United States Government Accountability Office

Report to Congressional Addressees

September 2022

TECHNOLOGY ASSESSMENT

Large Constellations of Satellites

Mitigating Environmental and Other Effects

GAO-22-105166

The cover image displays the Earth with stylized representation of multiple orbiting satellites.

Cover source: GAO; marcel/stock.adobe.com (globe); bluebay2014/phonlamaiphoto/stock.adobe.com (satellites). | GAO-22-105166

GAO

Highlights of GAO-22-105166, a report to congressional addressees

September 2022

Why GAO did this study

Enabled by declines in the costs of satellites and rocket launches, commercial enterprises are deploying large constellations of satellites into low Earth orbit. Satellites provide important data and services, such as communications, internet access, Earth observation, and technologies like GPS that provide positioning, navigation, and timing. However, the launch, operation, and disposal of an increasing number of satellites could cause or increase several potential effects.

This report discusses (1) the potential environmental or other effects of large constellations of satellites; (2) the current or emerging technologies and approaches to evaluate or mitigate these effects, along with challenges to developing or implementing these technologies and approaches; and (3) policy options that might help address these challenges.

To conduct this technology assessment, GAO reviewed technical studies, agency documents, and other key reports; interviewed government officials, industry representatives, and researchers; and convened a 2-day meeting of 15 experts from government, industry, academia, and a federally funded research and development center. GAO is identifying policy options in this report.

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TECHNOLOGY ASSESSMENT

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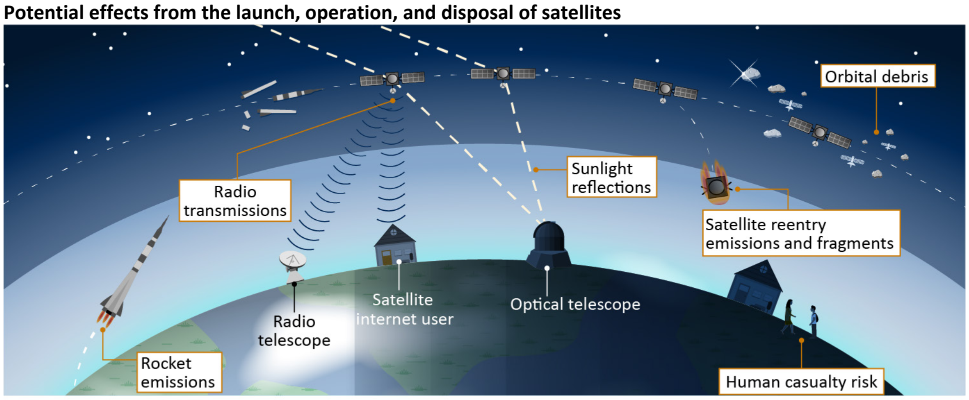
What GAO found

There are almost 5,500 active satellites in orbit as of spring 2022, and one estimate predicts the launch of an additional 58,000 by 2030. Large constellations of satellites in low Earth orbit are the primary drivers of the increase. Satellites provide important services, but there are potential environmental and other effects that this trend could produce (see figure).

Potential effects from the launch, operation, and disposal of satellites



Source: GAO. | GAO-22-105166
Note: Image not to scale.

GAO assessed technologies and approaches to evaluate and mitigate the following potential effects:

- **Increase in orbital debris.** Debris in space can damage or destroy satellites, affecting commercial services, scientific observation, and national security. Better characterizing debris, increasing adherence to operational guidelines, and removing debris are among the possible mitigations, but achieving these is challenging.
- **Emissions into the upper atmosphere.** Rocket launches and satellite reentries produce particles and gases that can affect atmospheric temperatures and deplete the ozone layer. Limiting use of rocket engines that produce certain harmful emissions could mitigate the effects. However, the size and significance of these effects are poorly understood due to a lack of observational data, and it is not yet clear if mitigation is warranted.
- **Disruption of astronomy.** Satellites can reflect sunlight and transmit radio signals that obstruct observations of natural phenomena. Satellite operators and astronomers are beginning to explore ways of mitigating these effects with technologies to darken satellites, and with tools to help astronomers avoid or filter out light reflections or radio transmissions. However, the efficacy of these techniques remains in question, and astronomers need more data about the satellites to improve mitigations.

GAO developed the following policy options to help address challenges with evaluating and mitigating the effects of large constellations of satellites. GAO developed the options by reviewing literature and documents, conducting interviews, and convening a 2-day meeting with 15 experts from government, industry, and academia. These policy options are not recommendations. GAO presents them to help policymakers consider and choose options appropriate to the goals they hope to achieve. Policymakers may include legislative bodies, government agencies, standards-setting organizations, industry, and other groups.

Policymakers may be better positioned to take action on this complex issue if they consider interrelationships among these policy options. For example, implementing the fourth option (improving organization and leadership) may improve policymakers' ability to implement the first and second options (building knowledge, developing technologies, and improving data sharing). Similarly, implementing the first option may help with the third option (establishing standards, regulations, and agreements). More generally, trade-offs between mitigations may emerge, the ongoing increase in new constellations may introduce unexpected changes, and a large and diverse set of interests from the global community may shift over time, all of which present persistent uncertainties. To address these complexities and uncertainties, the full report presents the policy options in a framework, which may help policymakers strategically choose options to both realize the benefits and mitigate the potential effects of large constellations of satellites.

Policy options for technologies and approaches to evaluate and mitigate potential effects of large constellations of satellites

Policy Option	Opportunities	Considerations
Build knowledge and develop technologies (report p. 57) Policymakers could support research on the extent of potential effects, as well as development of technologies to address them.	• Improving knowledge about potential effects of satellite constellations could help policymakers decide which mitigations to implement, if any. • Research on darkening satellites, removing orbital debris, and other technologies could lead to innovative mitigation.	• Resources for studying the potential effects of satellite constellations are limited, in both the government and private sectors, which could hamper efforts to build knowledge or develop technologies. • Knowledge of some effects, such as the long-term growth of orbital debris, may already be sufficient. Experts told us that in such cases, leadership and standards, regulations, and agreements could prompt action.
Improve data sharing (report p. 57) Policymakers could facilitate improved sharing of relevant data about satellite constellations.	• The ability to more easily share high-quality data could improve mitigation of potential effects. For example, better satellite position data might help astronomers avoid disruptions or help satellite operators avoid collisions. • Increased data sharing may create opportunities for increased collaboration and awareness across government, academia, and the satellite industry, which could in turn generate additional mitigation approaches.	• The ability to effectively share data will depend heavily on the willingness of stakeholders, particularly satellite operators. Some operators are willing to share data with entities that have a demonstrated need but expressed reservations about sharing certain detailed data more openly. • Collecting and updating data on satellite positions or other key information in a common format poses technical and logistical hurdles.
Establish standards, regulations, and agreements (report p. 58) Policymakers could establish appropriate standards, regulations, and agreements to help mitigate potential effects of satellite constellations.	• Establishing formalized standards, regulations, and agreements around potential effects of satellite constellations could help institutionalize successful mitigation approaches and make them standard practices for future operators. • Formalized regulations could provide enforcement avenues to help protect existing satellite operators and stakeholders and provide direction to new entrants.	• Regulations on satellite licensing or operation may create incentives for operators to pursue licensing in less-regulated venues. • Authors of voluntary standards and agreements might face difficulties incentivizing private operators to adopt new practices. • Existing laws and accepted practices vary across domains. For example, international law may only address certain types of effects.
Improve organization and leadership (report p. 59) Policymakers could build national and international organizational and leadership structures that facilitate effective mitigation of the potential effects of satellite constellations.	• Centralized leadership and coordination may improve mitigation. • Broader organization and leadership structures could pull together relevant stakeholders to implement mitigations.	• Unilateral leadership or mitigation action by one nation could cause satellite operators to license in less-regulated nations. • International agreements on satellite constellations may take longer to implement and may lag behind the need for timely mitigation. • Establishing effective organization and leadership structures may divert resources and personnel from other missions.

Source: GAO. | GAO-22-105166

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Abbreviations

DOD	Department of Defense
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
GEO	geosynchronous Earth orbit
ITU	International Telecommunication Union
LEO	low Earth orbit
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NTIA	National Telecommunications and Information Administration
UN	United Nations

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Introduction

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Congressional Addressees

Sputnik, the first artificial satellite in space, launched in 1957. The number of active satellites increased steadily for the next 50 years, then surged from around 1,400 in 2015 to almost 5,500 by spring of 2022.[1] This trend is expected to accelerate, with multiple experts mentioning around 58,000 additional satellites could be launched by the end of the decade, over 10 times the current number of active satellites. One reason for this acceleration is the ongoing and proposed launches of a series of large constellations of satellites, which private companies plan to use to provide important services, such as broadband internet access in underserved rural communities.

Satellites can have a number of environmental and other effects, especially as the number of satellites in orbit continues to increase. For example, emissions from the rockets that carry satellites into space could cause a change in the temperature of the upper atmosphere. The increasing numbers of satellites could create additional orbital debris, which complicates satellite operations. Sunlight reflections and radio transmissions from satellites could disrupt telescopes, which could make it more difficult for astronomers to assess risks associated with near-Earth asteroids or to observe other celestial objects.

Furthermore, the projected number of future satellites as well as some of the potential environmental and other effects still have considerable uncertainties, which we note throughout this report. Despite these uncertainties, we report projected numbers of satellites and their potential effects and their associated uncertainties, where available, to provide a descriptive account of the emergence of large constellations of satellites and what effects they might have.

In light of the broad congressional interest in commercial satellites, we prepared this technology assessment under the authority of the Comptroller General of the United States to assist Congress with its oversight responsibilities. This report: (1) describes the potential effects from projected increases in large constellations of satellites, (2) assesses the current or emerging technologies and approaches to evaluate and mitigate these effects, along with challenges to developing or implementing these technologies and approaches, and (3) identifies policy

[1]We followed the practice the Defense Intelligence Agency used in the *2022 Challenges to Security in Space* report and analyzed the public satellite database maintained by the Union of Concerned Scientists. Union of Concerned Scientists, "UCS Satellite Database," (Cambridge, Mass.: May 1, 2022), accessed Aug. 22, 2022, https://www.ucsusa.org/resources/satellite-database.

options that might help address the challenges as well as the opportunities and considerations that accompany these options.

We focused this technology assessment on large commercial constellations of satellites, considering direct environmental and other effects that the constellations may introduce or exacerbate. We reviewed literature; interviewed agency officials, industry representatives, and experts in academia and at a federally funded research and development center; and conducted a meeting of experts. The meeting included a nongeneralizable group of 15 experts—selected based on their technical, legal, economic, or policy expertise—that would represent a balanced and diverse set of views from government scientists, nongovernmental experts, industry representatives, and academic researchers. For more information on the objectives, scope, and methodology of this technology assessment, see Appendix I.

We conducted this technology assessment from April 2021 to September 2022 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background

1.1 Satellite services and orbits

Satellites provide a range of services: from broadcast television, phone, and broadband internet services, to Earth and weather observations. Remote sensing satellites that take pictures of the Earth help advance scientific goals, track natural disasters like forest fires, and support many other tasks. GPS satellites provide precise positioning, navigation, and timing information to civilians and the military. From a military perspective, satellites also provide secure communications, missile warnings, and intelligence.

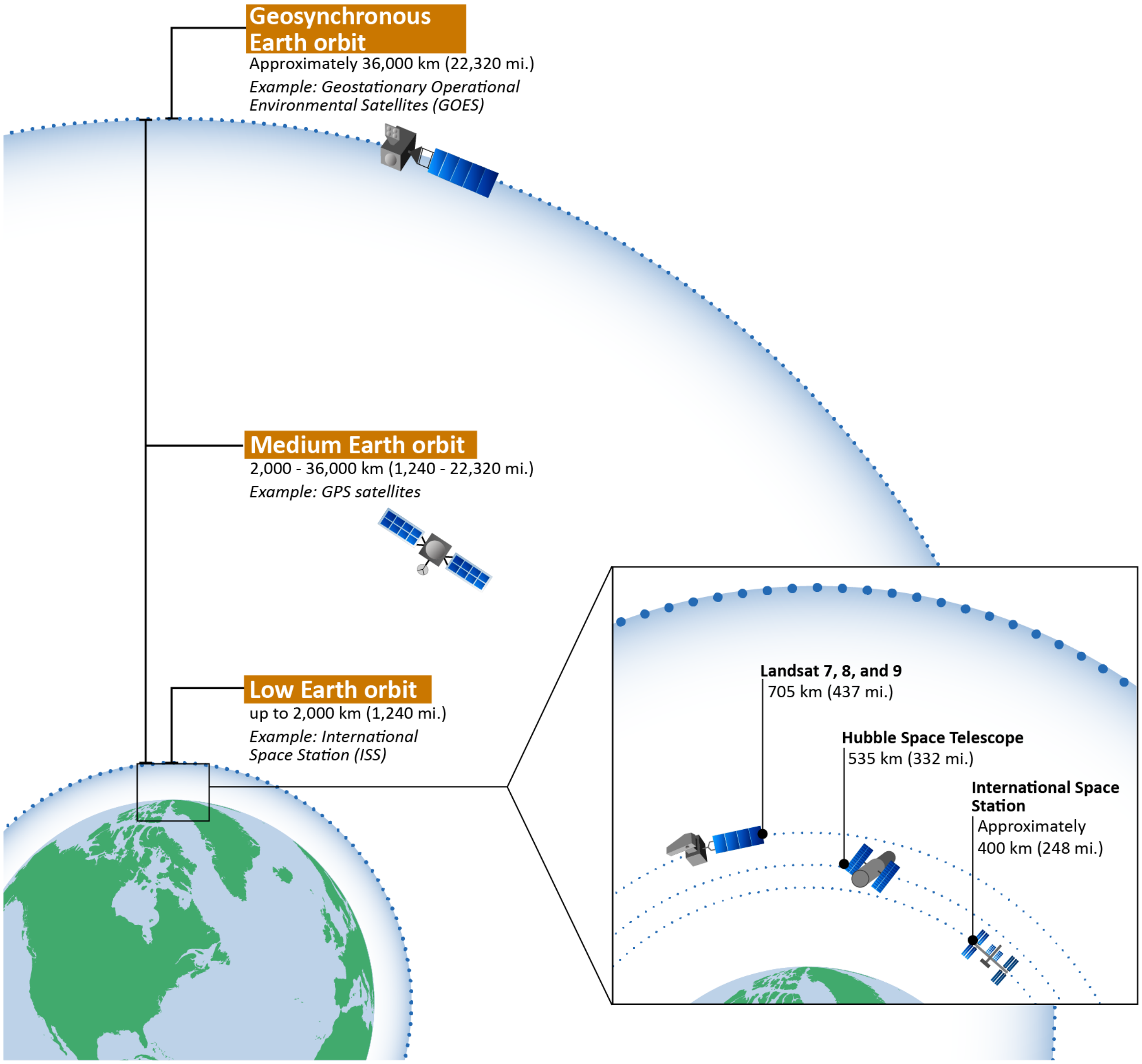
Satellites can operate collectively in groups called satellite constellations. The U.S. Government Orbital Debris Mitigation Standard Practices categorizes constellations of satellites that contain at least 100 active satellites as “large” constellations.[2]

The National Aeronautics and Space Administration (NASA) defines three categories of satellites in circular orbits (see fig.1 below). The most populated orbital location is low Earth orbit (LEO), which extends from Earth’s surface to 2,000 kilometers (1,240 miles) above the surface. Over 4,500 active satellites and the International Space Station orbited in LEO as of April 30, 2022.[3] One benefit of using this lower orbit is the shorter lag time in communications between satellites and the ground, which is beneficial in the case of internet access or other communications services. This shorter lag comes at the cost of a smaller field of view and faster orbital speed, such that a greater number of satellites is needed to cover the same service area.

[2]U.S. Government, *Orbital Debris Mitigation Standard Practices* (November 2019), 7.

[3]Union of Concerned Scientists, “UCS Satellite Database.”

Figure 1: Categories of Earth orbits with reference spacecraft



Source: GAO. | GAO-22-105166

Note: Image not to scale.

The second most populated orbital location is geosynchronous Earth orbit (GEO), around 36,000 kilometers (22,320 miles) from Earth's surface. Satellites in geosynchronous Earth orbit have speeds that match the rotation of the Earth, so they are able to orbit above the same longitude at all times.[4] These satellites provide many of the same services as LEO satellites, trading precise image resolution for wider fields of view.

[4]Lines of longitude are imaginary lines running north to south along the Earth, which are used to divide the Earth into slices. This allows people to measure distance going east or west. An example line of longitude is the Prime Meridian, extending through Greenwich, England.

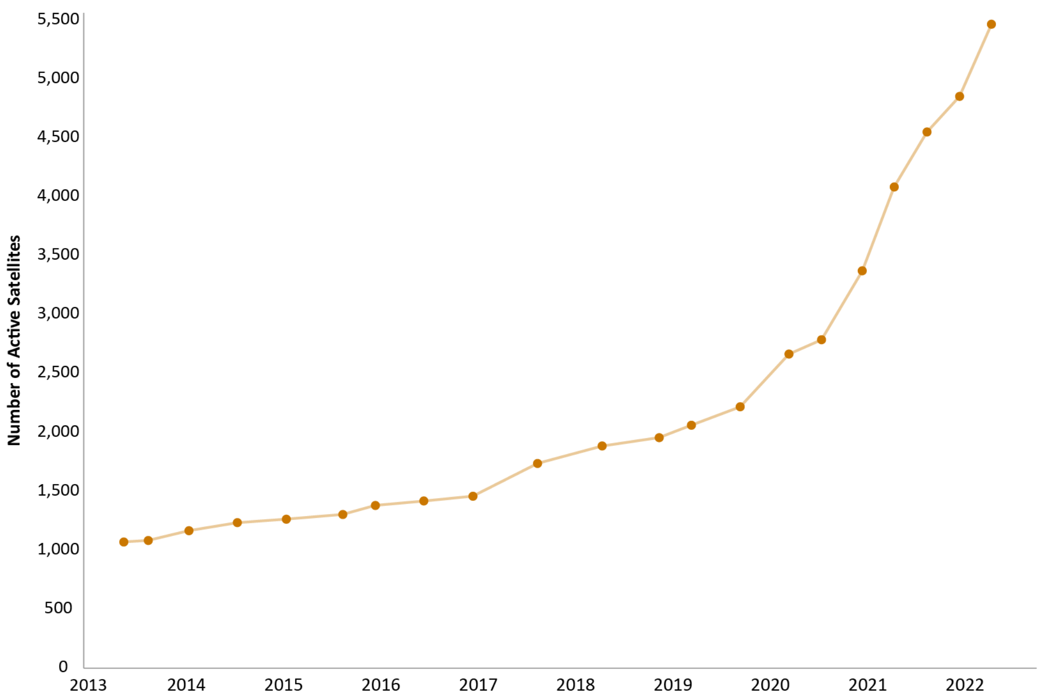
Lastly, in between these orbital positions (i.e., from 2,000 to about 36,000 kilometers above the Earth's surface, or 1,240 to 22,320 miles) is medium Earth orbit, which contains the fewest satellites. The GPS satellite constellation orbits in medium Earth orbit.

1.2 The rise of large constellations

1.2.1 Current status

The satellite industry has undergone significant changes, as satellite operators launch more satellites (see fig. 2), and use them to provide different services. According to the Union of Concerned Scientists Satellite Database, almost 5,500 active satellites orbited Earth as of April 30, 2022, an increase of almost 300 percent from approximately 1,400 satellites in 2015.[5] Communications satellites comprised 66 percent of active satellites in 2022, while 21 percent were for remote sensing, the next largest category. Of the total satellites in 2022, around 63 percent were operated by U.S.-based entities, including government and commercial operators.[6]

Figure 2: Approximate number of active satellites, 2013-2022



Source: GAO analysis of Union of Concerned Scientists (UCS) data. | GAO-22-105166

Note: Data are from the UCS Satellite Database (May 1, 2022). UCS maintains a database of publicly available data on active satellites, which is updated several times each year.

[5]All data included in the UCS satellite database are publicly available from different sources, including corporate, government, and scientific websites. The database only includes active satellites; however, in cases where the status of a satellite is unclear, the entry reflects the best judgment of the UCS. Information should therefore be considered approximate.

[6]Union of Concerned Scientists, "UCS Satellite Database."

1.2.2 Future projections

Technological advancements allow for more affordable satellites, improving the potential to deploy large constellations of satellites. These constellations can create communication networks that cover the entire globe, including rural locations that are underserved with respect to internet access. Multiple experts mentioned 58,000 additional active satellites could be launched by 2030, likely primarily in LEO.[7] Satellites in these constellations will have design lifetimes of 5 to 15 years, requiring new satellites to replenish the constellations. An official from the Aerospace Corporation projected that the rate of rocket launches to support satellite deployments will continue to increase for the rest of the decade. Operators balance the increase in launch frequency with lower launch costs.

Although the current driver of this potential increase is commercial, there is also the potential for increased military use of space. The Department of Defense's (DOD) Space Development Agency proposed a satellite constellation for communications and collecting military data. While it meets the definition of a large constellation, this constellation is comparatively smaller than current commercial proposals. In addition, DOD is working with commercial satellite operators to coordinate shared rocket launches when appropriate. Therefore, this report focuses on commercial satellite constellations.

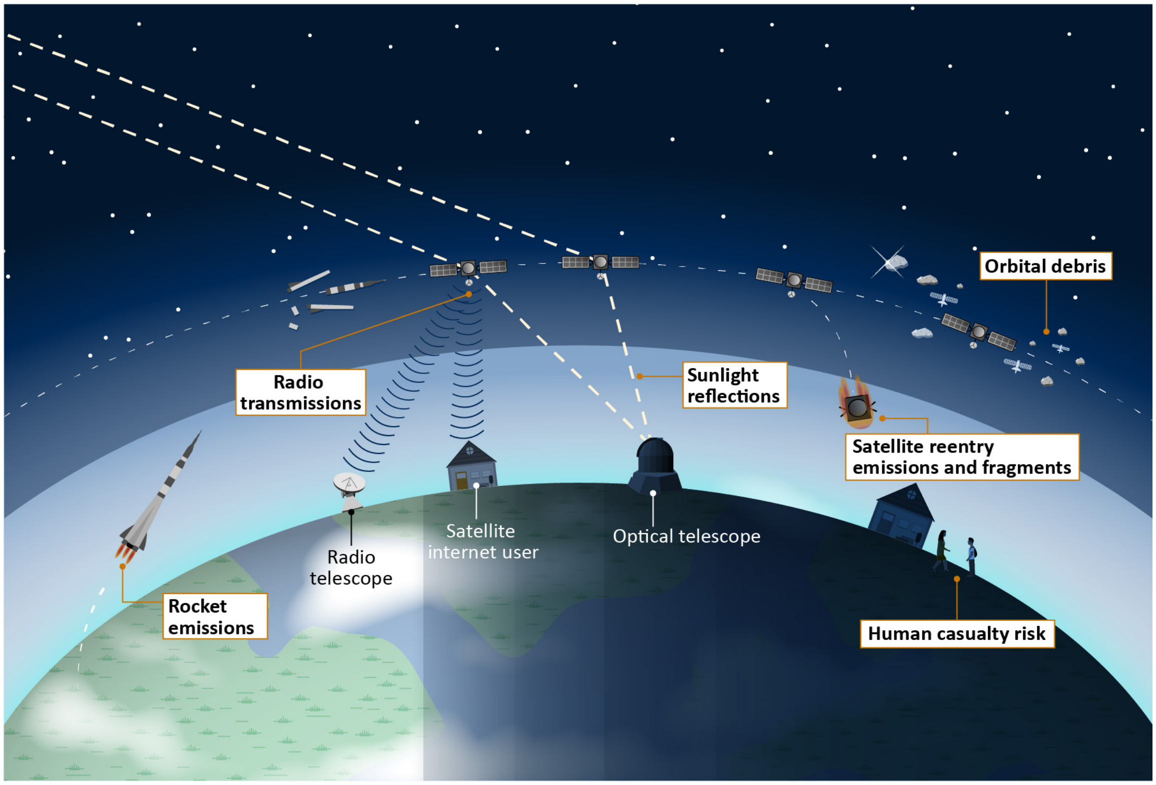
1.3 Categories of environmental and other effects

For the purposes of this report, we classified the environmental and other effects of satellite constellations into three categories based on location: (1) emissions from rocket launches and satellite reentry in the upper atmosphere and casualty risk from surviving fragments, (2) sunlight reflections and radio transmissions that affect Earth and space observations, and (3) orbital debris and risk to satellites in the space environment (see fig. 3).[8] Although these effects might be small for single satellites, the effects of many satellites operating in large constellations are larger, or in some cases, unknown.

[7]These estimates are based on proposals filed with the Federal Communications Commission (FCC) since approximately 2016. The exact number of active satellites may differ from the proposed number of satellites.

[8]In this report, we are using the term "environmental effect" to mean a potential change in the environment (surface, atmospheric, or orbital) caused or contributed to by the launch, operation, or disposal of large constellations of satellites. Although we describe certain relevant U.S. laws and regulations for context, we are not adopting the definitions used under the National Environmental Policy Act of 1969 (NEPA). We are also not commenting on whether or how these effects should be analyzed, regulated, or mitigated under NEPA or any other environmental legislation. On August 26, 2022, the U.S. Court of Appeals for the D.C. Circuit issued its final decision on litigation that, among other things, raised challenges under NEPA regarding FCC's modification of a satellite constellation license. *See Viasat, Inc v. FCC,* No. 21-1123 (D.C. Cir. filed Aug. 26, 2022). This decision is subject to appeal until late November 2022. In presenting the information in this report, we are not attempting to address any disputed facts or disputed legal issues that may be raised on appeal.

Figure 3: Categories of environmental and other effects of constellations of satellites



Source: GAO. | GAO-22-105166

Note: Image not to scale.

In the upper atmosphere, rockets can produce emissions of carbon dioxide, water vapor, black carbon, alumina (aluminum oxide), and chlorine-containing chemicals. These emissions can affect Earth's temperature and deplete ozone. Reentering satellites can also produce fragments and emissions when they burn up and begin to disintegrate on reentry. Satellites that do not completely disintegrate pose a casualty risk on the ground, because the surviving fragments could cause property damage, injury, or death.

Satellites can also obstruct observations of the night sky with sunlight reflections and radio transmissions. Satellites continue reflecting sunlight after sunset and so may appear as bright streaks in images of the night sky, especially immediately following launch when they are in a lower orbit. NASA experts say satellites can also obstruct observations made from other satellites in higher orbits as they pass underneath. This could mean losing data from remote sensing satellites on events like wildfires or hurricanes. In addition, radio communication with satellites occurs at signal strengths much stronger than the signals from astronomical phenomena. Therefore, satellites potentially obscure radio astronomy observations of deep-space objects such as black holes or distant galaxies.

In the space environment, satellite operators have to be aware of orbital debris and other satellites, so that their satellites can avoid collisions.[9] As the number of satellites increases, the amount of orbital debris and the operational risk to satellites will also increase.

1.4 Agencies and regulations

1.4.1 U.S. agencies and domestic regulations

In the U.S., the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) are involved in licensing use of radio frequencies for satellites. NTIA performs this radio frequency communication assignment and coordination function for satellites operated or managed by the federal government, while FCC is responsible for all nonfederal satellite operators, including commercial satellite operators. FCC and NTIA are responsible for ensuring that satellites do not interfere with other authorized users of the radio spectrum, by allocating and assigning specific radio frequency bands that satellites can use. FCC also works with the United Nations' (UN) International Telecommunication Union (ITU) and the Department of State to facilitate communication between domestic and international satellite operators.

Other agencies involved in the licensing process for the space industry are the National Oceanic and Atmospheric Administration (NOAA) and the Federal Aviation Administration (FAA). NOAA handles licensing for remote sensing activities of satellites and works to coordinate space-related issues via its nonregulatory Office of Space Commerce. FAA is responsible for licensing the operators of vehicles that launch satellites into orbit, including the launch and the purposeful reentry of vehicles from orbit.

1.4.2 International cooperation and regulation

Consistency between national and international regulations becomes more important as the global satellite community grows larger. Technological developments and the possibility of sharing launch capability increases the possibility of new entrants to space. For example, in September 2021, the government of Rwanda filed plans for a satellite constellation with the ITU, following the launch of its first satellite in September 2019. As of 2020, over 70 countries around the world have at least one satellite in orbit.

The Outer Space Treaty calls on nations to cooperate with other member States in the exploration and use of outer space, and requires each to supervise activities in outer space by nongovernmental entities that it has authorized. In addition, under the Convention on International Liability for Damage Caused by Space Objects (Liability Convention), a launching state could be held liable for damages, including property damage, injury, or death. The UN Office for Outer Space Affairs assists nations in implementing the treaty. This office also hosts space object registries and works with the UN Committee on the Peaceful Uses of Outer Space to

[9] We define orbital debris as "any human-made space object orbiting Earth that no longer serves any useful purpose." Space Policy Directive-3, National Space Traffic Management Policy, 83 Fed. Reg. 28,969, 28,970 (June 21, 2018). Orbital debris can vary in size from smaller than a grain of sand to as large as an entire spacecraft.

provide voluntary guidelines on satellite activities.

Another UN agency is the ITU, which manages global radio spectrum. The ITU also interfaces with FCC and the Department of State when international coordination between satellite operators is required.

Two other organizations also work to coordinate international space activities. The Inter-Agency Space Debris Coordination Committee is made up of 12 international space organizations and the European Space Agency, and is an international governmental forum for the worldwide coordination of activities related to orbital debris. The International Astronomical Union is an association of professional astronomers from 90 countries, and organizes scientific meetings to coordinate and share research on space issues.

2 Scientific Understanding of Atmospheric Effects Is Nascent

Rocket launches and satellite reentries produce emissions that can affect Earth's upper atmosphere.[10] However, there is large uncertainty in understanding how emissions will affect the atmosphere because of the lack of observational data.[11] As companies seek to put more satellites in orbit, the number of rocket launches will necessarily increase. Unlike other human-caused emissions sources, rocket launches produce atmospheric emissions extending to Earth's upper atmosphere. Satellites also produce emissions when they burn up and begin to disintegrate on reentry. Satellites that do not completely disintegrate can introduce casualty risks on the ground, because surviving fragments could cause property damage, injury, or death. This chapter will describe the known and unknown atmospheric effects associated with emissions and examine potential mitigation approaches.

2.1 Effects of particle and gas emissions on the atmosphere are unknown

2.1.1 Rocket and satellite emissions

As companies seek to put more satellites in orbit, the number of rocket launches and satellite reentries will necessarily increase. In 2021, 48 rockets were launched from the U.S. The number of annual U.S. launches is expected to reach 120 by 2030. An FAA official told us there were 144 global launches in 2021, but that the number of global launches is expected to reach 200 launches per year by 2030.[12] Rocket launches can emit both gases and particles into the atmosphere that could affect Earth's temperature and ozone.

The atmosphere consists of five layers, from nearest to farthest from Earth's surface:

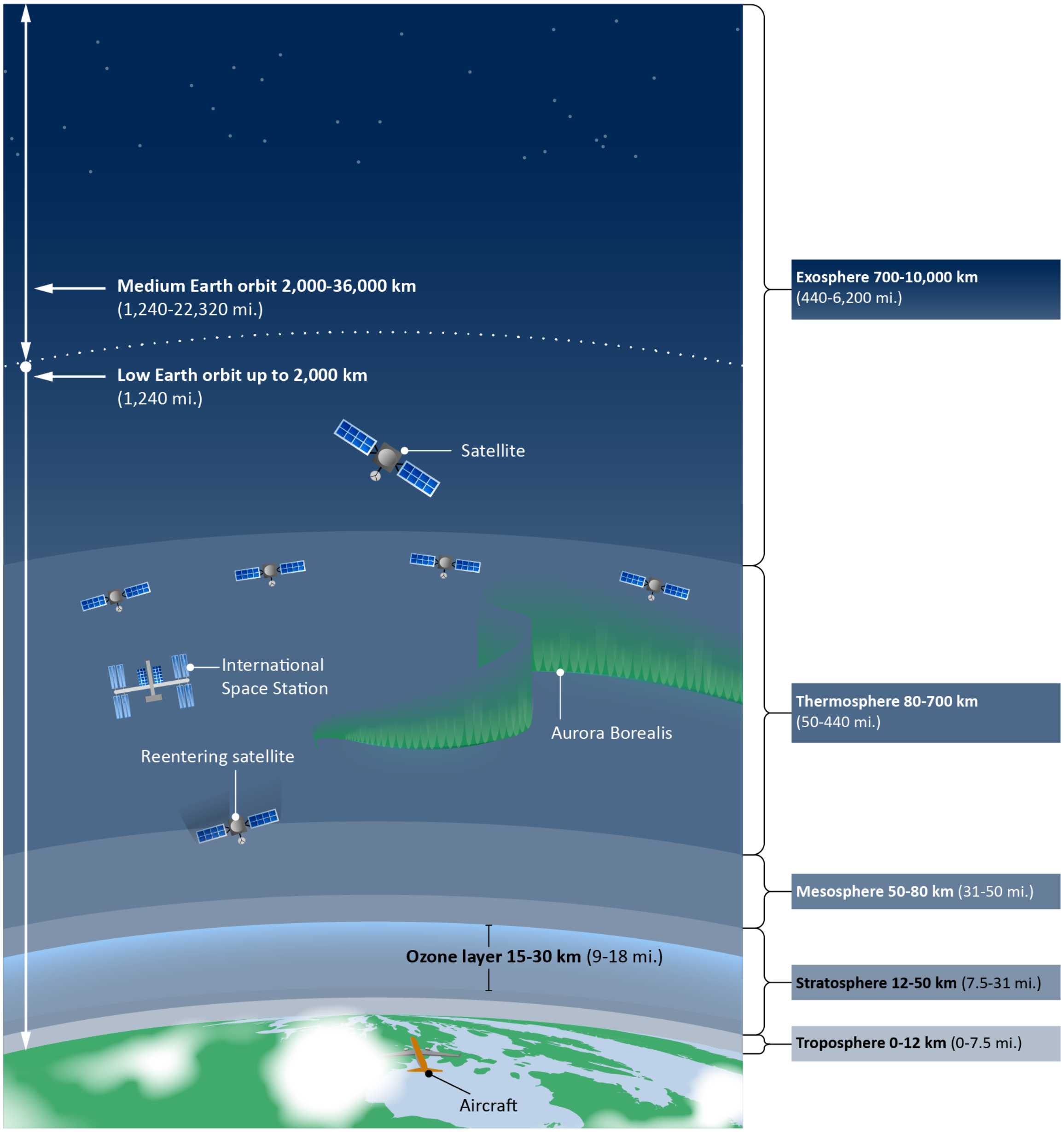
- Troposphere: where we live and airplanes fly
- Stratosphere: the location of the ozone layer that protects us from harmful solar radiation
- Mesosphere: where most meteors and LEO satellites burn up
- Thermosphere: where some LEO satellites and the International Space Station orbit
- Exosphere: where some LEO and medium-Earth-orbit satellites orbit

[10] "Upper atmosphere" is a general term that refers to all atmospheric layers above the troposphere.

[11] Observational data refers to data collected through instrumentation. For rocket launches, this could include in-situ data that are collected within the stratosphere and mesosphere.

[12] The European Space Agency has reported that over 130 launches occurred in the year 2021. See European Space Agency, ESA Space Debris Office, *ESA's Annual Space Environment Report* (Darmstadt, Germany: Apr. 22, 2022).

Figure 4: Layers of the Earth's atmosphere



Source: GAO. | GAO-22-105166

Note: Image not to scale.

Unlike other human-caused emission sources, such as aviation, rockets produce emissions extending to the upper atmosphere. Rockets use different types of propellants, with each producing different emissions (see table 1).

Table 1: Rocket engine propellants and their atmospheric emissions

		Carbon dioxide	Water vapor	Black carbon	Alumina[a]	Chlorine chemicals	Nitrogen oxides
Propellants	Kerosene & oxygen	X	X	X			X
	Hydrogen & oxygen		X				X
	Methane & oxygen	X	X	X			X
	Solid rocket fuel	X	X	X	X	X	X

Source: GAO analysis of literature. | GAO-22-105166

Notes: J. A. Dallas, S. Raval, J. P. Alvarez Gaitan, S. Saydam, and A. G. Dempster, "The Environmental Impact of Emissions from Space Launches: A Comprehensive Review," *Journal of Cleaner Production*, vol. 255 (2020): 1-12.

M. Ross and J. A. Vedda, *The Policy and Science of Rocket Emissions* (The Aerospace Corporation, 2018).

M. N. Ross, M. Y. Danilin, D. K. Weisenstein, and M. K. W. Ko, "Ozone Depletion Caused by NO and H_2O Emissions from Hydrazine-fueled Rockets," *Journal of Geophysical Research*, vol. 109 (2004): 1-7.

[a]Alumina is also referred to as aluminum oxide.

Satellites also produce emissions when they burn up on reentry. One study states that satellites could produce aluminum, nickel, titanium, iron, silicon, and other emissions during reentry, depending on the satellites' composition.[13] The study suggests that reentering satellites could produce around 7 times more aluminum emissions than natural reentry emissions from meteoroids. Additionally, experts told us satellite reentry emissions could include alumina (aluminum oxide) particles, nitrogen oxides, and potential exotic materials.[14]

2.1.2 Effects on stratospheric temperature and ozone

Emissions from rocket launches and satellite reentries could change the temperature of the stratosphere and deplete the ozone layer, which could increase the amount of harmful ultraviolet solar radiation reaching Earth. However, more information is needed to determine how significant these effects may be, particularly with the potential for almost 3 times the current number of rocket launches projected for the future. Chlorine and particle emissions, such as black carbon and alumina,

[13]The study assumes that there could be an increase of up to 75,000 satellites, each of which completely burn up on reentry. The authors assume the satellites become 75 percent aerosols when they burn up on reentry and that each satellite is made up of 40 percent aluminum, 10 percent iron, 8 percent silicon, 5 percent nickel, and 5 percent titanium. The rest of the material used have smaller percentages or are non-metals. This study states that meteoroids produce more reentry emissions than satellites overall; however, satellite emissions are mostly metal while meteoroid emissions are mostly non-metals. L. Schulz and K. Glassmeier, "On the Anthropogenic and Natural Injection of Matter into Earth's Atmosphere," *Advances in Space Research*, vol. 67, no. 3 (2021): 1002-1025.

[14]Exotic materials could include toxic and radioactive metals that are used within electronics and batteries, according to an expert.

are more concerning to experts than gas emissions, such as water vapor and carbon dioxide. However, the size of the potential effect from particle emissions is unknown because the observational data needed to validate modeling studies for rocket emissions are few, with most of the data collected in only the lower stratosphere.

To protect the ozone layer, the Montreal Protocol on Substances that Deplete the Ozone Layer sets limits on the production and consumption of chemicals that are known ozone-depleting substances.[15] However, the Montreal Protocol does not directly address rocket emissions into the stratosphere. A 2018 World Meteorological Organization report—the *Scientific Assessment of Ozone Depletion*—states that "rocket launches presently have a small effect on total stratospheric ozone (much less than 0.1%)."[16] However, the authors acknowledge that there are important gaps in understanding rocket emissions that limit the confidence level in the predictions of present and future effects.[17]

The following describes the major categories of emissions that are likely from rocket launches and satellite reentries:

<u>Particle emissions</u>

- **Alumina particles** emitted from rocket launches could accumulate in the stratosphere, causing both stratospheric warming and ozone depletion. Alumina particles in the stratosphere reflect solar energy back to space and absorb outgoing solar energy from the surface, resulting in a warmer stratosphere and cooler surface. A study comparing reflection versus absorption of alumina particles predicts that they absorb 3 times as much solar energy as they reflect to space, resulting in an overall warming effect.[18] Alumina particles can also enhance ozone depletion by creating a surface for ozone-depleting chemical reactions to occur. The warming effect and ozone depletion are dependent on particle size. However, because few observational data exist on particle sizes, the study assumes a size distribution that might not be accurate, resulting in significant uncertainty in the magnitude of the warming effect and contributions to ozone depletion. Experts suggest that satellites could also form alumina during reentry.
- **Black carbon particles** emitted into the stratosphere from rocket launches can warm the stratosphere and harm the ozone layer. The particles can remain in

[15]Montreal Protocol on Substances that Deplete the Ozone Layer art. 2, Sept. 16, 1987, 26 I.L.M. 1541. The Montreal Protocol on Substances that Deplete the Ozone Layer was created in 1987 and sets limits on the consumption and production of anthropogenic ozone-depleting substances. The Montreal Protocol requests quadrennial scientific assessment reports to base any decisions for adjustments or amendments needed in the protocol.

[16]World Meteorological Organization, *Scientific Assessment of Ozone Depletion: 2018*, Global Ozone Research and Monitoring Project Report No. 58 (Geneva, Switzerland: 2018).

[17]The *Scientific Assessment of Ozone Depletion* documents advances in scientific understanding of ozone depletion, which adds a scientific basis for decisions made by the parties of the Montreal Protocol.

[18]This estimate is based on the calculated change in temperature resulting from alumina emissions from a solid rocket launch. M. N. Ross and P. M. Sheaffer, "Radiative Forcing Caused by Rocket Engine Emissions," *Earth's Future*, vol. 2, no. 4 (2014): 177-196.

the stratosphere for 3 to 5 years, creating a persistent layer, according to one study.[19] Black carbon particles absorb incoming solar energy from space, slightly cooling the Earth's surface but also increasing the temperature of the stratosphere. In one study, an atmospheric model predicted that if 1,000 suborbital rockets were launched per year using hydrocarbon fuel, such as kerosene, they would emit enough black carbon particles to warm the stratosphere to a magnitude comparable to current aviation emissions.[20] Stratospheric warming also accelerates ozone-depleting reactions. In another study, scientists estimated the amount of black carbon emissions that would occur if rocket launches were to produce 10 times the amount of current rocket emissions over the next 20 years.[21] They estimated that black carbon emissions at this rate would contribute to stratospheric warming by 1.5 degrees Celsius (2.7 degrees Fahrenheit) annually and deplete ozone by about 1 percent for all latitudes north of 30°N throughout the year and up to 4 percent in the summer months at the North Pole.[22] These estimates are uncertain because there are currently no observational data for black carbon emissions from rockets, and as a result, both studies had to make assumptions about the amount and physical processes of black carbon emissions released from rockets.

Gas Emissions

- **Carbon dioxide** can affect Earth's climate; however, carbon dioxide emissions from rocket launches have little effect on Earth's temperature.[23] The magnitude of carbon dioxide emissions from rocket launches is significantly less than carbon dioxide emitted from aviation sources.[24] In one study, carbon dioxide emissions from historical launches were estimated using 150 rocket launches per year over a 25-year period and predicted that would not have a significant effect on Earth's temperature.[25]
- **Water vapor** emissions into the stratosphere can warm the troposphere

[19]Ross and Sheaffer, "Radiative Forcing," 177-196.

[20]This estimate is based on 10 years of continuous launches to achieve the same warming as current subsonic aviation when the paper was published. M. Ross, M. Mills, and D. Toohey, "Potential Climate Impacts of Black Carbon Emitted by Rockets," *Geophysical Research Letters*, vol. 37, no. 24 (2010): 1-6.

[21]In this study, researchers calculated emissions to be 1,000,000 kg for 150 rocket launches. To extrapolate the growth of rocket launches over the next 20 years, the researchers considered the effect of 10 times the amount of emissions (i.e., 10,000,000 kg). The study was conducted over a simulated future 50-year period with a quasi-steady state amount of black carbon present in the stratosphere after 6 years. C. M. Maloney et al., "The Climate and Ozone Impacts of Black Carbon Emissions from Global Rocket Launches," *Journal of Geophysical Research: Atmospheres*, vol. 127, no. 12 (2022): 1-17.

[22]Most of the U.S. resides above 30°N latitude.

[23]Carbon dioxide emissions from rocket launches include emissions from the surface to the upper atmosphere. This is different from the other particle and gas emissions, because carbon dioxide becomes well mixed throughout the atmosphere whereas particle emissions are considered in the upper atmosphere only because they accumulate within the stratosphere.

[24]The effect on Earth's temperature from carbon dioxide emitted from 150 rocket launches per year is about 0.1 percent of the temperature effect caused by carbon dioxide emissions from global aviation.

[25]The study considered emissions from hydrocarbon, hypergolic, and solid rocket engines. Ross and Sheaffer, "Radiative Forcing," 177-196.

while cooling the stratosphere. However, several studies suggest that water vapor emissions from rocket launches are not of concern compared with effects from particle emissions. One atmospheric model predicted that water vapor currently only accounts for approximately 3 percent of warming caused by rocket emissions.[26] Water vapor emissions from rocket launches can also increase the formation of polar stratospheric and mesospheric clouds, which could contribute to ozone depletion and warming. However, these effects would likely be small. Studies suggest that rocket propellants that emit mostly water vapor, such as hydrogen and oxygen, have fewer environmental effects than other propellants that emit particles.

- **Nitrogen oxides** emitted from rocket launches and reentries of rockets, satellites, and space debris can deplete ozone, but the extent is not well-understood. One study concluded that a very large number of rocket launches and reentries is needed to significantly affect global ozone.[27] Another study suggests that reentries of numerous satellites from LEO constellations are likely to contribute to an increase in nitrogen oxide emissions and that further study of how much these emissions deplete ozone would be beneficial.[28]
- **Chlorine chemicals** emitted from solid rocket engines contribute to stratospheric ozone loss. When these chemicals interact with alumina particles, ozone can decrease even further. A modeling study estimated that solid rocket emissions could cause an annually averaged global ozone loss of approximately 0.025 percent, with chlorine chemical emissions responsible for two-thirds of the ozone loss and chlorine production resulting from chemical reactions on the surface of alumina particles responsible for the rest.[29] Ozone loss caused by chlorine chemical emissions from solid rocket engines is well understood, but the chemical reactions on the surface of alumina particles are poorly understood.

Exotic material emissions

- **Exotic material emissions** can be produced during satellite reentry, according to experts**.** Exotic materials could include paints, resins, epoxies, toxic

[26]The authors acknowledge a large uncertainty in the ability for stratospheric water vapor to cause a change in Earth's temperature, as there is not complete agreement amongst literature. Ross and Sheaffer, "Radiative Forcing," 177-196.

[27]The process of forming nitrogen oxides is different between launch and reentry. During launch, nitrogen oxides are emitted directly from the rocket engine. During reentry, nitrogen oxides are formed through a shock wave effect that occurs through the heating of the air surrounding a spacecraft. This study models rocket launches and reentries of 100,000 hydrogen fueled rockets. The authors acknowledge high uncertainty in their estimates of the production of nitrogen oxides and that the values are only representative. E. J. L. Larson et al., "Global Atmospheric Response to Emissions from a Proposed Reusable Space Launch System," *Earth's Future*, vol. 5, no. 1 (2016): 37-48.

[28]M. N. Ross and K. L. Jones, "Implications of a Growing Spaceflight Industry: Climate Change," *Journal of Space Safety Engineering*, vol. 9, no. 3 (2022): 469-477.

[29]This estimate is based on the historical launch rate of solid rocket motors from 1970 to 1997. The maximum amount of ozone decrease at 0.025 percent occurred in 1997. J. A. Dallas et al., "The Environmental Impact of Emissions from Space Launches: A Comprehensive Review," *Journal of Cleaner Production*, vol. 255 (2020): 1-12.

materials, and radioactive materials used in spacecraft components such as electronics and batteries. Experts are uncertain whether toxic materials are used in satellites or if other materials, such as plastic, could be incorporated into satellite design, or how such materials will react during reentry. Experts told us that industry cooperation on the composition of satellites would help increase the understanding of how materials react during reentry. One expert told us there are few observational data for satellite reentry and accurate modeling data are limited because the industry has not released satellite composition data.

2.1.3 Mitigation technology and approaches

The following actions could help to evaluate and mitigate the effects of emissions from rocket launches and satellite reentries:

- **Collect observational data.** Observational data from rocket launches and satellite reentries are needed to fully understand the effects of emissions. Observational data for rocket launches are rare with most data collected in the low altitudes of the stratosphere. Because of the lack of observational data, some of the studies mentioned above had to make assumptions. Experts and agency officials told us that instruments exist to collect observational data for rocket launch and satellite reentry emissions. Collaboration between NASA, NOAA, industry, and other entities could combine resources to collect observational data and produce atmospheric models. One expert estimated that such a program could involve multiple agencies, organizations, and universities and could directly measure emissions using aircraft, ground-based sensors, and orbiting sensors, providing data for more accurate atmospheric modeling studies. Gathering observational data would aid in quantifying emissions and informing whether mitigation approaches to reduce emissions are needed. If emission reductions are necessary, additional steps would be required.
- **Establish metrics.** Experts suggest that scientists and policymakers could work together to establish metrics, which would be useful in comparing emissions from different rockets and satellites and their effects on atmospheric ozone and temperature. Metrics would also allow policymakers to compare emissions from rocket launches to other substances that deplete ozone and assess the net economic gains from rockets and satellites with ozone effects. Developing metrics would aid in quantifying emissions and informing whether mitigation approaches to reduce emissions are needed. If emission reductions are necessary, additional steps would be required.
- **Develop an emissions database.** An emissions database, similar to one that currently collects aircraft emissions data, could be developed for rocket launches.[30] This database could include the type of

[30] An emissions databank is used by the aviation community to collect information on exhaust emissions produced by aircraft engines.

propellant used in each rocket and the associated emissions. An agency official told us challenges to establishing a database are the lack of observational data and a centralized program. Developing an emissions database would aid in quantifying emissions and informing whether mitigation approaches to reduce emissions are needed. If emission reductions are necessary, additional steps would be required.

- **Share satellite composition data.** Policymakers could provide incentives to industry to provide satellite composition data to scientists so they can model the emissions from satellite reentries, according to experts. Experts told us they could more accurately model emissions from satellite reentries if they knew the materials used in satellites. Satellite composition data are proprietary, which presents a challenge to this mitigation because policymakers would have to balance information protection with the need for composition data. Improved sharing of satellite composition data would aid in quantifying emissions and informing whether mitigation approaches to reduce emissions are needed. If emission reductions are necessary, additional steps would be required.
- **Develop regulations or guidance for rockets.** Agreements or rules, similar to the Montreal Protocol and its implementing regulations that limit the consumption and production of chemicals that deplete ozone or change Earth's temperature, could help limit emissions from rocket launches. However, without observational data and emissions metrics, it is not clear what type or degree of regulation or guidance is needed. Once that is clear, regulations could, for example, require rocket operators to use propellants with cleaner emissions. Solid rocket and kerosene engines have more of an effect on Earth's temperature and ozone than methane and hydrogen rocket engines, according to some experts. Such regulation could also involve costs and trade-offs. For example, regulations that restrict emissions into the upper atmosphere from solid rocket and kerosene engines could prompt a switch to cleaner-burning hydrogen, which is more costly and dangerous because it requires storage at a very low temperature and carries greater risk of explosion. Similarly, an industry official told us a shift to methane engines would require investment in new testing infrastructure, because the current infrastructure is set up for kerosene or hydrogen engines.
- **Develop regulations for satellites.** Regulations could require satellite designers to limit the use of materials that are more likely to produce emissions that affect the atmosphere. However, experts said there is a lack of observational data and publicly available information about satellite composition, making it unclear whether such regulations are necessary. If such regulations were eventually created, they could come with trade-offs. For example, regulations requiring the use of different materials in satellites could increase casualty risk (see section 2.2) if the materials are less likely to fully disintegrate on reentry.

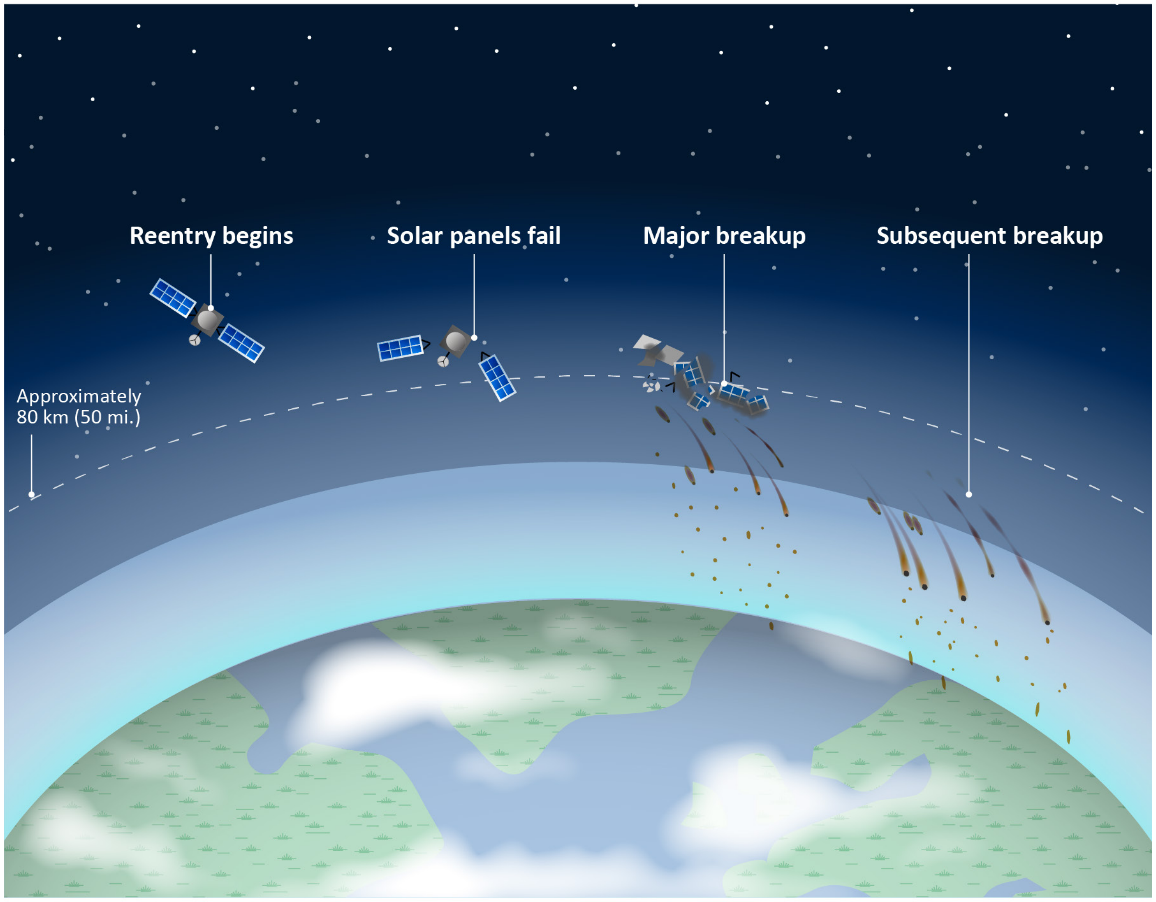
2.2 Satellite reentry fragments pose a human casualty risk

2.2.1 Human casualty risk

Satellites break apart upon reentry and begin to disintegrate, but pieces that remain intact may fall on populated areas, causing property damage, injury, or death (see fig. 5).[31] The industry is encouraged by FCC to design satellites to completely disintegrate during reentry, but the ability to do so depends on orbit characteristics, reentry trajectory, and satellite design (e.g., material, thickness, etc.). For example, a titanium satellite would be less likely to disintegrate than one made of aluminum because titanium has a much higher melting point than aluminum.

[31]The Convention on International Liability for Damage Caused by Space Objects (Liability Convention) holds that a launching state could be held liable for damages, including property damage, injury, or death. In 1981, the only claim thus far under the convention was settled between Canada and the Soviet Union to compensate for the cleanup in Canadian territory of the radioactive debris from the Soviet Cosmos 954 satellite reentry in 1978. Convention on International Liability for Damage Caused by Space Objects, Mar. 29, 1972, 24 U.S.T. 2389, 961 U.N.T.S. 187.

Figure 5: Satellite reentry and breakup



Source: Derived from image courtesy of The Aerospace Corporation and used with permission. | GAO-22-105166

Note: Image not to scale.

An FCC regulation requires satellite operators to submit a casualty risk assessment if planned postmission disposal involves atmospheric reentry of the satellite. Once in effect, an amendment to the regulation would require the satellite operator to demonstrate that portions of any reentering spacecraft have an expected human casualty risk less than 1:10,000.[32] A 1:10,000 risk means that if an object reentered 10,000 times, one person would be expected to be injured or die.

FCC's amended regulations would require that satellite operators demonstrate that their individual satellites are below the human casualty risk threshold by using NASA's Debris Assessment Software or a higher fidelity assessment tool.[33] NASA's software allows satellite operators to input

[32]85 Fed. Reg. 52422, 52451 (amending 47 C.F.R. § 25.114(d)(14)(vii)(D)(2)(ii)). The casualty risk assessment includes any surviving objects that would have an impacting kinetic energy of 15 joules or greater.

[33]85 Fed. Reg. 52422, 52451 (Aug. 25, 2020) (amending 47 C.F.R. § 25.114(d)(14)(vii)(D)(2)(ii)).

orbital plans and satellite materials. However, the software has limited capability. An agency official stated that there is a need for more data to aid the software, such as what new modern materials are being used within satellites.

As the number of satellites increases, the public could be subject to a higher total human casualty risk. The current human casualty risk limit is for single satellites and does not take into account the risk of a constellation as a whole. While individual satellites may not exceed FCC's casualty risk limit, having a larger number of satellite reentries from constellations could cause an overall human casualty risk higher than the acceptable human casualty risk for individual satellites. For example, a study predicted that debris from a 7,518-satellite constellation with 1,253 reentries per year could approach a 1:10 human casualty risk for the general population by 2030.[34] The study also predicted that having a total of 15,968 satellites in LEO by 2030 with 2,413 reentries per year could result in approximately a 1:4 human casualty risk. FCC stated in a 2020 further notice of proposed rulemaking in its proceeding on Mitigation of Orbital Debris in the New Space Age that it is considering whether a different casualty risk requirement is needed for satellite constellations as a whole.[35]

2.2.2 Mitigation technology and approaches

The following approaches could help reduce human casualty risk from satellite reentries:

- **Design satellites for disintegration.** One possible mitigation for human casualty risk is for satellite operators to design satellites that minimize the size of fragments produced during reentry or that completely disintegrate upon reentry to achieve a human casualty risk of zero.[36] However, limited data exist to show that a satellite will completely disintegrate. For example, the NASA Debris Assessment Software currently used to calculate the human casualty risk generated by surviving fragments of satellites is not fully accurate because it only has four general shape options to represent satellite components and only allows for four layers of materials within the satellite. Furthermore, satellite operators do not tend to share the composition of the satellites with researchers and software developers because it is often proprietary, which makes validation difficult and leaves them

[34]The number of reentries per year is assumed to equal approximately 17 percent of the satellites in the constellation. The study assumes an uncontrolled reentry for all constellations and a fragment survival rate at 10-40 percent of the mass of a satellite if the composition is unknown. The study assumes that the satellites are similar to Iridium satellites in calculating the casualty risks, but the actual risk depends on the satellite's design and materials, which are not publicly known. However, the author expects that the calculated casualty risks should be within an order of magnitude unless the satellite incorporates design-for-demise features. W. H. Ailor, *Large Constellation Disposal Hazards* (The Aerospace Corporation: 2020).

[35]Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd. 4156 (2020).

[36]In April 2020, FCC sought comment on adopting a presumptively acceptable human casualty risk threshold of zero, which could be achieved through satellites designed to disintegrate or controlled reentry. Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd. 4156 (2020).

unaware of any updated material changes needed to the software.

- **Control satellite reentry.** Another possible mitigation is to set standards requiring or providing incentives for operators to plan for their satellites to land in a designated, unpopulated area. A challenge to implementing this mitigation is that controlled reentries require satellites to be able to maintain attitude control and for more propellant to be saved onboard satellites to maneuver at the end of their missions, which shortens the lifetime of the satellites.

3 Sunlight Reflection and Radio Transmission Effects May Be Difficult to Mitigate

Large constellations of satellites in LEO affect various observations from the ground and space, such as optical and radio astronomy, remote sensing of Earth systems, as well as amateur astronomy, astrophotography, and cultural uses of the night sky. Mitigation technologies and approaches are under development, but the available evidence suggests it will be difficult to fully mitigate these effects as the number of additional satellites launched increases.

3.1 Sunlight reflections from satellites affect astronomy and space-based science missions and may be difficult to mitigate

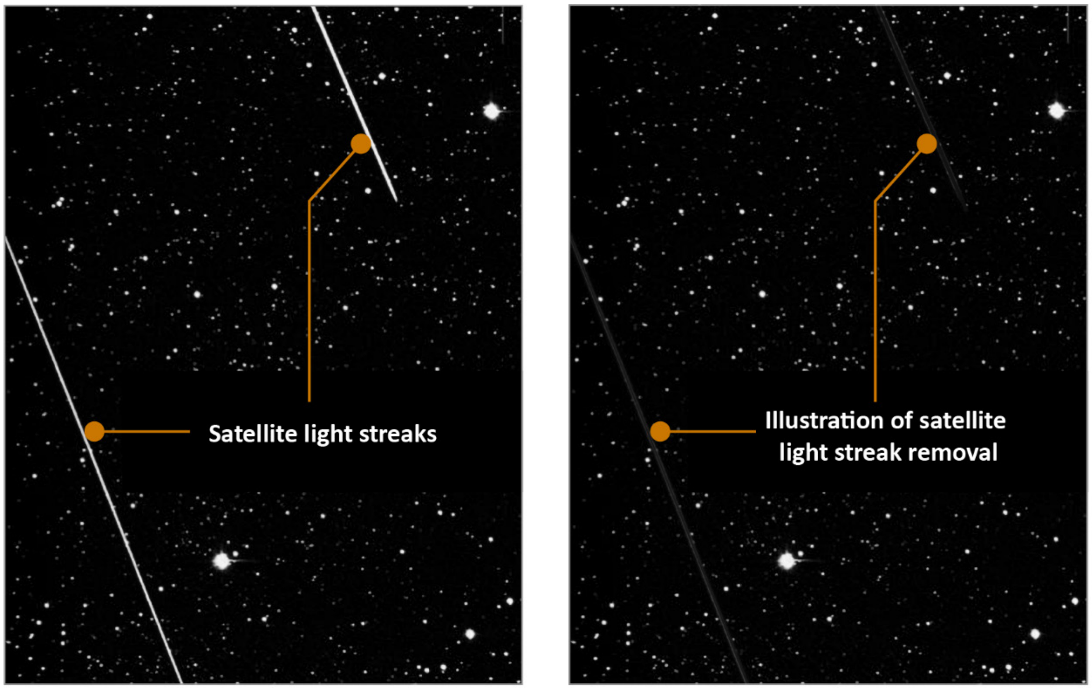
Satellites can affect ground-based optical astronomy and space-based science missions. For ground-based astronomy, which is affected by satellites reflecting sunlight, satellite operators and astronomers may have options to mitigate, but scientists report that no combination of mitigations will fully address the effects.[37] For space-based science, satellites can obscure or impede observations, and the effects and mitigations are not well understood.

3.1.1 Effects on ground-based optical astronomy

Satellites can affect optical telescopes by reflecting light from the sun, producing streaks or bright spots in images. The left side of figure 6 shows an astronomy image with light streaks caused by satellites. As more satellites are deployed into LEO, nearly all facets of optical astronomy may be negatively affected. Because satellites at higher LEO altitudes are illuminated by the sun for longer periods of time, such satellites generally produce greater reflection effects than those lower in LEO.

[37]C. Walker et al., *Impact of Satellite Constellations on Optical Astronomy and Recommendations Toward Mitigations* (SATCON1 report) (August 2020), https://aas.org/satellite-constellations-1-workshop-report.

Figure 6: Light streaks from large constellations of satellites in an optical astronomy image



Source: Jeremy Tregloan-Reed, Lizxandra Flores-Rivera, Maximilian Häberle. The Chilean Low Earth Orbit Satellite group/Max-Planck-Institut für Astronomie/Calar Alto Observatory. | GAO-22-105166

Optical telescopes collect light with a large mirror or optics and capture the image with a detector. They are a crucial tool for astronomy, a field whose contributions range from understanding the nature of the universe to tracking asteroids that threaten to collide with Earth.

The recent and rapid increase in the number of satellites has happened on a short timescale. Conversely, research-grade telescopes are massive national and international science investments, and each can cost many hundreds of millions of dollars and take years—sometimes decades—to build.[38] Thus, scientists may struggle to adopt current and near-future designs for observatories to the rapid growth of satellite constellations.

Of particular concern to scientists is the potential effect on wide-field imaging telescopes. These telescopes survey large swaths of the night sky, sometimes for long periods of time or over many years, to generate data that future observations can refer back to. For example, such surveys help to spot asteroids, some of which could collide with Earth—a low-probability event that could be catastrophic.[39] One study

[38]For example, the Vera C. Rubin Observatory is funded by the Department of Energy, the National Science Foundation, and private funding. In 2021, GAO reported that the National Science Foundation plans to spend at least $471 million to complete the Vera C. Rubin Observatory, formerly known as the Large Synoptic Survey Telescope. GAO, *National Science Foundation: COVID-19 Affected Ongoing Construction of Major Facilities Projects,* GAO-21-417 (Washington, D.C.: June 8, 2021).

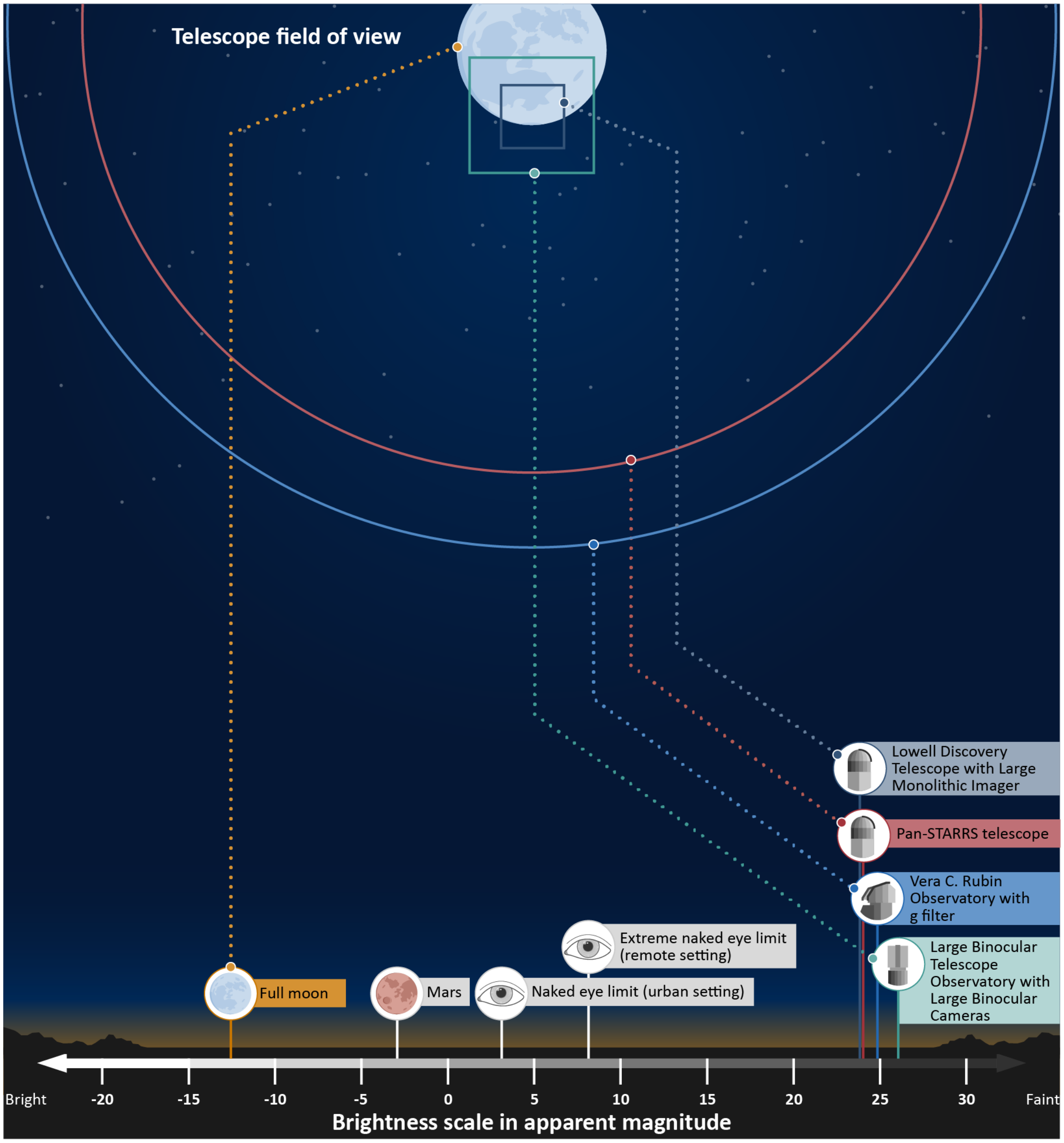
[39]NASA calculates that no known asteroid will likely strike Earth within the next 100 years. NASA Jet Propulsion

looking at the projected future effects of light streaks from satellites concluded that the streaks would compromise 30 to 40 percent of images from these surveys during the first few hours after dusk and before dawn.[40] Dusk and dawn windows are important time periods in which to spot near-Earth objects, such as asteroids, according to scientists. The study also concluded that light streaks from satellites could affect approximately 3 percent of wide-field and long-medium-field exposures, and less than 1 percent of narrow-field exposures during the first and last hours of night. Figure 7 compares wide, medium, and narrow field exposures from various telescopes.

Laboratory's Center for Near Earth Object Studies regularly monitors and tracks these asteroids, in addition to continuously searching for new asteroids. It updates projections as new asteroids are found and studied.

[40]A study published in 2020 looked at 18 proposed constellations by various satellite operators totaling approximately 26,000 satellites. Using simplifying assumptions, the study considered effects based on different types of observations, such as length of exposure, different telescope fields of view, and other factors. GAO is simplifying the language here in the report—O. R. Hainaut and A. P. Williams, "Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains," *Astronomy & Astrophysics*, 636 (April 2020): A121, https://doi.org/10.1051/0004-6361/202037501.

Figure 7: Brightness of astronomical objects, sensitivity of telescopes, and telescope fields of view compared to the moon



Source: GAO. | GAO-22-105166

Astronomers have organized workshops to discuss the effects of large constellations of satellites and potential mitigations. They identified different research areas that are potentially vulnerable to sunlight reflections, such as:[41]

- Detection of near-Earth objects, which are important to discover and track for planetary defense (i.e., ensuring no comets or asteroids hit Earth)
- Rare observations, such as gamma ray bursts, and new detections of phenomena
- Studies of dark matter and dark energy

3.1.2 Sunlight reflection mitigations for ground-based optical astronomy

Some current and future operators of large constellations of satellites said they have engaged with the astronomy community to receive input and feedback on suggestions for how to mitigate satellites' effects on astronomy. The International Astronomical Union recently established a Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference, which will help organize the astronomy community to respond to large constellations of satellites. These efforts have resulted in mitigation proposals, and one operator told us it has implemented some mitigations. Despite voluntary actions by astronomers and industry, however, experts have told us and a report has concluded that no combination of mitigations will be sufficient to eliminate the effects of light reflections on optical astronomy as the number of satellites increases.[42]

Astronomy researchers and satellite operators are exploring at least seven actions to mitigate the effects of satellites on optical astronomy:

- **Conduct research on effects.** More research could help quantify the effects on astronomy. More studies are necessary to evaluate the full effects of satellite constellations on the wide variety of astronomical research projects, including whether the effects would prevent some projects, according to an academic researcher. Resources are needed to study and better understand these effects, according to reports, and the resulting knowledge could help inform other mitigations.
- **Consider choice of orbit.** Experts and a report published by astronomers recommend that satellite operators place satellites in LEO below about 600 kilometers (approximately 372 miles), which would reduce the effect of sunlight streaks produced by a satellite constellation, although they were not sure by how much. To provide the same coverage, more satellites are required at lower altitudes and fewer satellites are required at higher altitudes, so there is a trade-off between orbit height and number of satellites. However, organizing satellite operators or setting standards for their choice of orbits presents challenges from both

[41]Walker et al., *Impact of Satellite Constellations* (SATCON1), 9.

[42]Walker et al., *Impact of Satellite Constellations* (SATCON1), 3.

organizational and regulatory perspectives. Domestically, no federal agency has responsibility for orbit designations of satellites in LEO, according to one operator. Internationally, setting orbit assignments for space assets in LEO could require coordination among ITU member states.

- **Set standards for brightness.** In two reports, astronomers and members of the satellite industry have proposed a brightness standard for satellites.[43] The brightness standard, which is based on experiments and simulations for the Vera C. Rubin Observatory, is a threshold below which it would be possible to handle light streaks from satellites in images with data processing tools. Regulations could incorporate brightness, for example, as part of the licensing process. However, additional observational data and studies are needed to further verify and refine the brightness standard.
- **Consider satellite design.** Satellite manufacturers and operators can reduce the reflectivity of satellites during the design process. Operators have piloted two options: optical darkening and a sunshade.[44] One operator we interviewed said it could adjust how the satellites face the sun and the Earth to reduce brightness when it deploys satellites into a low altitude (where they are brightest) before raising them to the higher mission altitude where brightness decreases and they become invisible to the naked eye. Even though many satellites are invisible to the naked eye at mission altitude, telescopes can still see the satellites. Mitigations have shown some success—optical darkening made one operator's satellites half as bright, according to a study looking at that operator's satellites actively in orbit—but may require additional technology development to meet desired standards set by astronomers.[45]
- **Develop models to predict brightness.** Two satellite manufacturers we interviewed told us they are working to predict satellite brightness with computer models. Such a model could tell designers earlier in the design phase, when changes are less costly, how effective mitigation measures are expected to be.
- **Share data to enable better predictions.** Satellite manufacturers and operators could share more data about the design and future positions of satellites. Astronomers could use these data to better predict when satellites will cross a telescope's field of view so

[43] Walker et al., *Impact of Satellite Constellations* (SATCON1).

C. Walker et al., *Report of the SATCON2 Workshop*, SATCON2 Workshop (October 2021), https://noirlab.edu/public/products/techdocs/techdoc031/.

[44] Optical darkening is akin to painting the satellite with a dark paint to reduce its reflectivity. A sunshade is a large umbrella-like covering affixed over the satellite to reduce reflectivity.

[45] The study reported, based on the authors' observations, a dimming from the optical darkening technology of 0.77 +/- 0.05 apparent magnitudes, which corresponds to a satellite about half as bright as the un-darkened satellite. J. Tregloan-Reed et al., "First observations and magnitude measurement of Starlink's Darksat," *Astronomy & Astrophysics*, 637 (April 2020): L1, https://doi.org/10.48550/arXiv.2003.07251.

they can close the shutters to preserve their measurements and data. Astronomers do not currently have access to enough high-quality data to accurately model when shutters need to close, nor can they predict with certainty where in the telescope field of view the satellite will be. Moreover, as the number of satellites increases, avoiding satellites in telescope images may require advanced techniques, even if astronomers have excellent location data, according to a report.[46]

- **Improve image processing.** Astronomers have technology to remove or mask light streaks in images (see right side of fig. 6) after obtaining the data from observations, and they are looking to create new tools. However, the tools may require additional development to be effective. When the image processing tools are fully operational, they will not solve the problem entirely.[47] According to one expert, the tools will remove some scientific data when removing the light streaks from satellites.

3.1.3 Optical effects on space-based science missions are poorly understood, and mitigations are uncertain

NASA officials told us the rise in the number of large constellations of satellites potentially creates risks for Earth science and space science missions, and the future optical effects are not well known for Earth science. NASA expects to lose scientific data, and more resources will be required to deal with many satellites in LEO. The agency has requested data and information from one operator to better understand how to mitigate potential effects on NASA missions.

NASA officials told us they expect the following effects on space science, Earth science, planetary defense, and future missions:

Space-based astronomy. The Hubble Space Telescope orbits at an altitude of 535 kilometers (332 miles) and is always looking away from Earth. Satellites in orbit currently affect around 2 percent of Hubble telescope images and around 8 percent of stacked (multi-color) images, according to NASA officials. As thousands of additional satellites begin to enter the same LEO environment as Hubble, the effect may be even more pronounced, potentially affecting more than 16 percent of images.

Earth science. Earth science satellites in LEO are always looking down at Earth, and constellations of satellites orbiting below them can pass through their field of view. According to a NASA scientist, Earth scientists prefer LEO over other orbits due to cost and resolution considerations.[48] Earth scientists cannot design around these constraints, according to the scientist,

[46] C. Walker et al., *Dark and Quiet Skies for Science and Society - Report and recommendations* (January 2021).

[47] J. McDowell et al., *SATCON2 Algorithms Working Group Report,* SATCON2 Workshop (October 2021), https://noirlab.edu/public/products/techdocs/techdoc033/.

[48] NASA makes science investments and supports commercial innovation of the "LEO economy." LEO is near enough to Earth to be a convenient orbit to transport, communicate with, observe, and resupply government and commercial missions.

which may affect scientific progress and understanding of important areas like climate change.

The biggest concern for NASA is the potential for its satellites—with active sensors that use lasers, masers, or lidar to measure reflections from Earth—to instead receive reflections from other satellites in lower orbits, which could damage sensitive instrument detectors.[49] Another concern is that NASA has to suspend laser-based measurements from its satellites to prevent causing damage to LEO satellites orbiting beneath them. In recent months, for example, NASA has suspended laser-based measurements from its Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) every other day, on average, to prevent laser reflections back into its own telescope and to protect the satellites operating below. NASA similarly suspends measurements on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission.[50] This suspension of service can potentially affect time-sensitive observations of wildfires or other natural disasters.

Some operators of large constellations of satellites currently use or plan to use laser communication links between satellites in the constellation or other spacecraft. Lasers inadvertently directed into NASA's space-based sensors and telescopes could damage or degrade instruments or star trackers.[51] A federally funded research and development center is assessing how often laser interactions may happen. There is no regulatory authority on laser communications in space, according to a NASA official.[52]

Planetary defense. Congress directed NASA to detect, catalog, track, and characterize the physical characteristics of near-Earth objects that could be hazardous if they collide with Earth, such as asteroids.[53] NASA and other observers search for new asteroids using ground-based surveys and a space-based telescope to look for moving objects against the background of stars. Looking close to the horizon, just after dusk and just before dawn are important times to search for asteroids, since the majority of asteroids are found during these times, according to an expert and a report. If tens of thousands of proposed additional satellites are in orbit, NASA estimates that every image looking for an asteroid could have a light streak from a satellite in it. At some point, NASA will have to remove so many light streaks that it may not detect an

[49]A laser is a narrow beam of high-energy light in which all the waves have a narrow range of wavelengths. A maser is a narrow beam of high-energy microwaves of one particular wavelength. Lidar is a remote sensing method that uses pulsed laser light to generate three-dimensional data for different Earth surface measurements, such as vegetation canopy, ice, and the seafloor.

[50]ICESat-2 is a satellite mission that measures ice sheets, sea ice, and the height of vegetation in forests. CALIPSO is a satellite mission that measures aerosols and clouds to better understand the climate system and global climate change.

[51]A star tracker is a device on a satellite to help it navigate in space. A NASA official told us that degrading or damaging a star tracker could affect the ability to determine the satellite attitude used for geolocation of science measurements, and could also pose a risk to satellite safety.

[52]FCC officials told us that FCC generally receives information about laser communications within a satellite constellation as part of the satellite operator's licensing application. However, FCC does not coordinate the laser communications.

[53]George E. Brown, Jr. Near-Earth Object Survey Act, Pub. L. No. 109-155, tit.III, § 321, 119 Stat. 2895, 2922-23 (2005).

asteroid, which can appear in a span as small as only two pixels in an image.

Other space science and effects for future planned missions. NASA's new SPHEREx mission has a wide field of view to map the entire sky and search for hundreds of millions of galaxies and stars.[54] NASA estimates it will lose 2 percent of mission data to light streaks from satellites when it is launched in 2025, but has not projected data loss over the mission lifetime. SPHEREx will likely last through 2030 when an estimated tens of thousands of additional satellites will be in LEO, and NASA will have to change the way it collects and processes data to find and mask light streaks so they do not contaminate the data.

According to a NASA scientist, there may be a point in the future where LEO could be effectively "closed" to astrophysics because of the high number of satellites. Scientists might be forced to choose other orbits, such as GEO or a faraway orbit beyond the moon's orbit. However, such orbits make missions much more expensive and challenging, or sometimes impossible, to operate.

NASA plans to model the future space environment to better understand all objects in LEO, but it is uncertain how many additional satellites will be in orbit. NASA is uncertain of the future magnitude of effects on space-based science missions from large constellations of satellites. NASA has requested data from one operator to better understand what mitigations, if any, exist, but some current mitigations are not effective with the present number of satellites, according to a NASA scientist.

3.2 Cultural, amateur astronomy and astrophotography, and light pollution effects may have some mitigations, but more stakeholder engagement is needed

Sunlight reflections from satellites may affect some Indigenous communities, amateur astronomy and astrophotography communities, and stargazers who wish to view the night sky. Satellites may also contribute to the overall background brightness of the night sky, but this effect is expected to be minimal.

Cultural effects. Sunlight reflections from satellites could affect the public's viewing experience of the night sky if the satellites are bright enough to be seen by the naked eye. For example, these reflections may affect some Native American or Indigenous communities' interactions with the night sky, which has cultural and religious implications for these groups.

[54] NASA plans to launch the Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer (SPHEREx) mission in 2025. It will gather data on hundreds of millions of stars and galaxies to search for water and other molecules necessary for life, as well as signs of planet formation.

"A key aspect of Indigenous identity and Indigenous knowledge is space referencing or 'Space and Place', learning in harmony with a specific time and place, which is part of a broader relational view of the Universe and our place in it… Numerous Indigenous and cultural practices around the world are based on this relational view of space, whether it is used for calendaring, sociocultural or religious events, agriculture and fishing cycles affecting food sovereignty, or celestial navigation or wayfinding."

Source: A. Venkatesan et al., "The impact of satellite constellations on space as an ancestral global commons," *Nature Astronomy,* vol. 4 (November 2020): 1043–1048, https://doi.org/10.1038/s41550-020-01238-3. | GAO-22-105166

Amateur astronomy and astrophotography effects. Sunlight reflections from satellites can affect amateur astronomy and astrophotography. Satellites already affect amateur astronomy,[55] but the effects from many additional satellites in orbit is expected to be minor, according to one report.[56] The effect on astrophotography is expected to range from minor to severe, depending on the camera's field of view, once many tens of thousands of satellites are in orbit according to the report.[57]

Light pollution effects. Satellites could increase the overall brightness of the sky, known as diffuse night sky brightness, but this effect is expected to be minimal even as the number of satellites grows significantly. The expected increase in diffuse night sky brightness is expected to be less than 1 percent, according to one study that estimated the effects of approximately 60,000 satellites in orbit, provided satellites remain intact and do not contribute significantly to orbital debris.[58] Small pieces of orbital debris are the primary drivers of diffuse night sky brightness, which could negatively affect astronomy by making faint objects harder to observe. This effect is similar to, but much smaller than, the ground-based "skyglow" or "light domes" of light pollution seen in and around cities at night caused by human-made light sources. The key mitigation approach is to limit the collisions and satellite degradation that generate orbital debris (see section 4.3), according to an expert and the study.

The space community needs more research and dialogue to understand the magnitude of the implications and what mitigation approaches, if any, may exist to address these cultural, amateur astronomy and astrophotography, and light pollution effects. Leaders and policymakers should engage with these affected groups early in the satellite design process to better understand their concerns, according to

[55]Amateur astronomy covers a diverse group of people for whom astronomy is a hobby, ranging from casual observers of the night sky to dedicated hobbyists who spend thousands of dollars on telescopes and belong to astronomy clubs.

[56]Walker et al., *Impact of Satellite Constellations* (SATCON1), 15.

[57]Astrophotography covers a range of people, from hobbyists to professional photographers, who use mobile phone cameras, professional cameras, or specialized photographic equipment to take pictures of celestial bodies such as stars and galaxies or events such as an eclipse.

[58]A study published in 2022 builds on the work and assumptions of the study listed in section 3.1.1 (Hainaut and Williams (2020)). In the 2022 study, the authors created two types of simulations for likely scenarios, assuming approximately 60,000 satellites in orbit by 2030. C. G. Bassa, O. R. Hainaut, and D. Galadí-Enríquez, "Analytical simulations of the effect of satellite constellations on optical and near-infrared observations," *Astronomy & Astrophysics*, 657 (2022): A75, https://doi.org/10.1051/0004-6361/202142101.

scientists and published reports by astronomers.[59]

3.3 Radio transmissions affect astronomy and may affect government space systems, although some mitigations are available

Satellites use radio transmissions to communicate with control stations and users on Earth, and these transmissions have long challenged radio astronomy. Radio astronomers have been able to manage the effects from radio transmissions. However, as the number of satellites is projected to grow significantly, particularly in LEO, the effects from radio transmissions may become more challenging for radio astronomy and some government space systems.[60]

3.3.1 Effects on radio astronomy

Radio astronomy studies radio signals emitted or absorbed by celestial objects. Astronomers look for radio waves from many different sources, including hydrogen and many different molecules in galaxies and newly-forming stars, black holes, and microwave radiation from the early universe. Radio telescopes work by collecting radio waves with large independent antennas or groups of antennas geographically dispersed, sometimes many hundreds to thousands of miles apart. Radio astronomers receive and measure faint signals from the ambient cosmic environment, and they often have to extract the signal from significant “noise” in the data.

These faint cosmic signals have specific frequencies along the radio spectrum, and transmissions from various sources can drown them out if the transmitting source uses the same or adjacent spectrum frequencies that the radio astronomy telescopes are measuring. Transmissions from various ground- and space-based sources, such as cell phones, computers and other electronics, and satellites providing communications and radio broadcasting services can make astronomical signals difficult or impossible to receive and detect because the transmitting sources are much stronger than the faint cosmic signals.

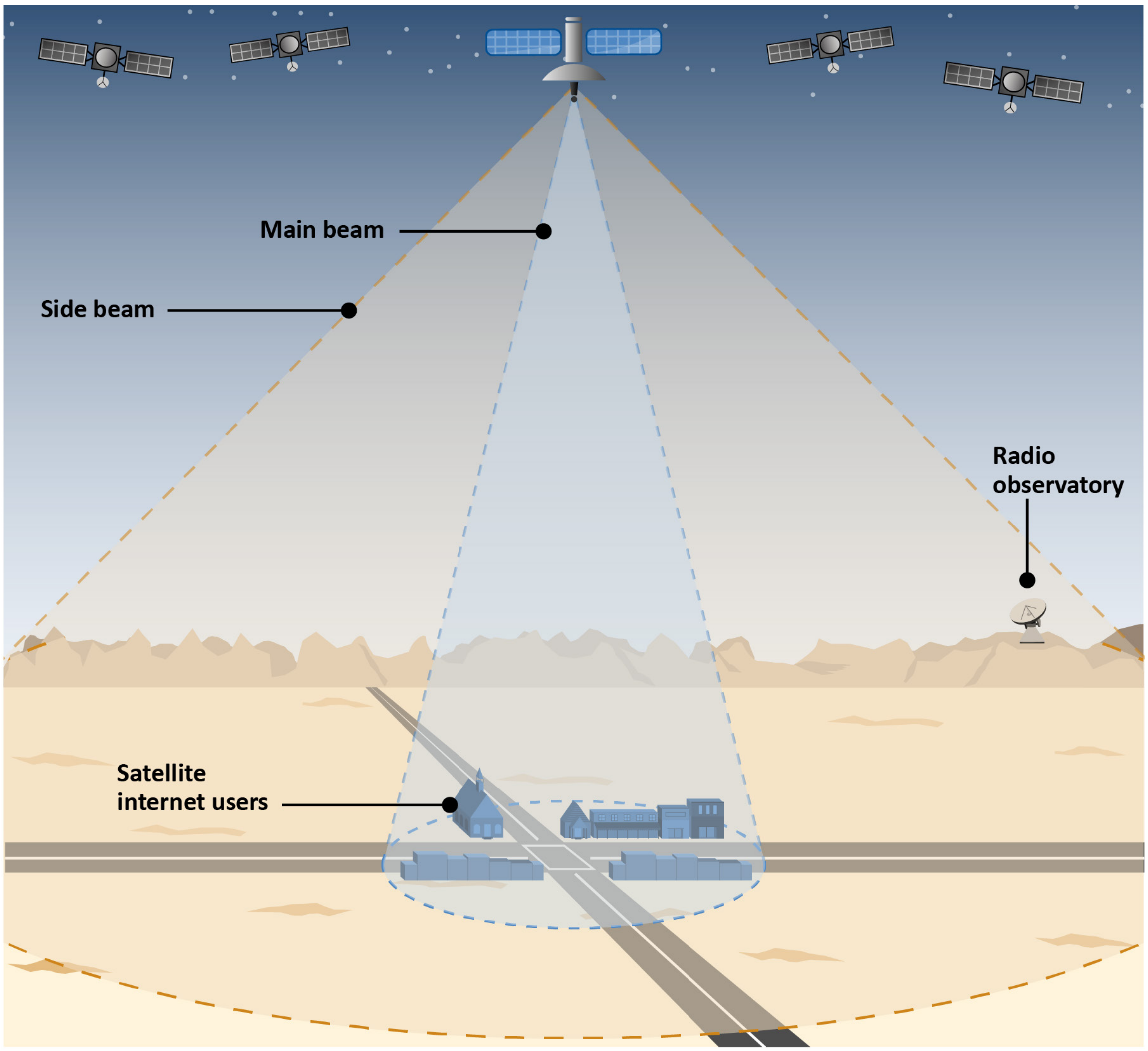
Transmission effects from satellites are not a new problem for radio astronomy, and astronomers have been able to mitigate those effects to some degree. However, as the number of satellites in LEO increases significantly, satellite transmissions may increasingly challenge radio astronomy’s ability to detect faint cosmic signals. The most disruptive effect occurs when a satellite points in a direction that concentrates its transmission power directly into where the radio telescope is most sensitive, and both the satellite and the radio telescope are using the same frequency band. A second potential effect is

[59]To obtain tribal perspectives, federal agencies typically engage with federally recognized tribes through tribal consultations. For more information on agency tribal consultation practices, see GAO, *Tribal Consultation: Additional Federal Actions Needed for Infrastructure Projects*, GAO-19-22 (Washington, D.C.: Mar. 20, 2019).

[60]In this technology assessment, we consider potential environmental and other effects to also include the concerns about radio transmissions from satellites. Satellites can affect the ability of radio astronomers to observe signals from the ambient cosmic environment.

transmissions from side beams that come off at an angle from the satellite's main beam (see fig. 8). As the number of satellites rapidly increases in LEO, there is an increased probability that there could be a satellite in the path of a radio telescope antenna no matter where it points in the sky.

Figure 8: Satellite effects for radio astronomy: Side beam transmissions



Source: GAO. | GAO-22-105166

Note: Image not to scale.

As we have previously reported, the radio frequency spectrum is a shared, limited resource that regulators must balance for different uses.[61] These uses include aeronautical navigation, FM radio, mobile communications, radio astronomy, satellite transmissions, and many others. In a report to a UN committee, radio astronomers said that the challenges of the effects of radio transmissions on radio astronomy will likely become even more pronounced as services, including new satellite entrants, seek to use more of the radio spectrum.

In the U.S., FCC and NTIA regulate and manage spectrum for nonfederal and federal uses, respectively. U.S.-licensed satellite operators and foreign-licensed satellites communicating with U.S. Earth stations are subject to FCC regulatory and licensing requirements. Regulations call for satellite operators in certain bands to "take all practicable steps" to avoid harmful interference with radio astronomy.[62]

The ITU Radio Regulations protect certain parts of the radio frequency spectrum, known as bands, for the exclusive use of radio astronomy.[63] However, satellite radio transmissions from an adjacent band can bleed into the protected passive service frequency band, affecting radio astronomy measurements. In addition, radio astronomy also makes observations in many other bands, where it typically does not have protected allocations.

Radio astronomy facilities have benefited from siting at remote or "radio quiet" locations to physically distance radio telescopes from ground-based sources of radio transmissions. For example, "radio quiet zones" prohibit ground-based radio transmissions in and around specific locations, such as the National Radio Astronomy Observatory where FCC established the National Radio Quiet Zone to protect the observatory.[64] According to some experts we interviewed and reports, neither of these measures—remote observatory sites and radio quiet zones—is likely to be effective in the case of increasing numbers of large constellations of satellites, which orbit the Earth and beam down their signals within their licensed frequency bands to reach large

[61]In 2021, GAO reported that "FCC and NTIA confront complex and challenging tasks in regulating and managing the diverse uses of spectrum and accommodating the growing needs of emerging spectrum-dependent technologies while protecting existing uses from harmful interference." GAO, *Spectrum Management: Agencies Should Strengthen Collaborative Mechanisms and Processes to Address Potential Interference*, GAO-21-474 (Washington, D.C.: June 29, 2021), 37.

[62]47 C.F.R. § 2.106 (2021).

[63]For example, the spectral line for atomic hydrogen at a frequency of 1,420 megahertz (MHz) falls within a protected frequency band. Observing hydrogen is important for understanding our galaxy and the early universe. Spectral lines for other atoms and fundamental molecules are in similarly protected bands. However, due to the expansion of the universe, the frequency of radio waves from distant objects shifts, which could mean that observations of those molecules need to occur outside the protected band.

[64]The U.S. and other governments created radio quiet zones to minimize ground-based sources of interference. FCC created the National Radio Quiet Zone, for example, to protect the National Radio Astronomy Observatory Green Bank Observatory—a site with multiple radio telescopes—in Green Bank, W.Va. The ITU prescribes different radio quiet zone characteristics and design considerations.

areas of the surface. A report submitted to the UN has raised concerns that existing radio quiet zone regulations in many nations might be insufficient to fully protect radio astronomy given the growing size of the satellite constellations, the focus of many regulations only on terrestrial transmitters, and the need for international coordination.[65] Even if operators turn off signals when directly above a radio quiet zone or remote observatory, the radio transmissions from side beams (see fig. 8) can still affect a radio astronomy receiver site when operators transmit to adjacent locations.

Most existing and anticipated satellite constellations have or will apply for spectrum allocation in certain high-frequency bands.[66] In the U.S., FCC follows well-established processes as it considers allocations to obtain stakeholder comments and to balance the needs of multiple uses. As services receive allocations and these bands fill up, new entrants may apply for allocations in higher bands where there is currently limited commercial activity, which would create further challenges for astronomy.

3.3.2 Mitigation technologies and approaches for radio astronomy

Even if operators of large constellations of satellites comply with their regulatory and license requirements, doing so does not completely mitigate radio transmission effects on astronomy with the current numbers of satellites in orbit. Looking to the future, the proliferation of satellites represents the greatest risk to radio astronomy, according to a report submitted by the radio astronomy community to the UN.[67] Researchers and satellite operators are exploring at least four actions to mitigate the effects of satellites on radio astronomy:

- **Consider the design and operation of satellites.** Satellite operators could seek to develop or implement technology to lessen radio transmission effects of their satellites when they pass over or near radio telescopes and transmit in or near radio frequency bands allocated to radio astronomy. Such technology might shut off satellite transmissions when they pass over or near telescopes, emit satellite beams with smaller footprints, or reduce radio beam interaction with the telescope, according to experts and reports. One satellite operator we interviewed said it would coordinate with radio astronomy in an effort to protect scientifically valuable signals in bands where radio astronomy has no allocations, as indicated by its FCC license. This operator urged the radio astronomy community to make observations in spectrum allocated to that service.
- **Strengthen protections for spectrum and radio astronomy observatories.** Stakeholders could advance protections

[65] Walker et al., *Dark and Quiet Skies*, 173-174.

[66] Current and many of the proposed satellite constellations will use the Ku (10.7-14.5 gigahertz [GHz]), Ka (17.3-30 GHz), and V (37-50.4 GHz) frequency bands.

[67] Walker et al., *Dark and Quiet Skies,* 181.

for existing protected astronomy bands and radio astronomy observatories. For example, a scientific advisory group reported that the National Science Foundation should support spectrum management efforts to further protect bands that are allocated on a primary basis to radio astronomy and that it also should support efforts to increase regulatory protection of radio astronomy sites, such as radio quiet zones.[68] Most radio quiet zones have little or no formal restrictions on space-based transmitters, and implementing such restrictions will require international cooperation. However, experts told us that international agreement could take years but that individual nation states could develop domestic regulations relatively quickly to keep up with the pace of space activity. Another expert told us that unilateral national regulations could drive satellite operators to license their satellites elsewhere to evade regulations.

- **Improve data sharing.** Similar to optical astronomers (see 3.1.2 above), reports written by working groups in the astronomy community have called for operators to share better data on satellite positions and radio transmission characteristics. Such data could allow astronomers to plan observations and identify those observations that satellite radio transmissions may have affected.
- **Consider hardware and data collection developments for radio telescopes**. To mitigate some effects on radio astronomy observations, astronomers could develop hardware technologies and data collection methods on current and future telescopes. One example of a hardware mitigation is a reference antenna—a small, separate antenna that can be used to help cancel unwanted radio frequency interference from satellites. Another is a more robust radio receiver, which can better cope with radio signal spikes from satellites while preserving the cosmic radio signals that astronomers want to observe. Hardware technologies and data collection methods may help mitigate radio transmission effects during or after data collection by removing unwanted artifacts. Astronomers could collect data at faster intervals, for example.

3.3.3 Effect on Earth observation satellites and NASA's communication signal relay system

Agency officials told us that they are concerned about radio transmissions from terrestrial stations to the large constellations of satellites in LEO affecting Earth observation satellites in LEO and NASA's communication signal relay system.[69] For example, satellite operators

[68]The MITRE Corporation, JASON, *The Impacts of Large Constellations of Satellites*, JSR-20-2H (McLean, Va.: Jan. 21, 2021).

[69]Agency officials and an industry representative told us that they have not received reports of radio transmissions from large constellations of satellites in LEO affecting satellites in GEO.

have frequency allocations that are near or adjacent to frequencies that LEO Earth observation satellites passively sense to collect data supporting weather forecasting. Because of how close the frequency allocations are and the inherent limitations in the design of radio components, an agency official and an expert expressed concerns of how the increased number of transmissions related to satellite constellations would affect Earth observations.[70] Additionally, an agency official told us that the extreme sensitivity to thermal emissions for many passive band sensors used on Earth observation satellites makes it essential to maintain protected allocations and properly manage use of spectrum near the protected allocations.

In a letter to FCC and in a meeting and correspondence with GAO, NASA said it is concerned about effects on the communication signal relay system once thousands of commercial satellites and tens of Earth stations are operating.[71] It said that changes in the angle between the user's ground station and the operator's satellite, as well as the proximity of user stations on Earth to the data relay facilities, could increase the probability of interference at NASA's ground-based data relay facilities. As the number of satellites is projected to grow significantly, more study and interagency coordination—involving FCC, NTIA, NASA, NOAA, and spectrum experts from the commercial satellite sector—may be needed to determine what effects may appear.

[70]In November 2019, the World Radiocommunication Conference 2019 revised limits on unwanted emissions into the 50.2-50.4 GHz band, among others, from the adjacent frequency bands used by terrestrial stations operating with satellites, such as those from large constellations.

[71]On February 8, 2022, NASA and the National Science Foundation sent a letter to FCC, via NTIA, outlining their concerns related to a proposed large constellation of satellites.

4 Orbital Debris Poses Risks to Satellites, and Further Development of Mitigation Technologies and Approaches Could Help

Decades of space operations have resulted in debris orbiting the Earth that can damage active satellites, and the increasing number of satellites further increases the amount of debris and operational risks to all space operators. Mitigation technologies and approaches require further development and implementation to address orbital debris.

4.1 Orbital debris is varied, and much is not trackable

U.S. space policy defines orbital debris as human-made objects orbiting Earth that no longer serve a useful purpose.[72] Debris ranges in size from paint flecks to large rocket bodies. According to the NASA Orbital Debris Program Office,[73] there are more than 25,000 objects larger than 10 cm (about 4 in.) known to exist in Earth orbit, and DOD tracks these objects and more using its Space Surveillance Network.[74] (See table 2 for the size and amount of orbital debris as published by NASA and the European Space Agency.) Existing sensor systems have routinely tracked and cataloged debris larger than about 10 cm in size in LEO; for smaller debris in LEO, NASA estimates the population of this debris using statistical methods.[75]

[72]Space Policy Directive-3, National Space Traffic Management Policy, 83 Fed. Reg. 28,969, 28,970 (June 21, 2018).

[73]The NASA Orbital Debris Program Office conducts measurements of the orbital environment and develops technical consensus for adopting mitigation approaches to protect users within the environment. The office develops an improved understanding of the orbital debris environment and the measures that could control the growth of debris.

[74]The U.S. Space Force tracks over 27,000 human-made objects, some of which are smaller than 10 cm in size.

[75]A January 2021 report by the NASA Office of Inspector General states that the NASA Orbital Debris Program Office uses ground-based radars, optical telescopes, and examination of returned spacecraft to sample and statistically estimate debris in LEO smaller than 10 cm. National Aeronautics and Space Administration, Office of Inspector General, *NASA's Efforts to Mitigate the Risks Posed by Orbital Debris*, IG-21-011 (Washington, D.C.: Jan. 27, 2021).

Radar systems that have recently come online can track debris in LEO as small as 2 cm (about 0.8 in.).

Table 2: Size and amount of orbital debris

Size / Source	Amount in Orbit: NASA Orbital Debris Program Office[a]	Amount in Orbit: ESA Space Debris Office[b] (estimated)
10 cm and larger (Approximately 4 in. and larger)	Over 25,000	36,500
Between 1 cm and 10 cm (Between 0.4 in. and 4 in.)	500,000 (estimate)	1,000,000
Between 1 mm and 1 cm (Between 0.04 in. and 0.4 in.)	Over 100,000,000 (estimate)	130,000,000

Source: National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) data. | GAO-22-105166

[a]NASA Orbital Debris Program Office, "Frequently Asked Questions," accessed May 10, 2022, https://orbitaldebris.jsc.nasa.gov/faq/.

[b]ESA Space Debris Office, "Space debris by the numbers," (Darmstadt, Germany: May 10, 2022), accessed May 21, 2022, https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers.

Orbital debris comes from multiple sources (see fig. 9). The collision of large debris could result in thousands of trackable pieces of debris and tens of thousands of smaller pieces of debris that are not trackable. Some of the large debris are rocket bodies that did not deorbit after completing their mission. Rockets can also create small pieces of debris, such as combustion byproducts from solid rocket engines.[76] Debris can also come from satellites that have become inactive or have broken apart because of explosions from batteries or residual propellants. In addition, satellites can collide with each other or with existing debris,[77] and satellites can be the target of antisatellite weapons, which have resulted in some of the most significant increases to the orbital debris population.[78]

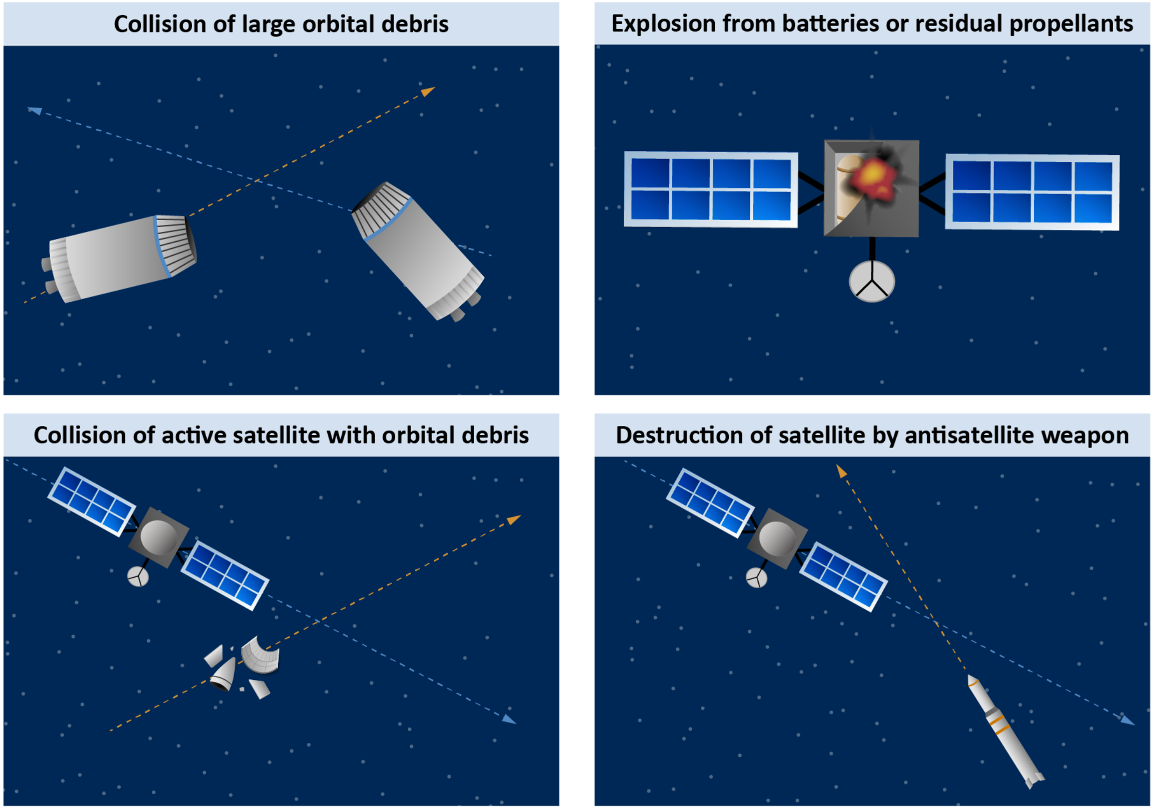
[76]One such combustion byproduct is small particles of alumina (aluminum oxide) formed during the end of a burn of a solid rocket engine by the rapid expansion, dissemination, and solidification of molten alumina. National Aeronautics and Space Administration. *Handbook for Limiting Orbital Debris*, NASA-HANDBOOK 8719.14 (Washington, D.C.: July 30, 2008), 27.

[77]Article III of the Liability Convention creates a fault-based liability regime for damages caused anywhere other than the surface of the Earth, such as in space, by a space object of one state to a space object, and persons or property onboard, of another state.

[78]Some examples of antisatellite (ASAT) weapons destroying satellites include:

- 1985 U.S. ASAT missile test destroying Solwind, a satellite with a dry mass of 850 kg (1,870 lb.), at an altitude of 525 km (about 325 mi.);
- 2007 Chinese ASAT test destroying Fengyun 1C, a satellite with a dry mass of 950 kg (2,090 lb.), at an altitude of 860 km (about 535 mi.);
- 2008 U.S. ASAT missile destroying the USA 193 satellite at an altitude of about 248 km (about 155 mi.);
- 2019 Indian ASAT missile test destroying an Indian satellite (according to the NASA Orbital Debris Program Office, the satellite was Microsat-R), which had a mass of 740 kg (about 1,630 lb.), and orbited at an altitude between 265 and 294 km (about 165 and 180 mi.); and
- 2021 Russian ASAT test destroying Cosmos 1408, a satellite with a mass of 1,750 kg (about 3,850 lb.) at launch, which orbited at an altitude between 465 and 490 km (about 290 and 305 mi.) prior to the test.

Figure 9: Orbital debris can come from various sources

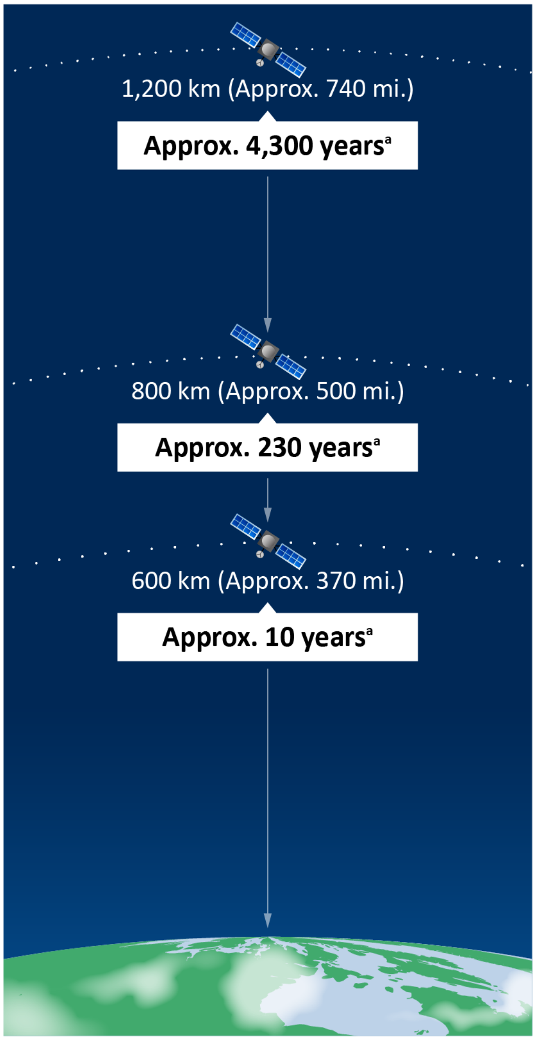


Source: GAO. | GAO-22-105166

Orbital debris is unevenly distributed, according to the NASA Orbital Debris Program Office. Most debris resides in LEO. Within LEO, the greatest concentration of debris resides between 750 and 1,000 km (465 and 620 mi.) above the Earth's surface. In lower LEO, debris (including abandoned satellites) will slowly come back to Earth and naturally deorbit because a thin atmosphere exists, exerting drag on the debris and lowering its orbit.[79] The time it takes for debris to deorbit depends on variables such as its altitude, cross-sectional area, and mass. Debris that is lower in altitude or has a higher ratio of area to mass generally takes less time to deorbit. Additionally, increased solar activity causes the density of Earth's atmosphere to increase, which increases drag on LEO satellites and decreases their orbital lifetimes. Figure 10 shows examples of the natural deorbit time for objects at various altitudes in LEO, though the actual time can vary significantly based on the variables discussed.

[79]One scientific study concluded that an increasing concentration of ground-level carbon dioxide would cause a decrease in the density of the thermosphere (see fig. 4), resulting in decreased atmospheric drag and an increase in orbital lifetimes. The study's authors calculated that orbital lifetimes in LEO would be about 30 percent longer compared to those in the year 2000 if carbon dioxide levels reach a level equating to a ground-level warming of 1.5 degrees Celsius set by the Paris agreement. The authors made key assumptions in the extrapolation of a model for the thermosphere, a constant level of solar activity, and the rate of energy transfer. M. K. Brown et al., "Future Decreases in Thermospheric Neutral Density in Low Earth Orbit due to Carbon Dioxide Emissions," *Journal of Geophysical Research: Atmospheres* (2021), https://doi.org/10.1029/2021JD034589.

Figure 10: Examples of natural deorbit time for objects in low Earth orbit



Source: GAO. | GAO-22-105166

Note: Image not to scale.

[a]Natural deorbit times can vary widely. In addition to altitude, deorbit times depend on a satellite's area-to-mass ratio, a satellite's shape, and the level of solar activity. The deorbit times shown here are approximate examples for an average level of solar activity for a satellite with an area-to-mass ratio of 0.015 m^2/kg. Natural deorbit times are shorter for lower altitudes, higher area-to-mass ratios, and higher levels of solar activity.

4.2 Additional satellites in orbit can increase orbital debris

Orbital debris can cause problems when it collides with satellites or other pieces of debris; the effects depend on the sizes, masses, and speeds of the objects involved. While the speed of an object in LEO generally ranges from 6.9 to 7.9 kilometers per second (about 4.3 to 4.9 miles per second), the average relative impact speed between objects is approximately 10 kilometers per second (about 6.2 miles per second) and can be as high as about 15 kilometers per second (about 9.3 miles per second). At those impact speeds, even paint flecks can damage a satellite.

If a collision with debris or a meteoroid causes a satellite to fail in orbit, the satellite becomes additional debris and operators experience a significant loss in terms of the cost of the launch of the satellite, the satellite itself, and the services the satellite could have provided. Collisions generate more debris that could cause further collisions; such a chain reaction or runaway effect is known as the Kessler syndrome.[80] According to the Organization for Economic Co-operation and Development (OECD), the Kessler syndrome could affect or cause the loss of several important space applications, such as space-based observations for weather forecasting and climate monitoring and satellite communications.[81] Such disruptions or losses would disproportionately affect certain geographic

[80]According to The Aerospace Corporation, the cascade or chain reaction of collisions occurs over decades and centuries. Increasing debris will make space operations more hazardous and costly but would not make it impossible to fly or operate in space.

[81]M. Undseth, C. Jolly, and M. Olivari, "Space Sustainability: The Economics of Space Debris in Perspective," *OECD Science, Technology and Industry Policy Papers*, no. 87 (OECD, April 2020), 7, https://doi.org/10.1787/a339de43-en.

areas and social groups, particularly those in rural areas with limited existing ground infrastructure and significant reliance on space infrastructure.

As the number of objects in orbit increases, such as by launching satellites, so does the number of potential collisions between two objects.[82] The number of potential collisions generally scales with the square of the number of objects; that is, if the number of objects doubles, the number of potential collisions will approximately quadruple. However, some active satellites can reduce their actual collision risk because they can maneuver to avoid collisions with trackable objects (generally larger than 10 cm in size), which could otherwise destroy the satellites. According to an FCC official, most commercial satellites deployed as part of large constellations have propulsion capabilities and are therefore able to undertake efforts to avoid collisions with trackable objects.

Satellites can fail and become debris themselves from collisions with nontrackable debris and meteoroids. Debris in LEO approximately between 5 and 100 mm in size presents the greatest collision risk because it can disable or destroy a satellite and is usually not trackable so satellites cannot maneuver to avoid them. For debris and meteoroids smaller than about 5 mm in size, designers can incorporate shielding to protect critical satellite components. Small debris can reduce satellite performance or degrade unprotected components such as solar panels, but debris and meteoroids smaller than 1 mm colliding with satellites usually cause little or no damage.

In addition, satellites can add orbital debris to the space environment without a collision. Satellites can and (occasionally do) fail and become debris, even though satellite operators take steps to ensure the reliability of their satellites. Satellites sometimes fail unexpectedly shortly after launch or early in their lifetimes. There are also concerns about the reliability of satellites near the end of their operational lifetimes because satellites that are part of the large LEO constellations are more affordable and manufactured more rapidly than previous satellites. For example, a design flaw that does not appear until the end of a satellite's operational lifetime may have been duplicated over thousands of satellites, potentially contributing to orbital debris in significant ways.

Another way satellites can add debris without colliding with other objects is through natural damage from the harsh environment of space. For example, solar events such as flares and coronal mass ejections can damage a satellite's electronics or disable satellites in general. They can also increase the atmospheric density at low orbital altitudes, which

[82]Multiple experts mentioned that there could be an additional 58,000 satellites launched by 2030 based on FCC filings since approximately 2016, though the exact number of satellites may differ from the proposed number of satellites. There were almost 5,500 active satellites in orbit as of April 2022 according to the Union of Concerned Scientists, which reviewed a variety of publicly available sources.

increases atmospheric drag on the satellites and affects their ability to maintain their orbits. The space environment also contains meteoroids that can impact satellites at speeds faster than that of orbital debris, causing electrical damage in addition to physical damage.

4.3 Mitigation technologies and approaches can address orbital debris but require further development and implementation

There are multiple possible mitigation technologies and approaches to address orbital debris. Mitigations to address the risk posed by orbital debris fall into three major categories: improving space situational awareness to characterize objects in space; reducing the creation of new debris; and altering, removing, or repurposing existing debris.[83]

4.3.1 Improved space situational awareness

To cope with the orbital debris environment and avoid collisions, satellite operators and other members of the space community must have space situational awareness. National space policy defines space situational awareness as the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities.[84]

Government and commercial space trackers obtain and provide data and services for space situational awareness. DOD's U.S. Space Command is the government entity responsible for providing space situational awareness data and services and making them publicly available.[85] In particular, the 18th Space Defense Squadron obtains data from the Space Surveillance Network and maintains a catalog of space objects it tracks.[86] Another government entity

[83]In January 2021, the National Science and Technology Council released the *National Orbital Debris Research and Development Plan* created by the Orbital Debris Research and Development Interagency Working Group to address science and technology issues related to orbital debris. In January 2022, the White House Office of Science and Technology Policy conducted two public virtual listening sessions to obtain input from academia and industry on how to reduce risks posed by debris already in orbit and how to limit the creation of new debris in orbit. In July 2022, the National Science and Technology Council published the *National Orbital Debris Implementation Plan* created by the Orbital Debris Interagency Working Group to guide and coordinate the actions of federal agencies in addressing orbital debris challenges facing the U.S. and other spacefaring nations. National Science and Technology Council, Orbital Debris Research and Development Interagency Working Group, *National Orbital Debris Research and Development Plan* (January 2021). National Science and Technology Council, Orbital Debris Interagency Working Group, *National Orbital Debris Implementation Plan* (July 2022).

[84]Space Policy Directive-3, National Space Traffic Management Policy, 83 Fed. Reg. 28,969, 28,970 (June 21, 2018).

[85]10 U.S.C. § 2274 states that DOD may provide space situational awareness services and information to non-United States Government entities if the Secretary of Defense determines that such action is consistent with the national security interests of the United States. However, beginning January 1, 2024, DOD may provide these services and information only to the extent that such actions are necessary to meet U.S. national security interests.

U.S. Space Command is a combatant command, actively employing forces from the U.S. Army, Marine Corps, Navy, Air Force, and Space Force to accomplish DOD's mission in space.

GAO has previously reported on DOD's space situational awareness efforts. GAO, *Space Situational Awareness: Status of Efforts and Planned Budgets,* GAO-16-6R (Washington, D.C.: Oct. 8, 2015).

[86]The Space Surveillance Network is composed of a variety of ground-based radar systems, ground-based and space-based optical telescopes, and space-based sensors.

involved with space situational awareness is the Office of Space Commerce within NOAA, which is part of the Department of Commerce. In accordance with national space policy, the Office of Space Commerce will assume the U.S. Space Force's current role of providing space situational awareness data and services to the public.[87] Commercially, at least one entity has established its own network of radar stations in geographically diverse locations around the world to generate data and track space objects in LEO more precisely.

Government and commercial trackers identify close approaches of trackable objects based on the objects' positions, sizes, and orbits, and provide assessments of potential collisions between two objects. In these assessments, trackers account for uncertainty in an object's position by treating the object not as a discrete point but rather as a "bubble," representing a certain statistical uncertainty, whose size can be many times larger than the object (see fig. 11). The assessments determine a probability of collision partly by evaluating the degree to which the bubbles of two objects intersect.[88] A higher degree of intersection generally indicates a higher probability of collision.

When the trackers identify a potential collision, they issue a warning message and notify the operators, if known. Satellite operators then have to assess how to respond to those warning messages, which burdens operators and requires resources. If a warning involves two active satellites, operators can coordinate their responses, but such coordination is largely a manual process without established protocols and relies on operators voluntarily sharing information. One potential response is to maneuver a satellite to reduce or eliminate the risk of collision, but this consumes part of the limited onboard supply of propellant, potentially reducing the satellite's operational lifetime. Because maneuvers alter the orbital motion of a satellite, operators and the trackers then have to consider whether the maneuvers create other collision risks.

Information in the catalog includes identification numbers and designators, responsible countries, orbit information, and radar cross-section sizes.

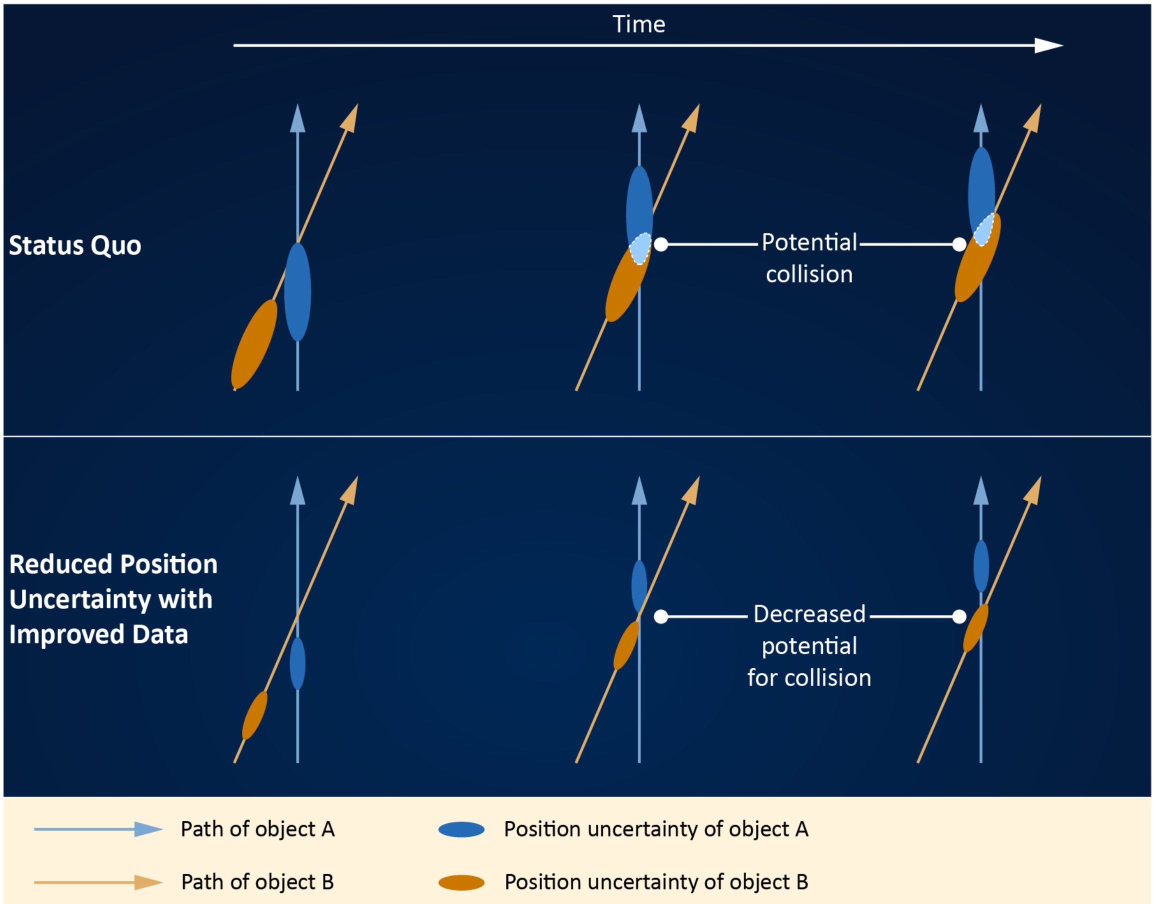
[87]Space Policy Directive-3 designates the Department of Commerce as the lead civilian agency for providing basic space situational awareness data and space traffic management services to commercial space operators. Space Policy Directive-3, National Space Traffic Management Policy, 83 Fed. Reg. 28,969, 28,972 (June 21, 2018).

In a February 2022 media briefing, a NOAA official said that NOAA expects to have an initial operational civilian space situational awareness capability by 2024.

In August 2020, a National Academy of Public Administration panel determined in a study requested by Congress that the Office of Space Commerce would be the civilian government agency best suited to perform space traffic management tasks within the federal government. National Academy of Public Administration, *Space Traffic Management: Assessment of the Feasibility, Expected Effectiveness, and Funding Implications of a Transfer of Space Traffic Management Functions* (Washington, D.C.: August 2020).

[88]The calculation of the probability of collision depends on the sizes, shapes, and orientations of the space objects; the sizes, shapes, and orientations of the uncertainty bubbles; and the nominal separation between the space objects. Combined Force Space Component Command, 18th Space Control Squadron, *Spaceflight Safety Handbook for Satellite Operators*, Version 1.5 (Vandenberg Air Force Base, Calif.: August 2020). S. Alfano and D. Oltrogge, "Probability of Collision: Valuation, variability, visualization, and validity," *Acta Astronautica*, vol. 148 (2018), https://doi.org/10.1016/j.actaastro.2018.04.023.

Figure 11: Reduced uncertainties in the positioning of space objects can decrease the potential of a collision



Source: GAO analysis of Department of Defense, National Oceanic and Atmospheric Administration, and The Aerospace Corporation images and information. | GAO-22-105166

Note: The calculation of the probability of a collision between two space objects depends on the sizes, shapes, and orientations of the "bubbles" of uncertainty in the positions of the space objects; the sizes, shapes, and orientations of the space objects themselves; and the nominal separation between the space objects.

Improved space situational awareness would help address increased orbital debris caused by the growth of satellite constellations. For example, if better data were available about objects' positions, the size of the uncertainty bubbles could decrease and reduce the number of warning messages of potential collisions. Better position data could result from, among other things, improved object tracking from additional sensor measurements, or improved position calculations from greater knowledge of atmospheric density and drag. Operators and others could add or improve capabilities and data sharing, which could enable satellite operators to have better information to assess and decide how to respond to collision warnings. In addition, space situational awareness capabilities along with timely and quality data are vital precursors to space traffic management.[89] The following are some of the possible improvements to space situational awareness:

- **Improve sensors used to track smaller debris.** Current sensors that provide space situational awareness data are not able to provide sufficient knowledge about the orbital debris environment. Government and commercial entities are deploying new technology in ground-based sensors to track debris smaller than 10 cm so satellites can avoid it. For example, advances in electronics technologies have enabled DOD and at least one commercial entity to use higher radio frequencies to track objects as small as 2 cm—about the size of a marble—in LEO, but an expert told us that power is an important consideration for radars detecting smaller objects.

  The Intelligence Advanced Research Projects Activity (IARPA), a component of the Office of the Director of National Intelligence (ODNI), has sought information on approaches to detect and track currently nontrackable debris. One potential approach involves detecting small orbital debris by its interaction with the electrically charged environment in space.

- **Add sensors to reduce uncertainty.** Additional sensors can improve data and enable the space community to reduce the sizes of the uncertainty bubbles of orbiting objects. This improvement would reduce the number of warnings of potential collisions because there would be fewer instances of overlaps of the objects' uncertainty bubbles (see fig. 11). The remaining warnings would then be more meaningful to operators and could increase operational efficiency, such as by reducing unnecessary maneuvers.

  Efforts to add sensors are ongoing. Government and commercial entities have established ground-based sensors to obtain improved data about space objects and orbital debris, and commercial entities are developing space-based sensors.[90] Knowledge of an object's position greatly improves by detecting that object at different points in its orbit, such as by placing additional sensors in the southern hemisphere where there is less sensor coverage.

- **Improve calculations to reduce uncertainty.** Multiple factors affect the position of an object in orbit and the ability to project where that object will be at some point in the future. Improving the methods to account for some of those factors, such as space weather, can improve estimates of

[89]National space policy defines space traffic management as the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment. Space Policy Directive-3, National Space Traffic Management Policy, 83 Fed. Reg. 28,969, 28,970 (June 21, 2018).

An agency official said that the federal government has started an interagency working group on space traffic management, and these discussions would include commercial entities.

[90]The U.S. military has space-based sensors, such as the Space Based Space Surveillance system with one satellite in LEO and the Geosynchronous Space Situational Awareness Program with multiple satellites in near-GEO.

those positions. The *National Orbital Debris Research and Development Plan* calls for agencies to support research and development to better understand the effect of space weather on debris. Better understanding could improve atmospheric drag predictions and reduce uncertainties in calculating object positions.

In addition, experts said that calculations of the future positions of objects currently assume that all of the objects are spheres. However, there are factors influencing an object's motion that depend on the objects' physical characteristics such as its shape. This assumption therefore increases the uncertainty in estimating where those objects will be in the future. To help improve the estimations, one expert said that space-based sensors could provide better characterization of objects that are near those sensors.

- **Improve data sharing.** Sharing data among U.S. and international entities can increase awareness and improve overall data quality and coordination. Data could include a satellite's size and shape, orbital parameters and their uncertainties, maneuvering capabilities, and collision avoidance processes as well as contact information to coordinate collision avoidance actions.

  Multiple entities have established ways to share space situational awareness data. For example, as of April 2022, U.S. Space Command has data sharing agreements with 149 entities, including commercial entities, academic partners, and other nations. NASA and a commercial satellite operator established a data sharing agreement to maintain and improve space safety. U.S. Space Command, through the 18th Space Defense Squadron, currently provides public access to the public portion of its space object catalog through the Space-Track website.[91] It issues warning messages of potential collisions through the same site.

  In 2018, the President issued Space Policy Directive-3, which began a process of transitioning responsibility for the public portion of the catalog to the Department of Commerce, and directed Commerce to administer an open-architecture data repository to provide space situational awareness services to satellite operators.[92] The Office of Space Commerce conducted a demonstration of a prototype of the repository in February 2022. The Office of Space Commerce designed the repository to improve the quality of space situational awareness services it can provide by incorporating data or analytical methods from a variety of sources. The repository will also enable the space community to test tools and improve services.

  In addition, there are grassroots organizations of satellite operators and other stakeholders to share data and

[91]https://www.space-track.org/.

[92]Space Policy Directive-3, National Space Traffic Management Policy, 83 Fed. Reg. 28,969, 28,972 (June 21, 2018).

promote best practices.[93] However, sharing of data and coordination with others is generally voluntary, and the level of sharing can vary.[94] In addition, entities coordinating data sharing and providing space situational awareness services must consider how to protect data rights, how to incorporate data of different formats and from different sources, and whether the quality of the data available meets their needs.

4.3.2 Reducing new debris

The space community can also mitigate the problem of orbital debris by reducing the amount of new debris generated by the satellites. According to one study, the majority of potential collisions of trackable objects involve debris only.[95] Because debris does not have the ability to maneuver or adjust its orbital motion, there is a higher probability of collision, which then generates more debris, increasing operational risk and cost to satellite operators. The space community could take the following actions to reduce orbital debris:

- **Revise or improve compliance with standard practices.** Standard practices can promote behaviors that limit contributions to the existing orbital debris environment. The federal government has established the U.S. Orbital Debris Mitigation Standard Practices, updated in 2019, for federal government space operators.[96] That update included new practices regarding the release of debris, collisions with large and small debris, and a threshold for successful disposal

[93]One such organization is the Space Data Association, which is an international organization to support data sharing and promote best practices among satellite operators. Another organization is the Space Safety Coalition, which is a group of space operators and stakeholders that develops and promotes space safety guidelines and practices, including data sharing. In September 2022, the companies Iridium, OneWeb, and SpaceX jointly issued a set of orbital safety best practices based on their operational experiences and cooperation. Space Safety Coalition, *Best Practices for the Sustainability of Space Operations* (Sept. 16, 2019). Iridium, OneWeb, and SpaceX, *Satellite Orbital Safety Best Practices* (American Institute of Aeronautics and Astronautics, September 2022), https://www.ascend.events/outcomes/satelittle-orbital-safety-best-practices-by-iridium-oneweb-spacex-aiaa/.

[94]In April 2020, FCC issued an order to amend its rules to require applicants requesting licensing of nongeostationary satellite systems to disclose "the extent to which the space station operator plans to share information regarding initial deployment, ephemeris, and/or planned maneuvers with the 18th Space Control Squadron or successor entity, other entities that engage in space situational awareness or space traffic management functions, and/or other operators." The order applied to three distinct parts of the rule covering amateur satellites, experimental satellites, and commercial satellites. The rule is now in effect for amateur and experimental satellites. However, for commercial satellites, the amendment is not effective until the Office of Management and Budget has approved it because of the need to address new information collection requirements to which some parties in industry raised objections. Mitigation of Orbital Debris in the New Space Age, 85 Fed. Reg. 52,422, 52,450 (Aug. 25, 2020) (to be codified at 47 C.F.R. § 25.114(d)(14)(v)(C)).

[95]The authors of the study identified over 400,000 potential collisions of about 15,000 objects with a probability of collision greater than 1 in 1,000,000 between July 1, 2020 and January 1, 2021. D. McKnight et al., "Updating the Massive Collision Monitoring Activity – Creating a LEO Collision Risk Continuum," *8th European Conference on Space Debris* (Apr. 20-23, 2021), accessed Oct. 27, 2021, https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/22.

[96]*U.S. Government Orbital Debris Mitigation Standard Practices* (November 2019), https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf.

In April 2020, FCC adopted revisions to its orbital debris rules based in part on the updated U.S. Government Orbital Debris Mitigation Standard Practices. Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd. 4156 (2020).

of space structures such as spacecraft after the end of a mission, along with new practices for large constellations of satellites.

With NASA's efforts and leadership, international groups such as the Inter-Agency Space Debris Coordination Committee and the UN's Committee on the Peaceful Uses of Outer Space have developed debris reduction practices.[97] One of the practices adopted by the Inter-Agency Space Debris Coordination Committee states that satellite operators should place LEO satellites at the end of their operational lifetimes in orbits where they will deorbit by atmospheric reentry within 25 years.[98] The U.S. Government Orbital Debris Mitigation Standard Practices also states a 25-year timeline for those satellite operators who wish to dispose of their satellites by atmospheric reentry. Some in the space community, including several experts and representatives we contacted, called for shortening the 25-year guideline, arguing that new propulsion technologies enable the shortening and that doing so would improve safety of space operations in the near term.[99]

Multiple studies have confirmed the importance of postmission disposal in limiting the increase in debris. However, the compliance rate with the existing guideline has historically been low[100] because, for example, some satellites fail in orbit, the guideline is nonbinding under international law, and some operators are unaware of the guideline. Studies by NASA and others have shown the importance of improving the compliance rate in reducing orbital debris over the long term.[101] However, there are not enough data to determine the actual compliance rate of the satellites in large LEO constellations, which are relatively new and, though designed to minimize cost, are designed to minimize deorbit time at the end of their missions.

- **Improve satellite design and operation.** Satellite operators can design and operate satellites in ways that reduce

[97]Inter-Agency Space Debris Coordination Committee, *IADC Space Debris Mitigation Guidelines*, IADC-02-01, Rev. 3 (June 2021). United Nations Office for Outer Space Affairs, *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space* (Vienna, Austria: January 2010).

[98]In a scientific study that predicted reduced atmospheric density and longer orbital lifetimes caused by an increasing concentration of ground-level carbon dioxide, the authors of the study stated that satellite operators who plan to meet the 25-year guideline by using atmospheric drag would need to account for the atmospheric density reduction. Brown et al., "Further Decreases in Thermospheric Neutral Density," 9.

[99]In April 2020, FCC sought comment on whether to adopt a shorter deorbit timeframe for LEO satellites disposed through uncontrolled reentry into Earth's atmosphere. In September 2022, FCC announced it was considering adopting rules shortening that timeframe to no more than 5 years following the end of a LEO satellite's mission. Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd. 4156(2020); and *FCC Fact Sheet: Space Innovation; Mitigation of Orbital Debris in the New Space Age* (Sept. 8, 2022).

[100]For example, the European Space Agency's annual space environment report states that between 20 and 50 percent of payloads (excluding human spaceflight) that reached end-of-life during the last decade in a noncompliant orbit (i.e., an orbit in which it would not naturally deorbit in 25 years) attempted to reach an orbit in which it would naturally deorbit in 25 years. European Space Agency, ESA Space Debris Office, *ESA's Annual Space Environment Report* (Darmstadt, Germany: Apr. 22, 2022).

[101]There is a tradeoff in that space operators who adjust the orbits of their assets to cross into lower LEO to comply with the 25-year guideline would increase collision risk in lower LEO.

the generation of debris.[102] For example, at least one satellite operator launches satellites into an altitude lower than their final operating altitude and conducts health checks of their satellites. If a satellite does not pass the check, it can deorbit more quickly, reducing collision risk. Satellite operators have incorporated propulsion systems for satellites to raise the satellite from the initial to the operational altitudes, maneuver to avoid collisions with trackable objects, or lower their altitudes at the end of their missions to deorbit sooner. One satellite operator has implemented an autonomous collision avoidance system onboard its satellites that can automatically plan maneuvers based on available space situational awareness data. These satellites can also adjust their configuration in orbit to reduce how much they are exposed to a possible collision. Satellites could have shielding in critical areas to mitigate the consequences of impacts with nontrackable debris. In addition, some satellite operators told us that they reduce the risk of inadvertent breakup of their satellites in orbit by discharging batteries or venting propellants at the end of a mission. Commercial entities have announced developments and demonstrations of tethers and sails that satellites at the end of their missions can deploy to increase drag and decrease the time to deorbit. Although these design and operational features can reduce the generation of debris, developing and incorporating them into the satellites can be costly.

4.3.3 Altering, removing, or repurposing existing debris

The space community could also mitigate the problem of orbital debris by altering, removing, or repurposing debris already in orbit. Methods to alter debris propose to adjust the motion of debris that cannot otherwise maneuver to avoid collisions and generation of orbital debris. These methods address collisions between debris objects, which compose the majority of potential collisions of trackable objects according to one study.[103]

In 2013 prior to the deployment of the large constellations of satellites, the Inter-Agency Space Debris Coordination Committee published a study including a recommendation that the international community begin investigating debris remediation efforts such as active debris removal.[104] Active debris removal of large

[102]The International Organization for Standardization has published requirements to reduce the growth of space debris by ensuring that spacecraft are designed, operated, and disposed of in a manner that prevents them from generating debris throughout their orbit lifetime. International Organization for Standardization, *Space systems—Space debris mitigation requirements*, ISO 24113:2019 (July 2019).

[103]McKnight et al., "Updating the Massive Collision Monitoring Activity."

[104]The study compared the results of six different debris propagation methods. The results of each method were consistent with each other, predicting an average 30 percent increase in the LEO debris population over the next 200 years. The methods assumed no spacecraft explosions and a 90 percent compliance rate of commonly adopted debris mitigation measures, which is higher than what actually occurs. J.-C. Liou et al., "Stability of the Future LEO Environment—An IADC Comparison Study," *6th European*

debris reduces the risk of such debris colliding and generating even more debris. In 2018, the NASA Orbital Debris Program Office published a study that in part showed that even without the addition of large constellations of satellites, the debris population in LEO would continue to grow.[105] The study also noted active debris removal as the only option to remove satellites that have failed in orbit and cannot meet postmission disposal requirements.

In addition to removing debris, the space community can repurpose debris. Because some large pieces of orbital debris are systems and processed materials that are already in orbit, some researchers and commercial entities view them as potential valuable resources. The cost of repurposing or salvaging these large debris objects may be more cost-effective than trying to deorbit them.[106]

Some entities are therefore exploring the following additional options:

- **Alter debris motion.** Methods to adjust the motion of debris that cannot otherwise maneuver include just-in-time collision avoidance and nano-tugs. Just-in-time collision avoidance methods lower the probability of collision between two pieces of debris by altering the motion of one of them. These methods include deflecting debris by using ground-based or space-based lasers impinging on the debris, and by placing clouds of gas and particles placed in the path of the debris. However, just-in-time collision avoidance requires additional study and higher accuracy data about the motion of debris. Nano-tugs are a proposed method to provide nonmaneuverable debris with maneuvering capabilities. Nano-tugs would be relatively small satellites that attach to a derelict object and cooperatively act to detumble objects and perform collision avoidance maneuvers.
- **Remove debris.** The space community has proposed several methods to deorbit large pieces of orbital debris to reduce or eliminate the risk of them colliding with other debris. These methods include capturing with harpoons or nets, grabbing them with grappler arms, or docking. Removing orbital debris is a very complex task, requiring the removing spacecraft to identify, approach, and capture debris before removing it.

  The federal government and commercial entities have nascent efforts to develop debris removal technologies. For example, SpaceWERX,

Conference on Space Debris (Darmstadt, Germany: Apr. 22-25, 2013).

[105]For the projections of debris population without large constellations of satellites, the study assumed the launch activities of the 8-year period from 2018 to 2015 rate would repeat and derived the probabilities of accidental explosions of upper rocket stages and spacecraft from historical explosion events. J.-C. Liou et al., "NASA ODPO's Large Constellation Study," O*rbital Debris Quarterly News*, vol. 22, no. 3 (2018): 4-7.

[106]National Science and Technology Council, Orbital Debris Research and Development Interagency Working Group, *National Orbital Debris Research and Development Plan* (January 2021), 11.

To guide further technology development, the National Orbital Debris Implementation Plan calls for a trade study to compare the efficacy and cost of ways to move, remove, or reuse debris. National Science and Technology Council, Orbital Debris Interagency Working Group, *National Orbital Debris Implementation Plan* (July 2022), 14.

a part of the Department of the Air Force's innovation arm named AFWERX, has an "Orbital Prime" program to advance commercially developed technologies for orbital operations including active debris removal. NASA is investing in crosscutting technologies such as autonomy and robotic manipulation that could enable debris removal. In addition, NASA is funding early-stage research identifying concepts to reduce the spinning of tumbling debris so that it can be captured, devices to increase atmospheric drag to deorbit debris in a controlled manner more quickly, and approaches to deorbiting large objects. Foreign commercial entities are conducting or planning technology demonstrations for active debris removal by using satellites that can maneuver close to debris, capture or dock with it, and deorbit it.

Concerns with debris removal include potentially creating additional debris. Attempts to capture debris may not be successful because of excessive motion or tumbling of the debris, which could disable the removing satellite and generate more debris. In addition, the debris may be fragile from being in the space environment and shatter into smaller pieces when contacted, and derelict spacecraft could have leftover propellant that could cause an explosion.

Debris removal capabilities could also raise national security concerns, since they could be used in an adversarial manner to disable or interfere with other active satellites. Nations and space operators could be transparent in their actions and establish norms of behavior to avoid misunderstandings.

There are various economic and legal concerns with removing debris as well. In particular, it is unclear how debris removal would be funded or how much it will cost, which has hindered the business cases for developing and fielding debris removal technologies. In addition, legal challenges regarding when an object is determined to be debris, ownership of the debris, and liability for any damage that may occur during removal may discourage debris removal.[107]

- **Repurpose debris.** Instead of removing debris from orbit, some of which is potentially valuable, commercial entities are developing technologies to repurpose or recycle it. For example, commercial entities have publicized plans to repurpose debris, such as large rocket bodies, or to recycle debris into propellants or materials for manufacturing new spacecraft. The technologies for these capabilities are still in development.

[107]See, e.g., R. Popova and V. Schaus, "The Legal Framework for Space Debris Remediation as a Tool for Sustainability in Outer Space," *Aerospace*, vol. 5, no. 2 (2018): 55, https://doi.org/10.3390/aerospace5020055; and C. R. May, *Game Changer: Triggers and Effects of an Active Debris Removal Market* (The Aerospace Corporation, January 2021).

5 A Policy Framework to Mitigate Potential Effects of Growth in Large Constellations of Satellites

A policy framework consisting of interrelated policy options could help policymakers and the space community mitigate the potential environmental and other effects of the growth in large constellations of satellites. We first describe four policy options we identified—through our meeting of experts, our review of relevant literature, and our interviews with officials in the public and private sector—to address the challenges to mitigation. However, our analysis suggests that these policy options are less likely to be effective if undertaken independently. Therefore, we developed a policy framework that uses the policy options in combination to address mitigation challenges and reduce or manage the persistent uncertainties in the field. Policymakers will face trade-offs between the options and an ongoing increase of new constellations, and must balance a large, diverse, and potentially changing set of interests from the global community. This or a similar policy framework could help policymakers take effective action in this complex and rapidly changing environment.

5.1 Several challenges hinder the development and adoption of mitigation approaches

As detailed throughout this report, the anticipated growth of large constellations of satellites is affecting the space and terrestrial environments in several ways. Researchers and stakeholders have already observed some effects—such as light streaks in astronomical observations—while other effects—such as atmospheric particle emissions—require further analysis. Experts, satellite operators, government officials, and other stakeholders identified a number of technologies and approaches that could help mitigate these effects. However, we found that effective mitigation faces the following five categories of challenges:

- **Insufficient knowledge of the effect.** Current knowledge is not sufficient to determine the extent to which some effects need to be mitigated. For example, researchers do not yet know the types and magnitude of rocket emissions that are likely to result from planned satellite launches. These data are necessary to accurately predict the potential environmental effects from rocket emissions through computer modeling.
- **Insufficient technology development.** For other effects, technology is not yet available for certain mitigation approaches. For example, mitigating orbital debris will require additional development of technologies to be able to track smaller debris.
- **Lack of shared data.** Stakeholders lack access to the necessary data to implement some mitigations. For example, most astronomers lack access to improved data on satellite positions, which might help astronomers reduce the effect of sunlight reflections.
- **Absence of standards, regulations, and agreements.** A uniform set of rules or

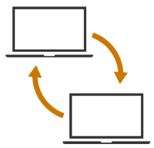
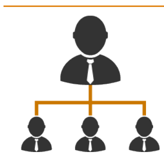
guidelines—whether set forth by a community of stakeholders, a national government, or an international organization—could help implement mitigations. For example, experts told us they need standard ways to measure and classify upper atmosphere emissions to potentially help establish acceptable levels of these emissions. Similarly, experts told us that updated standards or regulations for satellite postmission disposal might require satellite operators to remove a satellite from orbit more quickly after its mission is done.

- **Insufficient organization and leadership**. Experts and agency officials repeatedly brought up the need for more organization and leadership to advance mitigation approaches. For example, they recommended organizing the various stakeholders to build or improve databases on rocket emissions, satellite positions, and astronomical observations. They also called for coordination and leadership among national and international organizations to create agreements and establish widely accepted norms of behavior. This activity could fill significant gaps; for example, there is currently no international coordination on orbital altitudes for satellites.

Table 3 shows the set of challenges raised by experts, satellite operators, and other stakeholders when proposing mitigation approaches (presented in chapters 2, 3, and 4) for each identified effect. These challenges are further grouped into the five categories described above.

Table 3: Challenges to mitigating effects of large constellations of satellites, grouped into five challenge categories

	Identified effect				
	Upper atmosphere emissions (2.1)	*Human casualty risk (2.2)*	*Sunlight reflections (3.1 and 3.2)*	*Radio frequency transmissions (3.3)*	*Orbital debris (4.3)*
Knowledge	Scientists do not know the magnitude of effects from rocket launches and satellite reentry emissions.	Scientists have difficulty modeling and validating the extent of disintegration for satellites.	Astronomers do not know the extent of effects from satellites on astronomy. More engagement is needed with other users to better understand the effects of satellite sunlight reflections.	—	Space trackers do not know the positions of smaller orbital debris that can still disable or destroy satellites.
Technology	—	—	Technologies to reduce brightness of satellites, predict brightness with computer models, and remove effects from telescope images require further development.	Technologies for satellites to reduce radio transmission effects through design or operation require further development or implementation. Technologies for telescopes to reduce radio transmission effects with hardware or data collection methods require further development.	Hardware and computer models are still in development for precise detection, identification, and tracking of satellites, as are some technologies to deorbit satellites and remove or repurpose orbital debris.

 **Data sharing**	Scientists need a database of rocket emissions to share data gathered through observational studies to better assess the effects of upper atmospheric emissions. Concerns about sharing proprietary technology create a barrier to sharing data on satellite compositions.	Concerns about sharing proprietary technology create a barrier to sharing data on satellite compositions.	Astronomers need improved data on satellite position and design.	Astronomers need improved data on satellite position and radio transmission characteristics.	The space community needs improved data sharing on satellite position, satellite maneuvers, and debris tracking among operators.
 **Standards, regulations, and agreements**	Scientists and industry need established standard metrics of rocket launch and satellite reentry emissions to help guide potential regulations for rocket emissions in the upper atmosphere and for satellite designs	—	Some groups have said regulations could incorporate satellite brightness and have recommended an orbit altitude limit to control satellite brightness.	Some groups have concerns that existing regulations may be insufficient to protect radio astronomy from satellites' radio transmissions. Unilateral national regulations could drive satellite operators to license elsewhere.	Some experts have expressed a need for updated standards for postmission disposal. There are economic, legal, and security concerns regarding the removal of orbital debris.
 **Organization and leadership**	Establishing metrics or a database for rocket launch and satellite reentry emission requires organization between government and other entities.	—	Domestic and international organizations do not coordinate on satellite orbit assignments in low Earth orbit.	International agreements to protect radio astronomy sites, such as radio quiet zones, from space-based transmissions could take years.	Stakeholders have a need for increased coordination of data for tracking satellites and debris and between space operators and nations for debris removal.

Source: GAO. | GAO-22-105166

Note: A "—"mark indicates our discussions with experts, officials, and other stakeholders did not identify any specific challenges in that category related to that particular effect.

5.2 Policy options to address challenges

We identified four policy options that could help address challenges to mitigating potential environmental and other effects caused by the growth of satellite constellations.

Policy option: Build knowledge and develop technologies

Policymakers could support research on the extent of potential effects, as well as development of effective mitigation technologies to address them.

Policymakers could choose to implement this policy option in a number of ways, including, but not limited to:

- Targeted studies quantifying the amounts of emissions from rocket launches.
- Targeted studies characterizing the effect on scientific work from satellite sunlight reflections.
- Research into technologies that darken satellites to mitigate sunlight reflections.
- Research into technologies to help radio telescopes reduce the effects of radio transmissions.
- Research into technologies to remove orbital debris.

Opportunities:

Improving knowledge about effects could help policymakers better assess their true extent and understand which, if any, mitigation technologies or approaches to implement. Additionally, technology development could lead to innovative mitigation approaches.

Considerations:

Limited resources, in both the government and private sectors, could hamper efforts to build knowledge or develop technologies. For example, some agency officials and an expert said that are researchers are not generally assigned specifically to study potential environmental and other effects of satellites, making it difficult to quickly develop relevant knowledge or technology. Experts also expressed concerns about the need to balance the desire for improved knowledge with the need for timely decision-making. While nearly all of the effects we describe could benefit from improved knowledge, policymakers may already have necessary information available for some effects and thus may benefit more by devoting resources to pursuing other policy actions. For example, the orbital debris community has knowledge through multiple studies that the long-term population of orbital debris will grow, and experts called for leadership and for standards, regulations, and agreements to prompt action.

Policy option: Improve data sharing

Policymakers could facilitate improved data sharing of relevant information about satellite constellations.

Policymakers could choose to implement this policy option in a number of ways including, but not limited to:

- Establish and build centralized databases to collect and distribute data necessary for implementing mitigation approaches, such as position data on satellites, radio frequency characteristics of satellite transmitters, emissions data on rockets, and compositions of satellites.
- Establish pathways to more easily share data related to the progress of mitigation technologies (e.g., satellite darkening technologies) between stakeholders.

Opportunities:

The ability to more easily share high-quality data could improve mitigation approaches. For example, better position data on satellites might allow astronomers to more easily avoid sunlight reflections or radio transmissions or allow satellite operators to more efficiently avoid collisions. Increased data sharing may create opportunities for increased collaboration and awareness across government, academia, and the satellite industry, which could in turn generate additional mitigation approaches.

Considerations:

The ability to effectively share data will depend heavily on the willingness of stakeholders, particularly in the satellite industry. Our discussions with satellite operators revealed that multiple were willing to share data with certain entities that have a demonstrated need, but one expressed reservations over sharing certain detailed data more openly. Multiple stakeholders also expressed concerns about future satellite operators' willingness to share their data. In addition, collecting and updating data in a common format poses technical and logistical hurdles.

Policy option: Establish standards, regulations, and agreements

Policymakers could establish appropriate standards, regulations, and agreements to help mitigate potential effects of satellite constellations.

Policymakers could choose to implement this policy option in a number of ways including, but not limited to:

- Modify current or establish new orbital debris standards; for example, shorten the 25-year threshold for reentry or other standard practices for postmission disposal.
- Establish standard metrics to characterize and quantify upper atmosphere emissions from rocket launches or satellites disintegrating during reentry.
- Develop regulations to consider sunlight reflections when licensing satellites or increase regulatory protections to reduce the effects of radio transmissions.

Opportunities:

In some cases, establishing formalized standards, regulations, and agreements could help institutionalize successful mitigation approaches and make them standard practice for future operators. This may help spread practices that facilitate a long-term balance between satellite benefits and potential effects. Formalized regulations could also provide enforcement avenues to help protect existing satellite operators and stakeholders and provide direction to new entrants.

Considerations:

Several experts expressed concerns that regulations instituted by one nation could create incentives for satellite operators to seek licenses in less-regulated countries. However, experts expressed divided views on the likelihood of such moves by satellite operators. Conversely, without formal regulations, authors of voluntary standards and agreements might face difficulties incentivizing private operators to adopt these new practices. Finally, one expert explained that laws and accepted practices varied across different effects. For example, the expert noted that international laws exist where countries could hold each other liable for the collisions caused by their commercial operators in space, but these same laws would not apply to emissions in the upper part of the atmosphere.

Policy option: Improve organization and leadership

Policymakers could build organizational and leadership structures that facilitate effective mitigation of the potential effects of satellite constellations.

Policymakers could choose to implement these organizational and leadership structures in a number of ways including, but not limited to:

- A U.S. national framework that coordinates efforts of federal agencies and provides an example of global leadership for the international community.
- An international framework built through a combination of accepted international practices and formal treaties.
- A nongovernmental grassroots approach that brings together relevant stakeholders to take collective action.

Opportunities:

Centralized leadership and coordination may ease the implementation of many mitigation approaches. In addition, broader organizational and leadership structures could more easily pull together relevant stakeholders to implement mitigations.

Considerations:

Experts expressed concerns that aggressive leadership or mitigation action by one entity, such as the U.S., could cause satellite operators to license in less-regulated nations, although experts were divided on the likelihood of this outcome. On the international side, several experts noted that international agreements take longer to implement and may lag behind the need for timely implementation of mitigation approaches. Establishing effective organizational and leadership structures may also divert resources and personnel from other missions.

5.3 Policy framework: Putting the pieces together

As policymakers consider what actions, if any, are needed to mitigate the potential effects of satellite constellations, they will face persistent uncertainties, including the following:

Trade-offs. Action to mitigate one effect may exacerbate other effects or change the results of other mitigation efforts. For example:

- Some mitigations may have other negative consequences. For example, lower orbits can reduce light streak concerns for astronomical observations. However, lower orbits can hold fewer satellites without increasing collision risk, and a constellation would require more satellites for the same coverage.
- Some mitigations might have multiple positive effects, which would make them more attractive to policymakers. For example, reducing debris can help reduce orbital collisions and would help stave off increases in diffuse night sky brightness.
- If policymakers delay taking action and instead focus on developing relevant knowledge and technology, the results could come too late to mitigate the effects of ongoing launches and the increasing number of new satellite constellations. For example, multiple experts felt that current knowledge about the risks of orbital debris was sufficient to develop standards, regulations, and agreements, and that delaying the adoption of those measures could make the effects of orbital debris more difficult to manage.
- Experts mentioned resources as a constraint for several policy options. Devoting resources to one mitigation action or policy option may mean those resources are unavailable for other actions.

Changing landscape. The number of deployed commercial satellites has grown rapidly over the last decade, and current industry estimates expect the number of deployed satellites to continue to grow significantly. Many companies and countries are seeking to launch and operate satellite constellations, and the future number of operators, deployed satellites, and rocket launches is highly uncertain.

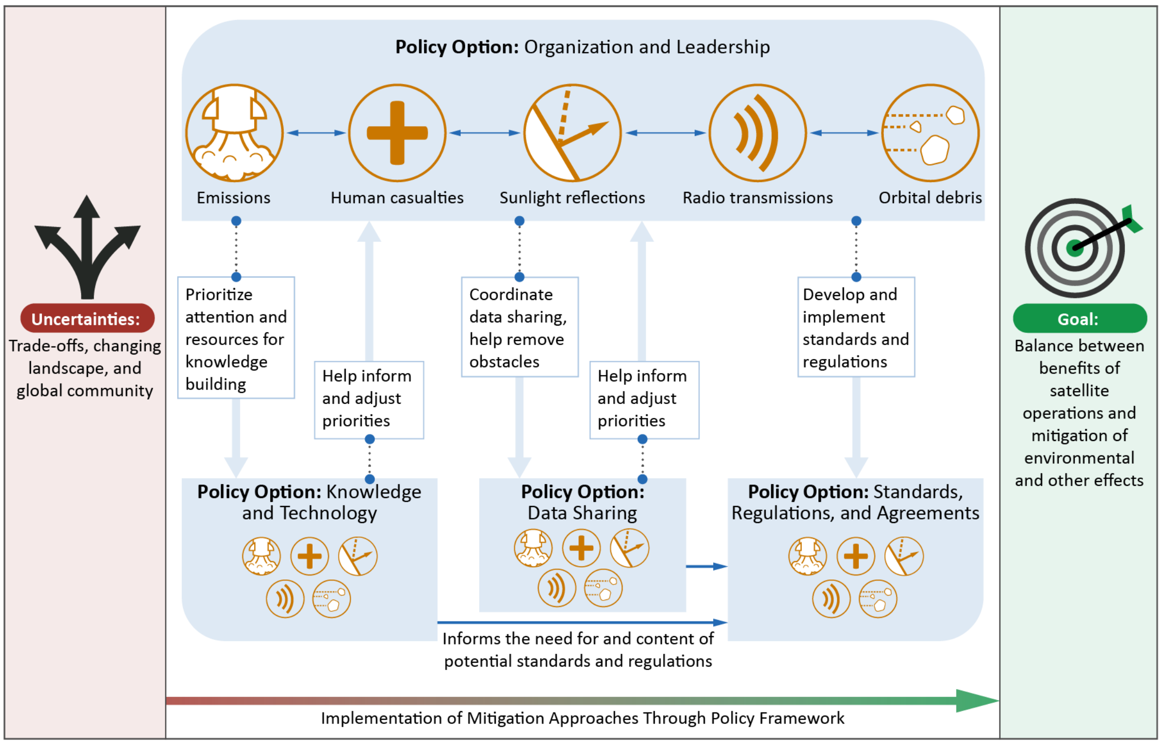
Global community. Many actors have an interest in both satellite deployments and the mitigation of their potential effects. The Outer Space Treaty of 1967 recognizes "the common interest…in the progress of the exploration and use of outer space for peaceful purposes."[108] While only some operators will deploy the constellations and a certain population will benefit from their services, the costs of potential effects will increasingly be felt by a broad community. As satellite constellations are deployed and mitigation actions taken, policymakers will have to deal with a broad and potentially changing set of concerns from stakeholders and nations across the globe.

For these reasons, policymakers may benefit from considering these policy options in a broader framework that

[108]Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, Jan. 27, 1967, 18 U.S.T. 2410, 610 U.N.T.S. 205.

accounts for the interrelationships between policy actions, as well as the uncertainties we identified: the possibility of trade-offs, the changing landscape, and the broad interests of the global community (see fig. 12).

Figure 12: Policy framework showing the interrelationship of challenges facing effect mitigations and the context of more persistent uncertainties



Source: GAO. | GAO-22-105166

In this framework, organizational and leadership structures prioritize attention and resources to the most urgent needs for knowledge building and technology development. Coordinated organization and leadership also help policymakers adjust their priorities when a policy option does not have the intended effect, or when trade-offs, the changing landscape, or interests of the global community introduce new challenges or obstacles to mitigation. Conversely, knowledge and data across different effects can inform an established organizational and leadership structure, helping it to set priorities and adapt to change.

Actions to build knowledge and share data can also inform the creation of more effective standards, regulations, and agreements. For example, regarding atmospheric emissions, building knowledge and sharing data may lead to agreement around the appropriate limits to place on such emissions and which technologies can best enable operators to stay within those limits.

Experts, government officials, and stakeholders we spoke with stressed the urgent need for policy action to mitigate the potential effects as large constellations of satellites are rapidly deployed. Satellite operators recognized these concerns but also noted the potential benefits of these constellations. Taking timely and effective action requires not just addressing the challenges to mitigation but also recognizing the inherent connections between policy options and effects. This policy framework helps provide a path for policymakers to take effective mitigation actions that balance the potential effects with the benefits of large constellations of satellites.

6 Agency and Expert Comments

We provided a draft of this product to DOD, FAA, FCC, NASA, and NOAA for review and comment. FAA, FCC, NASA, and NOAA provided us with technical comments, which we incorporated as appropriate. DOD did not have any technical comments to provide.

We invited the participants from our expert meeting to review a draft of this product and provide comments. Among those participants, nine experts provided technical comments, which we incorporated as appropriate.

We are sending copies of this report to the appropriate congressional committees, the Secretary of Defense, the Acting Administrator of the FAA, the Chairwoman of the FCC, the Administrator of NASA, and the Administrator of NOAA. In addition, the report is available at no charge on the GAO website at https://www.gao.gov.

If you or your staff have any questions about this report, please contact Karen L. Howard at (202) 512-6888 or HowardK@gao.gov or Andrew Von Ah at (202) 512-2834 or VonAhA@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made significant contributions to this report are listed in appendix III.

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The Honorable Tammy Duckworth
United States Senate

Appendix I: Objectives, Scope, and Methodology

Objectives

We prepared this report under the authority of the Comptroller General of the United States to assist Congress with its oversight responsibilities, in light of the evolving space environment, including the rapid increase in the number of space objects as commercial entities seek to provide services using large constellations of satellites.[109] We examined

1. the potential environmental or other effects introduced or exacerbated by the launch, operation, and disposal of large constellations of satellites;
2. the current or emerging technologies and approaches to evaluate or mitigate these effects, along with challenges to developing or implementing these technologies and approaches; and
3. policy options that might help address challenges to evaluating or mitigating the effects as well as opportunities and considerations associated with those options.

Scope

We focused the scope of this technology assessment on commercial large constellations of satellites. We considered direct environmental and other effects that may be introduced or exacerbated by the satellite constellations, in the atmospheric, electromagnetic, and space environments. These include the effects of: rocket launch and satellite reentry emissions on the atmosphere; surviving satellite fragments on human casualty risk; sunlight reflections on astronomy and other users of the night sky; radio transmissions on astronomy and other scientific work; and orbital debris on satellite operations. We excluded effects associated with the manufacturing of the satellites and the local, surface-level environmental effects of rocket launches such as noise, air quality, etc. We addressed both technologies and approaches as potential mitigations.

Methodology

To address all three research objectives, we reviewed literature and agency documents; interviewed a variety of agency officials, industry representatives, and experts in academia and at a federally funded research and development center; and conducted a meeting of experts.

<u>Review of literature and documents</u>

To inform all three research objectives, we reviewed relevant literature and documents such as peer-reviewed literature, conference papers, agency documents, industry articles, and technical publications identified by GAO, agencies, and experts. The literature and documents provided information and knowledge for our understanding of potential effects caused by satellite constellations and helped us identify expert individuals or groups to interview or consider for the meeting of experts. We searched databases including

[109] GAO, *Trends Affecting Government and Society,* GAO-22-3SP (Washington, D.C.: Mar. 15, 2022), 28-29.

ProQuest, Scopus, and Dialog and online sources for literature relevant to potential environmental effects from large constellations of satellites. In addition to our searches, we received literature and documents from agency officials and experts we interviewed.

We selected the most relevant literature for further review based on our objectives and cited salient studies that discuss key considerations or estimate the magnitude of potential effects related to the growth of large constellations of satellites. In our review of this data, we noted considerable uncertainties surrounding the projected growth of satellite constellations and their potential environmental and other effects. Thus, quantitative estimates that we report are descriptive and do not provide specific support for our findings. Our descriptions also include appropriate qualifiers about the associated uncertainties. Where possible, we verified key information from literature and documents with information from interviews, the meeting of experts that we conducted, or other publications. We also reviewed agency regulations and documents to inform our understanding of agencies' processes and activities in regards to potential effects caused by satellite constellations.

To document the growth in the number of active satellites in orbit, we used data from the Union of Concerned Scientists Satellite Database, which is updated several times each year. The database is an open source of data on active satellites that numerous government, academic, and think tank publications have cited. We assessed the database by reviewing database documentation and speaking with another government user of the database and determined that the database was sufficiently reliable for our purposes.

Interviews

To inform all three research objectives, we conducted semi-structured interviews focused on the different potential effects of large constellations of satellites, how those effects might change with the anticipated growth of large constellations of satellites, technologies or approaches to understand or mitigate the effects, challenges to understanding or mitigating the effects, and policy options that could help address the challenges. We tailored some of the interview questions based on the interviewees' roles, responsibilities, and expertise. We identified groups or individuals to interview who had relevant expertise in these areas through our review of literature and from recommendations from other interviewees. We selected our interviewees to complement the other parts of our methodology, such as verifying key information from literature and documents and supplementing the views provided by our expert panel.

We interviewed federal agency officials including, senior-level officials and technical experts from the Department of Defense (DOD), Federal Aviation Administration (FAA), Federal Communications Commission (FCC), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and National Science Foundation (NSF). We also interviewed industry representatives from trade associations based on the composition of their membership, satellite operators based on their current or planned satellite operations, and other companies based on the relevance of their activities to our scope.

We interviewed academic researchers or groups along with several experts at a federally funded research and development center, whom we identified based on our review of their roles or publications regarding the effects within our scope. Because we interviewed a nongeneralizable sample of stakeholders, the results of our interviews are illustrative and represent important perspectives, but are not generalizable.

Meeting of experts

In coordination with the National Academies of Sciences, Engineering, and Medicine (National Academies), we held an expert meeting on November 3 and 4, 2021 to help provide additional context and information for the evidence we obtained from literature, documents, and interviews; facilitate discussion of tradeoffs among different mitigation approaches; develop policy options; and discuss opportunities and considerations of the policy options. The session topics included rocket launch emissions, satellite reentry emissions, and satellite reentry debris; sunlight reflections and radio transmissions; orbital debris; and a capstone discussion to understand crosscutting effects or competing concerns. For each of the session topics, a GAO moderator posed open-ended questions to the experts such as the current scientific understanding of the potential effect, potential mitigation approaches, and actions that policymakers could take. The GAO moderator then facilitated the discussion within the topic area of each session. Prior to the meeting, we asked the experts to complete a questionnaire about the likelihood of potential effects from large constellations of satellites and what actions could be taken to understand or mitigate those effects. We used these responses to guide the meeting discussions and to discuss common themes across different kinds of effects.

The meeting included a nongeneralizable group of 15 experts from government agencies, industry, academia, and a federally funded research and development center. The experts and their affiliations are listed in Appendix II. Based on the session topics, the National Academies identified potential national and international experts. With assistance from the National Academies, we selected the experts based on their technical, legal, economic, or policy expertise and that would represent a balanced and diverse set of views from government scientists, nongovernmental experts, industry representatives, and academic researchers. Prior to the meeting, we asked the experts to identify any potential conflicts of interest, which we considered to be any current financial or other interest that might conflict with the service of an individual because it could impair objectivity. We judged the group as a whole to have no inappropriate biases.

This meeting was planned and convened with the assistance of the National Academies to better ensure that a breadth of expertise was brought to bear in its preparation; however, all final decisions regarding meeting substance and expert participation are the responsibility of GAO.

Following the meeting, we continued to draw on the expertise of those individuals who agreed to work with us during the remainder of our study. Consistent with GAO’s Quality Assurance Framework, we provided the experts an opportunity to review a draft of our report and provide technical comments, which we incorporated as appropriate.

Policy options

For our third objective, we developed a framework of policy options to address common challenges to understanding or mitigating potential effects from large constellations of satellites. From literature and documents; interviews with federal agency officials, industry representatives, academic researchers, and technical experts; and the meeting of experts, we identified challenges to individual mitigations for each of the effects we report. We categorized those challenges into sets of common challenges. To develop the policy options, we identified from literature, interviews, and the meeting of experts those policy ideas that may address the identified common challenges, and we grouped the ideas into broad policy options according to the common challenges they address. We identified multiple examples of specific policies under each broad policy option and report on selected examples as illustrations of how to implement the broad policy options. From our analysis, we also assessed potential benefits and considerations of implementing each policy option. To determine the uncertainties that policymakers face in implementing policy options, we analyzed information from literature, documentation, interviews, and the meeting of experts, and we categorized the information into common uncertainties. We developed a policy framework to assist policymakers recognize the interrelationships among different policy options and to provide flexibility in implementing policy options given the uncertainties in the evolving space environment.[110]

The policy options are neither recommendations to federal agencies nor matters for congressional consideration. We did not conduct work to assess how effective the options may be and express no view regarding the extent to which legal changes would be needed to implement them. While we present options to address the common challenges we identified, the options are not inclusive of all potential policy options.

Quality assurance

We conducted our work from April 2021 to September 2022 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

[110]Policymakers is a broad term including, for example, Congress, federal agencies, international agencies, academic and research institutions, and industry.

Appendix II: Expert Participation

With the assistance of the National Academies of Sciences, Engineering, and Medicine, we convened a meeting of experts to inform our work on the potential effects of large constellations of satellites, with a focus on developing policy options. The meeting was held virtually on November 3 and 4, 2021.

The 15 experts who participated in this meeting are listed below, along with their titles at the time of the meeting. These experts gave us additional assistance throughout our work, including nine experts who reviewed our draft report for accuracy and provided technical comment.

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In addition to the contacts named above, R. Scott Fletcher (Assistant Director), Chi L. Mai (Analyst-in-Charge), Will Bauder, Patrick Harner, Carolyn Johnson, Holley Kenward, Anika McMillon, AJ Melhus, Rebecca Pena, Ben Shouse, and Walter Vance made key contributions to this report. Sean Amberger, Bethany Benitez, Christina Bixby, Mark Braza, Rah Cantatore, Derrick Collins, Mike Dickens, Philip Farah, Yvette Gutierrez, Stephanie Purcell, Edward J. Rice, Bethann Ritter Snyder, Sandra Sokol, and Friendly Vang-Johnson also contributed to this report.

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