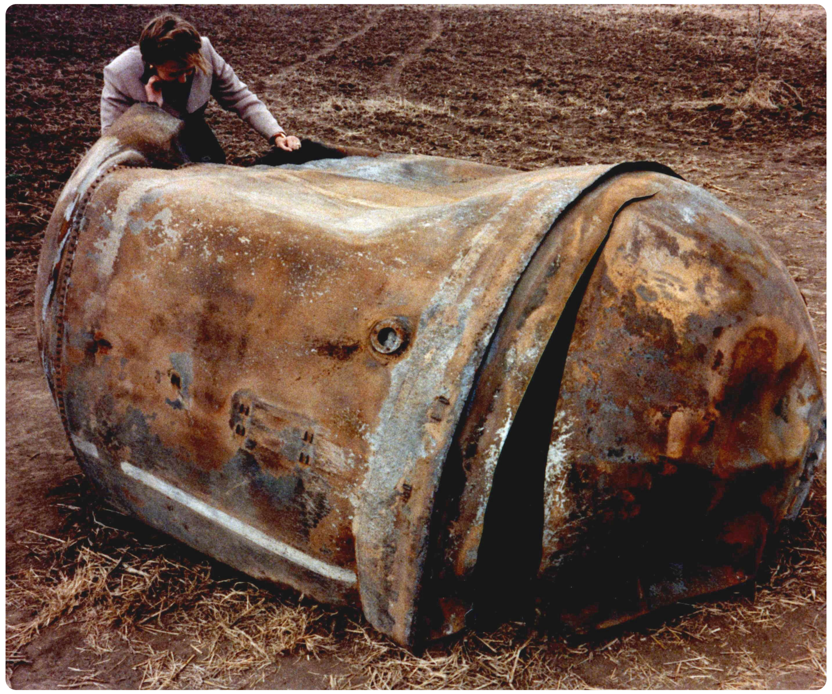
Supports NASA Headquarters and other governmental agencies or commercial endeavors by providing technical or policy-level assistance.

GLOBAL ENGAGEMENT

Engages with international bodies, such as the United Nations and the Inter-Agency Space Debris Coordination Committee (IADC), to discuss issues associated with orbital debris, set guidelines for international action, and develop protocols for moving forward.

EVALUATION

Evaluates the risk of human casualties from satellite reentries.



Gallery 1.2.1 **Exploring NASA Orbital Debris Program activities.**

Research: *The NASA Orbital Debris Program Office, recognized worldwide for its initiative in addressing orbital debris issues, determined that this large piece of debris was the main propellant tank of the second stage of a Delta II launch vehicle.*

Photo Credit: NASA

ORBITAL DEBRIS PROGRAM FOCUSES ON THREE KEY AREAS

MEASUREMENTS

The Orbital Debris Program conducts both ground-based and space-based observations of the orbital debris environment. Tools such as ground-based radars—like the Haystack X-Band Radar, which can view objects as small as 5 millimeters—as well as optical telescopes and space-based telescopes are used to gather data.

MODELING

NASA scientists have developed—and continually update—models that help describe and characterize the current and future orbital debris environment. Evolutionary models, such as **LEGEND**, predict the future debris environment. Engineering models, such as **ORDEM** 3.0, are used to assess the risk of debris impact for spacecraft.

RISK ASSESSMENT

NASA continually assesses risk for all NASA space projects, including both human and robotic spaceflight, by using specialized software tools developed by the Orbital Debris Program. One example is **SBRAM**, a software program that allows NASA to assess real-time collision threats to operational spacecraft immediately after a fragmentation in space.

Image 1.2.1 NASA Orbital Debris Program tools.

Data is gathered by using tools such as the Haystack and Haystack Auxiliary (HAX) Radars at the MIT Lincoln Laboratory in Massachusetts.

Photo Credit: MIT Lincoln Laboratory

Section 1.3

What is Orbital Debris?

Orbital debris is the term for any object in Earth orbit that no longer serves a useful function. These objects include non-operational spacecraft, derelict launch vehicle stages, mission-related debris, and fragmentation debris.

Image 1.3.1 Sources of orbital debris.

Derelict launch vehicle stages

Many discarded launch vehicle stages remain in orbit, and can be as large as 8 metric tons. Pictured above is a Delta II second stage being lifted along the mobile service tower on Pad 17-B at Cape Canaveral Air Force Station.

Photo Credit: NASA

NON-OPERATIONAL SPACECRAFT

Of the more than 6,800 spacecraft placed into Earth orbit since the 1957 launch of Sputnik 1, approximately 2,400 non-operational spacecraft are still in Earth orbit. Now considered orbital debris, these objects vary in size. Picosats and microsats may be small, weighing only a kilogram, but massive objects remain in orbit beyond their lifetimes as well. Geosynchronous spacecraft can be several metric tons. Small or large, these objects pose potentially mission-ending threats to operational spacecraft.

DERELICT LAUNCH VEHICLE STAGES

More than half a century has passed since the first launch vehicle stage was placed into Earth orbit. More than 30 percent—approximately 1,700—of the launch vehicle stages used since then remain in Earth orbit. Such debris can be as small as 100 kilograms (or even less) and as large as 8 metric tons.

MISSION-RELATED DEBRIS

Debris can be generated during the launch and satellite-deployment processes. Items such as sensor and engine covers, straps, springs, and yo-yo despin weights were frequently jettisoned into Earth orbit during the 1960s and 1970s. Such debris was typically created during the first day or within the first few weeks of launch. Today, design modifications on spacecraft and launch vehicles have virtually eliminated such potential for orbital debris.

FRAGMENTATION DEBRIS

Most of the debris in Earth orbit results from the fragmentation of spacecraft and rocket bodies on orbit after their mission has been completed. Fragmentation is generally due to one of three things: anomalous events, explosions, or collisions. Most are accidental, and can occur 25 hours after successful completion of the mission—or 25 years later. Guidelines and standards created by NASA, the U.S., and other nations seek to eliminate or limit the occurrence of satellite fragmentation of any kind.

WORST SATELLITE BREAKUPS

Cataloged debris refers to objects in Earth orbit that have been identified by DOD and the sources of the debris have been confirmed. In LEO, cataloged debris is larger than 10 centimeters, which is the size of the debris that can be tracked by the U.S. Space Surveillance Network.

The sensitivity of the U.S. Space Surveillance Network tracking instruments degrades in GEO, which means cataloged debris in that environment is generally larger than 70 centimeters. Based on cataloged debris, scientists know that one-third of the debris currently in Earth orbit originated from fragmentation resulting from just 10 satellite breakups. In actual numbers, over 5,000 objects came from the breakups listed above, out of about 15,000 total objects cataloged by DOD. Most of these events were accidental. Fortunately, from an environmental standpoint, most fragmentation debris has since fallen out of orbit: it has reentered Earth's atmosphere, burning up or disintegrating in the process, and is no longer orbital debris.

Figure 1.3.1 10 worst satellite breakups (based on cataloged debris).

Common Name	Owner	International Designator	Cataloged Debris*	Debris in Orbit*	Year of Breakup	Altitude of Breakup	Cause of Breakup
Fengyun-1C	China	199-025A	3218	2989	2007	850 km	Intentional Collision
Cosmos 2251	Russia	1993-036A	1559	1371	2009	790 km	Accidental Collision
STEP 2 Rocket Body	USA	1994-029B	710	58	1996	625 km	Accidental Explosion
Iridium 33	USA	1997-051C	567	487	2009	790 km	Accidental Collision
Cosmos 2421	Russian	2006-025A	509	0	2008	410 km	Unknown
SPOT 1 Rocket Body	France	1986-091C	492	32	1986	805 km	Accidental Explosion
OV 2-1 / LCS 2 Rocket Body	USA	1965-082DM	473	35	1965	740 km	Accidental Explosion
Nimbus 4 Rocket Body	USA	1970-025C	375	245	1970	1075 km	Accidental Explosion
TES Rocket Body	India	2001-049D	370	111	2001	670 km	Accidental Explosion
CBERS 1 Rocket Body	China	1999-057C	343	178	2000	740 km	Accidental Explosion
* As of March 2012			**Total: 8616**	**Total: 5506**			

Section 1.4

Anomalous Events, Explosions, and Collisions

The majority of the debris in Earth orbit originated from the fragmentation of spacecraft and rocket bodies. Usually accidental, fragmentation is generally due to one of three things: anomalous events, explosions, or collisions.

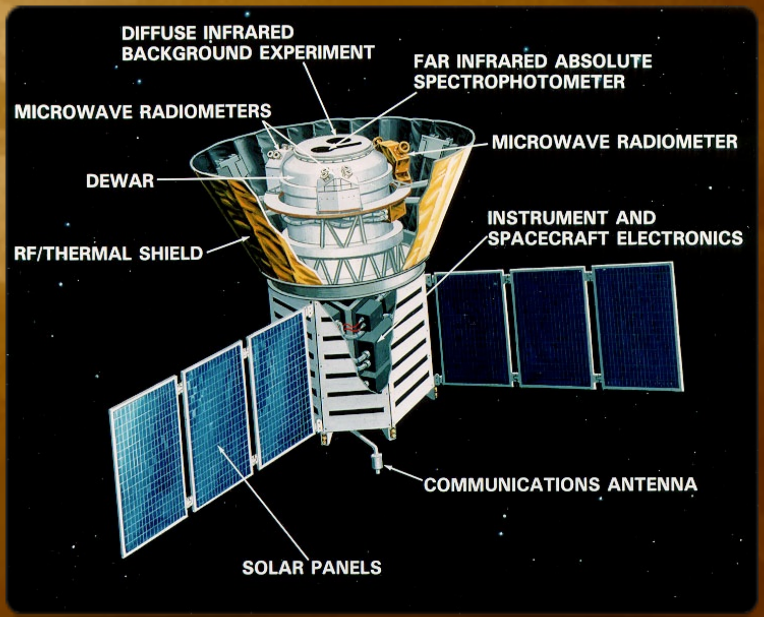


Image 1.4.1 Anomalous event: COBE satellite.

A few years after launch, the COBE satellite released 76 pieces of debris for unknown reasons. During the relatively short period of time in which the large quantity of debris was released, the satellite remained functional and operators didn't know anything was wrong. COBE went on to complete its mission.

Image Credit: NASA / Jet Propulsion Laboratory

ANOMALOUS EVENTS

More than 100 of these events have been associated with spacecraft and upper stages. Such events are mostly environmentally induced, occurring when either a non-operational satellite ages and falls apart or a satellite—active or not—collides with a small particle. Typically, one or two fragments are released, usually at low velocities. These fragments often have higher than normal area-to-mass ratios and are usually short-lived.

The Cosmic Background Explorer (COBE) debris cloud is an example of an anomalous event whose cause is unknown. Only a few years after it launched in 1989, the COBE satellite released 76 pieces of debris. The pieces were relatively large, each at least 10 centimeters, and were detected by the U.S. Space Surveillance Network. Because COBE was operational during the event, the project office was contacted to find out what had caused the debris release. COBE project managers knew nothing about it. Despite the volume of scientific instruments on the satellite, including many thermal sensors, no change had registered that could account for the release. COBE remained functional throughout the event and went on to complete its mission, which yielded Nobel Prize-winning science findings. To this day, no one knows why the debris was released. Fortunately, the debris decayed within four to five years, and all of the pieces have since burned up upon reentry into the Earth’s atmosphere. Since the origin of the event remains unknown, it is challenging for NASA to learn from the experience and develop corrective measures for future spacecraft.

EXPLOSIONS

Until 2007, launch vehicle upper stage explosions were the single greatest contributor to the creation of orbital debris. Most of the explosions were accidental and occurred after successful deployment of a satellite, generally within 24 hours to two decades after launch. Typically, the explosions were caused by leftover propellant that ignited long after launch. The results of such explosions ranged from a few pieces of debris to several hundred large fragments accompanied by many more small pieces. Ejection velocities ranged from less than one meter per second to hundreds of meters per second. Two hundred such events have been identified.

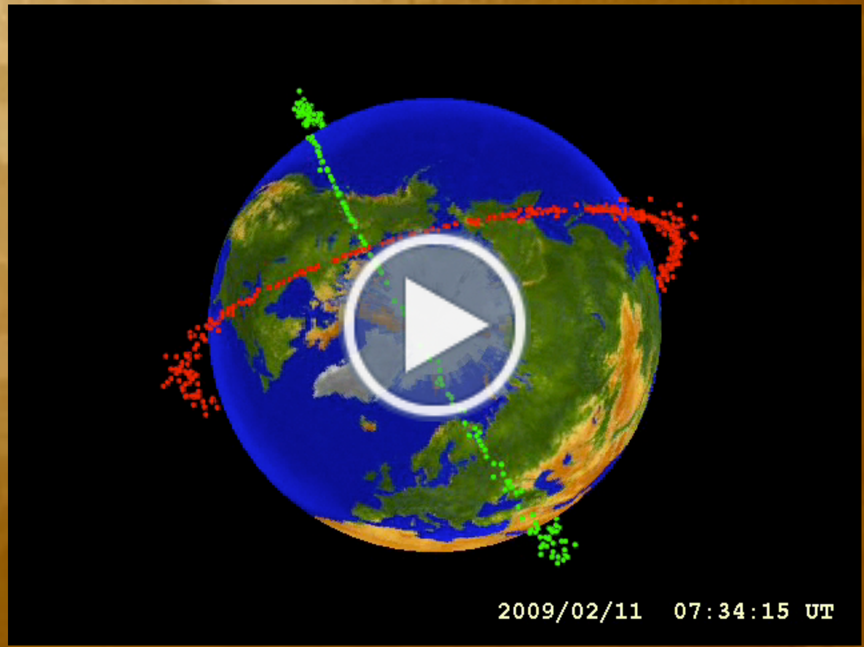
Today, **passivation** of the upper stages following mission completion is required to prevent explosions. This approach has been highly successful.

COLLISIONS

Collisions, both accidental and intentional, are responsible for much of the debris in Earth orbit. Hypervelocity collisions typically generate a large amount of debris, with distributions similar to those seen from explosions. Four known accidental hypervelocity collisions have occurred. The first three created little debris, but the fourth, between the U.S. satellite Iridium 33 and the Russian satellite Cosmos 2251, was different: that collision produced over 2,000 large, trackable pieces of debris, along with many more small, untrackable pieces.

Iridium 33, operational at the time of the collision, was one of 66 satellites that made up the Iridium communications constellation. Cosmos 2251 was no longer active; the satellite had been out of service for more than a decade and so was already orbital debris. The real casualty in the Iridium-Cosmos collision was the damage to the orbital environment. The debris dispersed through a section of LEO nearly 1,700 meters deep. Because of this wide area of dispersion, every operational satellite in low Earth orbit is now vulnerable to debris originating from the collision. The probability that a spacecraft will be hit by orbital debris has increased dramatically. The threat is present from particles of all sizes: even debris as small as 1 centimeter has mission-ending potential, depending on where it strikes a spacecraft.

Debris from the Iridium-Cosmos collision spread out very quickly. As you can see in the video to the right, within two hours of the collision the diffusion of debris was evident along each satellite's orbit. By June of 2012, the U.S. Space Surveillance Network had cataloged 598 pieces of debris associated with Iridium and 1,603 pieces from Cosmos. As of July 2012, nearly three and a half years after the event, 90 percent of the debris from the collision was still in orbit around Earth. Debris from Cosmos has now completely encircled Earth. Because Iridium was orbiting Earth at a higher inclination—nearly polar (86.4 degrees)—its debris is taking longer to diffuse. Debris from the two satellites now poses a potential threat to every spacecraft in LEO.



Video 1.4.1 Iridium-Cosmos collision: Initial debris spread.

Debris from the collision between Iridium 33 (green) and Cosmos 2251 (red) spread very quickly. These images show that within a few hours of the collision, the evolution of a debris cloud was already apparent along the orbital planes of both satellites.

Video Credit: NASA

Section 1.5

New Source of Debris Discovered

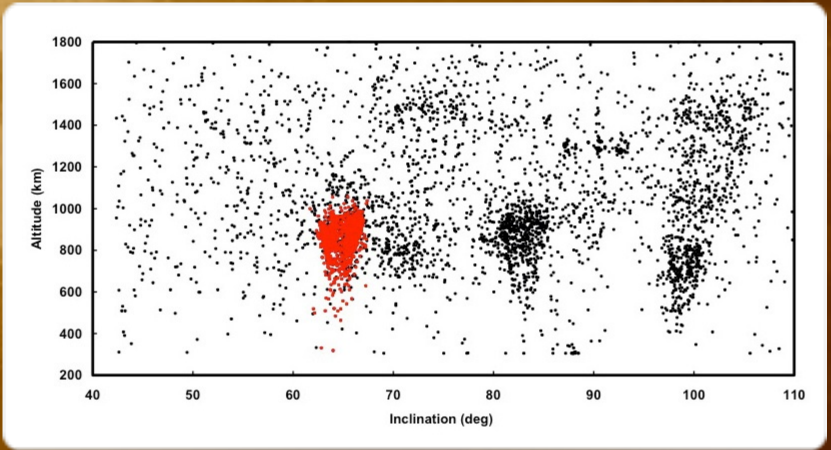


Figure 1.5.1 Sodium potassium droplets discovered.

During observations of the orbital debris environment in the 1990s, an unexpectedly dense population of small particles (in red) in orbits near 900-100 kilometers with 65-degree inclinations was discovered. These particles were identified as sodium potassium droplets released from ejected nuclear reactor cores.

Figure Credit: NASA

COOLANT RESIDUE

One objective of NASA's Orbital Debris Program is to not only look for debris in order to catalog it, but also understand its source. To achieve this goal, in the early 1990s NASA and DOD worked on a project in conjunction with the MIT Lincoln Laboratory that allowed them to detect debris as small as 5 millimeters. As this capacity was developed, scientists became aware of an unusual area of debris in a relatively confined altitude, centered on a 65-degree inclination at about 900-1,000 kilometers. There appeared to be more than 100,000 particles larger than 5 millimeters. Strangest of all, the objects looked like metallic spheres.

By analyzing their location and appearance, scientists determined that the particles were droplets of sodium potassium from Soviet spacecraft nuclear reactors. Starting in the late 1970s, the reactor cores were designed to eject when these spacecraft were disposed of in high altitude orbit. This action, performed for safety reasons, breached the primary coolant system and released sodium potassium. Unlike normal upper stage main propulsion propellants, which sublimate quickly and therefore do not persist as orbital debris, sodium potassium has a very long **sublimation rate**. From the 14 reactor ejections that occurred, scientists have recorded 70,000-100,000 small particles of sodium potassium in LEO. Some are on the larger size—between 5-7 centimeters—but the vast majority are so small that they cannot be tracked by the U.S. Space Surveillance Network and are only visible to NASA through the Lincoln Laboratory radars. As these particles fall through the orbit of operational spacecraft, those bigger than a centimeter pose a mission-terminating threat to satellites below 850 kilometers as well as to human spaceflight. Impacts from sodium potassium droplets have been seen on the International Space Station (ISS), though no detrimental effects have been observed. Fortunately, spacecraft using sodium potassium as coolant are no longer flown.

ADDITIONAL SOURCES OF DEBRIS

SOLID ROCKET MOTOR (SRM) EFFLUENTS

Another source of particle debris is **effluents** from solid rocket motors. During burn and after shut-down, solid rocket motors eject large quantities of aluminum oxide. Most of the ejected particles are extremely small, in the 10-20 micron size range, and have very short lifetimes. However, as the pressure drops after thrust and at the end of burn, larger aluminum oxide particles are ejected. This occurs because aluminum oxide pools inside the rocket motor during thrust. After thrust, as the pressure drops, the liquid comes out in large particles.

PAINT FLECKS

To enhance thermal control, almost every spacecraft and upper launch vehicle is painted. As the accumulation of large derelict vehicles in LEO increases, more paint particles chip off, creating greater potential for collision with active missions.

While a paint chip might not seem like a potential threat to a spacecraft, it can cause damage. In 1983, a 3-millimeter wide, 4-millimeter deep crater—considerably smaller than a Tic Tac mint—was discovered in a window of the space shuttle *Challenger*, following its STS-7 mission. Such a crater may not seem large; and since the windows on the shuttle were three layers deep, it wasn't a threat on reentry. But the danger increased for launch: because the launch environment was much more severe, even a crater that small could have had unwanted consequences for subsequent missions.

Because even microscopic craters from orbital debris can have mission-terminating effects at launch, engineers and technicians carefully scanned the body of the space shuttle between missions. Most of the impacts from debris as small as a paint particle cannot be seen by the naked eye, so microscopes were used to uncover debris hits. Scientists learned a great deal about the small-particle debris in LEO by examining the space shuttle each time it returned. Residue from each crater was carefully extracted and scrutinized to determine its source.

Video 1.5.1 Space shuttle SRM particle residue.

In this video of the space shuttle just 20.5 seconds after separation of the SRM from the main tank, individual particles of aluminum oxide are visible as the plume fades.

Video Credit: NASA

Gallery 1.5.1 Space shuttle windows were vulnerable to debris.

Technicians examine a 3-millimeter wide, 4-millimeter deep crater on the Challenger.

Photo Credit: NASA

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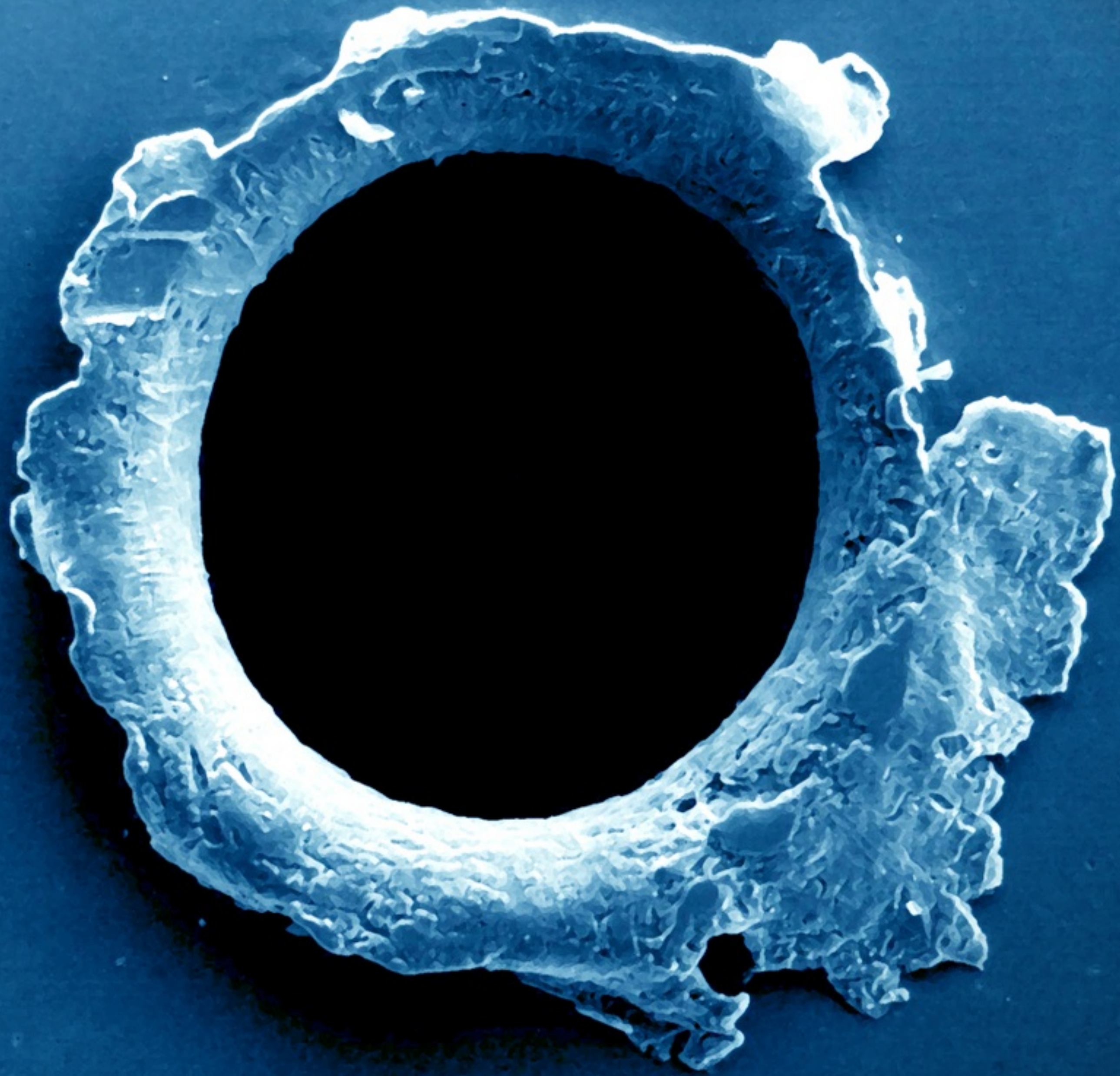


Tracking and Avoiding Collisions with Orbital Debris

Collisions between spacecraft and orbital debris are a concern for two reasons: the risk to space missions and the impact on the near-Earth space environment. Given the quantity of debris distributed over a variety of orbits from more than 50 years of space activity, the probability that a human spaceflight mission or a **robotic spacecraft** will collide with orbital debris is high. In fact, all spacecraft collide with orbital debris. The issue is the size of the debris and the velocity at which it strikes the craft.

View of an orbital debris hole made in the panel of the Solar Max experiment.

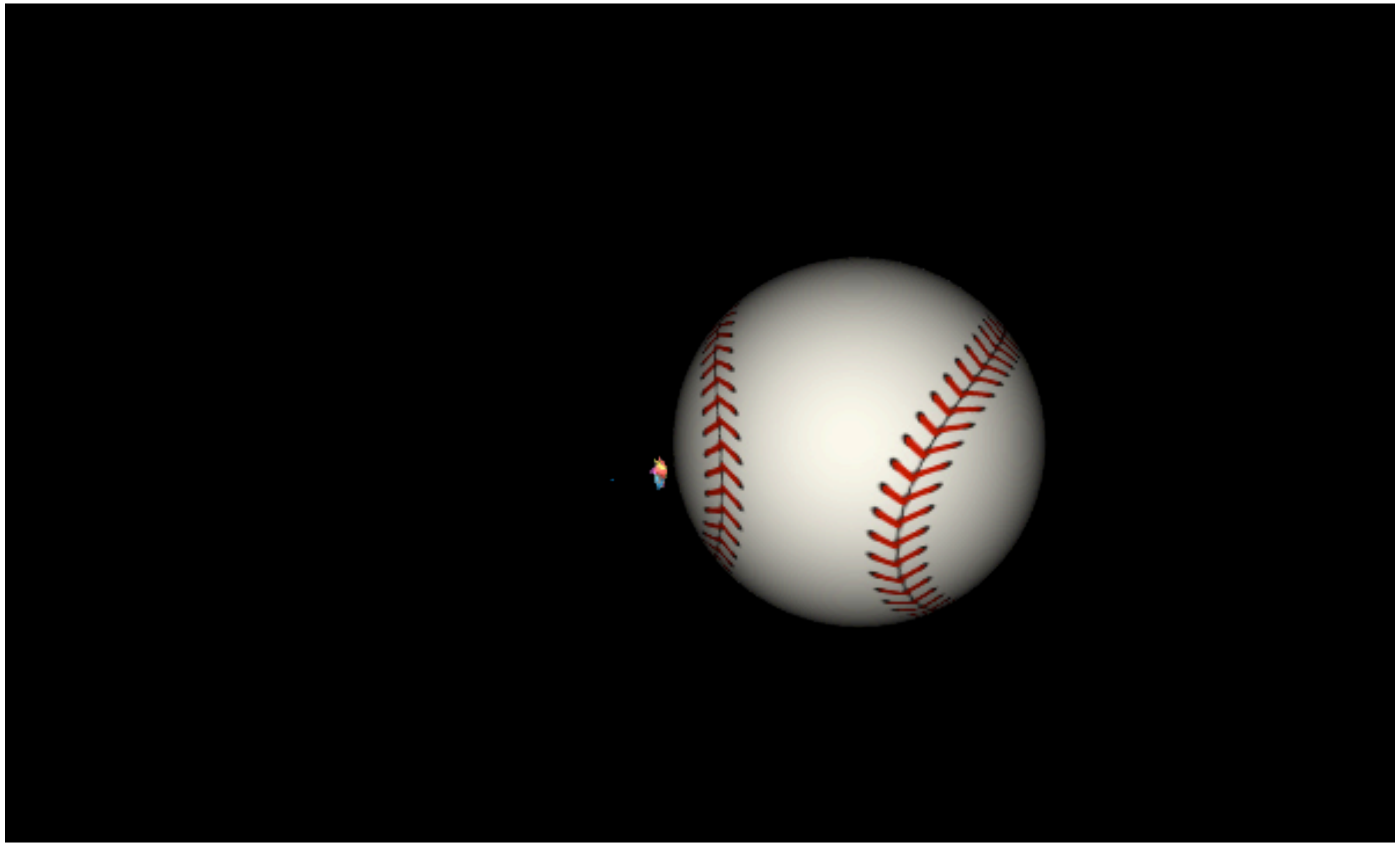
Photo Credit: NASA

Section 2.1

Determining the Quantity of Debris in Earth Orbit

Orbital debris accounts for 94 percent of all officially cataloged objects in Earth orbit. These objects vary greatly in size. Many are as small as the period at the end of this sentence and are unlikely to cause significant damage to operational spacecraft. However, more than 20,000 of these objects are at least the size of a softball, while even more are larger than a centimeter—a size that can have mission-terminating consequences after impact.

Interactive 2.1.1 **Different sizes of orbital debris.**



Interactive Credit: NASA

SOFTBALL OR LARGER	MARBLE OR LARGER	DOT OR LARGER
>10 cm	>1 cm	>1 mm
20,000 +	~ 500,000	~ 135,000,000

GROWTH OF DEBRIS IN LEO

In LEO, the number of cataloged objects has increased steadily since the launch of Sputnik 1 in 1957.

Fengyun-1C, a Chinese weather satellite that was deliberately destroyed in 2007, contributed a large increase in the quantity of orbital debris. Going forward, it is expected that the primary source of debris will be accidental collisions, due to the more than 2.5 million kilograms of objects now in Earth orbit.

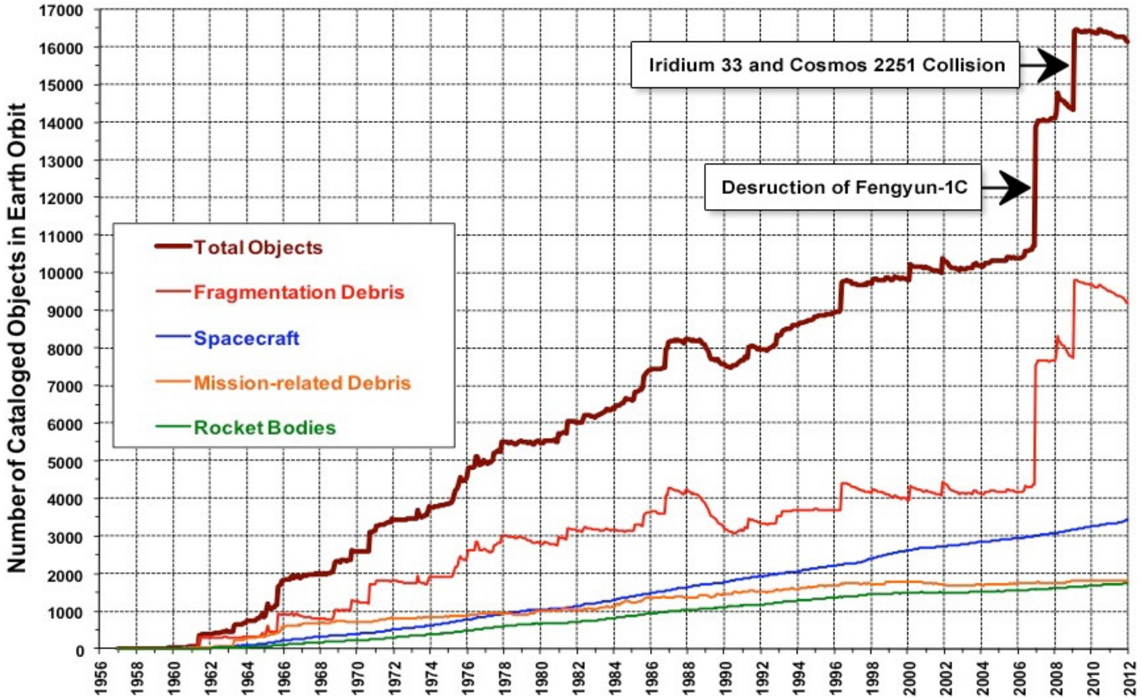


Figure 2.1.1 **Number of objects in LEO, 1956-2012.**

This graphic illustrates the steady growth of the official Earth satellite population of objects with sizes 10 cm or greater. Although the fragmentation debris population can be very dynamic, the rate of increase in the numbers of spacecraft and rocket bodies, which contain nearly all the mass in Earth orbit, is essentially constant.

"Solar max" indicates a period of high solar activity—such as increased sun spots and solar emissions—that occurs every 11 years and accelerates the decay of smaller orbital debris.

Figure Credit: NASA

OBJECTS IN GEO

Near GEO, scientists have uncovered a significant population of uncataloged debris. This debris is likely due to explosions, though only two such events have been recorded. Explosions in the area of GEO probably occurred before the practice of passivation was widely accepted.

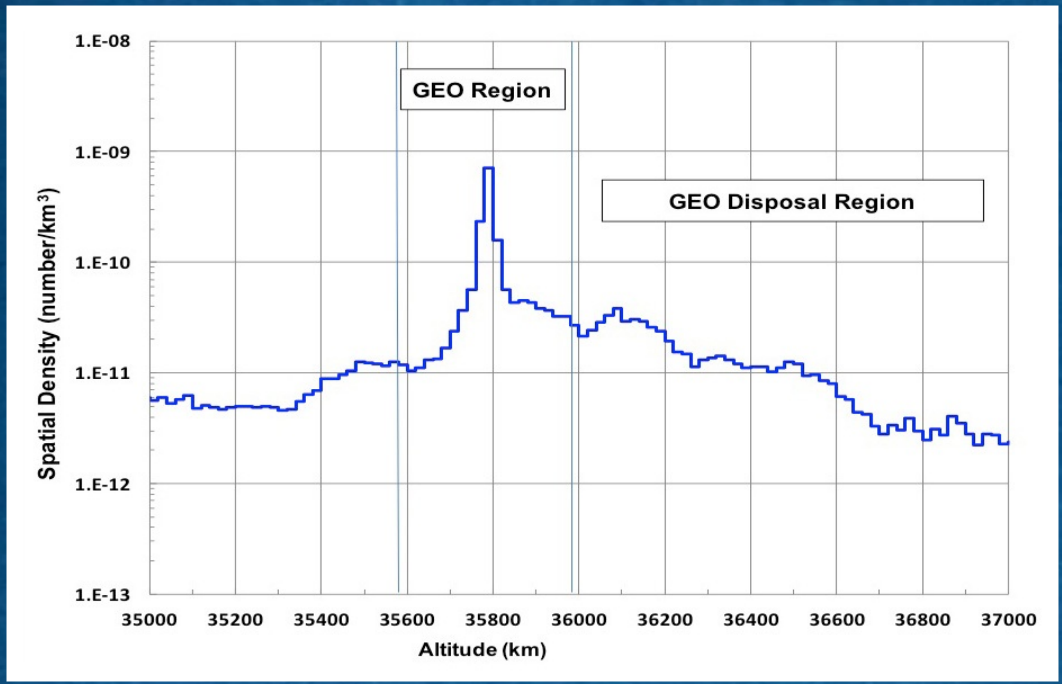


Figure 2.1.2 **GEO spatial densities.**

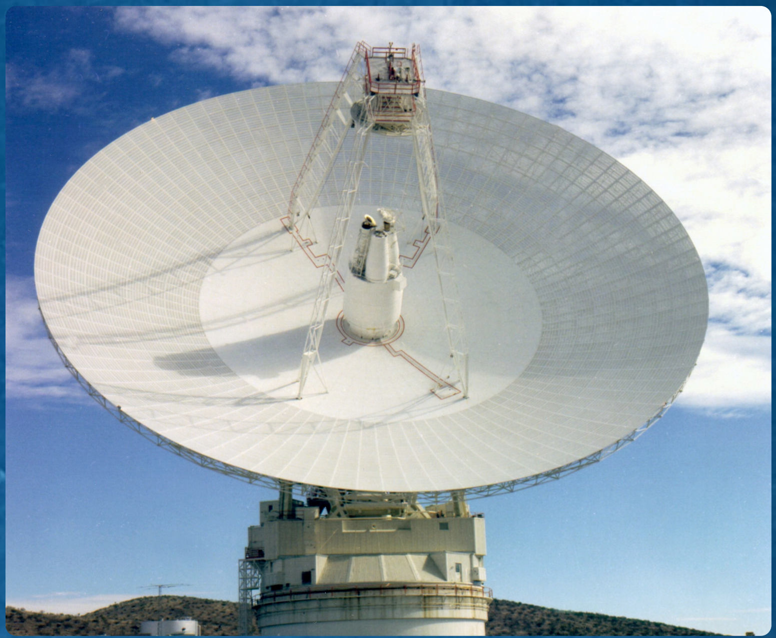
In general, the amount of space between objects increases above LEO. However, the region near GEO represents another congested environment.

Figure Credit: NASA

Section 2.2

Tracking Orbital Debris

NASA and DOD share responsibility for tracking and characterizing the Earth satellite population.



Gallery 2.2.1 **Orbital debris radars and telescopes.**

The 70-meter Goldstone antenna located near Barstow, CA. When operated as a bistatic radar, Goldstone is capable of detecting 2 mm debris at altitudes below 1,000 km.

Photo Credit: NASA / JPL-Caltech

DOD RESPONSIBILITIES

DOD focuses on objects in LEO that are 10 centimeters or larger, and objects in GEO that are 1 meter or larger. Because the objects are relatively large in size, DOD is able to track each object individually on a daily basis. In addition to tracking debris, DOD also notes the position of every operational spacecraft in the world, regardless of who owns or operates it, and provides information regarding collision potential, when appropriate.

NASA RESPONSIBILITIES

NASA tracks and characterizes objects in LEO that are smaller than 10 centimeters, and objects in GEO that are smaller than a meter. Due to their size, such objects cannot be tracked individually. Instead, NASA's assessments about size and position of objects are primarily statistical, offering information about the probability of collisions as well as projections about what the future LEO and GEO environments may be.

SOURCES OF INFORMATION: RADARS AND TELESCOPES

Together and separately, NASA and DOD use a wide variety of radars and electro-optical sensors to track and characterize orbital debris. DOD operates the U.S. Space Surveillance Network, which consists of radars and other sensors around the world. Using data from these sources, DOD maintains the official U.S. satellite catalog.

Section 2.3

Probability and Consequences of Collisions with Orbital Debris

COLLISION CONSEQUENCES

The consequences of a collision with orbital debris depend on the size and velocity of the debris. Operational spacecraft and satellites are frequently struck by debris as large as a millimeter because there is so much of it in the space environment. Such debris is not trackable, and so cannot be avoided. Fortunately, debris that size is unlikely to do significant damage. Risk from larger debris that is too small to track individually—such as debris that is less than 1 centimeter—is generally handled through shielding and orientation, as guided by NASA modeling software.

CALCULATING THE PROBABILITY OF COLLISION

There are two linear equations that allow NASA to calculate the probability of a collision between an operational spacecraft and orbital debris. If the orbital debris flux is known, the first equation provides probability of collision for a given vehicle. If the spatial density is known instead of the flux, the second equation provides the needed information.

(orbital debris **f**lux) x (cross-sectional **a**rea) x (**t**ime)	**FAT**
(average collision **v**elocity) x (cross-sectional **a**rea) x (**s**patial density) x (**t**ime)	**VAST**

Figure 2.3.1 **Probability of collision for a given vehicle.**

The U.S. Space Surveillance Network can individually track objects that are 10 centimeters or larger, which means DOD can inform NASA—or any other spacecraft owner/operator—if a spacecraft is in danger of colliding with a piece of trackable debris. This is important to both existing and future missions, as a collision with an object that is 10 centimeters or larger is highly likely to cause mission-terminating damage while also generating more debris.

Section 2.4

Countermeasures: Collision Avoidance for Human Spaceflight

To determine the risk of collision for active spacecraft, DOD continuously performs conjunction assessments for all trackable objects (spacecraft and debris) in LEO and GEO. A conjunction assessment determines the point at which two objects in space could collide. By examining the current location of each object and projecting its location into the future—via computations based on the complex orbital trajectory of the object—DOD can pinpoint potential collisions. Conjunction assessments identify collision potential days in advance. This gives spacecraft owners/operators sufficient notice to perform a collision avoidance maneuver if needed.

In 1988, a probability-based process to avoid collision with tracked space objects (those larger than 10 centimeters) was instituted with STS-26.

CRITERION FOR HUMAN SPACEFLIGHT COLLISION AVOIDANCE

The approach of an object within a box of 4 kilometers x 10 kilometers x 4 kilometers represents a collision risk on the order of 1 in 100,000, and a collision-avoidance maneuver is further evaluated.

COLLISION RISK THRESHOLDS FOR HUMAN SPACEFLIGHT

!	**RED Threshold** If the risk of collision is greater than 1 in 10,000, a collision-avoidance maneuver is performed.
!	**YELLOW Threshold** If the risk is greater than 1 in 100,000, a collision-avoidance maneuver is performed if it does not compromise the mission objectives.
!	**GREEN Threshold** No collision-avoidance maneuver needed.

Figure 2.4.1 Three levels of threshold for collision avoidance.

The threshold for collision avoidance for robotic spaceflight is lower, approximately 1 in 1,000.

Sometimes there isn't enough advance warning to perform a conjunction assessment or a maneuver. For example, in 2009 a collision threat to the ISS crossed the red threshold, meaning the risk of collision was greater than 1 in 10,000. Because there wasn't time to perform a collision avoidance maneuver, the ISS crew was instructed to get into the Soyuz spacecraft so that if the ISS were hit by debris, the crew would have a chance of undocking and going home.

INTERNATIONAL SPACE STATION CONJUNCTION ASSESSMENT PROCESS

Historically, the rate of collision-avoidance maneuvers has been less than one per year for both the space shuttle, when it was active, and the ISS. When an object violates the collision-avoidance criterion for human spaceflight for an asset such as the ISS, DOD immediately informs NASA and tracks the object closely to determine if its orbital trajectory will bring it near the asset. If it appears that the object can collide with the ISS, a collision-avoidance maneuver is considered.

ROBOTIC SPACECRAFT COLLISION AVOIDANCE

Due to the slight difference in orbit regimes and operations processes, the collision-avoidance procedure for robotic craft is different than the procedure for human spaceflight.

In 2004, NASA's Goddard Space Flight Center (GSFC) began conducting routine collision-avoidance operations to protect the Earth Observing Satellite Constellation. Although the collision-avoidance activities are managed by different NASA centers as well as by international partners, mission operators work together to ensure the health and safety of the satellite constellations.

In 2007, NASA introduced a policy of required routine collision-avoidance activities for all robotic spacecraft with maneuvering ability. The policy was extended, in 2009, to incorporate conjunction assessments for all NASA robotic assets, including those that are non-maneuverable or non-operational. This process gives NASA a better understanding of the probability of collisions across a range of scenarios throughout Earth orbit.

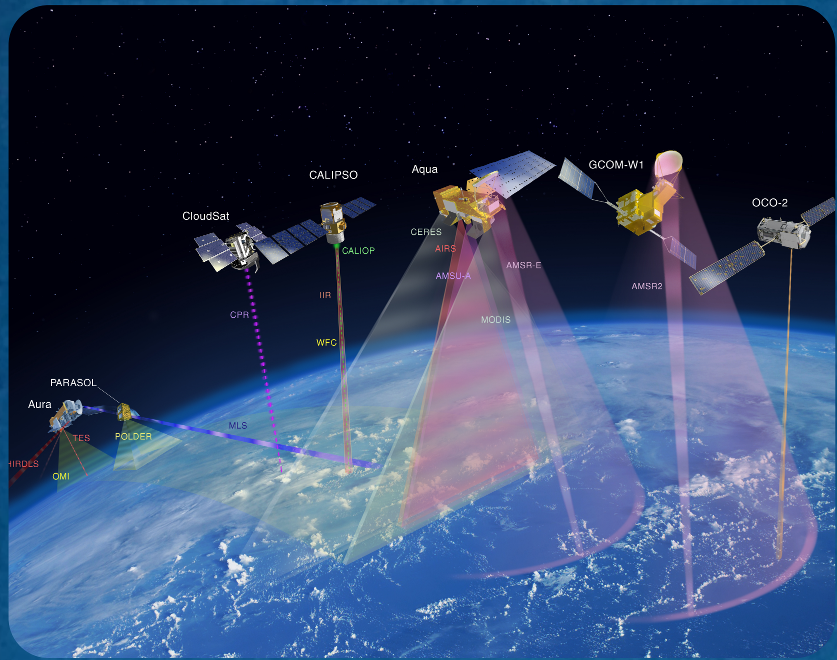


Image 2.4.1 Earth Observing Satellite Constellation.

The NASA-centered international Earth Observing System (EOS) employs a coordinated series of polar-orbiting and low-inclination satellites—known as "constellations"—that fly in tandem, taking pictures of the Earth to provide data on the land surface, biosphere, atmosphere, and oceans, with the goal of achieving an improved understanding of the Earth as an integrated system.

Image Credit: NASA

Section 2.5

Collision Countermeasures: Shielding

WHIPPLE SHIELDS

Whipple shields, designed in the mid-1940s by astronomer Fred Whipple, are used to protect operational spacecraft from potential penetration by orbital debris. Shielding is an effective means of protecting spacecraft from hypervelocity particle impacts. The goal in applying shields, however, is to do the least possible: provide enough shielding to protect critical spacecraft surface area per requirements, yet avoid adding so much extra weight that the spacecraft cannot fly.

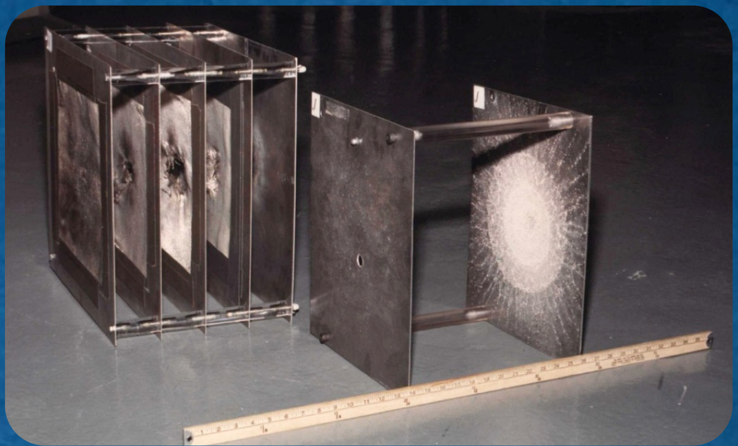


Image 2.5.1 How a Whipple shield works.

A Whipple shield is a single, thin aluminum plate that protects a critical surface area of the spacecraft. It stands off from the area, acting as a "bumper" to break up a high-velocity particle before it strikes the spacecraft's body. When a particle hits the Whipple shield, it breaks into many pieces, losing velocity in the process. This slows the particle so that the risk of penetration is lessened.

The image above shows a stuffed Whipple shield (left) and a simple Whipple shield (right).

Photo Credit: NASA

ENHANCING THE WHIPPLE SHIELD

A Whipple shield may be stuffed with additional sheets of material, such as ceramic materials like Kevlar or Nextel, to further absorb the energy of the fragmenting particle. New shielding designs are in development, featuring either aluminum honeycomb or metallic foam as Whipple shield fillers. The metallic foam, in particular, provides greater protection from hypervelocity particle impacts. In addition to their ability to break up particles and slow particle velocity, these new materials help reduce total shield mass.

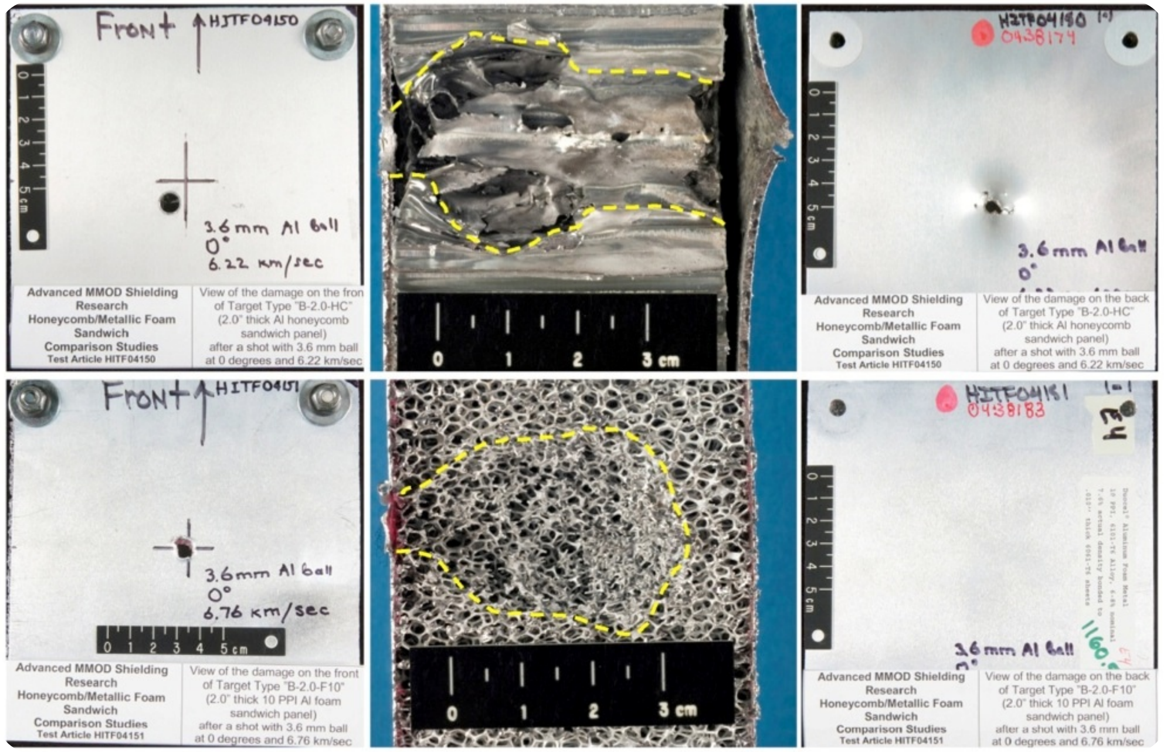


Image 2.5.2 Stuffed Whipple shields.

New Whipple shield fillers: aluminum honeycomb (top) and metallic foam (bottom).

Image Credit: NASA

PROTECTING THE INTERNATIONAL SPACE STATION

The ISS is the most heavily protected space vehicle. More than 200 different types of shields guard its critical surface areas, helping mitigate the effects of small-particle hypervelocity impacts.

Shielding for the ISS varies depending on the critical surface area being protected. Where module walls are thicker, less shielding is necessary; where module walls are thinner, more shielding is used. This applies to external components as well: those more exposed to the debris environment receive more shielding. Ensuring adequate shielding for the ISS is an ongoing concern and activity, with on-orbit shield repair or supplementation conducted as needed.

But the shielding on the ISS itself isn't the only concern. When a spacecraft is docked at the station, it becomes an integral part of the station. Its vulnerabilities become the station's vulnerabilities. Therefore, it is critical that not only does the ISS have adequate shielding, but any spacecraft docked at the station meets shielding requirements as well.

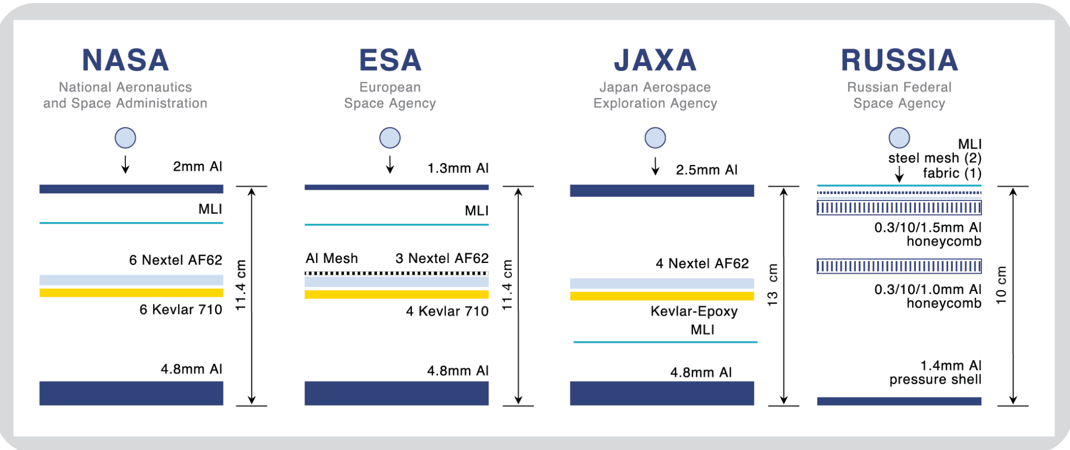
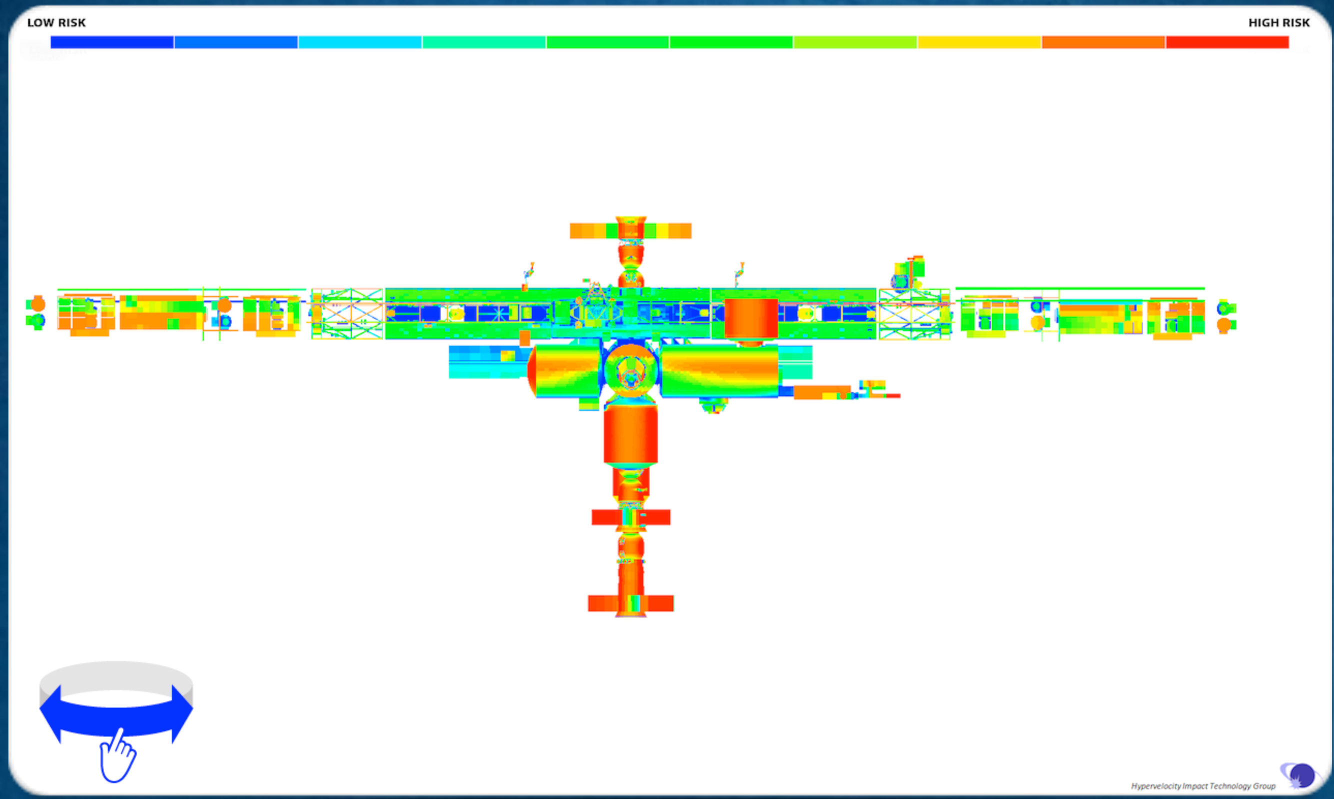


Figure 2.5.1 NASA, JAXA, ESA, and Russia's levels of protection on ISS.

The NASA, JAXA, and ESA sides of the ISS are protected from the hypervelocity impacts of particles up to one centimeter, as required. However, the Russian side presents greater risk, as it has critical surface areas that are vulnerable to particles as small as 3 millimeters. Some additional shielding has been added on-orbit, but the situation must continue to be improved.

Figure Credit: NASA



Interactive 2.5.1 Animation: ISS risk of impact from orbital debris.

Tap then slide your finger left and right in the interactive graphic above. *This animation shows the risk of impact from orbital debris particles on the different surfaces of the ISS in the future configuration, which includes the Russian Multipurpose Laboratory Module (MLM) and airlock. The bar at the top indicates the low to high risk color values. The image sequence begins with the bow (or front) of the station on the left, the stern (or back) on the right, the port (or left) side facing the viewer, and the starboard (or right) side of the station out of view. If in motion, the station would travel in an orbit that would move from the right side of the page to the left.*

As the viewer begins the animation, the ISS rotates about an axis that starts at the bottom of the page (where Earth is) and terminates at the top of the page (where space is). The color differences occur because orbital debris flux is directional. For instance, imagine the ISS is a car driving down a road in the rain. More rain is likely to impact the windshield than the trunk as the car travels forward. This is reflected in the animation of the ISS with the front side of the station, which is more red and orange, likely to encounter more debris than the back, which is primarily blue.

Interactive Credit: NASA / Hypervelocity Impact Technology Group

3

Mission Operations Control Room (MOCR) activities during STS-2 mission. President Ronald Reagan is briefed by Dr. Christopher C. Kraft, Jr., JSC Director, who points toward the orbiter spotter on the projection plotter at the front of the MOCR.

Photo Credit: NASA / Johnson Space Center

Orbital Debris Policies and Guidelines

The issue of orbital debris mitigation was first raised to the level of national consciousness in 1988, when President Ronald Reagan included it in his National Space Policy. Throughout the 1980s, NASA and the Department of Defense (DOD) had worked closely to characterize and model the orbital debris environment, bringing concerns to the fore and compelling President Reagan to address the issue. A year after the President's speech, the U.S. government released its first comprehensive assessment of orbital debris. The report encouraged further national research while galvanizing the international community to confront the problems posed by orbital debris to all spacefaring nations.

Since President Reagan's 1988 National Space Policy, each subsequent U.S. president has stressed the need for orbital debris mitigation. NASA, too, has made it a critical focus of policies and requirements. In 1993, NASA introduced the first Management Instruction (NMI 1700.8) to provide official guidance on orbital debris mitigation. A NASA Safety Standard regarding orbital debris (NSS 1740.14) followed in 1995, establishing the first detailed set of orbital debris mitigation guidelines for each NASA program and project. While continuing to refine and expand its internal policies and requirements regarding orbital debris, NASA also worked with DOD to develop the first U.S. Government Orbital Debris Mitigation Standard Practices. A draft Standard Practices was introduced in 1997, with the official version adopted in 2001. The U.S. Government Orbital Debris Mitigation Standard Practices has helped shape guidelines and policies issued by organizations such as DOD, Department of Transportation (DOT), Federal Aviation Administration (FAA), Federal Communications Commission (FCC), and the National Oceanic and Atmospheric Administration (NOAA) in the Department of Commerce.

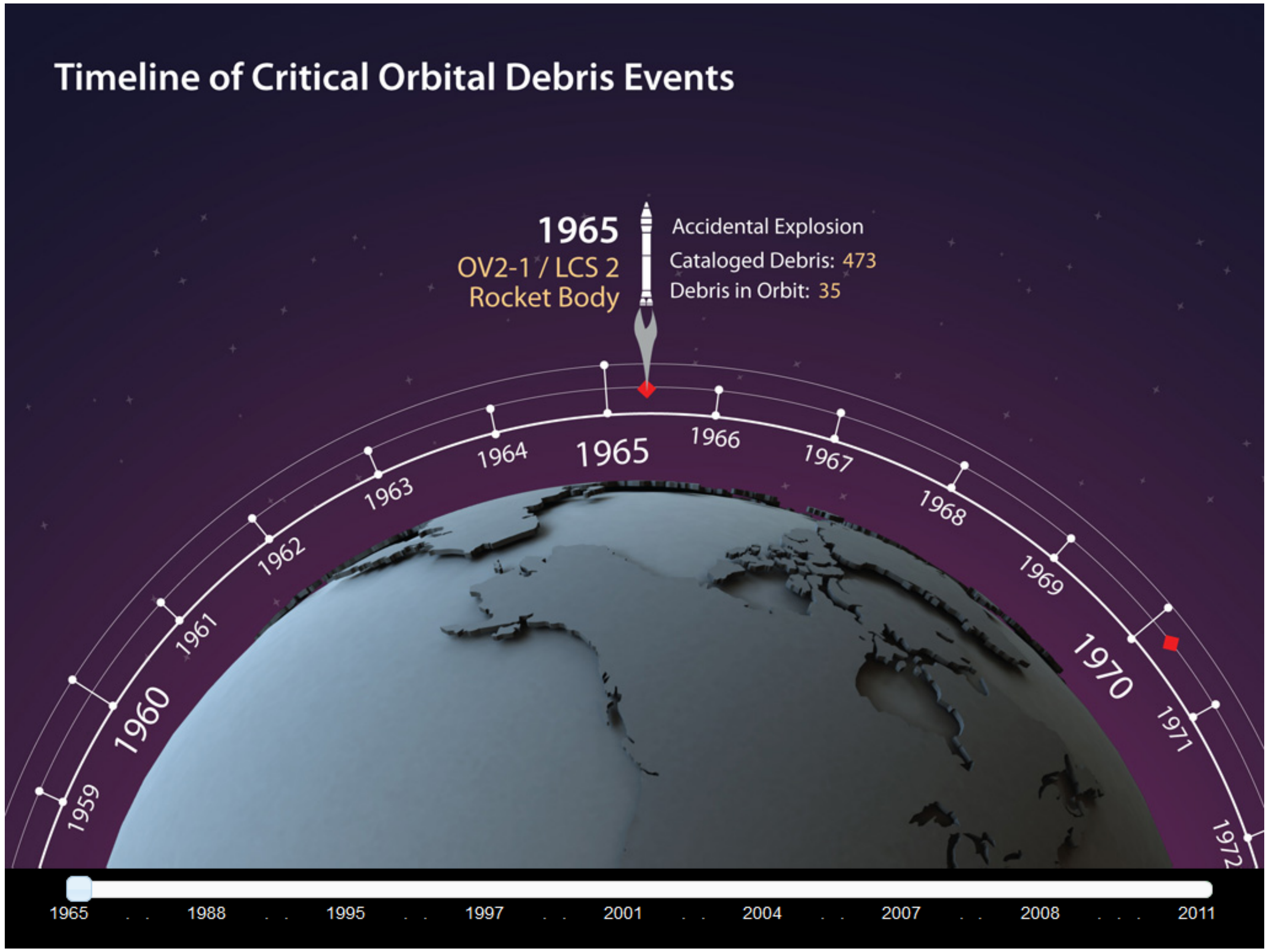
Section 3.1

History of U.S. and NASA Orbital Debris Mitigation Policies and Requirements

The U.S. Government Orbital Debris Mitigation Standard Practices addresses four key areas: control of debris during normal operations, minimization of debris generated by accidental explosions, mission planning to lower risk of debris generation, and post-mission disposal of spacecraft/structure. NASA Technical Standard 8719.14A expands on the U.S. Standard Practices, directing each space mission to assess its compliance with requirements in six critical areas: release of debris during normal mission operations, accidental explosions, intentional breakups, collisions, post-mission disposal, and reentry risk.

International guidelines and policies have been established as well, reinforcing the policies put forth by NASA and the U.S. government. These guidelines, which provide a model for the behavior of spacefaring nations in terms of orbital debris mitigation, have been set by such organizations as the Inter-Agency Space Debris Coordination Committee (IADC), the United Nations (UN), the International Academy of Astronautics (IAA), the International Organization for Standardization (ISO), and various foreign space agencies, including the European Space Agency (ESA) and organizations in China, France, Germany, Italy, Japan, Russia, and the United Kingdom.

Interactive 3.1.1 Timeline of critical orbital debris events.



Tap then slide your finger left and right in the interactive graphic above. *Learn more about satellite fragmentations and important advances in U.S. and NASA orbital debris policies, directives, standards, and requirements as of 2012.*

Interactive Credit: NASA

Section 3.2

Overview of Foreign Policies and Requirements

The U.S. was the first nation to include orbital debris mitigation as an important part of its space policy. Recognizing their vested interest in preserving LEO by minimizing the generation of orbital debris, other spacefaring nations followed suit by introducing their own national guidelines.

Figure 3.2.1 **Foreign orbital debris guidelines.**

Nation	Year	Guideline
Japan	1996	Space Debris Mitigation Standard (NASDA-STD-18A)
France	1999	CNES Space Debris—Safety Requirements (MPM-50-00-12)
Russia	2000	General Requirements for Mitigation of Space Debris Population (Branch Standard)
China	2005	Requirements for Space Debris Mitigation (QJ 3221-2005)

FOREIGN NATIONAL GUIDELINES FOR MITIGATING ORBITAL DEBRIS

In February 1999, ESA issued a Space Debris Mitigation Handbook, followed by a draft Space Debris Safety and Mitigation Standard in 2000.

Several years later, in 2004, the five leading space agencies in Europe—ESA, Italy's Agenzia Spaziale Italiana (ASI), the UK's British National Space Centre (BNSC), France's Centre National d'Etudes Spatiales (CNES), and the German Aerospace Center (DLR)—drafted a European Code of Conduct for Space Debris Mitigation. This document covers similar ground to that expressed in the U.S. Government Orbital Debris Mitigation Standard Practices, but adds specificity (such as measures of effectiveness), as found in NASA's Safety Standards.

GUIDELINES DEVELOPED BY MULTINATIONAL ORGANIZATIONS

The U.S. Government Orbital Debris Mitigation Standard Practices were the foundation for all existing orbital debris policies. The U.S. Standard Practices helped shape not only the country-specific guidelines listed above, but also guidelines and policies stemming from multinational organizations such as IADC, the UN, the **IAA**, and the **ISO**.

Figure 3.2.2 History of multinational orbital debris mitigation guideline development.

1993	***The IADC was established in 1993*** with only four member agencies specifically to address the issue of orbital debris. The 12-member multinational organization now includes representatives from Canada, China, France, Germany, India, Italy, Japan, Russia, Ukraine, the United Kingdom, and the U.S., as well as from ESA.
1994	***The subject of orbital debris was first introduced to the agenda of the Scientific and Technical Subcommittee (STSC)*** of the UN's Committee on the Peaceful Uses of Outer Space (COPUOS).
1995	***The IAA published its first position on space debris,*** which included a section on "Implementation of Debris Control Methods."
1999	***The Steering Group of the IADC*** approved an Action Item to develop a consensus set of space debris mitigation guidelines. In addition, the ***UN COPUOS STSC*** released a "Technical Report on Space Debris." The report summarized global understanding of orbital debris measurements and environmental modeling, and identified orbital debris mitigation measures.
2002	***The IADC released its first consensus international guidelines***: the IADC Space Debris Mitigation Guidelines. Similar in content to the U.S. Standard Practices, the IADC guidelines focused on the same four areas of concern: limiting debris release during normal operations, minimizing potential for on-orbit breakups, managing post-mission disposal, and preventing on-orbit collisions.
2003	***The IADC presented its guidelines*** to the UN COPUOS STSC. Additionally, ***The Orbital Debris Coordination Group of the ISO*** began developing a series of space debris mitigation standards based on the IADC Space Debris Mitigation Guidelines. 24113, Space Debris Mitigation Requirements, is their overarching standard.
2004	***The IADC developed a complementary document***: "Support to the IADC Space Debris Mitigation Guidelines." ***The IADC guidelines*** were again discussed by the UN COPUOS STSC.
2005	***The IAA released a "Position Paper on Space Debris Mitigation,"*** which addressed recommended mitigation measures separately for spacecraft and launch vehicles.
2007	***The IADC released slight*** modifications to the IADC Space Debris Mitigation Guidelines.
	Meanwhile, the ***UN STSC Member States adopted the UN COPUOS STSC Space Debris Mitigation Guidelines*** in early 2007. These guidelines were based on the IADC guidelines.
	The full UN General Assembly subsequently adopted the UN COPUOS STSC Space Debris Mitigation Guidelines in late 2007. Like the IADC Guidelines, the UN COPUOS STSC Space Debris Mitigation Guidelines followed the same general principles as established in the U.S. Standard Practices. Although the UN identifies seven guidelines, including a specific focus on passivation, the guidelines are no more stringent than those expressed in the U.S. Standard Practices and the IADC Guidelines.
	The IAA studied techniques for removing orbital debris from the near-Earth environment. The investigation concluded in 2011.

MULTIPLE GUIDELINES, COMMON GOALS

Because all spacefaring nations have a vested interest in keeping LEO as safe as possible for future generations of space explorers, many countries and multinational organizations have established and adopted guidelines that shape their commitment to mitigating orbital debris. Although each country and organization has developed its own set of policies or standards, varying in level of detail and degree of enforcement, all the guidelines have certain fundamental elements in common and so are grounded in the components set forth originally in the U.S. Government Orbital Debris Mitigation Standard Practices and NASA Standard 8719.14A. For all, the focus remains on four core areas: control of debris during normal operations, minimization of debris generated by accidental explosions, mission planning to lower risk of creating orbital debris, and post-mission disposal of spacecraft and structures.

Video 3.2.1 **Global discussion on orbital debris.**

Nicholas L. Johnson, NASA Chief Scientist for Orbital Debris, discusses the current international focus on developing best-practice guidelines regarding space debris.

Video Credit: NASA

4

Overview of Issues in Orbital Debris Mitigation and Risk Management

As NASA and other organizations that operate in space have come to realize, if the amount of orbital debris in LEO is not curtailed, it could limit—or potentially eliminate—space exploration.

Nicholas L. Johnson, NASA Chief Scientist for Orbital Debris, leading a discussion on orbital debris mitigation.

Photo Credit: NASA

Section 4.1

Predicting the Future of the Orbital Debris Environment

In 1978, a NASA scientist named Donald J. Kessler proposed a nightmare scenario, which came to be known as the Kessler Syndrome. He stated that if the growth of orbital debris in LEO continued unchecked, the density of objects could become so great that the objects would increasingly collide, each collision generating more debris, which would cause space exploration and satellite use to become more hazardous.

While Kessler's prediction might have seemed overly negative, by 2006 scientists were forecasting a similar scenario. In their article, "Risk in Space from Orbiting Debris," Jer-Chyi Liou and Nicholas L. Johnson stated that even if no new launches were conducted after 2006, "The current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future."

In the chart to the left, you can see that although mission-related debris and debris from non-operational spacecraft was expected to start declining by the late 2000s, the authors proposed that debris arising from collisions would increase dramatically and consistently in the years to come.

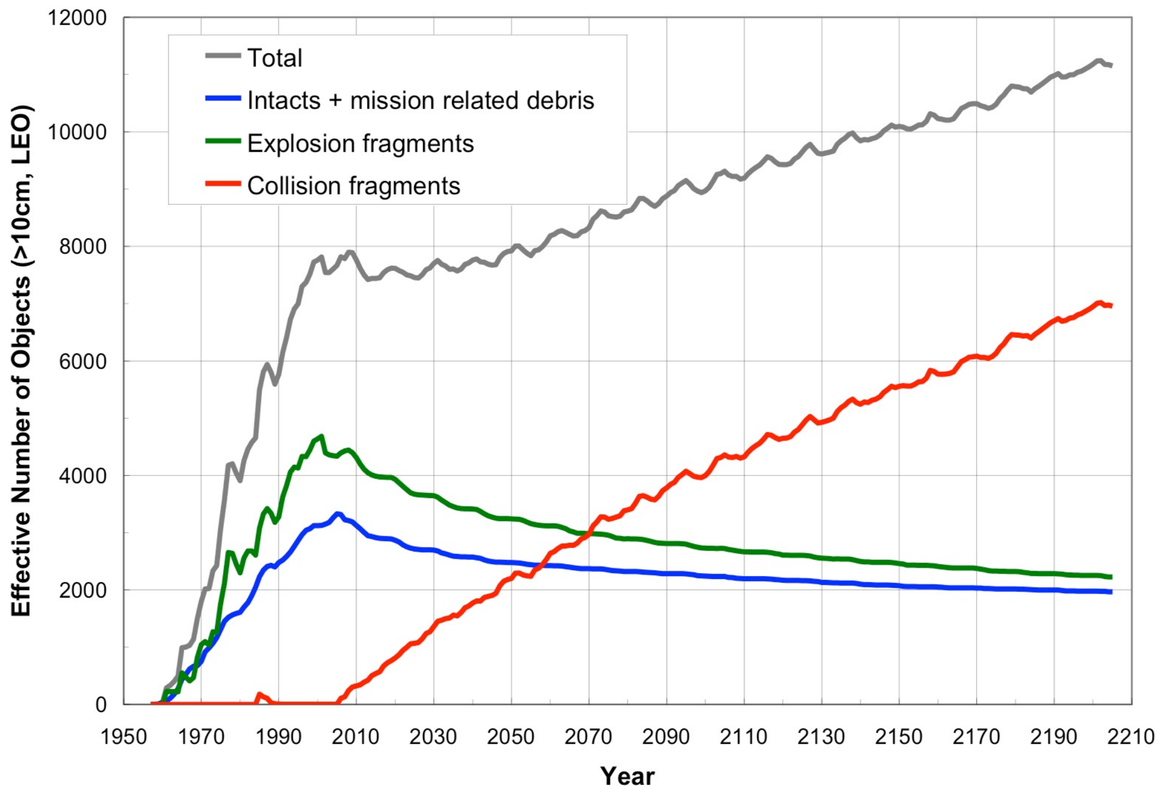


Figure 4.1.1 Projected instability of the LEO population.

As predicted in 2006: mission-related debris, intact objects, and explosion fragments would decrease, but debris generated by collisions would increase dramatically.

Figure Credit: NASA

By 2009, the scenario looked even worse. The intentional destruction of the Chinese weather satellite Fengyun-1C in 2007, along with the accidental collision between Iridium 33 and Cosmos 2251 in 2009, greatly increased the amount of debris in LEO. As a result, the likelihood that active spacecraft would collide with orbital debris increased significantly.

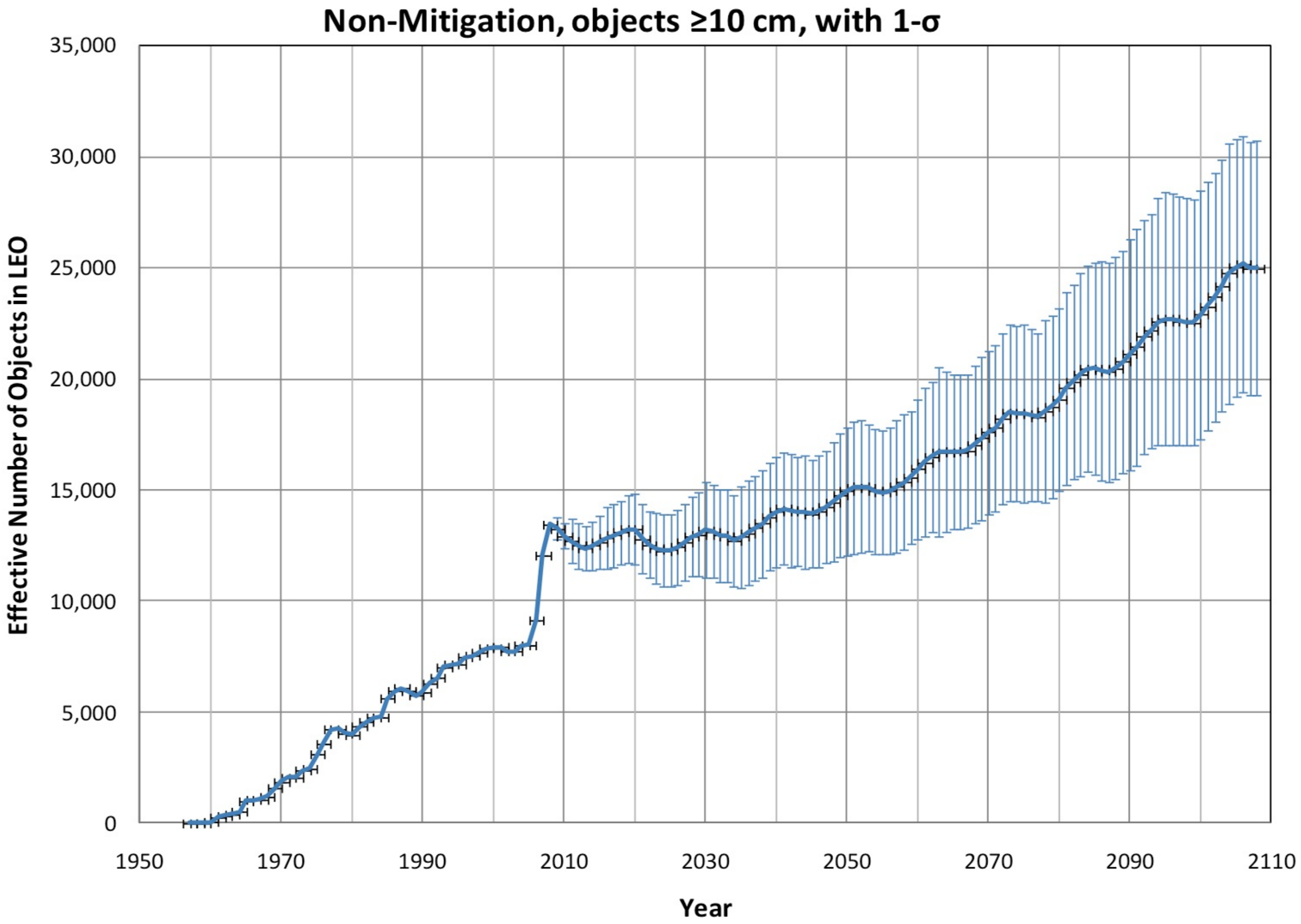


Figure 4.1.2 2009 projection of orbital debris in LEO.

Due to two large-scale collisions after 2006, the orbital debris scenario is increasingly bleak. Uncertainty (1-sigma sign) is shown.

Figure Credit: NASA

Section 4.2

Actively Removing Orbital Debris

The good news is that the regulations and standards put into place by NASA, the U.S. government, and global governing bodies have had a positive effect. One key means of mitigating orbital debris has been to limit the amount of time a spacecraft can remain in orbit once its mission is complete. The accepted “25-year rule” states that spacecraft components must be removed from LEO within 25 years of mission termination. As a result, spacecraft engineers now plan for the disposal of a spacecraft *before* it is built.

But NASA is not only concerned with decreasing the generation of new orbital debris. The agency has also looked at the possibility of removing existing debris from LEO. Tools such as tethers, lasers, and space tugs have been explored for their potential to de-orbit debris, a process that would cause orbital debris to reenter Earth atmosphere more quickly than it otherwise would.

PROPOSED METHODS OF DEBRIS REMOVAL

TETHERS

Although this complex process has not yet been proven, removal of a large-mass piece of orbital debris might be achieved by using tethers. A *conductive tether*—also known as an electrodynamic tether—is a long conducting wire that generates electric potential by its motion through the Earth’s magnetic field. Such a tether could be attached to the targeted piece of orbital debris. The current generated by the tether would produce a charge that de-orbits the object, causing it to reenter the Earth’s atmosphere more quickly than if it had stayed on-orbit. While this procedure could be effective for de-orbiting large objects in LEO, it would be complex and costly to use.

Momentum tethers might provide another means of de-orbiting a large object. In this scenario, a non-conductive tether is attached to the piece of orbital debris. The tether is first swung back and forth to generate momentum, then severed. Once the tether is cut, the resulting momentum swings the object out of orbit. Like conductive tethers, momentum tethers might effectively de-orbit large masses; but they, too, would be complex and costly to use.

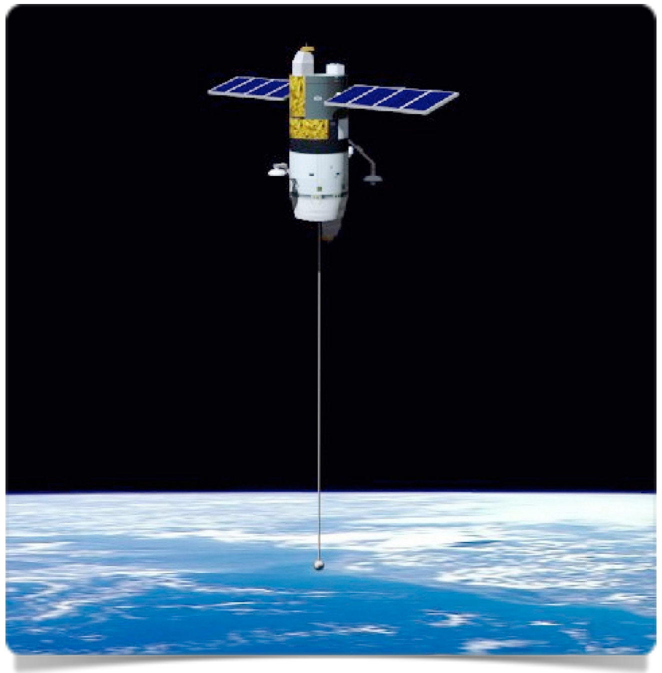


Image 4.2.1 Conductive tether.

The force created by current flowing through a conductive tether can slow a spacecraft down and take energy out of its orbit. The spacecraft would deploy the tether, the object would slow down, and eventually reenter Earth's atmosphere where it will burn up.

Image Credit: NASA

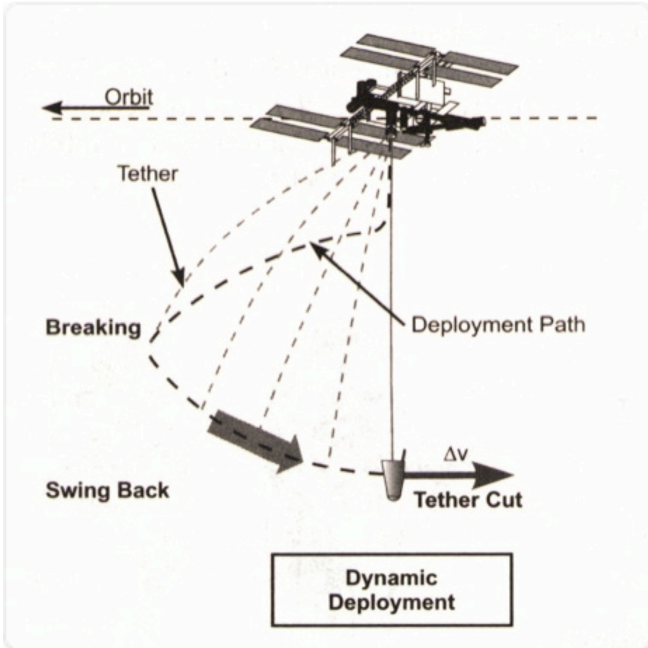


Image 4.2.2 Momentum tether.

A momentum tether would function on the principle of dynamic release to de-orbit large pieces of orbital debris.

Image Credit: NASA

LASERS

Laser technologies could potentially remove a large quantity of small debris. The concept is to lock onto the orbital debris using ground-, air-, or space-based lasers, then vaporize some part of the debris, creating a thrust that causes the debris to alter its orbit. This would lessen the lifetime of the debris. However, such an approach raises issues of arms control (for ground- and air-based lasers) and U.N. treaty violations (for space-based lasers). In addition, it would be an enormous undertaking, as the number of hazardous small debris is quite large—many millions.

SPACE TUGS

A space tug is actually a spacecraft that would be used to move multiple pieces of debris to disposal orbits in GEO. In this scenario, a tether is attached to one object; after a link is achieved, the object is transferred to disposal orbit, and the process is repeated with a second piece of orbital debris. This approach could be effective for disposing of objects in GEO, and its multi-target capability makes it attractive. Again, however, it is unproven, and would be complex and costly to use.

OTHER DEBRIS-REMOVAL TECHNIQUES

There are additional proposed means of removing debris from orbit, ranging from solid rocket propulsion modules to magnetic sails. All of these, however, would be costly to administer and complex to use. The preferred means of mitigating orbital debris is simple but challenging: to design spacecraft such that they adhere to the 25-year rule by reentering Earth's atmosphere in a timely manner, and then burn up or break apart into small pieces during the reentry process so that they do not threaten human life as they fall to Earth.

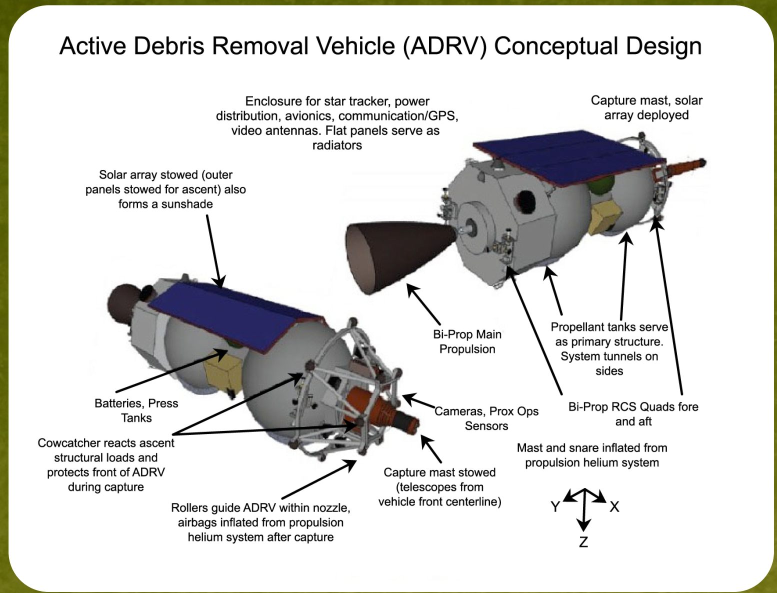


Figure 4.2.1 Space tugs.

Space tugs are spacecraft that would be used to remove large objects from GEO. These tugs are particularly attractive due to their multi-target capability. Above figure depicts an ADRV conceptual design.

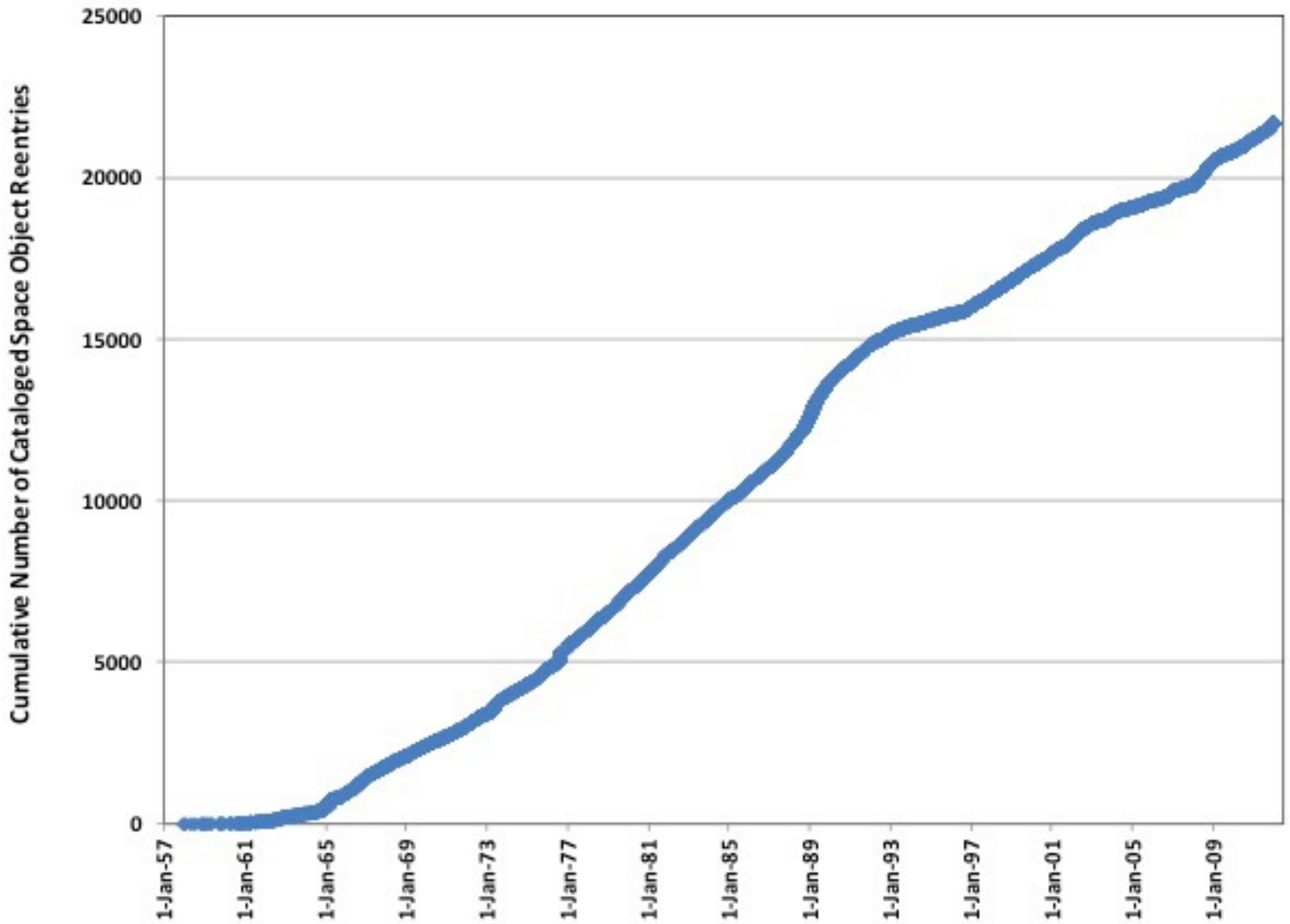
Image Credit: NASA

Section 4.3

Risk of Reentry

Given the global commitment to mitigating orbital debris, along with the developing capacity for de-orbiting debris so that it reenters Earth’s atmosphere quickly, it seems hopeful that the dire predictions regarding LEO congestion may not come to pass. But what happens when all of the orbital debris that is expunged from LEO reenters the Earth's atmosphere?

Figure 4.3.1 **Rate of space object reentries over the past 50 years.**



On average, one uncontrolled man-made object has fallen back to Earth every day for the past 50 years.

Figure Credit: NASA

Simply put, there is a tradeoff. While the 25-year rule helps limit the risk posed by orbital debris to active spacecraft—because it helps prevent a build up of debris in LEO—it increases the risk to humans of being hit by a piece of orbital debris that reenter Earth’s atmosphere. The more pieces of orbital debris after it reenters Earth's atmosphere, the greater the chance that a reentering spacecraft component will pose a danger to people and property. Fortunately, most pieces of orbital debris burn up as they reenter. The rule of thumb is that if the piece of orbital debris is too small to be tracked individually by the U.S. Space Surveillance Network—in other words, if it is less than 10 centimeters—it will not pose a threat to humans on reentry. But larger items—in particular, intact spacecraft and intact rocket bodies—can present a threat to humans. For the past 50 years, on average one piece of orbital debris has fallen from LEO back to Earth each day. Most are small and burn up on reentry, posing no danger to humans.

Components made from these materials, such as propellant or pressurant tanks, solar array drive mechanisms, reaction wheel assemblies, hinges, and valves, typically survive reentry in whole or in part. If one of these large items struck a person after reentry, chances are the person would be harmed, perhaps fatally. Taking shelter indoors does not guarantee safety, as these larger objects can penetrate a one- or two-story building, endangering people inside.

A number of satellite components have been recovered in populated areas. In 1997, a Delta II second stage stainless steel propellant tank landed right next to a Texas farmer's house. The farmer didn't hear the satellite land, though his neighbor did; but when he got up the following day, he discovered the tank just yards from his home. Around the world, people have discovered large objects of "space junk" that have fallen back to Earth. Fortunately, the majority of the larger components that survive reentry typically fall into bodies of water or sparsely populated regions, such as the Canadian tundra or Australian outback.

Gallery 4.3.1 **Examples of recovered satellite components.**

This is the main propellant tank of the second stage of a Delta II launch vehicle, which landed near Georgetown, TX, on January 22, 1997. This approximately 250-kilogram tank is primarily a stainless steel structure and survived reentry relatively intact.

Photo Credit: NASA

WHAT HAPPENS WHEN A SPACECRAFT REENTERS EARTH'S ATMOSPHERE?

Video 4.3.1 **ATV-1 reentry.**

Captured in real time, successive breakups of the ATV-1 are visible during reentry.

Video Credit: NASA / ESA

The breakup of a satellite usually occurs at about 80 kilometers above Earth as it reenters the atmosphere. The impact is like hitting a brick wall: due to a sudden increase in aerodynamic drag, the object breaks up. By the time a reentering object reaches 50 kilometers, the pieces have slowed down enough that very little heat is being generated. The pieces begin cooling at this point, and when they reach Earth they are cold.

One example of reentry is the ATV-1, a European satellite that was de-orbited over the Pacific Ocean on September 29, 2008. Two highly instrumented aircraft were flown near the ATV-1 to record the reentry. The ATV-1 had a number of pressurized tanks containing fluid—some with propellant—that can be seen exploding as the spacecraft reentered Earth's atmosphere. Individual pieces then began to burn up and separate. Eventually, the pieces of the ATV-1 dispersed and cooled until no longer visible.

Section 4.4

Design for Demise

Space agencies and spacecraft engineers now have two critical areas of focus in terms of orbital debris management: to limit the risk to spacecraft in orbit and to limit the risk to humans following spacecraft reentry. The risk of human casualty from a spacecraft component reentry should be no more than 1 in 10,000. However, many vehicles larger than 500 kilograms increase the risk beyond 1 in 10,000.

There are three ways to manage this elevated risk to humans. First, the space system operator can execute a controlled reentry over a broad ocean area. While this approach greatly reduces the risk to humans, the process of controlled reentry is complex and costly, making it a last resort. A second option is to maneuver the spacecraft into a "graveyard orbit": a long-term storage orbit above 2,000 kilometers. But this approach is also costly and not a good long-term solution. The ideal scenario from the perspective of orbital debris mitigation and reduction of human risk is to redesign the spacecraft before it is built to reduce the risk of human casualty upon reentry. In this case, the spacecraft is designed to promote more complete component demise. This process is referred to as "design for demise" or D4D.

KEY PRINCIPLES OF D4D

- **Substitute materials:** Whenever feasible, replace materials that can withstand high heat—and could therefore survive reentry—with low-melting-temperature materials that will burn up on reentry.
- **Reduce component mass:** If possible, reduce the mass of individual components to decrease their likelihood of reentry survival, but only if each component still meets structural requirements.
- **Redesign simple components:** Convert single components—such as plates—into layers, which will more easily burn up on reentry. The challenge is to build components that are designed for demise yet can absorb launch stresses.
- **Combine multiple components:** Design a single container that can contain multiple surviving components. This way, although a number of components may survive reentry, the overall risk is reduced to the single container.

D4D may be the most cost-effective means of complying with NASA Standard 8719.14A: mitigating orbital debris impact.

Section 4.5

More about NASA and Orbital Debris Mitigation

The issues associated with orbital debris, which range from threats to active spacecraft or humans to driving global consensus on debris mitigation, are complex. This book has attempted to provide an overview of some of the concerns and proposed solutions. To learn more about NASA's commitment to orbital debris research and control, visit the NASA Orbital Debris Program Office website at **http://orbitaldebris.jsc.nasa.gov**

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As NASA Chief Scientist for Orbital Debris at the Lyndon B. Johnson Space Center, Mr. Johnson serves as the agency authority in the field of orbital debris, including all aspects of environment definition, present and future, and the operational and design implications of the environment to both manned and robotic space vehicles operating in Earth orbit. He is responsible for conceiving, conducting, and directing research to define the orbital debris environment, for determining operational techniques for spacecraft to protect themselves from the environment, and for recommending techniques to minimize the growth in the future orbital debris environment. Mr. Johnson coordinates NASA's orbital debris research with similar research conducted by other U.S agencies, other national space agencies, and international organizations. Mr. Johnson serves as the head of the U.S. delegation to the Inter-Agency Space Debris Coordination Committee (IADC), comprised of the world's 12 leading space agencies, and serves as the U.S. expert at United Nations in matters concerning orbital debris. He is recognized internationally as an authority on orbital debris and foreign space systems and is the author of eighteen books and more than 200 papers on these topics during the past 34 years.

Video 4.5.1 **Nicholas L. Johnson on the future of space pollution.**

NASA Chief Scientist for Orbital Debris Nicholas L. Johnson addresses the pressing need for national and international policies to curtail the growth of orbital debris.

Video Credit: NASA

Credits

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Effluents

"Solid rocket motor effluents" refers to particles that are emitted from the motor during burn and after shut-down.

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Geosynchronous orbit (GEO)

GEO circles the Earth at 35,786 kilometers above the equator. It follows the direction of the Earth's rotation and matches Earth's rotation period.

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Chapter 1 - An Introduction to Orbital Debris

IAA

The International Academy of Astronautics, established in 1960, is a professional organization of approximately 1,200 individuals with demonstrated expertise in one or more fields of astronautics.

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ISO

The International Organization for Standardization was founded in 1946 as a non-governmental developer and publisher of international standards. Now a network of the national standards institutes of 164 countries, ISO's members include government and industry representatives.

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LEGEND

LEO-to-GEO Environment Debris Model

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Low Earth orbit

LEO is the region of space within 2,000 kilometers of the Earth’s surface. It is the most concentrated area for orbital debris.

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Orbital debris

Orbital debris is any object in Earth orbit that no longer serves a useful function.

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ORDEM

Orbital Debris Engineering Model

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Passivation

Getting rid of stored energy on a spacecraft or upper stage vehicle after launch to prevent in-orbit explosion.

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Robotic spacecraft

Spacecraft that are operated without humans on board.

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Chapter 2 - Tracking and Avoiding Collisions with Orbital Debris

SBRAM

Satellite Breakup Risk Assessment Model

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Sublimation rate

The amount of time it takes a substance to transition directly from the solid phase to the gas phase.

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