

Nov 6th, 1:30 PM

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Hall, Loretta, "The History of Space Debris" (2014). *Space Traffic Management Conference*. 19.
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The History of Space Debris

Loretta Hall

In the past fifty-five years, the space around the Earth has gone from a virtually debris-free environment to a zone cluttered with man-made objects that threaten launches, active satellites, and the International Space Station (ISS). NASA reports that as of 2013, more than 21,000 pieces at least the size of a softball were being tracked, and an estimated 500,000 pieces at least the size of a marble are thought to exist. More than 100 million even smaller objects, ranging down to the size of a tiny fleck of paint, are too small to detect or track. Active satellites, numbering about 1,100, comprise about 6 percent of Earth-orbiting objects; the rest is junk, commonly called space debris. This paper examines what space debris consists of, where it came from, and what problems it is causing.

An Empirical Baseline

In the first half of the twentieth century, before man-made objects were launched into space, some scientists suggested that the space around the Earth might be littered with undetectably small chunks of natural debris that could hinder manned spaceflight. Some, like astronomer Fred Whipple, were concerned about small meteors streaking past the planet. In 1946, Whipple warned that a spaceship traveling toward the moon would have a one in twenty-five chance of being destroyed by a meteoroid.[1] Others, like astronomer William Henry Pickering, envisioned small natural satellites orbiting the Earth.[2] As recently as 1954, Dr. G. M. Clemence, director of the Nautical Almanac office of the US Naval Observatory, said that the chances that there were one or more small satellites orbiting the Earth nearer than the moon were “very good.” He explained that they would be difficult to find because they would be moving too fast to be captured by usual photographic methods and that “most of the time they are in the Earth’s shadow, and thus do not shine.”[3]

Amid such speculation, astronomer Clyde Tombaugh formulated a plan to search for natural debris near both the Earth and its moon. Among the purposes he thought this project would address were the threat of collision with space vehicles and the possibility of using a natural satellite near the Earth as a “base in the establishment of an artificial satellite or space station.” Tombaugh, who had discovered the then-planet Pluto in 1930 and was head of the Optical Measurements Section for missile tracking at White Sands Proving Ground from 1946 to 1955, devised new techniques and equipment for conducting the search. Funded by the Army Office of Ordnance Research, Tombaugh and his staff used photography and visual sightings in the project from 1953 to 1958, first at the Lowell Observatory in Arizona and later at an equatorial site near Quito, Ecuador. The 1959 final report stated that no natural satellites had been discovered. Tombaugh concluded that “we could send rockets out in space with very little risk of collision with natural objects.”[4]

The timing of Tombaugh’s “Search for Small Satellites of the Earth” was fortuitous. Just before he planned to stop the observations, the Soviet Union launched Sputnik 1, the first artificial satellite, into orbit on October 2, 1957. Tombaugh’s telescopes detected the 58 cm (23 in.) diameter sphere and photographed it as it orbited elliptically between 215 km (134 mi) and 939 km (584 mi) above the Earth. Not only was this observation important in itself, but it

supported the conclusion that if natural satellites had existed in low-Earth orbit (LEO), they would have been detected as well.

Sputnik 1 did not start the accumulation of space debris the world now faces. The core stage of its launch rocket remained in orbit only two months, and the satellite itself burned up on atmospheric re-entry a month later. However, the long-term problem began to grow soon afterward. Vanguard 1, the second satellite launched by the United States, was placed in orbit in March 1958 and stopped radio transmissions six years later; but the 1.47 kg (3.25 lb) satellite is still in medium-Earth orbit (MEO) and is expected to remain so for nearly 200 more years. Its elliptical orbit ranges from 654 km (406 mi) to 3,969 km (2,466 mi) above the Earth.[5] Two other Vanguard satellites, launched in 1959, are inactive but remain in similar orbits. Since they are no longer operational, they are categorized as space debris.

Since the flight of Sputnik 1, the US Air Force has maintained a catalog of objects in orbit. Entries in this "Space Object Catalog" constitute items larger than 10 cm (4 in.) identified by launch date, country of origin, and launch site. When an object has fragmented, each catalogued portion of that object is given a separate catalog identifier. When an identified object is determined to no longer be in orbit, it is removed from the catalog.[6]

Sources of the Problem

The space debris problem is more complicated than whole satellites. NASA's preferred terminology is "orbital debris," which it defines as "all man-made objects in orbit about the Earth which no longer serve a useful purpose." [7] The debris may originate in one of three ways: mission-related operations, accidents, or intentional creation. A few illustrative examples are included in the following descriptions.

Mission-Related Debris

Satellite deployment operations can generate many objects of various sizes, and they account for about 12 percent of the currently cataloged debris.[8] Exhaust from solid-fuel upper rocket stages contains small particles of aluminum oxide that can remain in orbit up to two weeks. Larger aluminum oxide particles, which are ejected at very low velocities and remain in the same orbit as the satellite, may remain in space longer.[9] Separation of the satellite from its launch vehicle's upper stage often uses explosive bolts that disintegrate into smaller particles. Protective shields and other incidental hardware items have typically been discarded into orbit as well.[10]

As awareness of the dangers posed by space debris has increased, voluntary international guidelines have been developed to reduce the amount of mission-related debris that is generated.[11] For example, lens covers can be tethered to satellite cameras so they do not become detached. Rocket stages can be designed to fall from orbit and burn up on re-entry rather than staying in LEO or being boosted to a parking orbit.

Accidental Debris

Occasionally, astronauts have lost control of objects while working outside their spacecraft. For instance, during America's first extravehicular activity (EVA) in 1965, a spare thermal glove floated out of the Gemini IV capsule's open hatch. A year later, Mike Collins lost hold of a Hasselblad camera while working outside the Gemini X capsule. Then, as he was re-entering the capsule, a micrometeoroid and orbital debris (MMOD) experiment he had retrieved from the spacecraft's exterior also floated away. In 2008, Heidemarie Stefanyshyn-Piper was working outside the International Space Station when a grease gun leaked inside her tool bag. As she was trying to clean up the spill, the backpack-size tool bag slipped away. The bag, which contained several other tools, remained in orbit for eight months before burning up on atmospheric re-entry.

More typically, accidental debris is a result of an explosion or collision. A 2005 position paper reported that 73 percent of break-up debris in orbit was associated with rocket body fragmentations.[8] Liquid-fuel rocket stages left in orbit with fuel remaining in their tanks have exploded, between a few months and a few years after they were launched. Exposure to solar heat can increase pressure enough in a propellant tank to explode the tank. Or temperature fluctuations between heat and cold can weaken the wall separating hypergolic propellants, allowing them to mix and ignite. This problem can be avoided by running the rocket engine long enough to deplete the fuel or by venting excess fuel into space. Many mission operators have begun using those procedures.[12]

In some cases, a satellite can spontaneously release fragments. For example, in July 2008, a dormant Soviet satellite released thirty trackable debris objects and an unknown amount of smaller debris. The nuclear-powered Cosmos 1818 was placed in an 800 km (500 mi) high orbit in 1987 and remained active for five months. Two decades later, it began releasing metallic spheres that probably consisting of sodium-potassium reactor coolant. While this may have been caused by impact with space debris, it could also have resulted from a break in a coolant tube caused by long-term thermal stress.[13]

Collisions between two debris objects or between a debris object and an active satellite or spacecraft are becoming increasingly likely as the amount of space debris continues to increase. Relative velocities of objects in LEO can be 10 km/s (22,000 mph) or more.[7] Even a very small particle such as a fleck of paint striking a larger object at that speed can cause damage. For instance, during the 1983 STS-7 mission, a 0.2 mm paint chip hit a window of the space shuttle Challenger and created the 0.4 mm-diameter pit shown in Figure 1. During the first 63 space shuttle missions, 177 impact features were found on the shuttles' exterior windows, with 45 of them being large enough to require replacing windows.[14] Further, during the first 88 space shuttle missions, between 1981 and 1998, more than 70 shuttle windows had to be replaced because of significant debris impacts.[1]

Replacing space shuttle windows was costly, about

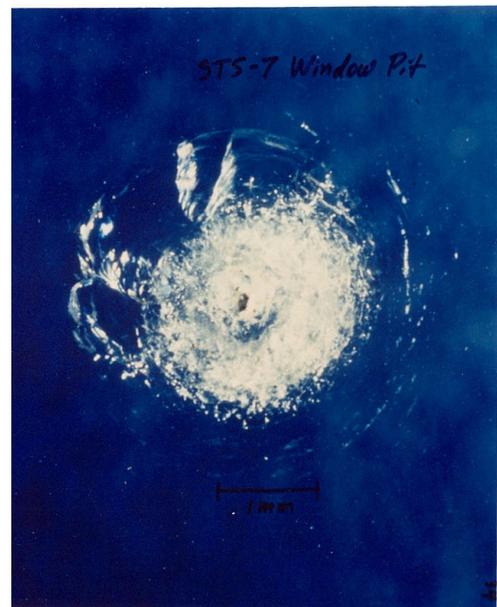


Figure 1 [NASA]

\$50,000 per window, but those episodes did not interfere with missions. A much more serious event, which occurred in February 2009, was a collision between two complete satellites. One was a 560 kg (1,230 lb) operational communication satellite owned by Virginia-based Iridium Satellite LLC. The other was a 950 kg (2,090 lb), deactivated (hence, orbiting debris) Russian communication satellite, Cosmos 2251. When they collided at an altitude of 770 km (470 mi), both satellites were destroyed, resulting in large debris clouds, one traveling the original orbit of each satellite. Over the following several months, more than 1,600 fragments from the two satellites were catalogued. A 2010 analysis concluded that about 20 percent of them would remain in orbit for thirty years, but 70 percent of them will descend through the orbit of the International Space Station by 2030.[15]

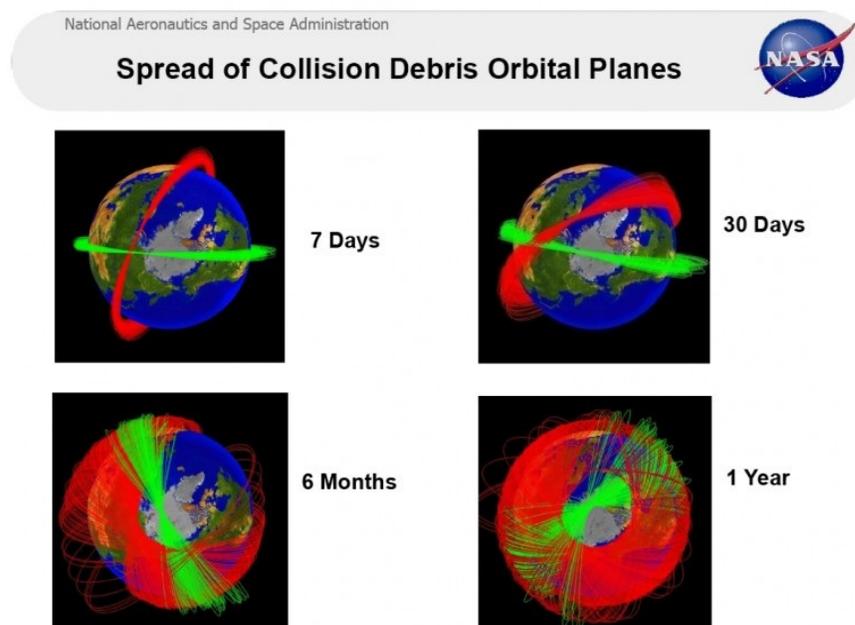


Figure 2 [NASA]

Figure 2 shows the expected dispersion of the debris clouds over time, based on a NASA model. Green represents the Iridium fragments, and red represents the Cosmos 2251 fragments, which virtually surrounded the Earth after one year. Tracking of debris objects revealed greater dispersion of Cosmos fragments than expected. A month after the collision, the altitude of Cosmos fragments ranged from 198 km (123 mi) to 1,689 km (1,050 mi), whereas the altitude of Iridium fragments ranged from 582 km (362 mi) to 1,262 km (784 mi). The heavier Cosmos had broken into more fragments; and because it was internally pressurized, it may have actually exploded during the collision.[16]

Intentional Acts Creating Debris

Between 1968 and 1985, the United States and the Soviet Union conducted tests of anti-satellite weapons (ASATs).[1] The Soviet version was designed to explode near its target and destroy it with shrapnel. The American system did not carry explosives, but was designed to

destroy its target by direct impact. By 1990, twelve such tests had produced 7 percent of the catalogued orbital debris.[10] How much smaller debris they produced is unknown.

In the last US ASAT test, in 1985, an aircraft-launched missile destroyed a failing American satellite at a relatively low orbit of 525 km (326 mi). The collision debris would deorbit sooner than it would from a higher orbit. In fact, solar activity was greater than expected in 1989–1991, causing expansion of the Earth’s atmosphere and slowing the fragments even more quickly. By January 1, 1998, all but eight of the 285 trackable debris objects had fallen from orbit.

The only ASAT test conducted after that was in 2007, when China launched a ballistic missile that hit and destroyed a nonoperational Chinese weather satellite, Fengyun-1C (FY-1C), at an altitude of 863 km (534 mi). The 20,000-mph collision created more than 3,000 pieces of space debris. Ten days after the test, its debris had spread throughout what had been the satellite’s orbit. After three years, the debris had scattered much further, surrounding the Earth at altitudes ranging from 175 km (110 mi) to 3,600 km (2,235 mi).[17]

Deliberate destruction of satellites is not the only instance of intentional debris creation. The West Ford project conducted by the MIT Lincoln Laboratory for the US Air Force in the early 1960s was a notable example. The project’s purpose was to create an 8 km (5 mi) wide, 40 km (25 mi) thick band of tiny copper wire segments in a near-polar orbit around the Earth as a passive radio reflector for military communications. In the first attempted deployment, in October 1961, the payload failed to disperse as planned. Eventually, seven small objects from the failed attempt were catalogued as orbital debris. The objects, with radar cross-sections between 0.06 m² (0.6 ft²) and 0.6 (6.5 ft²), are still in orbit at an altitude of about 3,600 km (2,250 mi).

A second West Ford project deployment attempt in May 1963 carried a payload of 480 million copper needles, each 1.8 cm (0.7 in.) long and 0.00178 cm (0.0007 in.) in diameter. Project planners expected solar radiation pressure to deorbit the needles in only a few years. However, only one-fourth to one-half of the needles dispersed as planned. Most remained in clumps that were more resistant to orbital decay. Eventually, 144 clumps from that attempt were identified and tracked; forty-six of them remained in orbit in 2013, but only nine of them had perigees less than 2,000 km (1,240 mi). Individual needles are too small to track.[18]

A new gray area has developed in the last fifteen years as miniature satellites have come into use. Many of these lack maneuverability and cannot evade space debris. However, they are less expensive to insert into orbit, and further miniaturization is an attractive goal. The potential of extreme miniaturization is illustrated by Cornell University graduate student Zachary Manchester’s experiment. He planned to deploy 104 tiny ChipSats, each measuring 3.5 cm (1.4 in.) square and “a few millimeters” thick, at an altitude of 325 km (200 mi). The ChipSats would remain in orbit only a few days, and the CubeSat that deployed them would deorbit after a few weeks. The experiment was deployed April 18, 2014, by a SpaceX rocket during a cargo resupply mission for the ISS. The deployment mechanism failed to operate properly, and the ChipSats remained in the CubeSat when it burned up on re-entry on May 4, 2014.[19]

Manchester said his goal was “to bring down the huge cost of spaceflight, allowing anyone from a curious high school student or basement tinkerer to a professional scientist to explore what has until now been the exclusive realm of governments and large companies.”

Proliferation of Space Debris

Ordinarily, space debris is detected and tracked using radar and telescopes. Between April 1984 and January 1990, NASA's Long Duration Exposure Facility (LDEF) gathered information in orbit about debris too small to be detected otherwise. It completed 32,422 Earth orbits during its 5.7 years in LEO. The exterior of the 9 m (30 ft) long, 4.3 m (14 ft) diameter cylindrical satellite was covered with flat plates. After its retrieval from orbit by the space shuttle Columbia, its entire exterior surface of about 130 m² (1,400 ft²) was thoroughly examined for MMOD impacts. More than 4,600 individual impact craters were documented. They ranged in size from 0.3mm to 5mm. Further investigation found 15,000 smaller impact features.[20] Figure 3 shows impacts to one panel of the satellite.

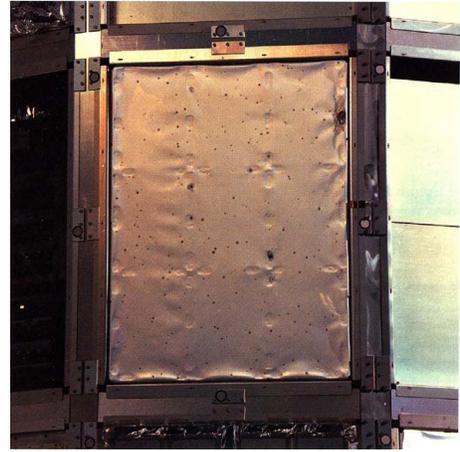


Figure 3 [NASA]

The amount of debris in orbit has been increasing since 1958. The rate of growth slowed for a decade beginning in 1996, as national and international debris-mitigation guidelines were voluntarily implemented. However, the Fengyun and Iridium incidents in 2007 and 2009 reversed that trend.[21] In addition, the upper stage of a Russian Briz-M rocket, stranded in orbit with half-full fuel tanks, exploded in October 2012, creating at least 1,000 trackable fragments.[21] Figure 4 illustrates those trends.

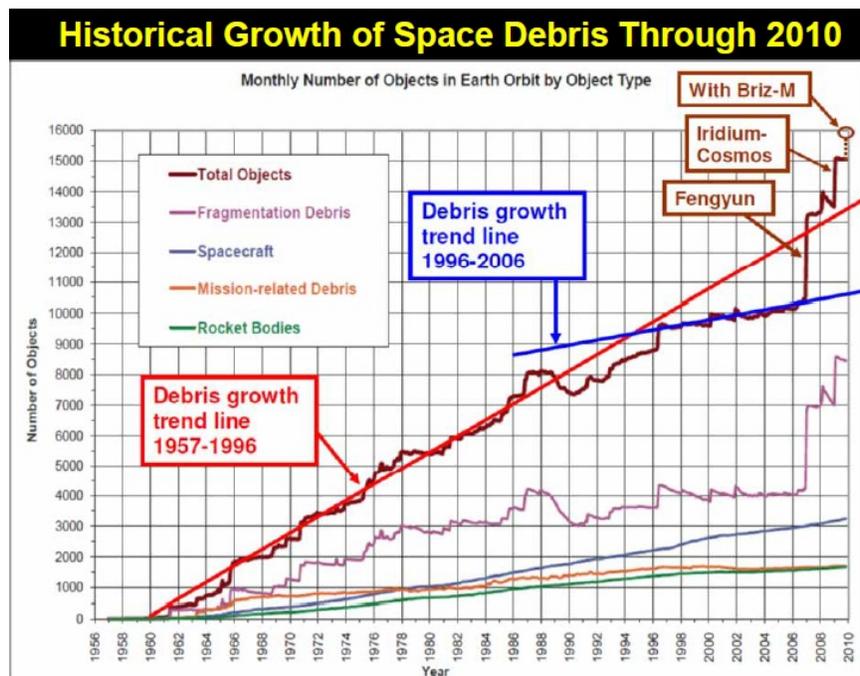


Figure 4 [21]

Evolution of Collision Probabilities

Estimations of the likelihood of a collision with space debris have evolved over the years as the amount of debris has increased, observed collisions have been analyzed, and modeling techniques have improved. The following estimates illustrate that evolution:

1966: Probability of a collision with the Gemini 8 space capsule during its 10.7-hour mission = 2.3×10^{-9} . [1]

1967: Probability of a collision with an Apollo spacecraft during a year in orbit = 11.16×10^{-4} . [1]

1970: Probability of a collision with the planned Skylab space station during an eight-month mission = 2.27×10^{-4} . [1]

1971: Probability of a collision with a space station = 2–3% over a ten-year period by one analyst who ignored debris too small to be catalogued. Another analyst factored in an estimated amount of undetected debris and calculated a probability of up to 8% over ten years. [1]

1981: Probability of a collision between any two objects = 6%/year, or 1 collision every 17 years. The analyst compared this figure to his 1976 estimate of 1.3%/year (1 collision every 77 years). He projected that by 1998, the collision frequency would be between 0.24/year and 1/year (1 collision every 1 to 4 years). [22]

1990: Probability of a collision between an orbiting satellite and space debris = 10^{-7} to 10^{-4} per year in LEO, and 10^{-12} to 10^{-7} per year in geostationary orbit (GEO). [10]

1997: Probability of an object (space debris or meteorite) entering a 2 km × 5 km × 2 km (1.25 mi × 3 mi × 1.25 mi) “maneuver box” around the space shuttle during 9.7 days in orbit = 86%. Probability of a space shuttle window needing to be replaced after the mission = 60%. [1]

2007: Likelihood that a piece of debris larger than 1 cm (0.4 in.) would collide with an active satellite in LEO = once every 5–6 years (17–20%/year) before the FY-1C destruction, but once every 3–4 years (25–33%/year) after that event. [23]

2010: Collision risk of space debris hitting or nearly hitting a satellite in LEO doubled between 2006 and 2009 due to FY-1C ASAT test and collision between the Iridium and Cosmos 2251 satellites. [21] The Briz-M explosion in 2012 further increased the risk.

2013: Likelihood of collision between a spacecraft and space debris larger than 1 cm (0.4 in.) = 1 every 1.5–2 years (50–67%/year), according to the Head of the Russian Federal

Space Agency. The analyst compared that with a 2010 estimated likelihood of 1 every 5 years (20%/year).[24]

Consequences

The proliferation of orbital debris creates problems both in space and on the ground.

In Space

Figure 5 illustrates the accumulation of objects surrounding the Earth (not to scale). LEO is densely occupied, and the GEO ring is clearly visible. Launching and maintaining spacecraft and satellites requires constant vigilance to try to avoid a potentially disastrous collision.

Rocket launches can be delayed if their path will be intersected by the projected path of a tracked debris object. A recent example was a three-minute delay in the launch of an Indian rocket carrying satellites for four foreign countries in late June 2014.[25]

Maneuverable satellites can be repositioned to avoid orbital debris. More than 100 such maneuvers were reported in 2010 alone.[26] In one dramatic example, in April 2012, debris tracking revealed that a defunct Russian satellite and NASA's Fermi Gamma Ray Telescope would cross each other's paths within 30 milliseconds of one another. Fermi's thrusters were fired for one second, and the debris missed Fermi by 9.7 km (6 mi). The avoidance maneuver took Fermi out of operation for only one hour.[27]

The Joint Space Operations Center (JSpOC) at Vandenberg Air Force Base tracks more than 800 maneuverable satellites and compares their paths with the orbital debris being tracked by the Space Surveillance Network. When JSpOC personnel detect a potential collision, they notify NASA, which notifies the satellite owners. In 2013, NASA performed or assisted with a record twenty-nine collision avoidance maneuvers by satellites.[28]

From 1988 through 2011, NASA monitored objects that might collide with a space shuttle. They watched for objects whose paths would take them into a maneuver box 2 km × 5 km × 2 km (1.25 mi × 3 mi × 1.25 mi) surrounding the shuttle. If such a conjunction was predicted, the shuttle would make a collision avoidance maneuver unless it would interfere with "either primary payload or mission objectives." [1] Between September 1988 and February 1997, nine catalogued objects entered a space shuttle's maneuver box. The shuttle conducted a collision avoidance maneuver on only four of those instances; in the other five instances, the maneuver would have interfered with its mission.[29] The first of those maneuvers, conducted in September 1991, avoided collision with a spent upper stage rocket body that had launched the Soviet Cosmos 955 satellite in 1977.[1]

Similarly, the International Space Station has had to dodge space debris. Its habitable

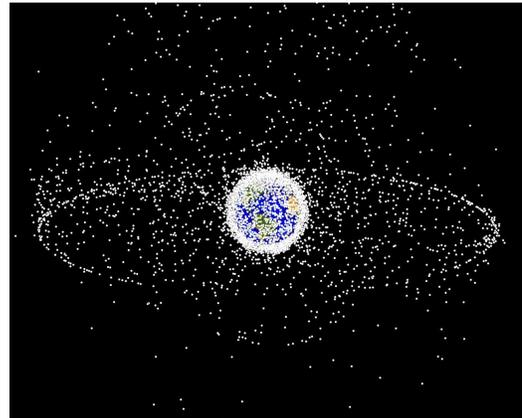


Figure 5 [NASA]

compartments are shielded against debris up to 1 cm (0.4 in.), but smaller particles can damage other portions of the station, including its solar panels. Recently, in July 2014, space debris tore a 30 cm (12 in.) long rip in a cover sheet of a radiator panel. Since 1999, the ISS has undergone nineteen collision avoidance maneuvers. Two such maneuvers were conducted within three weeks in March and April 2014 to avoid debris from two different spacecraft. Most recently, on October 27, 2014, the ISS sidestepped debris from the Cosmos 2251 satellite. On three other occasions, the approach of space debris was detected too late to conduct an avoidance maneuver, and the crew aboard the ISS took refuge in the attached Soyuz crew transportation vessel. Despite these precautions, the ISS has sustained damage to several of its components, including thermal radiators, solar panels, and a window.

On the Ground

Small particles of space debris falling out of orbit burn up in the atmosphere, but larger pieces can reach the ground intact or in chunks. On average, one uncontrolled re-entry of a spacecraft or rocket body weighing about 2,000 kg (4,400 lbs) occurs every week. For those, 10–40 percent of their mass reaches the ground.[30] Because 70 percent of the Earth's surface is covered with water, most of the debris falls into oceans.

However, numerous large pieces have fallen on land. One notable example involved the uncontrolled re-entry of the US space station Skylab in July 1979. The 76,000 kg (84 ton) object broke up as it streaked through the atmosphere. Residents in two cities in southwestern Australia heard sonic booms as the chunks approached the ground. Debris was scattered over a 200 km (125 mi) by 1,000 km (620 mi) area, and more than 500 pieces weighing a total of 20,000 kg (22 tons) were found in the Australian Outback.[1]

In February 2003, the space shuttle Columbia disintegrated on re-entry, scattering debris over Texas and Louisiana. More than 84,000 pieces were recovered, weighing almost 38,500 kg (85,000 lbs) and constituting about 40 percent of the vehicle's mass.[31]

Although it did not produce nearly as many debris objects, a Delta II booster that re-entered the atmosphere in January 1997 attracted attention for being the only documented event of space debris striking a person. Lottie Williams was walking in a park in Tulsa, Oklahoma, when she felt something touch her shoulder. She looked back and saw an object on the ground behind her. "It looked like a piece of fabric, except when you tap it, it sounded metallic," Williams said. The crumpled, 15 cm (6 in.) long object was described as being about as heavy as an empty soda can. The Center for Orbital and Reentry Debris Studies determined that it was woven material used on the fuel tank of a Delta II rocket used to launch an Air Force satellite in 1996.[32] Lottie was lucky. That was one of the smallest pieces of debris from that rocket re-entry. A 30 kg (66 lb) titanium pressurant tank landed near Seguin, Texas; and a 250 kg (550 lb) stainless-steel, upper-stage propellant tank landed near Georgetown, Texas.[33]

History's Impact on the Future

In the late 1950s, the space around the Earth may have seemed unlimited. History has proved otherwise. The accumulation of orbital debris presents a real threat to the future

productive use of space. Some analysts believe that regions of LEO have already reached “critical density,” meaning more fragments will be generated by collisions than will be removed by atmospheric drag, even if no further objects are added.[9]

Public and private researchers are actively seeking solutions. Improved detection devices, both ground-based and orbital, are being developed and deployed. Various techniques for removing orbital debris are being investigated. They include capture mechanisms, laser beams that would slow their orbits to promote decay, or techniques to boost debris to a higher orbit above the most useful zones for satellites. Some schemes even call for repurposing functional parts of defunct satellites.

Solving the problem of space debris has been put off for decades because it is technologically difficult and costly. At last, the space community is realizing that the failure to solve the problem would be disastrous.

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