

Space debris

David Wright

Controlling the production of debris is crucial to the sustainable use of space. But even without additional launches, let alone antisatellite tests, the amount of debris orbiting Earth will continue to increase far into the future.

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The space age began 50 years ago with the launch of *Sputnik 1* by the Soviet Union on 4 October 1957. Since that time, some 4500 additional launches have taken place. Today 850 active satellites are in orbit, supporting a wide range of civil and military uses. The US owns and operates roughly half of those satellites, as shown in figure 1.

As a result of this space activity, a tremendous amount of debris has been left orbiting in space. Orbital debris is any human-made object in orbit that no longer serves a useful purpose. It comes in the form of discarded equipment and rocket stages, defunct satellites, bolts and other hardware released during the deployment of satellites, and fragments from the breakup of satellites and rocket stages.

Space debris is a growing concern. With their high speed in orbit, even relatively small pieces of debris can damage or destroy satellites in a collision. Since debris at high altitudes can stay in orbit for decades or longer, it accumulates as more

is produced. As the amount grows, the risk of collisions with satellites also grows. If the amount of debris at some altitudes becomes sufficiently large, it could become difficult to use those regions for satellites. There is currently no effective way to remove large amounts of debris from orbit, so controlling the production of debris is essential for preserving the long-term use of space.

The debris issue gained prominence in January 2007 when China tested an antisatellite (ASAT) weapon that destroyed one of its defunct weather satellites, the *Feng Yun-1C* (FY-1C), at an altitude of about 850 km. The test added significantly to the debris population near that altitude. (See PHYSICS TODAY, March 2007, pages 29 and 100.)

Current space debris

The first two rows of the table on page 36 give estimates of the amount of orbital debris in space, by size. In reality,

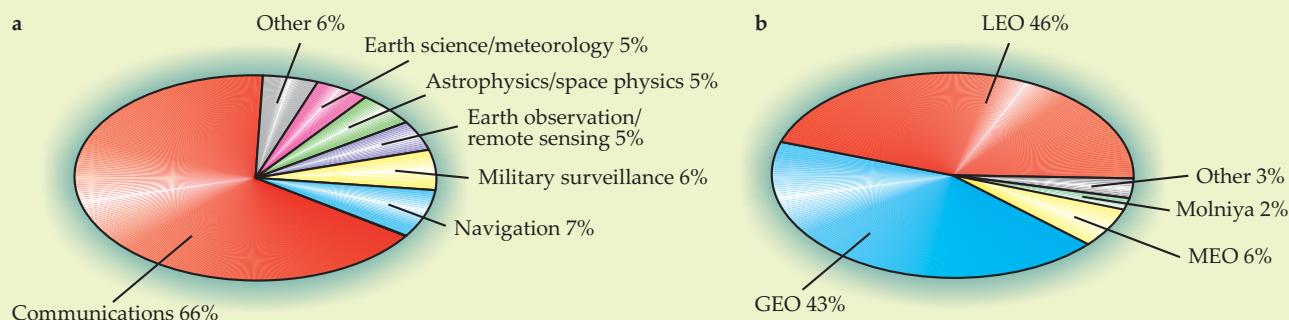


Figure 1. Current satellite population. (a) A rough breakdown of how satellites are being used. (b) Altitudes at which satellites currently reside. Satellites in low-Earth orbit (LEO) have altitudes less than 2000 km. Those in geosynchronous orbit (GEO) have an altitude of 35 876 km and an orbital period of one day. Satellites in medium-Earth orbit (MEO) have altitudes between LEO and GEO. Molniya orbits are highly elliptical orbits with a 12-hour period. (c) A breakdown of the current satellite population by country and use. For detailed information on active satellites, see the Union of Concerned Scientists Satellite Database, which is updated quarterly and is available free online.¹⁶ (Data from the UCS Satellite Database.)

debris particles have irregular shapes, so “size” refers to some characteristic dimension of the object. Also found in space are naturally occurring meteoroids, which add significantly to the number of objects in the 0.1- to 1-cm range. But they pose less of a threat to satellites due to the small population density of meteoroids large enough to cause significant damage.

The orbiting objects that are sufficiently large are tracked by the US Space Surveillance Network (SSN), which consists of a mix of radars and optical sensors. That system can track objects in low-Earth orbit (LEO, defined as altitudes less than 2000 km) with size larger than 5–10 cm and objects in geosynchronous orbit (GEO, at an altitude of 35 876 km) larger than roughly a meter. Using SSN data, US Strategic Command maintains a catalog of objects;¹ to be in the catalog, the object must be tracked by the SSN and its origin must be known. Currently the catalog contains some 12 000 objects, including about 850 active satellites. The SSN also tracks several thousand additional objects whose origins are not known.

Debris is not uniformly distributed in space but is concentrated in those regions that are heavily used by satellites. Figure 2 shows the distribution of LEO debris as a function of altitude before and after China’s January test. More than 3000 of the 12 000 objects in the US catalog lie in the altitude band from 800 to 1000 km.² The bulk of the debris at higher altitudes is concentrated in the geosynchronous band (figure 3).

Orbital speeds in LEO are greater than 7 km/s, and the relative speed of a piece of debris approaching a satellite in an intersecting orbit may be 10 km/s or higher. To give a sense of the potential destructiveness of debris at those speeds, note that a 1-g mass traveling at 10 km/s has the same kinetic energy as a 100-kg mass traveling in excess of 100 km/hr. Alternately, at 10 km/s, the kinetic energy of a mass *m* is roughly equal to the energy released in an explosion of a mass 10*m* of high explosive.

Debris between 1 mm and 1 cm in size can damage a satellite if it hits a vulnerable area. Shielding can protect against objects of that size, but adding shielding increases the cost both of building satellites and of launching them, and many satellites have minimal shielding.

Debris larger than about 1 cm can seriously damage or destroy a satellite in a collision, and there is no effective shielding against such particles. Debris particles larger than 1 cm but too small to be tracked are especially dangerous because satellites are unlikely to have warning to allow them to avoid colliding with such objects.

Debris larger than 10 cm may be massive enough to create large amounts of additional debris in a collision with a satellite or another large piece of debris.

Sources of debris

There are two main sources of orbital debris. The first source is routine space activity and the accidental breakup of objects placed in orbit by such activity. The international community is attempting to address this source, in part by developing debris-mitigation guidelines to limit the debris created as a result of routine space activities.

The second source of debris is the intentional creation of debris in orbit by the testing or use of destructive ASAT weapons. Kinetic-energy ASAT weapons, such as the one tested by China in January, are intended to destroy satellites by

physically colliding with them at high speed. Such collisions can create tremendous amounts of orbital debris—much more than is generally realized. We discuss such events in detail below.

To provide a sense of the origin of the debris population, figure 4 shows a rough breakdown of the cataloged objects in orbit. One-quarter of the “payloads” are active satellites; the rest are satellites that are no longer active and are therefore considered to be debris. The largest category of debris—nearly half of the total—is that caused by both accidental and intentional breakups of objects in orbit. Explosions due to malfunctions of propulsion systems or the ignition of residual propellant in a rocket stage are the largest source of accidental-breakup debris. The Chinese ASAT test added some 2000 fragments to the catalog; they make up about 35% of the breakup-debris total. The Soviet ASAT program in the 1970s and early 1980s, which attempted to destroy a satellite by shrapnel from an exploding ASAT weapon, created more than 700 pieces of large debris, roughly 300 of which remain in orbit. The last piece of cataloged debris from the one US ASAT test, in September 1985, decayed from orbit in 2004.³

Currently the US and Russia are each responsible for about 35% of the cataloged objects in space, and China for about 20% following its ASAT test. The Russian percentage is expected to increase to roughly 40% in the next year as debris from the February 2007 breakup of a Briz-M booster stage launched in 2006 is cataloged.

International efforts are under way to control the production of debris from routine space activity. In the mid-1990s the US developed and released a set of debris-mitigation guidelines; subsequently other countries developed similar national guidelines. In 2002 the Inter-Agency Space Debris Coordination Committee adopted a consensus set of guidelines,⁴ and in June 2007 the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) adopted a set of mitigation guidelines based on the IADC guidelines.⁵ To reduce the production of debris in space, all the guidelines call for measures such as designing satellites and rocket stages to limit the release of mission-related debris and depleting propellant from nonoperational satellites or stages to reduce the risk of explosions. By calling for spent stages and satellites to be removed from orbit, the guidelines also attempt to control the number of large objects in space that could break up due to collisions. Unfortunately, the guidelines are not legally binding.

Nevertheless, those efforts appear to have been partially successful. The number of objects in the catalog increased roughly linearly from 1960 through the mid-1990s, but it rose at a much slower rate from 1997 through 2006, in part due to a significant reduction in the release of mission-related and fragmentation debris.⁶ Unfortunately, the January ASAT test and the Briz-M explosion in February that is estimated to have created at least 1000 trackable fragments appear to have essentially undone the gains in the previous decade. The ex-

Estimated amount of orbital debris, by size

	0.1–1 cm	1–10 cm	> 10 cm
Total debris at all altitudes	150 million	650 000	22 000
Debris in low-Earth orbit	16 million	270 000	14 000
Debris from the breakup of a 5- to 10-ton satellite	8–14 million	150 000–250 000	3000–5000
Debris from the <i>Feng Yun-1C</i> breakup	2 million	40 000	2000

Source: European Space Agency MASTER 2005 Debris Environment Model, plus estimates of debris from China’s January 2007 antisatellite test.

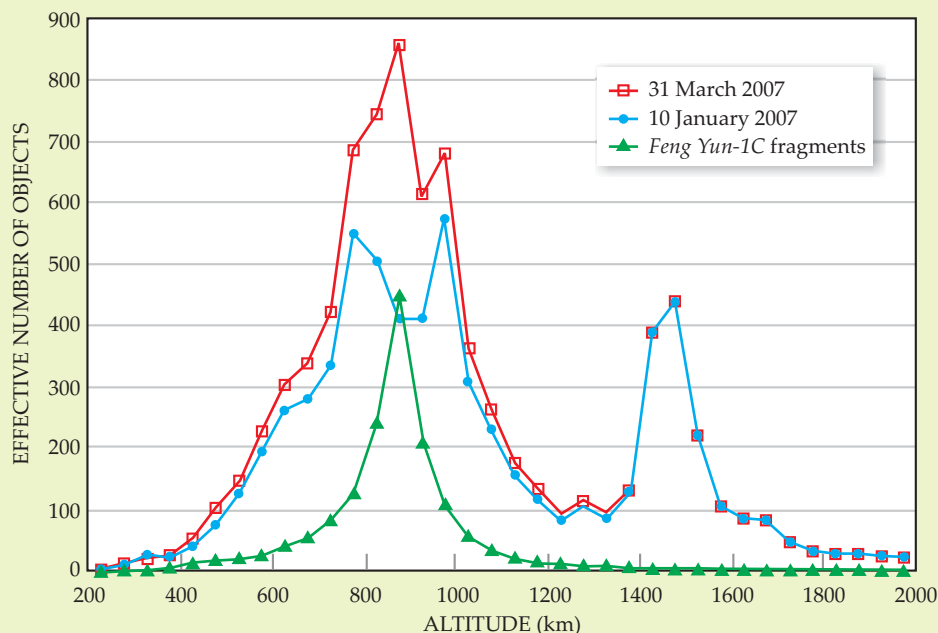


Figure 2. Altitude distribution of cataloged debris for low-Earth orbit. Objects in noncircular orbits are distributed in the plot according to the amount of time they spend in each 50-km altitude bin. The differences between the 10 January (blue) and 31 March (red) curves are due to the tracked debris (green) from China's *Feng Yun-1C* satellite, destroyed in an antisatellite test in January 2007. (Adapted from ref. 2.)

plosion of the Briz-M stage could likely have been prevented by strict adherence to the IADC guidelines, which call for venting unused propellants.

There are currently no international restrictions on the testing or use of military systems intended to destroy satellites.

The threat to satellites

The debris threat to satellites has two aspects. The first is the near-term threat due to the current or near-term debris population. The second is the long-term evolution of the space environment as the debris population increases over the next few centuries due to the continuing release of debris from ongoing space activities and to breakups of large objects that are already in space.

In the near term, the density of debris large enough to cause serious damage to satellites is sufficiently low that the risk of a damaging collision over the operational lifetime of a satellite is small. However, at some altitudes the risk is approaching the level of risk from other problems that may affect the operation of a satellite. If the debris density increases significantly, the probability of damage from debris could become the primary threat to satellites in some parts of space.

Although the debris risk to satellites is relatively low, such collisions have taken place. In 1996 the French military satellite *Cerise* had its stabilization arm severed by a briefcase-sized piece of an Ariane rocket. Debris collisions with inactive satellites have also been seen. In 1991 the defunct Russian *Cosmos 1934* satellite was hit by a piece of debris from the *Cosmos 926* satellite.⁷ Orbital changes of the *NOAA 7* satellite in 1997 and the *Cosmos 539* satellite in 2002, accompanied by the release of small amounts of debris, are believed to have been caused by collisions with debris in the 1- to 10-cm range.⁸ And in January 2005 a fragment from a Chinese rocket body that exploded in March 2000 struck a 31-year-old US rocket body.

A number of additional events, including satellite breakups and malfunctions of unknown cause, may have been due to debris that was too small to be tracked. With the current number of satellites and debris, hundreds of close approaches, in which the objects pass within less than one kilometer of each other, occur every day between cataloged objects.⁹

Since the distribution of debris is not uniform in space, the threat to a satellite depends on its orbit. And the regions most heavily used by satellites are also the most heavily populated with debris.

Before China's ASAT test in January 2007, the average time between collisions of two large, cataloged objects in LEO was estimated to be 11–12 years.¹⁰ As noted above, three such events have been identified historically—in 1991, 1996, and 2005—a rate that is roughly consistent with that average. (The collision rate was much lower in the first few decades of the space age.) A “catastrophic” collision—one that causes the objects to completely fragment into debris—was estimated to take place every 19 years. For the coming decades, the debris from the Chinese test is expected to increase the collision rate to one roughly every 7–8 years, with a catastrophic collision every 12–14 years.

A more relevant measure of risk is that before the Chinese test, a piece of debris larger than 1 cm was estimated to collide with one of the active satellites in LEO every 5–6 years. Such collisions can cause significant damage to a satellite but may not cause it to malfunction. And attributing a satellite malfunction to debris may be difficult because much of the debris is too small to be observed by the SSN. The debris from the Chinese test is expected to increase the malfunction probability by more than 50%, so a collision of this kind would be expected roughly every 3–4 years during the next decade.

Another measure of the current debris risk is that in the heavily used altitude band around 800–900 km, the chance that any given satellite will be hit by debris larger than 1 cm is approaching 1% over the satellite's 5- to 10-year lifetime. Since debris from the Chinese test is concentrated near that altitude band, it will roughly double the threat for the next 5–10 years.

Long-term evolution

If the debris density becomes large enough at some altitudes, those regions of space can become “supercritical,” meaning that collisions between objects are frequent enough that they produce additional debris faster than atmospheric drag removes debris from the region. The additional particles further increase the collision probability in the region, which

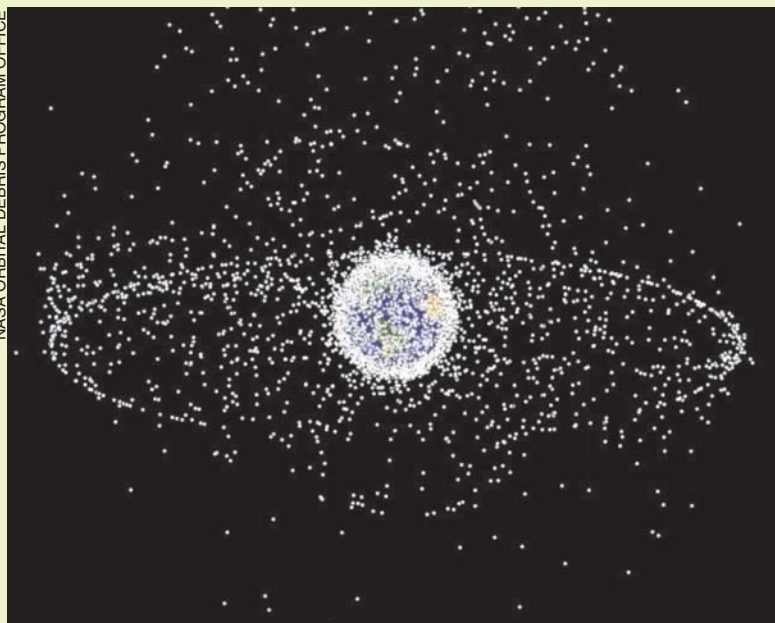


Figure 3. Distribution of cataloged debris. In addition to a dense shell of debris within 2000 km of Earth, debris is concentrated in the geosynchronous band at an altitude of 35 876 km.

the collision rate and therefore the rate at which cascades would increase the debris population.

Kinetic-energy ASATs

In principle, a country could use several types of weapons, such as lasers or electromagnetic jammers, to interfere with the operation of satellites.¹³ However, the effectiveness of many of those weapons is uncertain and difficult to verify. A successful attack by a kinetic-energy ASAT weapon would likely cause damage that could be detected by sensors on the ground, and detection of severe physical damage would strongly imply that the satellite was no longer functioning. If a satellite were deemed an important enough military threat that a

country decided to attack it, that country might have a strong incentive to use a kinetic-energy ASAT.

Hypervelocity collisions—those occurring at relative speeds greater than a few kilometers per second—lead to extreme temperatures and pressures and occur over very short time scales, so modeling the response of materials to the impact is complex. Hydrodynamics codes have been developed to simulate relatively simple impact geometries, but modeling the effects of an impact on a satellite or other complicated body is beyond current capabilities. However, computer models developed in the past decade and based on ground tests and observed breakups in space can give a good approximate description of the debris resulting from the destruction of a satellite in a high-speed collision. The most comprehensive is NASA's Standard Breakup Model.¹⁴

Applying NASA's breakup model to the case of a mass of a few tens of kilograms colliding at velocities in excess of 7 km/s with a satellite having a mass of 1–10 tons illustrates the potential effects of a kinetic-energy ASAT.¹⁵ The calculation gives the number of debris particles created and the size, mass, area-to-mass ratio, and velocity distributions of the particles. That information, along with data on the atmospheric density, can be used to calculate the orbits of the particles and estimate their lifetimes.

Such a collision would be catastrophic if there is a direct

leads to a slow-motion chain reaction or cascade as the large objects in orbit are ground into smaller fragments. That situation is sometimes called the Kessler syndrome after Donald Kessler, who studied the possibility.¹¹

A study released by NASA's Orbital Debris Program Office in 2006, before the Chinese test, showed that parts of space have already reached supercritical debris densities.¹² In particular, the study shows that in the heavily used altitude band from 900 to 1000 km, the number of debris fragments larger than 10 cm is expected to more than triple over the next 200 years, even assuming no additional objects are launched into the band. The study estimates that the total population of large debris in LEO will increase by nearly 40% during that time, still under the assumption of no additional launches. The debris from the Chinese test will make matters worse.

An important implication of the study is that while mitigation efforts are important for slowing the increases, only debris-remediation measures such as removing large, massive objects already in orbit can hope to prevent their consequences. Remediation efforts such as robotic missions to remove defunct satellites and rocket stages are very expensive, but are being studied.

A second implication is that the intentional destruction of satellites would add large amounts of debris at already-crowded altitudes and thus would significantly increase

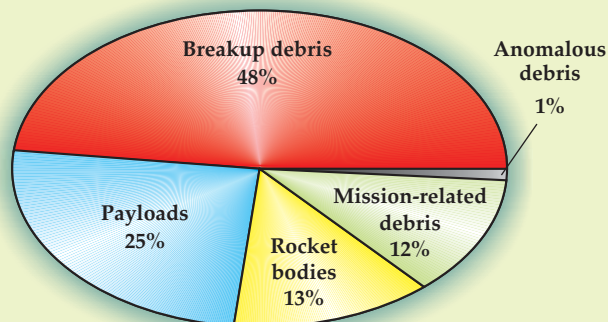


Figure 4. Cataloged objects in orbit around the earth as of mid-2007. Only about one-quarter of the “payloads” are active satellites; the remainder are inactive. “Mission-related debris” refers to objects released intentionally during routine operations, such as during the deployment of a satellite. “Anomalous debris” refers to the unplanned release of objects due, for example, to the deterioration of thermal blankets or shielding around a satellite. (Data from ref. 6, with debris from China’s antisatellite test added.)

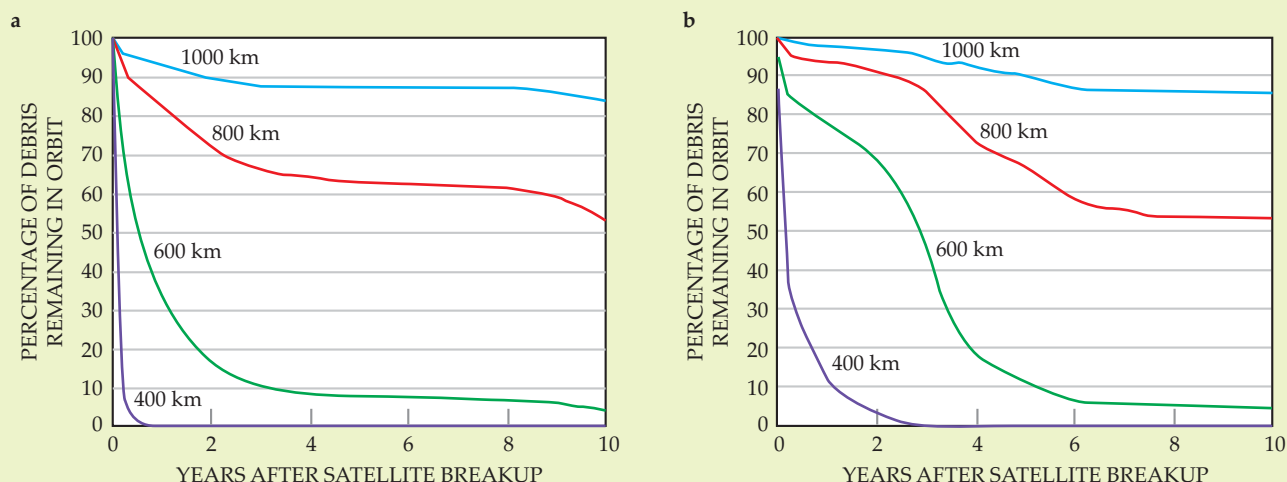


Figure 5. Effect of the 11-year solar cycle on the fraction of debris particles greater than 10 cm that remain in orbit following the catastrophic breakup of a satellite. The results are shown for a satellite in a circular orbit at four different altitudes, with the debris population given by the NASA breakup model. Calculations were made using atmosphere models that reflect the conditions (a) at a time of maximum solar activity (1 January 1980) and (b) at a time of minimum solar activity (1 January 1986).

hit on the central mass of the satellite. Indeed, according to the NASA model, a collision between a large object and a smaller one will be catastrophic if the ratio of the impact kinetic energy of the smaller object to the mass of the larger object is greater than 40 kJ/kg. That condition implies that an interceptor of 20 kg striking a large satellite at 7.5 km/s could completely fragment a satellite with a mass up to about 14 tons. The situation is relevant to satellites in LEO, since their orbital speed is roughly 7.5 km/s, which sets the scale of the intercept speed for attacks. Of the nearly 400 active satellites in LEO, more than 200 have mass greater than 450 kg, more than 60 have mass greater than 1 ton, and roughly 15 have mass greater than 5 tons.¹⁶

The catastrophic breakup of satellites in orbit could produce a dramatic increase in the amount of space debris. The NASA breakup model shows that the catastrophic breakup of a single satellite of 5–10 tons would roughly double the amount of debris larger than 1 mm currently in LEO (see the table). That scenario is particularly applicable to US reconnaissance satellites, which are often discussed as likely targets of ASAT attacks, have masses of roughly 10 tons, and orbit in LEO to allow them to collect high-resolution images of Earth.

The 3000–5000 pieces of large debris estimated to be produced in such a breakup is two to three times the roughly 1500 pieces larger than 10 cm currently in the heavily used altitude band between 800 and 900 km. If the satellite that was attacked had its orbit within that band, the resulting debris would be concentrated in the same region and would make the debris problem at those altitudes much worse. For attacks at other altitudes, the amount of debris would represent a much larger percentage increase over the existing amount.

The table also shows estimates of the debris created by China's destruction of the *FY-1C* satellite in January 2007. That added significantly to the debris population at altitudes between 800 and 900 km (see figure 2).

Debris lifetime

The orbital lifetime of a piece of debris depends on how strongly it is affected by atmospheric drag. That, in turn, de-

pends on the object's mass, size, and shape, and on the atmospheric density at its orbital altitude. Since atmospheric density drops off roughly exponentially with altitude, orbital altitude has a dramatic effect on drag and debris lifetime. For example, an object that would have a lifetime of a couple weeks if it were orbiting at 300 km would have a lifetime of a year if it were orbiting at 500 km, several decades at 700 km, and more than a century at 800 km. If a satellite destroyed by an ASAT weapon were orbiting at an altitude above about 800 km, then a large fraction of the debris particles created in the collision would remain in orbit for decades or longer.

The atmospheric density at a given altitude also changes periodically with the 11-year solar cycle as variations in solar activity cause the outer regions of the atmosphere to expand and contract. That effect can be significant at low altitudes; for example, the atmospheric density at an altitude of 500 km can vary by more than a factor of 10 over the cycle. Thus the debris lifetime is strongly affected by the solar cycle, as shown in figure 5.

Before the Chinese test, the only other test of a kinetic-energy interceptor destroying a satellite was conducted by the US in September 1985. The US test created roughly the same amount of debris larger than 1 cm as did the Chinese test (although apparently less large debris), since both satellites had masses of roughly 1 ton. Because the US test took place at an altitude of about 500 km, compared with about 850 km for the Chinese test, the debris from the US test remained in orbit for a significantly shorter time. Most of the large debris from the US test decayed within 10 years, while a significant fraction of debris from the Chinese test is expected to remain in orbit for decades.

ASAT debris distribution

A common assumption is that the debris created from the fragmentation of a satellite in an attack expands outward with a spherically symmetric distribution relative to the center of mass of the original satellite. According to the NASA breakup model, the speeds of the vast majority of the debris particles created in such a collision, measured relative to the center of mass of the debris cloud, would be much smaller

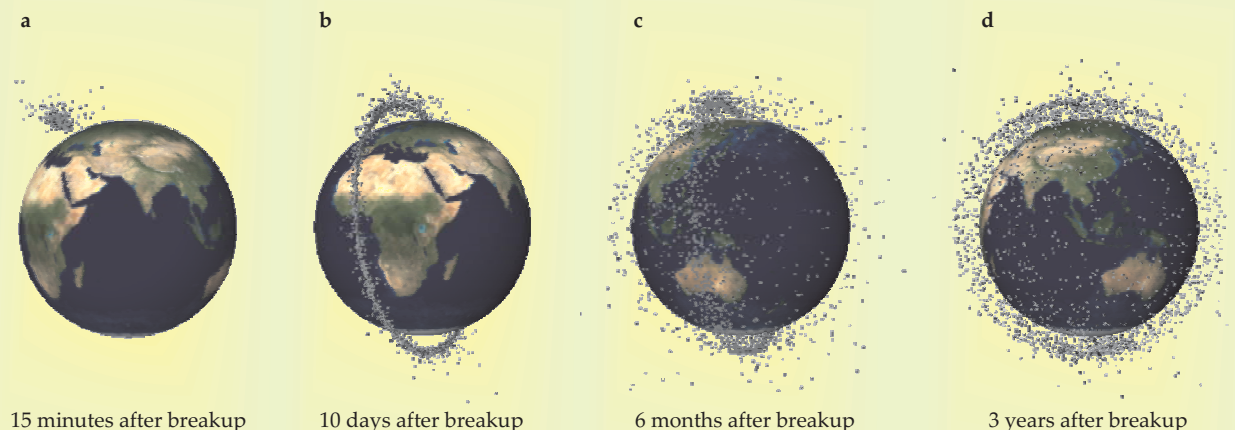


Figure 6. Evolution of orbits for debris larger than 10 cm, following the breakup of a satellite due to an antisatellite attack as described in the text. If the original satellite followed a nearly circular orbit, the debris remains concentrated at altitudes near that of the satellite.

than the orbital speed of the satellite. In particular, for debris larger than 10 cm resulting from a collision of the type being considered here, 80% of the particles would have relative speeds less than 0.25 km/s, which is only 3% of the 7.5 km/s speed of the orbiting satellite. A similar result holds for smaller debris particles.

Because the relative speed of most debris particles is small compared with the orbital speed of the satellite, the total velocity of the particles would be very close to the original orbital velocity of the satellite, and the particles, especially those with large mass, would follow orbits at an altitude close to that of the original satellite.

The distribution of speeds of the debris particles will cause the debris to spread out along the orbit of the original satellite within several days (see figures 6a and 6b). Once it is spread out, the debris will pose a collision threat to essentially all satellites whose orbits pass through that altitude.

Over time, forces due to anisotropies in Earth's gravitational field will cause the debris orbits to precess around Earth's axis at slightly varying rates, so the debris will spread out of the plane of the original orbit (figure 6c). For debris in a nearly polar orbit, after a few years the particles would be essentially uniformly distributed within a shell around Earth (figure 6d). Debris in orbits near the equator would slowly spread into a band around it.

Preserving the space environment

Space is uniquely suited for a range of important uses, such as communication, Earth observation, and navigation, and in the 50 years since *Sputnik 1*, society has become highly dependent on satellites. As we start the second 50 years of the space age, failing to take steps to preserve humanity's ability to use space would be incredibly short-sighted. Controlling the production of debris is crucial to the sustainable use of space.

The international community has begun to take steps in the right direction by developing debris-mitigation guidelines for routine activity in space. However, there are no legal restrictions on the testing or use of weapons intended to destroy satellites in orbit. Given the very large quantities of debris that would be created by destroying satellites, such weapons could have a significant, long-term impact on the

space environment. Developing international measures to prohibit the testing or use of kinetic-energy ASAT weapons should therefore be an international priority.

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