What Can Be Done About Space Debris?

Collisions in orbit pose a serious threat to satellites and spacecraft. But even if they can be predicted, it could be impossible to prevent them.

David Finkleman

On February 10, 2009, two communications satellites—Cosmos 2251 and Iridium 33—collided catastrophically in Earth orbit, 789 kilometers above northern Siberia. The event was not entirely a surprise: Many observers had recorded and tracked noticeably close approaches between the pair. However, in terms of both the minimum distance between the satellites and the complicated calculations that predict the probability of collision, these satellites were not considered particularly at high risk. Among all the known close-approaching satellites, these two were hardly even in the top 200. Yet, they collided.

Both Cosmos 2251 and Iridium 33 were in orbits highly inclined relative to the Earth's equator. Such paths cross the orbital planes of many satellites in low Earth orbit, although the crossings do not necessarily intersect the orbits themselves. Every day there are dozens of approaches within 100 kilometers between such satellites, many within 10 kilometers or less. But the 2009 collision is the only one ever to occur between two distinctly different, unrelated satellites, illustrating the complexity of the issue.

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Even when orbital experts can perceive that satellites might be threatened, most warnings cannot be acted on. Either the danger is calculated too late for the satellite to be maneuvered, or the objects involved are not maneuverable at all.

Such impacts are only the start of the problem. The debris generated from a collision then becomes a hazard to other orbiting objects. Observers perceived 598 Iridium fragments and 1,603 Cosmos fragments from the impact, implying a relatively glancing blow. This debris continues to be monitored as closely as any object in orbit, but it is infeasible either to see or keep track of all that there might be. The mechanics of satellite breakup are also not well understood. What we do know is that all materials fragment differently, and that the numbers, size ranges, and masses of fragments have a finite limit. Debris in space does not grind itself down into dust.

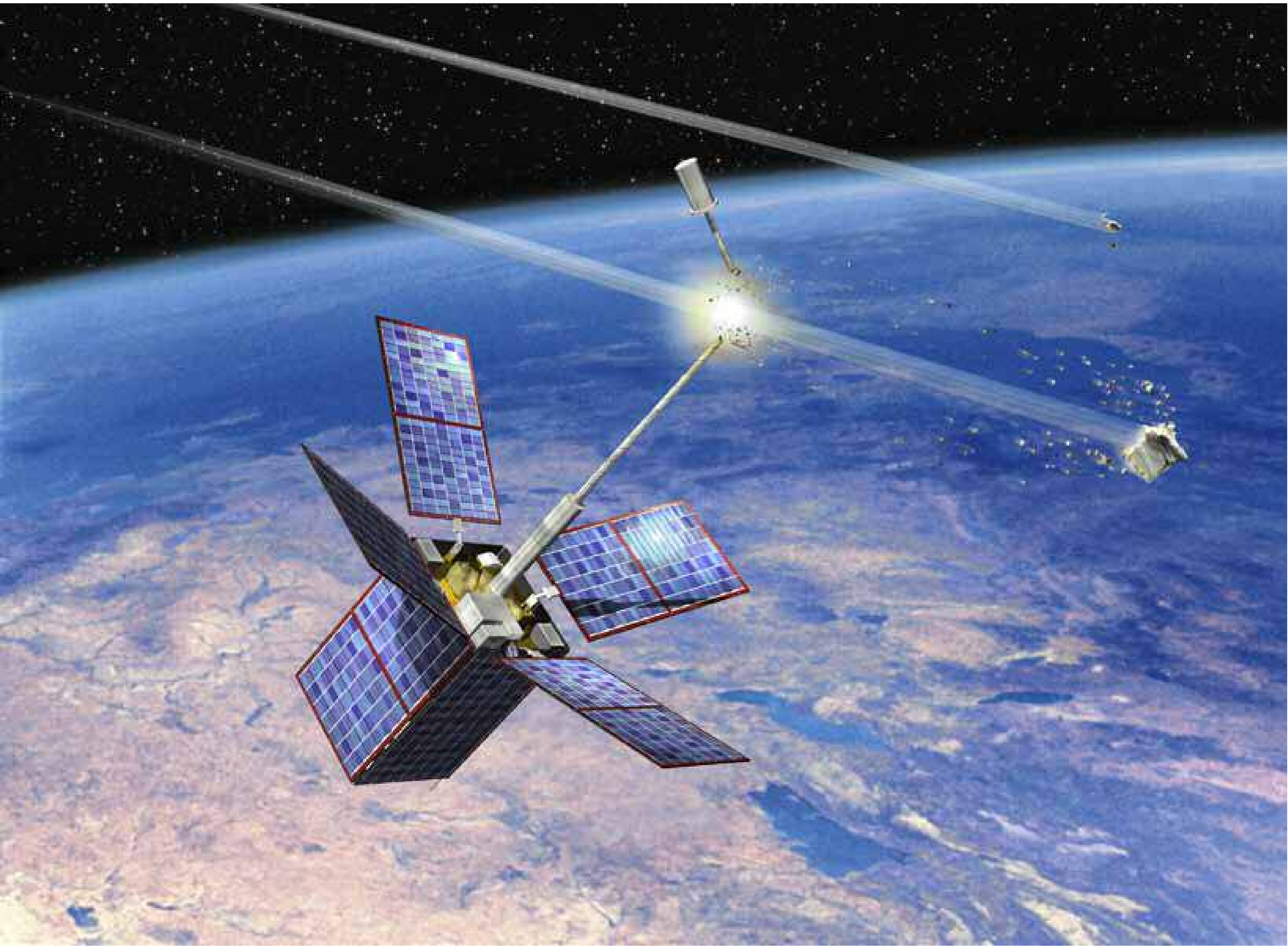
NASA's Orbital Debris Program Office estimates that there are currently over 21,000 fragments larger than 10 centimeters in orbit. Particles between 1 and 10 centimeters might number about 500,000, and those under 1 centimeter could exceed 100 million. We will never know for certain, and we cannot act on what we can only conjecture. NASA policy is that the International Space Station has to maneuver away from an object if the chance of collision exceeds 1 in 100,000, which occurs about once a year, on average. Extremely fine particles hit the ISS all the time, without much effect.

With the increasing number of launches comes a growing space debris challenge. In February 2013, the United Nations' Inter-Agency Space Debris Coordination Committee released a report projecting that, over the next 200 years, the rate of catastrophic collisions—defined to involve debris larger than 10 centimeters and an impact energy of more than 40 joules per gram—might occur once in every five to nine years. Most of the accumulation of space debris is expected to happen in orbits low around the Earth, at an altitude of 800 to 1,000 kilometers, because those orbits are highly populated (and at lower altitudes, debris tends to fall into the Earth's atmosphere and burn up).

All of those pieces of information still leave a lot of questions. The Cosmos-Iridium collision exemplifies that the separation between satellites is not the only factor determining their risk of collision. If we do not know where a satellite is, the mean miss distance could be very wrong. The amount of debris in Earth orbit makes it seem like a huge problem—but is it really? Is the space debris hazard headed for a tipping point? At present it is still not clear that the risks and costs of collisions are frequent enough to warrant the expense of cleaning up that debris, as opposed to not creating more debris in the future.

Answering those questions will require addressing how to determine actual risks, how to correctly model the consequences of the debris in orbit, and how to present the situation clearly to the public and those who can act on these problems. The roadblocks to working out these dilemmas are both scientific and political. The scientific conundrum is that there is little relevant information on the possible magnitude of the problem. The political conundrum is that measures to mitigate dangerous events do not produce immediately quantifiable results and may require decades or centuries to yield concrete benefits.

Fortunately, a modest investment—a minor fraction of the millions it takes to build and launch a satellite—if correctly applied, might have great leverage to mitigate the consequences of space debris. Perhaps no other human



The French satellite Cerise was hit by debris from an expended Arianne rocket on July 24, 1996, in what was likely the first documented case of a collision between two manmade objects in space. The impact, illustrated here, caused the satellite to start tumbling, but it was reprogrammed and the mission continued. This and a few other high-profile orbital collisions have produced trackable debris, but as yet there have been no secondary collisions with other satellites.

endeavor has encompassed such diverse scientific, technical, practical, and legal disciplines. How we address these concerns may have great influence on the increasingly complex issues of human commerce. Satellites and their related space operations are pivotal to the world's economy, encompassing about $80 billion in annual revenue. Through everything from spy satellites to satellite TV, they are key to global safety and to sustaining our quality of life.

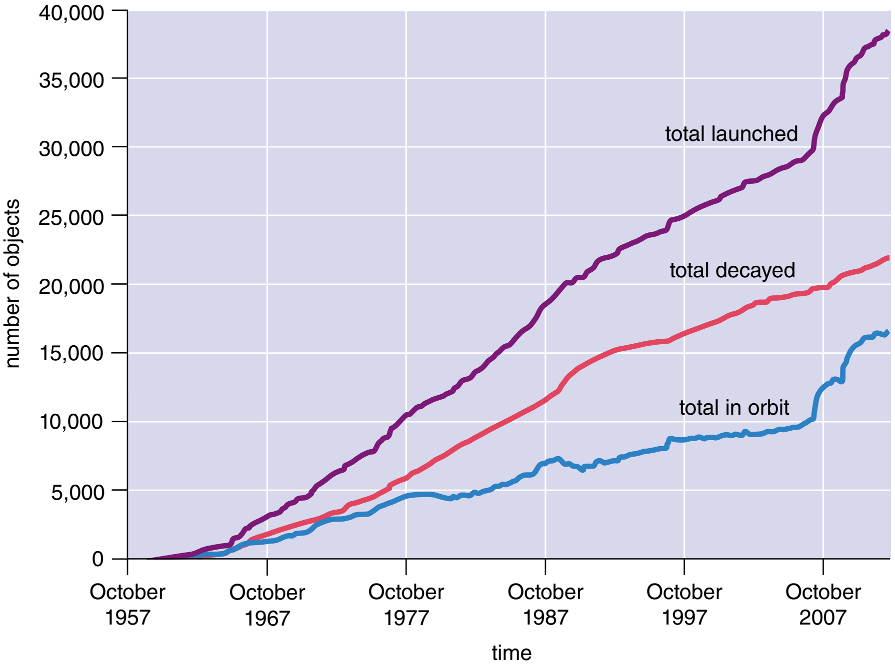
Orbits on the Move

At least 100 new satellites are launched every year, and there are currently over 1,000 operational ones in orbit, each of which can have a lifetime of 10 to 15 years. This population has ballooned since the first launches in the 1950s, as shown in the graph on page 28.

Although the combined number of orbiting spacecraft and pieces of space debris sounds enormous, extraterrestrial space is actually relatively empty. The chance of collision depends on the density of the traffic and on the trajectories of the objects. NASA has to use measures for collision avoidance among the spacecraft orbiting Mars, even though they are relatively few in number, because they may need to be in close proximity to communicate with experiments in approximately fixed locations on the surface. Satellites in the most productive orbits about the Earth also are at higher risk of collisions (*see the top figure on page 29*).

The most heavily populated paths in Earth orbit are ones where the satellite's orbit passes over the same spot on the ground at the same time every day (Sun synchronous), ones where the orbit speed is the same as the rate that the Earth rotates (geostationary), and orbits whose planes are highly inclined relative to the equatorial plane (*as shown in the bottom figure on page 29*). The Global Positioning System (GPS) satellites are placed mid-way to synchronous, at altitudes of about 20,000 kilometers, where there is no atmospheric drag and light pressure from the Sun is small.

To determine the risk to a satellite, we have to know where it is, and to do that we must distinguish between the characteristics of an orbit and the loca-



Nearly 40,000 discernible mamade objects orbit the Earth, of which fewer than 4,000 are active satellites. Space debris resides in diverse orbits and encompasses a wide range of sizes and masses. Roughly 95 percent of the mass is contained in the largest 5 percent of the objects. Just two orbital encounters caused the jump in the number of fragments shown at the right end of the blue line.

tion and state of motion of a satellite in that orbit. Classically, the shape of orbits has been defined with a mathematical construct called a *conic section*—an oval-shaped slice through a cone—but this is not sufficiently precise. We now know that the Earth's internal mass is nonuniform and dynamic: There are tides in the solid parts of the Earth just as there are in the oceans. This variation causes fluctuations in the paths of satellites orbiting the Earth. In addition, the Moon, the Sun, and other massive bodies perturb satellite orbits about the Earth.

At high altitudes, such as 35,780 kilometers up, where geostationary satellites are placed, momentum transfer from photons (called *radiation pressure*) can be comparable to or greater than the effects of gravity. At low altitudes, such as the 250-kilometer-high orbit of the Hubble Space Telescope, there is aerodynamic drag even in the tenuous atmosphere. Drag and radiation pressure dissipate energy and change orbits (although radiation pressure can also add energy).

The upshot is that orbits are not pristine conic sections. At best one can describe the instantaneous states of satellites in terms of a conic section that is tangent to the satellite's trajectory at that moment, an osculating (or kissing) orbit. Moreover, there are notable gaps in knowledge of the integrated effect of the space environment on space object dynamics.

When describing orbits, astronomers and astrodynamicists are trapped with arcane terminology developed over centuries of observation and inference. The box on page 30 explains this classical vocabulary. Perturbations cause the orbit to rotate, or *precess,* about the Earth's axis and force the orbit's semi-major axis to rotate within the orbit plane. All orbits change all of the time. Geostationary satellites are not truly stationary, but require regular propulsive maneuvers to maintain their positions. Therefore, we often speak of satellite *trajectories* rather than satellite orbits. Although simple Keplerian orbits are closed curves, perturbations mean that satellites never return to the exact same location as in a previous revolution. These changes are minute for some orbits, and are used as calibration sources for sensors and orbit determination techniques.

Companies and government agencies choose certain trajectories because they might require the least energy to maintain, have favorable geometries for missions, or are easiest to analyze. But regulations for NASA, the European Space Agency (ESA), and others also require the testing of proposed orbits against the likelihood of collisions over the lifetime of a satellite and beyond. The probability of collisions is estimated statistically using models of the near-Earth population and its possible evolution. These models do not evaluate space object trajectories and their uncertainties, but rather attempt to infer densities of objects in orbit and predict collisions from the evolution of these densities.

Orbits that exceed collision probability thresholds are rejected even if they might be the most efficacious. Such estimates are extremely uncertain, however. The box on page 31 demonstrates that the greater the uncertainty, the lower the probability of collisions, because we are so ignorant of where a satellite might be far in the future that it could be almost anywhere: It is unlikely that two would be in the same place at the same time. It is not ideal to make decisions based on ignorance, but it is very hard to gain more knowledge. One answer is to err on the side of conservatism, avoiding as much risk as possible.

A Universe of Uncertainty

Despite the best efforts of mission planners, the quality of satellite trajectories is limited by imprecise and sparse measurements with much uncertainty. Models of physical phenomena are incomplete and not consistently integrated. Both measurement and modeling errors affect estimates of the future locations of spacecraft.

Such estimates are created using three methods: filtering, smoothing, and estimation. Filtering estimates states using data acquired up to the present, whereas smoothing progresses backwards using data acquired or inferred prior to and after the time of interest. Estimation uses the trajectory and its uncertainties that were developed with filtering and smoothing to approximate a future location of the satellite.

There is an extensive history of research into orbit determination. Some methods are the equivalent of minimizing the sum of the squares of the differences between an assumed trajectory and available data, a technique called *least squares.* Some orbital dynamicists augment their data set as new observations arrive, and diminish or eliminate data from a past event that might have been influenced by physics different than the present.

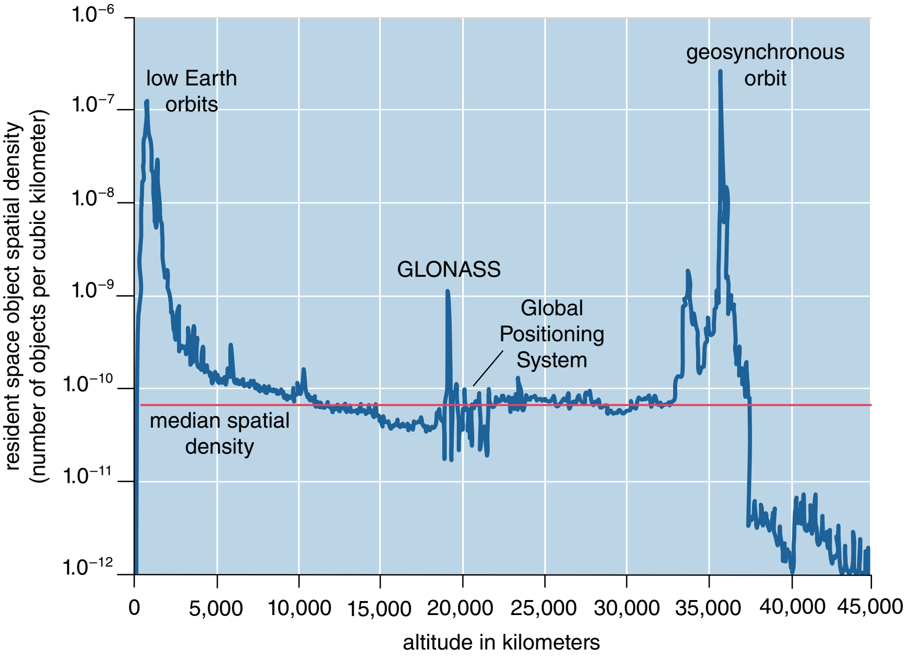
The more sparse and imprecise the observations of a satellite's current location, the greater the uncertainty. A satellite's orientation, mass, and physical characteristics are not always known well, either. Rigorous quantification of this uncertainty is essential. Satellites in orbit are observed from Earth by a number of telescopes and radars, as shown in the map on page 32. Additional groups also play a role. For example, the team that discovered Comet ISON is actually dedicated to monitoring satellites and debris. Relative to the number of objects in orbit, these monitoring stations are far too few, and they are not necessarily well equipped to support the precision that operators need. Even those who operate satellites other than in geostationary orbit know less and less precisely where their satellites are as the spacecraft migrate out of control station visibility.

Observers and operators all over the world collaborate to achieve the best trajectories they can, but still the states of individual objects in Earth orbit can be predicted confidently only a few days in the future. The farther out we look, the less detail we can predict. Decades in the future, the best we can do is estimate probabilities that there might be collisions, but not what objects might collide or when over a long interval.

We predict close approaches and possible collisions by convolving the growing uncertainties of objects in orbit. This process is very much like quantum mechanics, in which an entity is described by a probability density and a future state can only be estimated statistically. Although current practice is dominated by estimating the minimum separation between averaged orbits, depending on how imprecise the estimates are, this method may be neither necessary nor sufficient to perceive the likelihood of collisions. The large numbers of "close approaches" are frequently cited in the media, but they do not imply that there might be many collisions (a close approach is defined as anywhere from 5 to 50 kilometers, depending on the operator). But as shown in the box on page 31, the greater the intersection of the volumes of two approaching satellites, the higher the probability of collision.

The most precise estimates of orbits and collisions are those made closest to the time and location of the putative event, ideally with the input of recent observations and orbit determination. But such predictions do not come far enough in advance to avoid a collision if one is imminent. Satellite operators can rarely develop and execute maneuvers in a few hours, and maneuvers close to the moment of contact require much more energy than ones planned deliberately far in advance. Such actions could waste a spacecraft's limited supply of fuel, reducing its active lifetime.

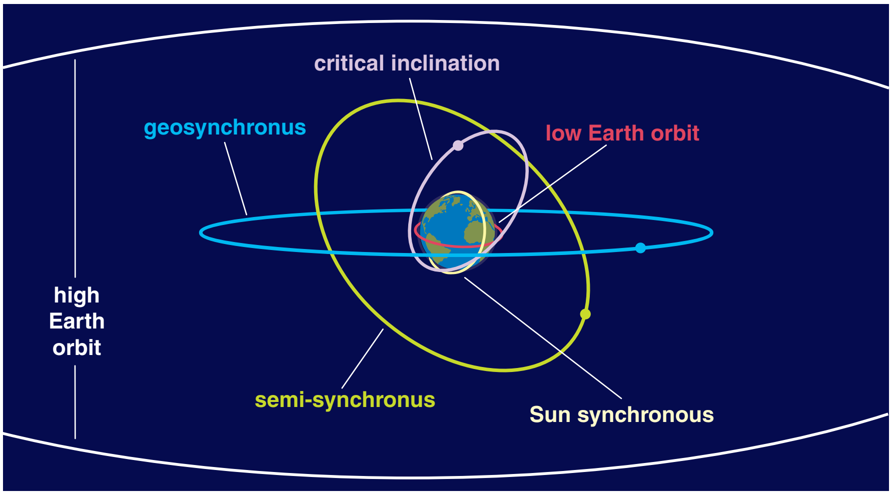
The conflict between precise knowledge and the ability to plan and execute maneuvers is called actionability. Many warnings of possible collisions are not actionable, and many actionable warnings are based on so much uncertainty that the probability of collision is (ignorantly) low. Maneuvers performed ostensibly to avoid collisions have often been unnecessary or even increased the likelihood of disaster by placing the satellite in the path of an even greater danger in the future.



Density of objects at different altitudes is a useful, though incomplete, measure of risk. Low Earth orbit and geosynchronous orbit are the most crowded regimes; other peaks correspond to the GPS satellites and the Russian equivalent, GLONASS. The greatest density corresponds to only about one object per 10 billion cubic kilometers; average separation between orbiting objects is a few hundred kilometers in the densest regions, a few thousand elsewhere.

Breaking It Down

Satellites are extremely complex and fragile devices. They must produce power and propulsion, storing as much energy as densely as possible, yet en-



The most heavily populated orbis around the Earth, shown schematically: Sun synchronous orbits pass over a given point on the ground at the same time every day. Geosynchronous orbits have an orbital period of one day, so satellites there remain locked over one location on the Earth. Semi-synchronous orbits are useful for navigation satellites. Critical inclination orbits maintain a stable longitude of their semi-major axis. Low Earth orbits are at about 200 to 2,000 kilometers; high Earth orbits are at altitudes above about 36,000 kilometers.

able sufficient heat transfer to dispose of inevitable thermodynamic waste. Their structure must withstand launch stresses and vibration, support sensitive instruments, and still be as light as possible. These characteristics lead to complicated structural failure modes and fragmentation, most of which have not been well described.

Representative satellites have been destroyed intentionally, in closed-space impact tests conducted by the Air Force Arnold Engineering and Development Center in Tullahoma, TN. Fragments are collected and their mass and size distributions are studied statistically. These results can be used to model the distribution of energy among the fragments. Detailed gas and structural dynamics simulations also have been developed for pressurized tanks. However, none of these data are widely accepted. Most space agencies, NASA among them, maintain their own fragmentation models.

Because collisions at hypervelocity speeds—from 1 to 20 kilometers a second—are nonequilibrium phenomena, mechanical energy and momentum are not necessarily conserved. The duration of the encounter is less than the time required for the disturbance to be communicated throughout the structure. Ordinarily flexible materials behave as solid, brittle masses because stress-relieving energy transfer within the material cannot occur in the short duration of the encounter. Eventually, plastic deformation dissipates energy.

Some initial energy emerges as heat and the tumbling dynamics of individual fragments. The energy of the colliding masses includes not only that stored for propulsion and power but also the strain energy stored in the structure. For example, a spring stores energy in the form of unrelieved stresses in the material. When the spring breaks, this is the source of energy that makes the broken piece fly away. Observations of some of the few collisions that have occurred suggest that the objects seem literally to pass through each other, emerging as clouds of fragments with a mean velocity the same as that of the parent object before the collision. This outcome has been called *ghosting,* and simulations assuming the existence of that activity seem to agree better with the observed consequences of collisions.

To assess the effects of even a single collision, we must divine the geometry of the collision, the orientations of the objects, the amount and distribution of stored energy, and fragment numbers, sizes, and energies. Gathering all that data is virtually impossible, but we can limit the problem somewhat. For example, the range of fragment sizes is finite. Structures disassemble where there are stress concentrations, such as where the external surfaces are attached to underlying structure. This event creates an upper bound to fragmentation. The lower bound can be estimated by the material composition, because all materials are nonuniform at a small scale. Metals have what are called *grain boundaries,* places where their crystalline structure doesn't align on the molecular scale. They also contain voids and inclusions. All of these faults create places of preferential fracturing.

What Makes an Orbit?

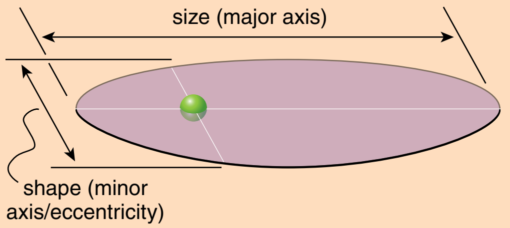
The terminology used to describe an orbit has been developed over centuries of astronomical observation, and the vocabulary can therefore seem a bit arcane. An orbit about a massive body is described by five independent parameters: size, shape, twist, inclination and rotation. All orbits (that do not escape gravitation) are ellipses, mathematical forms that have two foci, points that define the shape of the curve; the central body (*green sphere*) is located at one of them (the foci meet at the center if the ellipse is a circle).

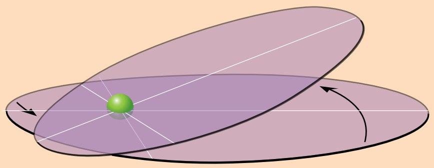
The size of the ellipse is specified by its perpendicular major and minor axes (*top diagram*). The ratio of the major to the minor axis is one plus the *eccentricity* (the amount the shape deviates from a circle).

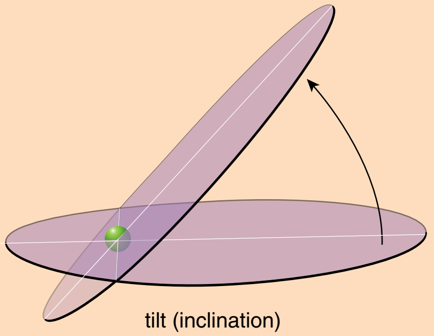
The major axis twists side to side relative to the Greenwich Meridian, and where the orbit plane intersects the Earth's equatorial plane is called the *longitude of the ascending node (second diagram*).

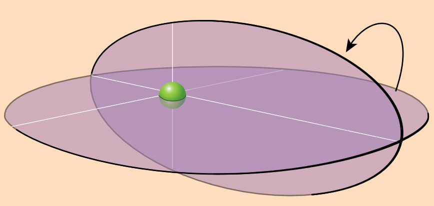
The angle that the orbit plane tilts up or down from a reference plane is called its *inclination* (*third diagram*). It is rotated from left to right about the major axis as well, so that the closest point to Earth is at a longitude called the *argument of perigee* (*fourth diagram*).

A final quantity is required to determine the position and velocity of a satellite in orbit: the angle around the orbit from the minor axis, a parameter called the *true anomaly.*




twist (longitude of the ascending node)


tilt (inclination)


rotation in plane (argument of perigee)

The vulnerability of satellites to encounters with small debris fragments can also be contained using a concept taken from the science of guns, ammunition, and armor: The *ballistic limit,* the velocity required for a particular projectile to reliably (at least 50 percent of the time) penetrate a particular piece of material.

The problem can be further limited if one considers the configurations of many satellites. Direct, complete contact between two colliding bodies in a conjunction with arbitrary geometry is unlikely. Solar panels are the greatest fraction of the cross-sections of many satellites. The panels are also a small fraction of the total mass. If a small satellite collides with a large one, it is unlikely that the large satellite would disassemble completely into a cloud of small fragments. The most consequential collision geometry in terms of the dispersion and energies of fragments is when the velocity vectors of the two objects are nearly perpendicular. Collisions between satellites in nearly the same orbit are mild in that the objects' relative velocities are low (but still at hypervelocity) and fragments should continue in nearly the original orbit. These thought processes narrow the possible outcomes but are extremely difficult to apply simultaneously to thousands of objects in diverse orbits.

Even if one knew well the distribution of fragment masses, sizes, and velocities, that still leaves open questions about where these fragments would go, and what damage they might cause. These problems are also difficult to solve. Propagation only a few days in the future is extremely imprecise. Long-term propagation of orbital objects is statistical and highly aggregated. It cannot reveal which satellites might be at risk.

Additionally, we do not know essential initial conditions well. At best, we have concepts of the statistical distributions of characteristics. One approach is to propagate the fragments taken as samples of the statistics. Conjunctions among these and resident satellites might indicate risk. Then these secondary collisions also generate fragments that must be propagated along with the initial population, and so on, with the assumption that the statistics of the outcome are trustworthy. Tests of this kind have been done only at the Lawrence Livermore National Laboratory, and only for a few specific initial states.

Putting It Together

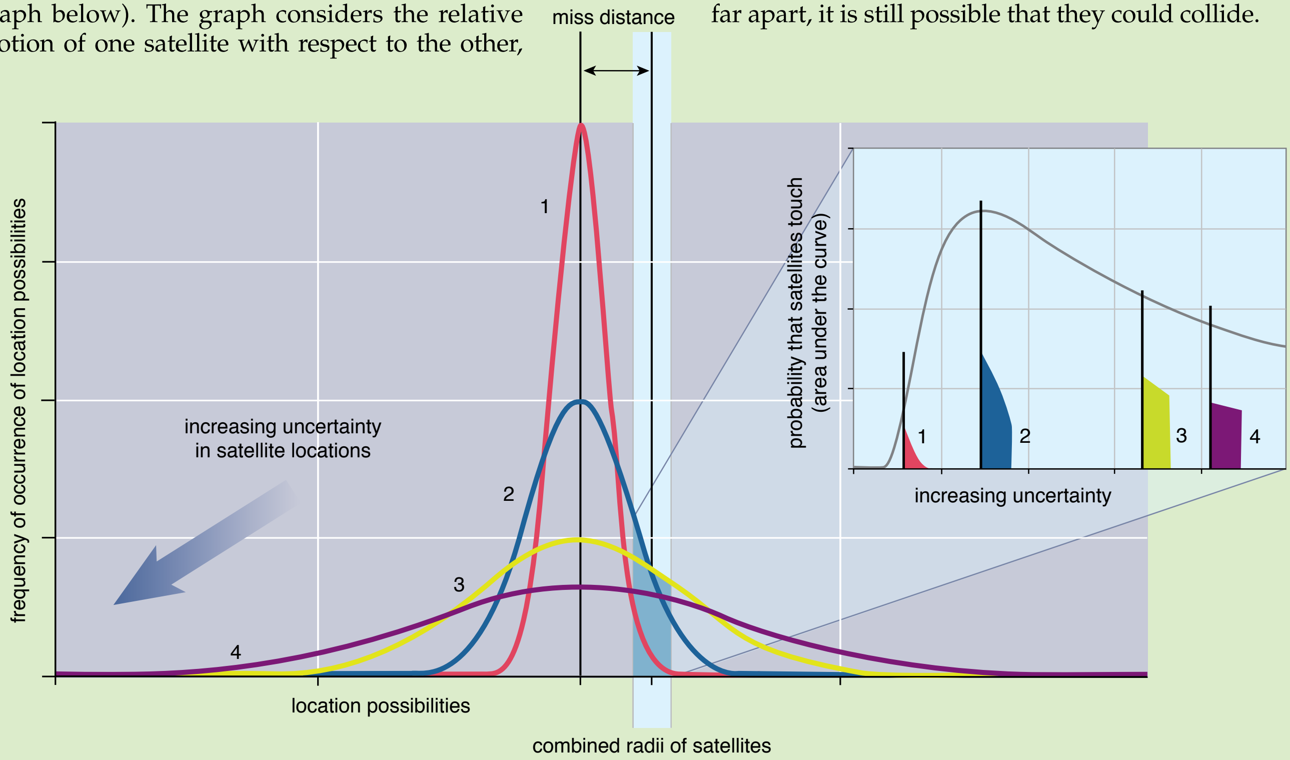
There is now a broad consensus that proliferating space debris is a serious matter. But the degree of uncertainty in fragmentation and the imprecision of long-term propagation of trajectories, poses serious challenges in quantifying the problem and identifying which actions would best diminish the risk.

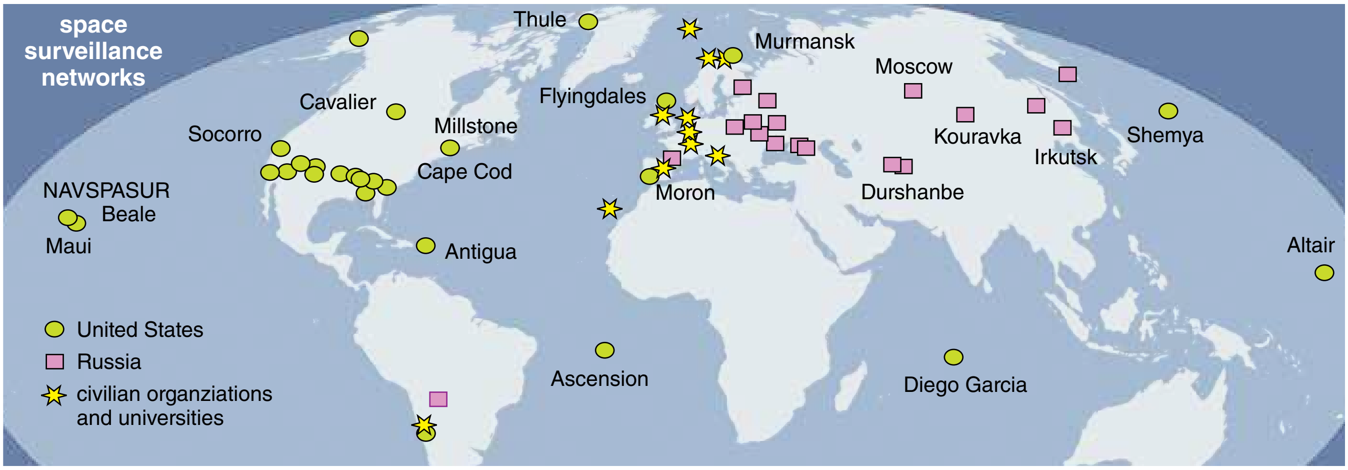
The first step is to estimate the likelihood that objects in orbit might collide. Recognizing the myriad uncertainties in knowing what is there, estimating trajectories of even known and observed satellites, determining conjunction geometries, and constructing probability densities, we do the best we can as collaboratively as possible.

The U.S. Air Force Space Surveillance Network is acknowledged as the best capability in the world, but it is

Fuzzy Physics of Satellite Collisions

The probability of a collision between two satellites is governed by a series of complex mathematics and physics, and it is dominated by uncertainty. Satellite trajectories are estimates developed with incomplete physical knowledge and with measurements that contain inherent errors. It is extremely unlikely that two satellites will come into head-on contact with each other; we can only estimate the probability that they might collide somewhere on their surfaces. For the purpose of this estimation, we assume the two satellites to be spherical, so there will be physical overlap whenever their centers are within a sphere whose radius is equal to the combined radii of the two idealized objects (as shown in the vertical blue strip on the graph below). The graph considers the relative motion of one satellite with respect to the other, and shows what's called a probability density function of the one-dimensional statistics of their relative positions. The numbered curves illustrate increasing combined orbital uncertainty. The shaded area under the curves in the blue strip gives the probability that the two satellites are within their combined radii. As shown in the inset chart, this area varies with increasing orbital uncertainty. The maximum value of this curve is called the "dilution threshold" and represents the greatest possible probability of a collision—a useful upper bound when the real uncertainties are unavailable. However, the fact that two satellites' mean orbits are predicted to be close at a given time does not necessarily imply that they will collide. Conversely, if the orbits are far apart, it is still possible that they could collide.





Dozens of telescopes and radar installations around the world are used to monitor objects in orbit, including debris fragments. These instruments are operated by multiple countries and entities, but they share data to provide the best overall view of the orbital environment.

not sufficient on its own. Other observation sources collaborate in some way. Recent consensus standards for exchanging orbit data and close approach warnings facilitate collaboration but do not ensure it. ESA has made a significant investment in this area, and Russia's support is emerging, both of which will help greatly.

The companies and agencies that operate satellites know best the states of their vehicles, but they do not know well where everyone else is. Most are reluctant to release their orbit data and maneuvers for reasons of competition or national security (although the efficacy of either is arguable, as North Korea has conducted rocket launch activities during gaps in surveillance satellite coverage). That said, there are a few objective, trusted agents to which some operators provide such sensitive data so that affected parties can be alerted to dangerous situations. The Space Data Center, under the auspices of a consortium of communication satellite operators, is the only private service of this nature.

Discerning the possibility of collision between anything and everything is an immense computational task. Although rapidly advancing computer capability is beating down this obstacle significantly, it is not necessary to examine "all on all." At least on a statistical basis, many such encounters are infeasible, due to a hierarchy of conditions. The objects must be in the same place at the same time. Not only must the continuously changing orbits intersect, but the objects must be in the right places in each orbit. Within the uncertainties of propagation, particularly long-term propagation, one can perceive which satellites are not even close at a given time. The many techniques to filter the sets of potential collision partners are well documented and evolving.

Because the fundamentals of quantifying space debris risk are statistical, we will always miss some serious situations and also include nonthreatening encounters (so-called type I and type II statistical errors, respectively). The statistical operating behaviors of any approach may be estimated, characterizing performance in terms of false alarm rates and valid perceptions. Such results will not reveal which encounters are statistical errors, but the degree of failure can be determined. It is not surprising that the space operations community reacted to, rather than prepared for, the Cosmos-Iridium collision. The possibility of the event was recognized, but the calculated probabilities were actually much lower than for other possible encounters during the same period.

The second step is refining estimates to gain confidence. Those who operate relatively small numbers of critical satellites usually can observe and communicate with their charges. If an object will actually come close, they can observe that object, too, and determine much more precise orbits than synoptic space surveillance networks can. ESA and France's Centre National d'Etudes Spatiales (CNES) do this very well. Within proprietary considerations, if two active satellites are a mutual hazard, the operators can communicate with each other and collaborate for mitigation. Only governments can force satellites to maneuver, and then only for assets under

A Starring Role for Space Debris

The science fiction thriller film *Gravity* has received both acclaim and criticism for its depiction of orbit physics. In the film, astronauts on a spacewalk from a Space Shuttle to fix the Hubble Space Telescope first have their communications cut off, then both the shuttle and the International Space Station (ISS) damaged, by a debris cloud created when a Russian missile is used to destroy a defunct satellite. The debris cloud is shown to orbit the Earth for a second strike 90 minutes later.

Several problems exist with the film's scenario. Debris from a missile or satellite intercept could not migrate into the plane of the ISS that quickly. It would take weeks or months, and then there would be only a few fragments, not a dense stream. Converserly, debris in the orbit of the ISS would be traveling at the same speed as the ISS, so it would not blow past and circle around 90 minutes later. If the debris were moving faster than the ISS, it would have to be in an orbit below the ISS. If it were higher, it would be moving more slowly and would never catch up. The only viable option realistically fitting with the movie's plot is debris moving in the same plane but in the opposite direction. The relative velocity of the fragments would be more than 10 kilometers per second. At such speeds, the debris would whiz by almost imperceptibly in less than 1/1000 of a second. Materials impacted at such velocities just shatter; they do not flutter or bend. And if the objects hit head-on from opposite directions, most of the debris would just fall straight down.

Space debris is a serious problem and *Gravity* should be commended for focusing attention on this issue, but it's important not to take "movie physics" as reality without checking it first.

its control. Objective collaboration is essential, although there are currently no objective mediators or analysts.

The third step in addressing the space debris issue is developing maneuvers or other mitigation. The considerations are often very private and introspective, such as the energy cost of avoidance and restoring the original orbit, which can reduce useful lifetime and thus future revenue. But the possibilities increase and costs diminish the further in advance a dangerous situation is recognized.

The Practicalities and Realities

The most serious issue with taking action to avoid collisions in orbit is that we can never be sure that anything we do actually made a difference. It is impossible to prove why something did not happen. We have revealed that some maneuvers might have increased risk rather than diminished it. Investors resist large investments in debris removal because the outcomes might not be discernible, and if they were, the results would not be known for decades or centuries.

Competition and national interests may also hinder collaboration. Some may take advantage of conjunction and collision avoidance to hamper competitors, providing false data to force an expensive and disadvantageous maneuver. Some might refuse to act to coerce the conjunction partner to bear the expense of mitigation.

Arguably the best approach is adopting practices that prevent creating debris in the first place. Operationally, there are sparsely populated orbit regimes from which useful missions can be performed. Heavily populated regimes are used so often because of historical limitations—with computing orbits, communications, or launch vehicles—not because they are the only alternatives. Although there are legal and political impediments, the world may have to develop schemes to allocate orbits, establish keepout zones around satellites, and administer maneuver plans much like aircraft flight plans. The words "traffic control" are anathema in the commercial satellite sector and intimidating politically. Currently, there are no enforceable regulations governing who can put what where, although some parties make concessions to promise safe disposal after a satellite's lifetime ends.

Best practices and standards for mitigating debris exist and are continuously under development. Surveys reveal that satellite producers and operators—particularly government-owned and -controlled operators—have been remarkably diligent in following such rules. There are associated costs, and danger persists even if there is no new debris, but the outcome is immediate, if not precisely measurable.

One interesting proposal was raised by a 2013 economics paper that calls for a "user tax" on every launch to pay for the clean-up of space debris. Such proposals come with far more political hurdles than technical ones. Additional changes to international law would be needed to implement any clean-up system: Right now, even defunct satellites are considered private property, so the owners must give express permission before anyone else can touch them. Nonetheless, a Swiss company has announced plans to launch a debris-cleaning satellite in 2018, which is planned to rendezvous with a small, decommissioned Swiss satellite and push it out of orbit into the Earth's atmosphere, where it will be obliterated. The cost of this proof-of-concept mission has been quoted as $16 million.

Even when rules are in place, it can be hard to enforce them. Since 2002, the Federal Communications Commission has required that all satellites launched into geosynchronous orbit have a means to be pushed into a higher, "graveyard" orbit at the end of their life spans. But a 2005 ESA study found that only a third of such satellites actually did so, with the others either not pushing out far enough or not moving at all.

Econometrics has many characteristics similar to those of space debris: sparse observations, a continuously variable environment, and the effects of human interaction. Elements of the space debris situation are also similar to those of epidemics, particularly approaches to containing and eradicating diseases. There is even room for game theory research, with all the players trying to do the best they can when everyone else is trying to do the best he can.

It is important to present objectively the state of the art in scoping the risks of space debris and understanding both mitigations and consequences, without judgment of how serious the threat might be to any stakeholder or what level of investment in any aspect of the problem might be appropriate.

Whatever steps are taken next, they will undoubtedly require serious international collaboration—in regulating orbits, discussing techniques for handling dead satellites, and elucidating the concepts of de-orbiting missions. No nation or industry has the resources to minimize the risk of orbital debris, even to protect its own space interests.

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