Evolution of Space Traffic and Space Traffic Management

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Abstract

In 2016, the notion that the local space environment would continue to evolve at rates defined by previous satellite launch histories changed dramatically when SpaceX requested permission to place over 4400 satellites in low Earth orbits. Prior to that time, predictions were that the space environment could be stabilized by space operators abiding by rules and guidelines designed to limit the growth of debris. While all proposed satellites might not be realized, major changes in the

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near-space environment are coming and may come quickly. This chapter provides background, discusses potential changes, and highlights new polices and services that could arise.

Introduction

Objects in Orbit

Figure 1 shows the growth in the number of operating satellites and debris since the beginning of the space age by object type, Fig. 2 shows orbiting objects sorted by orbit class, and Fig. 3 shows the number of objects per cubic kilometer as a function of altitude.

Protected Regions

Several years ago, spacefaring nations recognized that two regions of near-Earth space are particularly important to space-based services and set these regions aside as “protected regions.” The first is the low Earth orbit (LEO) protected region shown in Fig. 4 (Region 4). This region extends to 2000 km above the Earth’s surface and is heavily used by satellites that provide communication, Earth monitoring, and other services.

The second protected region is the ring of space surrounding Earth where satellites in geosynchronous equatorial orbits (GEO) operate (Region 3). This is

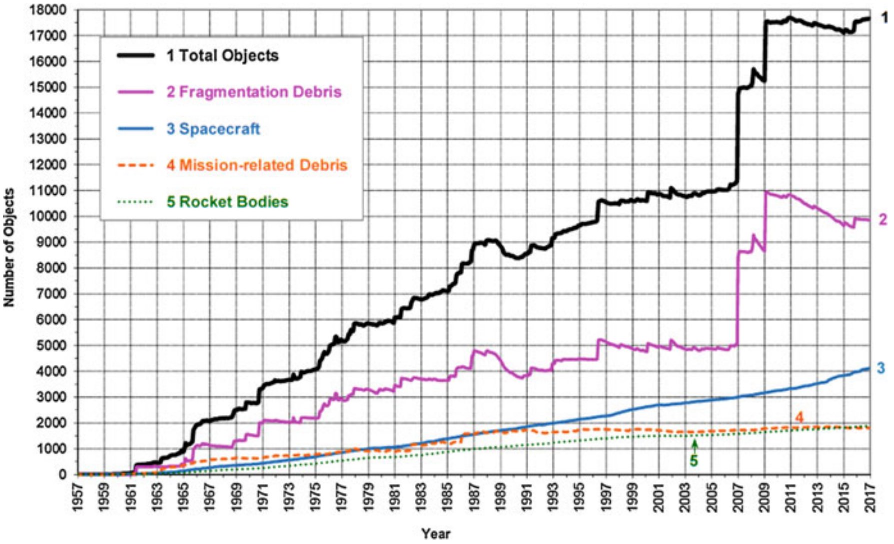


Fig. 1 Number of objects in Earth orbit by year and object type (courtesy NASA)

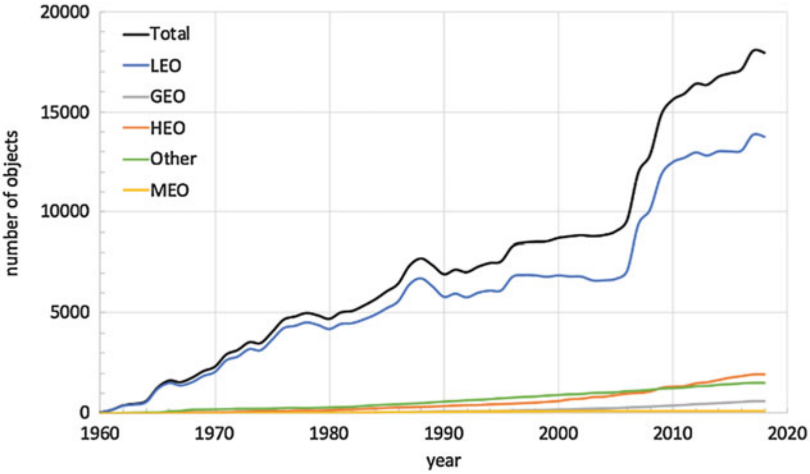
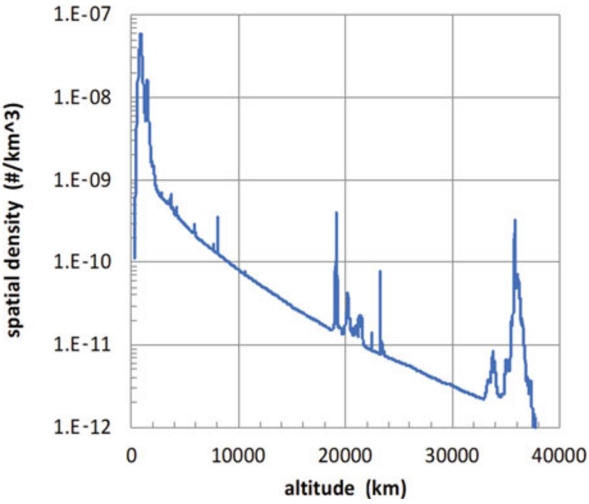


Fig. 2 Number of objects by year and orbit class (LEO, MEO, GEO, HEO)

Fig. 3 Number of objects/ cubic km as a function of altitude in 2018



where many large communication and weather monitoring satellites operate at fixed locations above specific regions of Earth.

A region not formally protected but should be avoided when disposing of satellites is the medium Earth orbit (MEO) region between 19,700 and 20,700 km above the Earth's surface. This region is home to Global Positioning System (GPS), Glonass, Compass, and Galileo constellations. Due to the critical nature of the navigation and other services these constellations support, current end-of-mission satellite disposal guidelines recommend that orbits for space hardware being disposed avoid passing through this region.

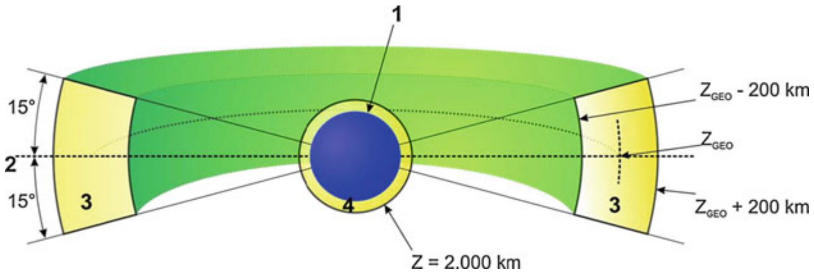


Fig. 4 Protected regions (Key: 1 Earth; 2 equatorial plane; 3 GEO protected region; 4 LEO protected region; Z altitude measured with respect to a spherical Earth whose radius is 6378 km; ZGEO altitude of the geostationary orbit with respect to a spherical Earth whose radius is 6378 km) (from ISO 24113:2019)

Highly elliptical orbits (HEOs) are orbits with high eccentricity, and vehicles in these orbits can pass through LEO, MEO, and GEO regions.

GEO Protected Region

In addition to approximately 470 operating satellites in the GEO protected regime, there are more than 1300 tracked objects (objects larger than 1 meter) and also a number of untracked objects, as well. Based on recent research (Oltrogge et al. 2018), there could be over 1600 objects between 10 cm and 1 m in size and 33,000 objects larger than 1 cm that cross the GEO protected region. The reference argues that a collision of a small, untracked 1 cm-class object with an operating satellite might occur as frequently as every 4 years and every 50 years for an object larger than 20 cm. In the GEO region, collision velocities could reach as high as 4 km/sec with objects in highly eccentric orbits piercing the GEO protected region. More common collisions would be at relative velocities of less than 1 km/sec.

One of the largest and oldest GEO operators is Intelsat, now a commercial company but originally established as an intergovernmental consortium in the 1970s. Intelsat currently operates a fleet of 52 communications satellites. The operating GEO satellites are large, and they have long lifetimes, some exceeding 30 years. Their locations are known well, and many of the satellites operate in orbits very near to Earth's equatorial plane, so they move slowly relative to one another. As a result, operators of GEO satellites generally have more time to make adjustments to avoid close approaches with known objects and maintain their satellites' orbital positions than those in LEO.

Satellites in GEO can provide services to a relatively large area of the Earth's surface, and their 24-hour orbits essentially fix them in place over specific points on the equator, so ground antennas can be pointed at predefined locations to send and receive signals. Satellites in GEO are designed to be very reliable and to operate within predefined slots for long periods. In the past, very large ground antennas were required for communicating with these satellites. The size requirements have been reduced substantially over time. An antenna on a home or business that is pointing to the sky is generally pointing to a satellite in a GEO orbit.

For the near-term, major changes in the design and operational characteristics of GEO satellites or the GEO environment are not expected. An area where we might expect advancements is in the maintenance and disposal of GEO satellites, and some commercial companies are developing satellite servicing and potentially active debris removal (ADR) services as well. These services would perform satellite refueling and disposal services, potentially extending the life of operational satellites by replenishing station-keeping propellant and offering disposal options when satellites fail or end their missions. Since longer lifetimes have economic benefits to the owners, satellite operators could pay for servicing and disposal services. In the future, GEO operators might create a fund that would cover costs of removal of existing derelict satellites or satellites that fail prematurely.

For the GEO region, satellites are to be disposed in orbits above the GEO protected region where they will not reenter that region for at least 100 years. Design of disposal orbits must account for the long-term effects of solar wind, the gravitational attraction of the sun and moon, and other small forces.

LEO Protected Region

Satellites in LEO are at lower altitudes (altitudes less than 2000 km), so their coverage on the Earth's surface is less. They do not operate over fixed regions of the Earth surface but make a complete orbit around Earth in 90 to 120 min. If services are desired by a customer at a fixed location, orbits must be designed to pass within range of that spot at prescribed intervals; if continuous communications is required, a constellation of LEO satellites is necessary, and multiple satellites in that constellation must provide coverage and make and hand off connections with that customer as services are provided. The communications pathway is completed by ground antennas that receive data from linked satellites and pass that data to ground-based users.

Since they are at lower altitudes, LEO satellites have the advantages that they require much less power to communicate with customers on the ground than satellites in GEO. That makes the individual satellites much less expensive to fabricate and put into orbit and enables a customer on the ground to use a low-power, hand-held instrument for communications. The communications time lag is also substantially lower, which is important for machine-to-machine communications.

These features were incorporated in the design of the Iridium satellite system, which includes a relatively large constellation of 66 satellites in low Earth orbit plus several on-orbit spares and provides voice and limited data communication to people located anywhere on Earth. All satellites in the Iridium constellation are essentially of the same design, enabling production on an assembly line. Iridium's first constellation became operational in 1998 and is now being replaced with more capable satellites.

Following Iridium's lead, a revolution is on the horizon as new operators propose very large constellations in the LEO regime. But given the realities illustrated in

Figs. 2 and 3, the environment in LEO – and on the ground – must be considered carefully as this revolution moves forward.

Over 1800 satellites currently operate in the LEO regime, joined by over 13,000 debris objects large enough to be tracked (i.e., larger than 10 square centimeters) plus possibly over 500,000 objects between 1 and 10 cm in size that are harmful to operating satellites but can’t currently be tracked. ln addition to the large population of orbiting objects, LEO is a more challenging environment than GEO for space operators for several reasons:

- Satellite orbits in LEO are affected by aerodynamic forces that are amplified by environmental factors such as the day/night cycle, solar storms, carbon dioxide in the environment, and other factors that make accurate predictions of where the satellites will be in the future much more challenging.
- For an object to be tracked, it must pass over tracking radar sites on the ground, which will limit the frequency of updates available of the object’s orbit. These updates are required to correct for the effects of the atmosphere and other forces on the object’s orbit. Without frequent updates, the uncertainty in an object’s position at a given time increases, affecting the quality of a collision warning.
- While there are exceptions, operating satellites in the GEO protected region are taking advantage of circular orbits that are at very low inclinations, and positions are well known and well controlled, so most operating satellites move slowly relative to each other compared to those in LEO, where operating satellites are in multiple orbit planes and approach velocities for objects in different planes can be 10 km/sec or higher. As a result, a collision in LEO, even with a small debris object, can destroy an operating satellite and add large numbers of debris objects to the orbital environment.
- There are lots of dead satellites and other debris in LEO that must be frequently tracked, can’t maneuver, and must be avoided.

As noted, orbits of satellites in LEO are affected by very small aerodynamic forces that increase as altitude decreases. While these forces help remove debris in low orbits, the lifetime of orbits increases substantially with altitude. For example, the orbit of a dead satellite in a 250-km circular orbit will decay, and the object will reenter in less than a year; a dead satellite in a 1000-km orbit will remain in orbit and be a hazard to other satellites for over a thousand years. Lifetimes of circular orbits continue to increase as altitude increases. Estimates of the lifetime for a particular satellite depend on the satellite’s mass, physical dimensions, orientation, and environmental factors such as solar activity as it descends.

Space Debris

Inoperable, human-made objects orbiting Earth are space debris, and space debris can be created by collisions and explosions, by release of objects during satellite deployments and normal operations, by strikes by micrometeoroids and small space debris fragments, and by long-term exposure to the orbital environment. A collision or explosion involving a large object such as a satellite or launch stage creates an expanding cloud of debris objects that eventually blends into the background of debris objects in the orbital environment, slightly increasing the background risk to all satellites in the region. Traveling at orbital speeds, even a flecks of paint can gradually degrade solar panels and damage optical sensors, reducing the mission lifetime of the damaged vehicle. It should be noted that satellites with no maneuver capability are effectively space debris to an operating satellite, which must move to avoid a collision.)

Current guidelines and standards require that satellites in both the LEO and GEO protected regions remove themselves at end of mission to minimize the growth of space debris and minimize the possibility of interfering with other operating satellites in those regions.

At end of life, satellites in LEO orbits should be reentered into the atmosphere for disposal. The reentry process does not necessarily completely “burn up” a reentering object, and some fragments that are potentially hazardous to people on the ground can survive. For this reason, requirements state that if the casualty expectation per reentry exceeds 1 in 10,000 (i.e., surviving fragments might injure or kill one person on Earth should the object reenter 10,000 times), the object should be directed to reenter into a region where there is minimal hazard to people (e.g., an open ocean area). Otherwise, the object may be allowed to simply reenter as its orbit decays – as long as that process takes fewer than 25 years. (As will be discussed later, requirements to minimize hazards due to reentries of large numbers of satellites from large constellations may be a possibility for the future.)

The approximately 20,000 objects included in the figures are only those tracked by ground and optical sensors, and these generally range from 10 cm and larger in the LEO regime to 1 m and larger in the vicinity of the GEO regime. As noted, the orbital environment includes many thousands of objects smaller than 10 cm in size that have resulted from satellite explosions, collisions, debris expelled during normal operations, and other sources over the years. As a result, the total population of orbiting objects is actually considerably higher than the figures indicate, with estimates that the actual total includes as many as 500,000 small, currently untrackable (due to their size) objects in LEO, each of which is large enough to seriously damage a satellite on impact.

The jumps in the population of LEO objects shown in Fig. 1 are due to debris created by the 2007 Chinese anti-satellite (ASAT) test, where a ground-launched vehicle impacted an aging Chinese weather satellite, and collision of the active Iridium 33 satellite and inoperative Russian Cosmos 2251 satellite in 2009. The latter collision ended the operations of the Iridium satellite and also created a debris cloud that included several thousand additional objects, many of which will remain in orbit for decades to come. While some debris from these events has subsequent reentered and is no longer in orbit, Fig. 1 shows that many of the larger tracked objects (and likely many smaller, currently untrackable objects) remain in orbit. And given the altitude where the events occurred, some of these objects will remain hazards to other objects for centuries to come.

The Iridium-Cosmos collision changed the perspective on orbital risks and resulted in a new focus on providing better information to satellite operators on possible threats to their space assets.

Space Situational Awareness Services

Prior to the Iridium-Cosmos collision, the "big sky" perspective, which said that space was so vast that collisions would be very rare, prevailed. Only a few satellite operators felt the need for real collision avoidance and other space situation awareness (SSA) services.

At that time, services were provided by the US Air Force using tracking data collected using government-owned sensor systems. And many operators felt that the available services were not "actionable," meaning that predictions informed a satellite operator when an object might pierce the physical space surrounding a satellite, but that space could be kilometers in size. Given that level of uncertainty, operators did not feel there was sufficient information to warrant moving a satellite, since moving requires expenditure of propellant, with each maneuver fractionally reducing a satellite's lifetime. And a move based on inaccurate data might actually increase the risk of a collision with the approaching object or possibly with another at a later time. Moving a satellite can also affect its ability to fulfil its basic mission objectives. For example, if a satellite must maneuver to avoid a possible collision, its ground coverage area will also move, potentially requiring operator actions to avoid loss of valuable data or service interruptions.

Over the years, new sensors and analysis techniques emerged. Shortly after the Iridium-Cosmos collision, the USA provided close approach distances and probabilities of collision to satellite operators. While this is an improvement over earlier formats for conjunction assessments, some satellite operators still felt that the information from the USA was insufficient for their needs.

In 2009, several operators of satellites in GEO orbits formed the Space Data Association (SDA) to "improve the accuracy and timeliness of collision warning notifications. . .via sharing of operational data." The SDA, through its Space Data Center, supplements catalog data from the US government with information provided by operators of GEO satellites, who generally know very accurately where their satellites are and also know when satellite maneuvers will occur. The SDA also provides radio frequency interference and other support and assists operator efforts to coordinate maneuvers to avoid interference with other objects.

Today, in addition to the SDA and the US Air Force, several governments provide similar services for operators of their own satellites. But most use the US catalog of resident space objects, supplemented with information from their own sensors and satellite operators, as the basis for their services.

Space Situational Awareness Data

Since the beginning of the space age, the primary catalog used for SSA services has been created and maintained by the US Air Force. This Resident Space Object (RSO) catalog is generally considered to be the most complete of any currently available, and unclassified portions of this catalog have been made available for years (Space-Track.org is the current source). Data for this catalog has been collected primarily by ground-based radar and visual telescope systems operated by the US government. Planned enhancements to tracking resources may decrease the minimum size of tracked objects to as small as 2 cm. As a result, the number of objects in the RSO catalog is expected to increase from approximately 20,000 to over 200,000.

At present, new commercial and international entities are adding their data to the mix. For example, one company currently has two phased-array radar sites in operations and is building a third. That company is currently tracking more than 14,000 objects in LEO and expects to track as many as 250,000 objects 2 cm and larger several times a day when its radars are fully deployed and operational. A second company is operating a global SSA telescope network with more than 25 observatories and 250 telescopes that is tracking man-made space objects in GEO, highly elliptical orbits (HEO), and medium Earth orbits (MEO). Both of these companies offer a variety of services based on the data they collect.

Collecting data on most objects several times a day will enable space situational awareness services of unprecedented accuracy. This type of data will be essential as SSA service providers, who will need to provide accurate and timely warnings of collisions and other interference as the number of objects increases over the next 10–20 years.

Best Practices and Standards

As the number of objects in orbit increased, it became apparent that best practices, guidelines, and even regulations were required to prevent the growth of the space debris population. If this was not done, predictions were that the debris population could continue to increase in an uncontrolled manner as objects and fragments of objects impacted other objects, creating more fragments, etc. (the Kessler effect), eventually making space operations much more difficult and expensive.

And even small, untracked debris can cause problems. For example, impacts of a small debris particle on a solar panel can reduce the power output from that panel – and a large number of impacts can drop the power output so low that the satellite is not able to perform its designated mission and must be deorbited. Ailor (2010) concluded there would be a relatively small decrease in the mean satellite lifetime due to operating in the debris environment for the next 30 to 50 years based on the then-projected environment (an environment with no very large constellations in LEO). A primary driver in the lifetime reduction was the solar panel degradation due to impacts by small debris – impacts that gradually lowered the power provided by the solar panels until power dropped below a critical value, ending the satellite's mission. The effect of the addition of large LEO constellations on these projections will be discussed later.

During this period, it was also recognized that when a launch vehicle or spacecraft reentered the atmosphere at end of life, the object would not completely "burn up." Fragments that could injure or kill a human on the ground might survive.

In the late 1990s, the Inter-Agency Space Debris Coordination Committee (IADC) developed guidelines stating that satellites in LEO should be disposed before their end of life, either by moving them to an orbit that would naturally decay in 25 years or less or preferably by direct reentry – controlling the deorbit process so the debris surviving reentry lands in a safe area. Direct reentry into the atmosphere was recommended for objects where surviving debris might have casualty expectations exceeding 1 in 10,000 (i.e., reentries of that object 10,000 times would be expected to cause one casualty somewhere on Earth). Many nations have incorporated these guidelines into regulations.

The IADC guidelines were developed for reentries of individual satellites. Current proposals suggest that several constellations containing many satellites may be in the offing for the next decades. As will be discussed later, this may lead to new guidelines designed to limit the creation of space debris and hazards to people on the ground and in aircraft as we move forward.

Changes Coming

From the beginning of the space age to the early 1990s, satellites were essentially one-of-a-kind items – each was built with specific capabilities designed for specific missions, and each launch carried only one or, at most, two satellites to orbit. The Iridium satellite system changed that paradigm with its factory-built satellites. The release of the iPhone in June 2007 was another paradigm shifter and was described as “revolutionary” and a “game changer” for the mobile phone industry. These events and subsequent releases of smart phones that included small accelerometers, sensors, cameras, microprocessor, and other technologies encouraged innovators to see how these new satellite manufacturing processes and microelectronics capabilities might be used more broadly in space systems.

During this period, a standard size for a new class of small satellites was defined – a cube 10 × 10 × 10 cm in size – and launch service providers included “piggyback” launchers for these CubeSats that could deploy many such satellites per launch. Most of these small satellites were placed in the low Earth orbit regime, and many were low enough that their orbits would decay within a few years – an important feature given the increasing recognition of a growing space debris problem. Very few of these satellites carried significant propulsion capabilities, and most were experimental in nature, so many rapidly became “space junk,” joining the population of nonfunctioning, human-made debris circling our planet.

These new technologies led to a decrease in cost and mass of very capable satellites, enabling providers of space-based services to consider providing worldwide communication and internet services via constellations consisting of large numbers of small satellites (satellites less than 500 kg) in LEO. These satellites would follow the approach used by Iridium: a large number of satellites based on a fixed design would be mass-produced on an assembly line.

A benefit of the smaller satellite size and mass is that launch vehicles could carry more than one satellite to orbit, and Fig. 5 shows the number of launches and the number of satellites carried to orbit per launch from 2005 through 2018. While the number of launches per year has been relatively stable, the number of payloads per

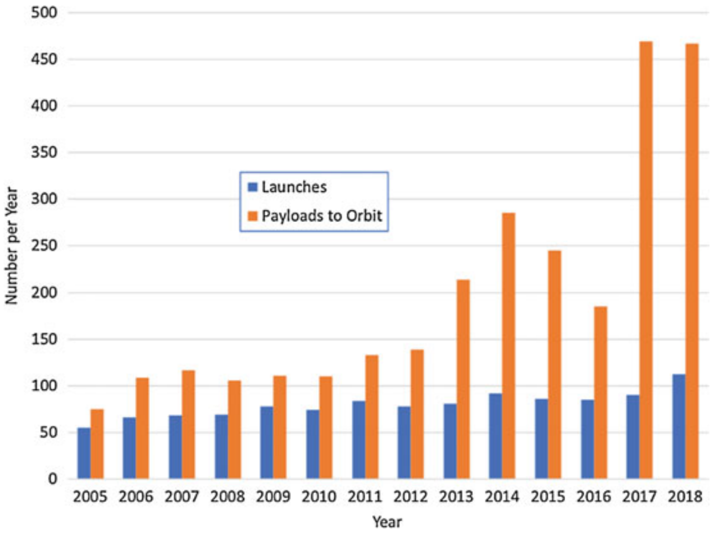


Fig. 5 Number of worldwide launches and payloads carried to orbit from 2005 through 2018

launch has increased substantially (launch failures affected the number of launches and payloads to orbit in 2015 and 2016).

Large LEO Constellations

The lower costs associated with satellite manufacture and launch have led to proposals for placing really large constellations of satellites in LEO, with some exceeding over 1000 satellites in orbit with multiple satellites in each orbit plane. Table 1 lists some organizations that have announced such plans.

The largest proposed constellation to date is SpaceX's StarLink constellation, which would have over 7500 satellites orbiting at 346 km (below the orbit of the International Space Station). If completed, that one constellation would have over four times the total number of satellites that were operating in orbit at the beginning of 2019. SpaceX has proposed locating another 4425 satellites at 1100–1300 km as part of that constellation. While some of the constellations in Table 1 may not materialize, it is evident that the LEO space environment may change dramatically over the next decades.

Clearly the addition of such large numbers of satellites into the LEO regime will raise a number of questions that should be answered. These include:

1. **How will satellites in these constellations be delivered to their operational orbits?** Satellites can be inserted relatively quickly into their orbital positions by launch stages, a common practice today, or they may be inserted into a lower orbit, where they can be deployed, checked out, and then boosted to a higher

Table 1 Proposed constellations

Proposed constellations	Number of satellites
SpaceX K-band (high altitude)	4425
OneWeb	720
LeoSat	120
Theia	112
Telestar	117
Boeing	2956
SpaceX V-band (low altitude)	7518

mission orbit. The advantage of the latter approach is that the checkout orbit can be low enough that the orbit will decay quickly if the satellite is faulty, minimizing the likelihood of subsequent failure and leaving a dead satellite at higher constellation altitudes. If the satellite is found to be healthy during checkout, it can then be put on course to its final orbit.

Some are considering using an electric propulsion system for the transfer from the low orbit to the constellation altitude. While this technique minimizes propellant consumption, it produces a very low thrust, so the satellite will move relatively slowly through altitudes where other satellites operate as it spirals upward, increasing the potential collision threat during transit and the load on operators of space traffic management systems as they seek to minimize the possibility of collisions.

2. **With so many satellites in a large constellation, how will risks to satellites passing through be managed?** In GEO, the International Telecommunications Union (ITU) assigns satellites to operate in specific orbital slots, typically two degrees in size, to minimize frequency interference problems. Since GEO satellites provide services over specific ground areas, these restrictions work well: operators of GEO satellites know whose satellites are operating where and announce moves and activities to avoid interference.

   In LEO, the situation is different: satellites in LEO circle Earth about every 90 minutes and collect data and provide services over relatively small areas as they pass overhead. As a result, an operator wishing to add a satellite to a constellation at a higher altitude must coordinate the passage of that satellite with operators of constellations below that altitude. And if the satellite being moved uses low-thrust propulsion, the transit time will not be quick. The concept of assigning a constellation responsibility for its “shell” and providing best practices for operators wishing to pass through that shell has been suggested. No formal arrangements have been made along these lines.
3. **What is the expected lifetime of satellites in the constellation?** An advantage of the LEO constellations is that it is relatively inexpensive to launch replacement satellites that incorporate the latest systems and capabilities, so some constellation designers might use satellites with 5- to 10-year lifetimes. That could mean a large fraction of each constellation would be moving toward disposal each year as constellations are maintained. For example, assuming a 10-year lifetime, a large

fraction of the satellites could be moving down through lower altitudes toward reentry on a yearly basis. And if electric propulsion is used, that transit could take significant time. All of these satellites in transit to and from the constellations add to the risks of collisions in LEO, so satellite lifetime and constellation disposal plans and strategies will be important considerations as plans for constellations develop.

4. **What happens if a satellite fails while operating in the constellation?** It is inevitable that satellites operating in constellations will fail. These large constellations in low Earth orbit must necessarily have multiple satellites in each orbit plane to provide ground coverage to service their customers (e.g., there are 11 satellites in each of the 6 orbit planes in the 66-satellite Iridium system, and Iridium also maintains several in-orbit spares). A constellation with thousands of satellites could have a hundred or more satellites in each plane, and the operations of each must be well controlled and well-coordinated in orbit. If a satellite fails or communications is lost, it could become a threat to others in the same plane and in the constellation itself. Active support from a space situational awareness service would be required in this case. Clearly, satellites in constellations should be designed with very high reliability for disposal.
5. **How will satellites be disposed at their end of life?** The preferred approach for disposing satellites is to have them leave orbit and reenter the atmosphere in a location where surviving debris will impact in an uninhabited area such as the South Pacific Ocean. In this case, surviving debris has minimal chance of injuring a human or damaging an aircraft. As noted earlier, if the casualty expectation for a reentry is less than 1 in 10,000, current guidelines and regulations say that the satellite can simply be left in an orbit that will decay in less than 25 years. As large constellations emerge, regulators may choose to also limit the hazard posed by cumulative reentries of satellites from these constellations (more on this later). And the 25-year time allotment could be shortened to reduce the transit time to reentry, or might even be eliminated in favor of requiring direct disposal of satellites of larger sizes to minimize ground hazards arising from reentries of large numbers of satellites per year.
6. **How important is satellite disposal?** A key factor in determining the future of debris growth in LEO is the reliability of disposal at end of mission or end of life. Dead satellites in some constellations could remain a threat for hundreds or thousands of years, so managing the LEO environment will require satellites to have disposal systems that can deorbit constellation members with a very high probability of success – some argue the probability of success should be over 90% if we are to maintain some control on the growth of the LEO population.
7. **Since satellites from large constellations will be disposed by reentry into the atmosphere, will risks of hazards to people on the ground or in aircraft increase?** Studies are showing that yes, hazards to people on the ground and in aircraft could increase substantially as a result of hardware associated with large constellations reentering Earth's atmosphere. More on this later.
8. **How will the increase in space traffic be managed?** The current SSA system tracks 20,000 to 30,000 objects, and, as noted earlier, satellite operators in the

> LEO regime are calling for services that provide more and more accurate information to help them protect their on-orbit assets. Upcoming improvements in ground-based tracking services may increase the number of objects tracked by a factor of 10. Satellite operators, SSA service providers, and government regulators must work together with regulators to develop best practices, standards, regulations, and policies designed to assure the long-term sustainability of space activities in the LEO environment.

So, given the advent of large LEO constellations, what challenges might be expected in efforts to maintain the long-term sustainability of the space environment and management of space traffic and limit potential hazards to spacecraft in orbit and people on the ground?

Environmental Effects on Satellite Lifetime

The study conducted by Ailor et al. (2010) with no large constellations and assuming business-as-usual satellite operations, disposal, and replenishment activities found that large satellites operating in the LEO regime could experience a mean lifetime reduction over the next 50 years of about 13% (e.g., a satellite with a mean lifetime of 10 years in a no-debris environment would see a reduction of 1.3 years in an environment that included space debris). Much of this reduction would come from degradation of solar panels by small, untrackable debris that would “sandblast” and reduce the power output of solar panels.

An update to that study (Ailor et al. 2017) assumed that over 5000 new small satellites are operating in high LEO orbits, consistent with proposals announced by commercial companies in the 2015–2017 timeframe. As with the 2010 study, this projection included the effects of collisions of both tracked objects, objects greater than 10 cm in LEO, and small debris down to 1 mm and adds changes in the debris environment due to the previously un-modeled new satellites colliding in their constellations and with other objects as they undergo constellation replenishment activities.

Primary results were that satellites being disposed from or added to the new constellations and debris associated with collisions involving these objects could potentially double the reduction in the mean operational lifetime of satellites operating in LEO over that predicted under the business-as-usual approach. As in the 2010 study, the degradation of solar panels due to small debris impacts was a significant factor in this degradation, with the mean lifetime reduction increasing from the 13% predicted in the earlier study to as much as 60% in some cases (i.e., a large satellite with a mean lifetime of 20 years in a no-debris environment could have its mean lifetime reduced by as many as 12 years in an environment that included debris associated with constellation satellite operations). Results suggest that minimizing collisions during replenishment activities and making solar panels and space hardware more resilient to small debris impacts will be increasingly important in the future.

Reentry Disposal of Satellites from Large Constellations

As noted earlier, current regulations limit the casualty expectation for a single satellite reentering in a random, uncontrolled manner to less than 1 in 10,000. If the predicted hazard exceeds that number, the satellite should be commanded to reenter into a safe area such as the South Pacific Ocean. The original Iridium satellites were predicted to each have a casualty expectation of 1 in 17,000, so random reentries were acceptable as the Iridium system evolved.

In 2000, Iridium was having significant financial problems, and as a part of bankruptcy considerations, the government asked that NASA develop an estimate of the cumulative hazard should Iridium be required to dispose all 74 of its satellites. The estimated *cumulative* hazard for reentering all 74 satellites was 1 in 250, well above the 1/10,000 limit for a single satellite. Fortunately, Iridium's financial problems eased, and the constellation has remained in operation. (Notably, satellites from the original constellation are gradually being disposed and replaced by the new Iridium Next satellites, and no fatalities from the disposal operations have been reported to date.)

Similar to the Iridium process, some current proposers of large constellations plan to dispose of their satellites at end of mission by lowering their orbits so random reentries into the Earth's atmosphere would occur within the 25-year timeframe.

A recent study (Ailor 2019) used the past history of debris surviving satellite reentries to develop a first-order estimate of the hazard to people and aircraft from falling debris that could survive reentries of constellation-sized satellites. Projecting to the year 2030, when several proposed constellations were assumed to be operational and were disposing a fraction of their satellites each year, the results show that hazards to people on the ground posed by debris from multiple satellite reentries from a single large LEO constellation could exceed the 1 in 10,000 threshold for a single satellite by 2 to 3 orders of magnitude.

That same study used radar observations of debris falling from a satellite reentry in the 1970s and US departures and destinations of 17 types of large, commercial aircraft to estimate the probability of hazardous debris striking an aircraft given possible masses of satellites proposed for a LEO constellation would be 0.001, corresponding to a maximum yearly casualty expectation for reentries from a single large constellation of nearly 3 in 10 without emergency action by a pilot after such an impact. That estimate would be higher if commercial air traffic was updated to include worldwide flights.

It should be noted that while reentry hazard prediction models can be verified to some degree based on recovered debris (Ailor et al. 2011) and actual data collected during breakup (Feistel et al. 2013), there is very little data on small objects that might survive and be a hazards to aircraft. As large constellations evolve, satellite designs that minimize the number and size of surviving debris should be considered, as should means to verify that the designs are preforming as predicted.

To summarize, there are currently no guidelines or requirements to manage cumulative risks for either ground or aircraft casualties. While new satellite design practices might lower the number of hazardous fragments that result from reentries, the most effective mitigation technique would be to deorbit all satellites into a safe ocean area.

Active Debris Removal (ADR)

Systems are being developed for servicing satellites in GEO orbits, and these systems might also be used to move satellites from the GEO protected region to disposal orbits. There is a potential market for satellite servicing given the "more civilized" operating environment in GEO, where a servicing vehicle could visit several operating satellites travelling in virtually the same orbit. Satellites operating in GEO are generally more expensive to build and launch and are designed with long lifetimes, so servicing that extends a satellite's lifetime could be less expensive and more cost-effective than replacement in some cases.

As noted, the LEO operating environment is different, with satellites operating in multiple orbits with inclinations varying from near zero to over 90 degrees. In addition, satellites are smaller and less expensive to build and launch and offer the advantage that new technologies can be infused quickly by replacing older satellites with newer versions. As a result, while proposals using electrodynamic tether systems and other approaches have been suggested for removal and a new company has announced plans to develop and demonstrate ADR technologies to approach and capture space debris, satellite servicing has not been a potentially attractive market in LEO to date.

But, the addition of new LEO constellations with large numbers of satellites in roughly the same orbits could encourage a new look at LEO satellite servicing and removal, perhaps as part of a constellation's design. For example, given the possibility that new requirements might emerge that would limit the cumulative hazard posed by reentry disposal of satellites from a constellation, constellation designers might include satellites specially designed to remove and dispose of dead satellites or satellites that have reached their end of life via direct disposal into a remote area. And given that a large constellation could have many satellites in the same orbit and orbit plane, a servicer could replace or update components in multiple satellites as an alternative to totally replacing those satellites.

In addition, the LEO environment currently includes several very large, dead satellites and rocket stages that will remain in orbit for many years. Should any of these be impacted by another debris object or an operating satellite, the number of debris objects created could be much larger than that from the Iridium-Cosmos and the Chinese ASAT tests. These objects should be priority targets for an ADR system. To encourage development of ADR capabilities, the International Association for the Advancement of Space Safety (IAASS) has proposed an international grand challenge for ADR (Position Paper 2017).

Effect of Large Constellations on SSA Service Requirements

As noted earlier, space situational awareness services (e.g., predicting close approaches that might threaten an operating satellite) are currently based on databases of some 20,000 objects. New tracking services will increase the size of these catalogs by a factor of at least ten as currently existing small objects, objects from 2 to 10 cm in size, are added. Objects in this size range are capable of seriously damaging or ending the operational lifetime of a satellite.

Recent studies (Peterson et al. 2018) are showing that, using current practices, the addition of large constellations plus the large numbers of satellites transiting the LEO regime as they dispose and replace satellites in these constellations are likely to increase the number of conjunction alerts sent to satellite operators to possibly over 1000 alerts per day. Many of these would not be alerts if tracking uncertainties on all orbiting objects, both operating satellites and hazardous debris objects, were reduced. Installing tracking aids such as transponders on operating satellites and including satellite owner/operator data in conjunction assessments will improve the situation somewhat, but given that debris dominates the population of orbiting objects in LEO, only basic improvements in the tracking accuracy for all objects and in information provided to operators by space situational awareness services will improve the situation substantially.

Space Situational Awareness and Traffic Management Service Providers

As noted earlier, the major provider of SSA services and space tracking data to date has been the US government via the US military. The military manages the collection of data from US-owned ground-based and optical sensors and processes this data to provide conjunction assessment services to satellite operators around the world and basic data to the public. But changes are coming.

The growth in the number of nongovernment satellites and satellite operators is placing an increasing demand on the current military operations, and in response, responsibilities for providing these services may be transferred to a civil agency within the US government. A new civil space traffic management (CSTM) system would likely maximize the use of commercial capabilities and data sources to provide enhanced SSA services as a public good (i.e., at no cost) and could make data available to support the development of specialized, higher level support by commercial entities.

The migration of basic space situational awareness capabilities from the Air Force to a new CSTM entity will likely be complete in the early to mid-2020s. Given its responsibilities, the new organization, likely using data that includes data from commercial data providers, will play an increasingly important role in protecting the near-space environment and shaping the standards, best practices, and regulations that will guide space operations for decades to come.

Conclusions

Specific areas where new services, best practices, standards, and regulations are likely to evolve are:

- **Minimizing the growth of space debris:** Unfortunately, the LEO regime already has a large population of uncontrolled debris objects that can collide with other objects and generate more long-lasting debris. The addition of large numbers of new satellites as large constellations are inserted and maintained has the potential to make operations in LEO much more expensive, forcing satellite designs that are more robust to small debris impacts and have very reliable systems for deorbit at end of mission or after an on-orbit failure. In addition, it is likely that guidelines will be developed encouraging operators of large constellations to deorbit satellites at end of mission quickly, possibly within 5 years or even via direct disposal, to minimize the possibility of collisions. It should be noted that active debris removal could also play an important role: removal of one large, dead satellite or launch stage could eliminate a potential source of debris objects equivalent in number to that possible by decades of mitigation.
- **Providing services to satellite operators:** Services that alert satellite operators of an approaching threat will have a critical role as the number of tracked objects increases due to addition of hundreds of thousands of existing small and hazardous debris objects and satellites associated with large constellations are added to SSA databases. Satellite operators need predictions that are accurate and timely to avoid unnecessary moves. Fortunately, commercial data providers are emerging that promise data that meet necessary requirements, and it is expected that this data will reduce the overall number of alerts to satellite operators. At the same time, the nature of the service providers will also change as providers for SSA and space traffic management services enhance their predictions by incorporating data acquired from commercial entities. Services provided by the US government are sure to evolve as they move from the US military to a civil agency. Active debris removal and satellite servicing may evolve as cost-effective ways to maintain GEO satellites. Similar systems could emerge to maintain and update satellites in large LEO constellations.
- **Addressing needs of governments and regulators:** There will be increased attention to the space environment as proposals for large constellations are realized over the coming years. And if a serious collision occurs, governments will be more likely to collect and analyze data to assure that operators are abiding by agreed restrictions. Governments are also more likely to support regulations to assure that current and future space operators have reasonable access to space and minimal interference with space operations.
- **Assuring safe on-orbit operations and disposal of space systems:** Collection, maintenance, and sharing of accurate data required for assessing possible conjunctions involving all orbiting objects larger than 2 cm will be increasingly important. Included will be sharing of data among satellite operators and space traffic management service providers. This data will be essential for services that provide timely, accurate services to prevent conjunctions among operating satellites and debris and assist with anomaly resolution and mission planning. In addition, the spacefaring community will need to verify proposals that would limit casualties on the ground and in aircraft via "design for demise" techniques and potentially develop cost-effective techniques that will enable direct disposal

of space hardware into safe areas. Finally, practices that minimize interference to satellites and launching systems transiting shells where large constellations are operating need to be developed.

The addition of large constellations of satellites to the LEO environment presents the opportunity to, in effect, re-architect LEO operations for the future. For the last 50 years, satellite operators have operated essentially unfettered by regulations on where they can operate, how they can maneuver, or concepts of "ownership" of a particular region of space. The introduction of thousands of new satellites to this region will make the development of best practices and possibly imposition of restrictions and limitations on where and how satellites can operate necessary if humanity is to preserve that environment for the future.

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