ORBITAL DEBRIS PRODUCED BY KINETIC-ENERGY ANTI-SATELLITE WEAPONS

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INTRODUCTION

Space debris can pose a long-term threat to the future use of outer space.[1] One of the biggest sources of such debris would be the intentional destruction of satellites by anti-satellite (ASAT) weapons.

Due to their very high speeds in orbit, even relatively small pieces of debris can damage or destroy satellites. Since debris at high altitudes can stay in orbit for decades or longer, it accumulates with time as more is produced. As the amount grows, the risk of collisions with satellites also grows. If the amount of debris at some altitude becomes sufficiently large, it could become difficult to use that region for satellites.

Since there is currently no effective way to remove large amounts of debris from orbit, controlling the production of debris is essential for preserving the long-term use of outer space.

There are two main sources of debris. The first source is routine space activity. This includes debris released in the process of launching satellites and debris created by the break-up of defunct satellites or booster stages in orbit, either due to explosions from leftover fuel or collisions with a second object.

The international community is attempting to address this issue, in part by developing debris mitigation guidelines to limit the debris created during routine space activities. This includes efforts by the Inter-Agency Space Debris Coordination Committee (IADC),[2] as well as guidelines developed by the UN Committee on the Peaceful Uses of Outer Space (COPUOS), which call for actions such as removing satellites from orbit when they are no longer operational.

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The second source of debris is the intentional destruction of satellites in orbit by the testing or use of kinetic-energy ASAT weapons, which are intended to destroy satellites by physically colliding with them at high speed.

The use of such weapons can create enormous amounts of long-lived debris in orbit. While there is a general recognition that the debris created by such events is a problem for the space environment, the scale and severity of this problem does not appear to be widely understood.

This paper provides an introduction to the current debris population in outer space, and presents the results of calculations that show that the destruction of a *single* large satellite, similar to many of the current military reconnaissance and surveillance satellites, could have a significant, long-term impact on the space environment. Such an event could create as much large debris as would be generated in 70 to 80 years of routine space activity under strict debris mitigation measures of the kind mentioned above.

The calculations discussed in this paper use a model developed by the US National Aeronautics and Space Administration (NASA) to describe the break-up of satellites. This model is based on ground tests and historical break-up events, and has become the standard model for estimating the amount of debris resulting from the break-up of a satellite and the characteristics of that debris.

Orbital debris

Table 1 gives current estimates of the amount of orbiting space debris larger than 1mm. Roughly half of the total debris population is in low Earth orbit (LEO), that being at altitudes less than 2,000km.

The US Space Surveillance Network currently catalogues more than 11,000 objects.[3] This number is a small fraction of the total debris population, since for an object to be placed in the catalogue it must be tracked by ground sensors and its origin must be known. The objects in the catalogue primarily include debris particles with size greater than 5–10cm that orbit at relatively low altitude, as well as roughly 850 active satellites.[4]

Table 1. Estimated amount of debris in LEO

	Debris size		
	1mm to 1cm	**1cm to 10cm**	**> 10cm**
LEO debris	16 million	270,000	14,000
Total debris at all altitudes	150 million	650,000	22,000

Source: European Space Agency MASTER 2005, plus estimate of debris from the January 2007 Chinese test.

Since any object in a circular orbit at an altitude of 500km travels at 7.6km/s, even small pieces of debris can seriously damage or destroy a satellite.[5]

Debris between 1mm and 1cm in size can cause significant damage if it hits vulnerable parts of a satellite. While shielding exists that can protect against objects of this size, adding shielding increases the cost of satellites, and many satellites have minimal shielding.

Debris greater than about 1cm in size is dangerous since it can seriously damage or destroy a satellite in a collision, and there is no effective shielding against such particles. Debris between 1 and 10cm in size is especially dangerous because it is difficult to shield against, and since it cannot be reliably detected or tracked, satellites are unlikely to have warning to allow them to avoid colliding with such objects.

Debris greater than 10cm in size is a concern because it may be massive enough to cause a satellite to break up in a collision, creating large amounts of additional debris.

It is important to recognize that the altitude at which a satellite orbits is closely related to its function. For example, Earth imaging satellites are typically in orbits between about 300 and 1,000km altitude, since orbiting at higher altitudes would lower their resolution, and orbiting at lower altitudes would decrease the ground area they can see and increase the atmospheric drag, which would reduce their lifetime. As a result, creating debris at these altitudes can inhibit the ability to use outer space for these purposes.

Orbital debris is concentrated in those altitude bands that are heavily used, especially the bands from 800 to 1,000km, 1,400 to 1,500km, and the geostationary belt (36,000km). Nearly 3,000 of the 11,000 objects in the US catalogue lie in the altitude band from 800 to 1,000km.[6]

The lifetime of a piece of debris—the length of time it remains in orbit—depends on how strongly it is affected by atmospheric drag. This depends on the object's mass, size, and shape, and on the atmospheric density at the altitude at which it is orbiting. Since atmospheric density drops off roughly exponentially with altitude, orbital altitude has a dramatic effect on drag and debris lifetime. For example, an object with a lifetime of a couple of weeks if it were orbiting at 300km would have a lifetime of a year if it were orbiting at 500km altitude, a lifetime of several decades if it were orbiting at 700km and more than a century at 800km.

Kinetic-energy ASATs

In principle there are many types of weapons a state could use to interfere with the operation of a satellite, some of which are reversible (such as electronic jamming of satellite communications or laser dazzling of imaging satellites) and some of which are intended to damage the satellite (such as kinetic-energy weapons, high-power microwave weapons, or high-power lasers).

However, if attacks on satellites were to become viewed as legitimate acts during a conflict, there are incentives that could push states to use kinetic-energy ASATs for such attacks. In particular, the effectiveness of many of the ASAT weapons mentioned above is uncertain and difficult to verify. For example, the vulnerability of a satellite to a microwave weapon would depend on details of the satellite's design that the attacker is unlikely to know. Moreover, even if such an attack were successful and damaged the satellite's electronics, the satellite might not be completely disabled, and the attacker might not be able to verify how successful the attack was.

A successful attack by a kinetic-energy ASAT weapon, however, would likely cause damage that could be seen by sensors on the ground, and detecting severe physical damage would strongly imply that the satellite was no longer functioning. As a result, if a satellite were deemed an important enough military asset that a state decided to attack it, that country might have a strong incentive to use a kinetic-energy ASAT.

DEBRIS FROM A KINETIC-ENERGY ASAT ATTACK

Computer models developed in the past decade give a good approximate description of the debris resulting from the destruction of a satellite by a high-speed collision. The most comprehensive is NASA's Standard Break-up Model.[7]

We apply this model to the case of a kinetic-energy ASAT weapon with a mass of a few tens of kilograms colliding at velocities in excess of 7km/s with a satellite having a mass of 1 to 10 tons. This calculation gives the number of debris particles created and the size, mass and velocity distribution of these particles. This information, along with data on atmospheric density, can be used to calculate the orbits of these particles and estimate their lifetimes.

A collision of this kind would be "catastrophic", meaning that it would cause the satellite to completely fragment into debris particles (assuming a direct hit on the central mass of the satellite). This fragmentation occurs since the energy of the collision would be equivalent to detonating several hundred kilograms of high explosives.

The NASA model gives a condition for when a collision between a large object and a smaller one will be catastrophic.[8] According to this condition, an interceptor of 20kg striking a large satellite at 7.5km/s could completely fragment a satellite with a mass up to about 14 tons. This situation is relevant to satellites in LEO, since the orbital speed of satellites is roughly 7.5km/s, which sets the scale of the intercept speed for these attacks.[9] Of the nearly 400 active satellites in LEO, more than 200 have a mass greater than 450kg, more than 60 have a mass greater than one ton, and roughly 15 have a mass greater than five tons.

For an attack on a satellite in geostationary orbit (GEO), typical intercept speeds would be roughly 3km/s, which is the orbital speed of a satellite in GEO. At this speed, a 50kg ASAT could completely fragment satellites with mass up to about 5 tons. There are currently well over 300 active satellites in GEO with a mass of 1 to 5 tons; the vast majority of these are communication satellites, but they include US early warning satellites as well.

NUMBER OF DEBRIS FRAGMENTS FROM AN ATTACK

The catastrophic break-up of satellites in orbit could produce a dramatic increase in the amount of space debris.

Applying the NASA model shows that the catastrophic break-up of a single 5- to 10-ton satellite would roughly double the total amount of debris currently in LEO greater than 1cm in size (Table 2).

Table 2. Estimated current debris population in LEO compared with the debris created by the catastrophic breakup of a 5- to 10-ton satellite

	Debris size		
	1mm to 1cm	**1cm to 10cm**	**> 10cm**
Current debris in LEO	16 million	270,000	14,000
Debris from the breakup of a 5- to 10-ton satellite	8–14 million	150,000–250,000	3,000–5,000

Note that the 3,000 to 5,000 pieces of large debris listed in Table 2 is two to three times the roughly 1,500 pieces of debris with size greater than 10cm currently in the heavily used altitude band between 800 and 900km. If the satellite that was attacked had its orbit within that band, the resulting debris would be concentrated in that same region and would make the debris problem much worse. At other altitudes, this amount of debris would represent a much larger percentage increase over the existing debris.

Table 3 shows estimates of the debris created by China's destruction of the FY-1C satellite in January 2007. This debris added significantly to debris population between 800 and 900km altitude.

Table 3. Estimated debris from the destruction of the Chinese FY-1C satellite in January 2007

	Debris size		
	1mm to 1cm	**1cm to 10cm**	**> 10cm**
Estimated debris from FY-1C breakup	2 million	40,000	1,500

DEBRIS LIFETIME

If the targeted satellite was orbiting at an altitude above about 800km, then a large fraction of the debris particles created in such a collision would remain in orbit for decades or longer. The debris lifetime would increase rapidly with altitude.

The only previous test of a kinetic-energy interceptor that destroyed a satellite was conducted by the United States in September 1985.[10] This test created roughly the same amount of debris as the Chinese test since both satellites had masses of roughly one ton. Improvements in the US Space Surveillance System between 1985 and 2007 mean that the system is capable of detecting many more particles today than in 1985.

Because the US test took place at an altitude of roughly 500km, compared to about 850km 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 had decayed within a decade, while a significant fraction of debris from the Chinese test is expected to remain in orbit for decades.

DEBRIS DISTRIBUTION IN SPACE

Most of the debris created when a satellite is destroyed in a collision will follow orbits with altitudes that are close to that of the original satellite; this is especially true for large fragments. Over time, the cloud of debris fragments will spread out in a band or shell around the Earth.

The distribution of speeds of the debris particles will cause the debris to quickly spread out along the orbit of the original satellite within several days (see Figures 1 and 2). Once it is spread out, the debris will pose a collision threat to essentially all satellites whose orbits pass through that altitude.

Over time, various forces[11] will cause the particles to spread out of the plane of the original orbit (Figure 3). For debris in a nearly polar orbit, after several years the particles would be essentially uniformly distributed within a shell around the Earth (Figure 4). Debris in an equatorial orbit would slowly spread into a band around the equator.

Figure 1. Cloud of debris of size greater than 10cm after 15 minutes

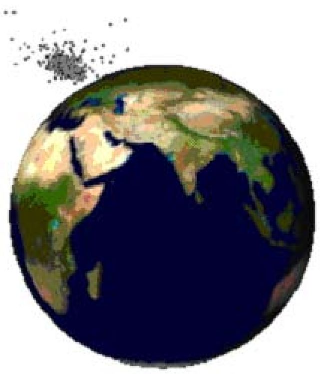


Figure 2. Debris cloud after 10 days

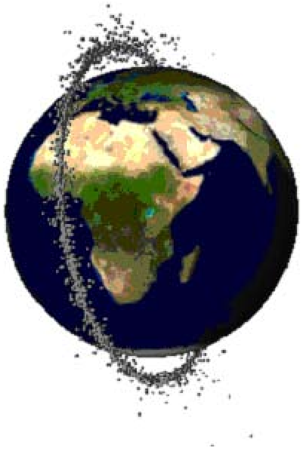


Figure 3. Debris cloud after 6 months

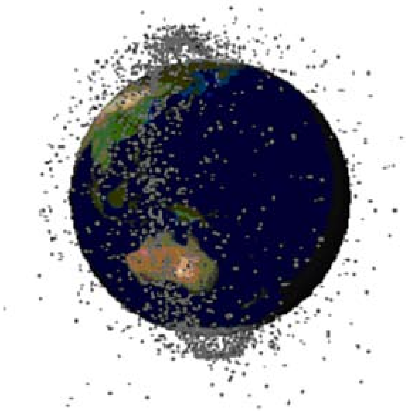
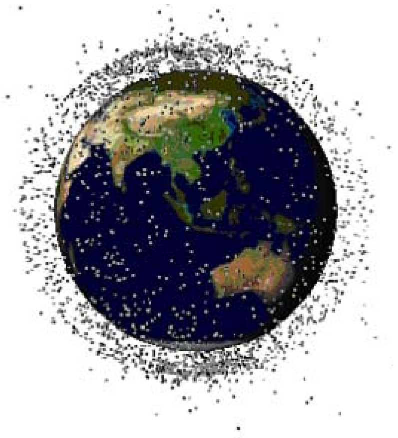


Figure 4. Debris cloud after 3 years



Conclusion

The risk of collision between an individual satellite with a piece of debris large enough to significantly damage or destroy it is currently small, but not negligible. For a medium-size satellite in the altitude band in LEO where the debris density is the largest, this risk is approaching 1% over a satellite's 5- to 10-year lifetime. At that level this risk is likely comparable to other reasons that a satellite might fail.

The debris from the Chinese test may have roughly doubled that probability for the next few years at altitudes near the altitude of the test. But the absolute threat is still small. However, more such events, and especially the break-ups of larger satellites, could significantly increase this threat and could make certain altitude bands unsuitable for use by satellites.

Controlling the production of space debris is therefore crucial for the sustainable use of outer space. Such controls must limit both the debris production by routine space activity and by intentional attacks on satellites.

Some altitude bands in outer space already have such a high density of debris and satellites that collisions will occur among these objects, creating more debris. As a result of this slow-motion chain reaction, the number of debris particles will continue to increase even if no additional objects are launched into these bands.

A recent study showed that the number of debris particles in the heavily used band between 900 and 1,000km altitude is expected to more than triple in the next 200 years, even if no new satellites or debris are launched into this altitude band.[12] The intentional destruction of a satellite at this altitude could add a significant amount of large debris, which could speed up this chain reaction considerably.

Outer space is uniquely suited for a range of important uses, such as communications, Earth observation and navigation. Interfering with the ability to use outer space for those purposes would be incredibly short sighted. An urgent and important step toward this goal is an international agreement to ban the testing and use of destructive ASAT weapons.

Notes

[1] Orbital space debris is any human-made object in orbit that no longer serves a useful purpose.

[2] See, for example, the Inter-Agency Space Debris Coordination Committee at <www.iadc-online.org>.

[3] NASA Orbital Debris Program Office, The Orbital Debris Quarterly News, vol. 11, no. 2, April 2007, <http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv11i2.pdf>.

[4] For a database of active satellites, see <www.ucsusa.org/global_security/space_weapons/satellite_database.html>.

[5] This speed corresponds to roughly 30,000km/hr (approximately 20,000 miles per hour).

[6] NASA Orbital Debris Program Office, The Orbital Debris Quarterly News, vol. 11, no. 2, April 2007, <http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv11i2.pdf>.

[7] N.L. Johnson, P.H. Krisko, J.-C. Liou and P.D. Amz-Meador, "NASA'S New Breakup Model of EVOLVE 4.0", Advances in Space Research, vol. 28, no. 9, 2001, pp. 1377–84.

[8] The condition given in the NASA model for a catastrophic collision is that the kinetic energy of the smaller object divided by the mass of the larger object must be greater than 40J/g.

[9] This is true of ground-based direct-ascent ASATs and orbiting ASATs that lie in orbits that cross the orbit of the target satellite. Co-orbital ASATs would typically have a much lower speed, but may not rely on the kinetic energy of collision as the kill mechanism.

[10] Laura Grego, "A History of U.S. and Soviet ASAT Programs", Union of Concerned Scientists Background Paper, 9 April 2003,<www.ucsusa.org/global_security/space_weapons/a-history-of-asat-programs.html>.

[11] The primary force that rotates the orbital plane of objects in low Earth orbit arises from variations in the Earth's gravitational field.

[12] J.-C. Liou and N.L. Johnson, "Risk in Space from Orbiting Debris", *Science*, vol. 311, no. 5759, 20 January 2006, pp. 340–341.