U.S. Department of Transportation
Federal Aviation Administration

Office of the Administrator

800 Independence Ave., S.W.
Washington, DC 20591

September 22, 2023

The Honorable Patty Murray
Chair, Committee on Appropriations
United States Senate
Washington, DC 20510

Dear Chair Murray:

Enclosed is the Federal Aviation Administration's (FAA) Report to Congress on the Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbit. Consistent with the Joint Explanatory Statement accompanying the Consolidated Appropriations Act of 2021 (Public Law 116-260), this report to the House and Senate Committees on Appropriations discusses how the FAA launch and reentry licensing process can be leveraged to address the risk associated with reentry disposal of satellites from proposed large constellations in low Earth orbit.

A similar letter has been sent to the Vice Chair of the Senate Committee on Appropriations and the Chairwoman and Ranking Member of the House Committee on Appropriations.

Sincerely,

Polly Trottenberg
Acting Administrator

Enclosure

U.S. Department
of Transportation
Federal Aviation
Administration

Office of the Administrator

800 Independence Ave., S.W.
Washington, DC 20591

September 22, 2023

The Honorable Susan M. Collins
Vice Chair, Committee on Appropriations
United States Senate
Washington, DC 20515

Dear Vice Chair Collins:

Enclosed is the Federal Aviation Administration's (FAA) Report to Congress on the Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbit. Consistent with the Joint Explanatory Statement accompanying the Consolidated Appropriations Act of 2021 (Public Law 116-260), this report to the House and Senate Committees on Appropriations discusses how the FAA launch and reentry licensing process can be leveraged to address the risk associated with reentry disposal of satellites from proposed large constellations in low Earth orbit.

A similar letter has been sent to the Chair of the Senate Committee on Appropriations and the Chairwoman and Ranking Member of the House Committee on Appropriations.

Sincerely,

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U.S. Department
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**Federal Aviation
Administration**

Office of the Administrator

800 Independence Ave., S.W.
Washington, DC 20591

September 22, 2023

The Honorable Kay Granger
Chairwoman, Committee on Appropriations
U.S. House of Representatives
Washington, DC 20515

Dear Chairwoman Granger:

Enclosed is the Federal Aviation Administration's (FAA) Report to Congress on the Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbit. Consistent with the Joint Explanatory Statement accompanying the Consolidated Appropriations Act of 2021 (Public Law 116-260), this report to the House and Senate Committees on Appropriations discusses how the FAA launch and reentry licensing process can be leveraged to address the risk associated with reentry disposal of satellites from proposed large constellations in low Earth orbit.

A similar letter has been sent to the Ranking Member of the House Committee on Appropriations and the Chair and Vice Chair of the Senate Committee on Appropriations.

Sincerely,

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800 Independence Ave., S.W.
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September 22, 2023

The Honorable Rose L. DeLauro
Ranking Member, Committee on Appropriations
U.S. House of Representatives
Washington, DC 20515

Dear Ranking Member DeLauro:

Enclosed is the Federal Aviation Administration's (FAA) Report to Congress on the Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbit. Consistent with the Joint Explanatory Statement accompanying the Consolidated Appropriations Act of 2021 (Public Law 116-260), this report to the House and Senate Committees on Appropriations discusses how the FAA launch and reentry licensing process can be leveraged to address the risk associated with reentry disposal of satellites from proposed large constellations in low Earth orbit.

A similar letter has been sent to the Chairwoman of the House Committee on Appropriations and the Chair and Vice Chair of the Senate Committee on Appropriations.

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FEDERAL AVIATION
ADMINISTRATION

Report to Congress:

Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbit

Public Law No. 116-260, Consolidated Appropriations Act, 2021

2021 Transportation Housing and Urban Development Joint Explanatory Statement

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Executive Summary

The Federal Aviation Administration (FAA) submits this report in response to the 2021 Transportation, Housing, and Urban Development explanatory statement for the Consolidated Appropriations Act of 2021, Public Law No. 116-260. The report informs Congress of ways that the FAA's launch and reentry licensing process may be leveraged to address the risk from reentering space debris. This report provides the results of the FAA's analysis.

The dramatic rise of non-geostationary satellites, particularly those in low Earth orbit (LEO), poses an increased risk to people on Earth and aviation due to reentering debris. To support the FAA technical and policy review of the issue, the FAA contracted The Aerospace Corporation (Aerospace) to provide a technical report that assesses the following: 1) The rise of non-geostationary satellites (launched by the United States under FAA licenses and otherwise); 2) The risks associated with random and controlled (targeted) reentries of the satellites identified in part 1; and 3) Current FAA licensing processes that may be applicable to addressing reentry risks identified in part 2. The final Aerospace report is attached to this FAA report.

This report evaluates the risk to people on the ground and in aircraft due to debris from random and controlled (targeted) reentries of non-geostationary satellites located in LEO, as well as the launch vehicles that deliver those satellites to orbit. The FAA limited its review to the reentry of objects from LEO constellations since the current disposal practice for satellites launched into medium Earth orbit (MEO) and above does not include reentry. Additionally, while the launch and disposal of all non-geostationary satellites present risk from debris (from both the satellite and any launch vehicle components), for the reasons discussed in this report, it is the launch and disposal of large satellite constellations, not individual satellites, that poses the most significant risk to people on the ground and in aircraft. Since large constellations are responsible for the "exponential rise of non-geostationary satellites," this report focuses on the debris risks associated with debris reentering from large satellite constellations in LEO. The report bases its estimates on the assumption that 12 large constellations proposed in applications to the U.S. Federal Communications Commission (FCC) as of March 2021 will be fully constituted and functioning in orbit in 2035 and will deorbit satellites for disposal according to the design lifetime of their satellites.

This report identifies how the FAA launch and reentry licensing process might be leveraged to address the risk to people on the ground and in aircraft. The FAA currently regulates the launch and reentry of a launch or reentry vehicle, including the safety of the vehicle's upper stage at the end of the launch on an individual launch basis. Although the FAA's current regulations address risks posed by the controlled reentry of launch and reentry vehicles and their components, the FAA would need to pursue notice and comment rulemaking to adequately address the risks associated with satellite constellations reentering from LEO. Specifically, the FAA could amend its payload review to address the reentry risk of large constellations through a rulemaking activity. Consistent with the authority granted under Title 51 of United States Code (51 U.S.C.) § 50904(c),[1] the FAA reviews payloads to ensure that all necessary authorizations have been obtained and the launch or reentry of the payload will not jeopardize public health and safety, safety of property, U.S. national security or foreign policy interests, or international obligations of the United States.[2] Through notice and comment rulemaking, the FAA could amend its payload review regulation to address the public health and safety implications of cumulative payloads reentering Earth's atmosphere. However, as discussed in greater detail in this report, since the FAA does not conduct a payload review for aspects of payloads subject to FCC or Department of Commerce regulation, the FAA would not amend the payload review regulation in this manner if either of these agencies were to begin regulating debris impacts from reentering satellite constellations.

Even if the FAA amended its regulations through rulemaking, the FAA's requirements would fall short of addressing all reentry risks to people on the ground or in aircraft since the FAA's authority does not extend to payloads launched from outside the United States by a person who is not a U.S. citizen or an entity organized under the laws of the United States. This could result in the FAA only authorizing a portion of a full constellation of satellites if an operator launches part of its constellation from the United States and another part outside the FAA's jurisdiction. At this time, the FCC regulates the reentry risk of a constellation of U.S. spacecraft to people on the ground on an individual spacecraft basis, which does not account for cumulative risk.

In evaluating the debris risks associated with satellite constellations reentering Earth's atmosphere, the FAA assessed the debris risks associated with the satellites themselves, as well as the launch vehicles that deliver those payloads to orbit. Increased launches of satellite constellations mean increased launches of launch vehicles capable of leaving large pieces of debris (i.e., upper stages of launch vehicles) in orbit for eventual reentry into the atmosphere. A stack of 60 Starlink first generation satellites has a mass of just over 17 tons, whereas the upper stage that placed those satellites in orbit has a mass of over 25 tons. Therefore, the FAA notes in this report that a safety assessment of large constellations must consider all reentry risks, including both satellite and launch vehicle stages. The FAA regulates purposeful, controlled disposal of upper stages at the end of a launch operation when it is planned, but the controlled disposal is not mandated in FAA regulation. A rulemaking is in process to address the risks associated with reentering debris and more closely align the FAA's orbital debris mitigation regulations with the U.S. Government Orbital Debris Mitigation Standard Practices (USG ODMSP).

[1] 51 U.S.C. § 50904(c) ("The Secretary of Transportation shall establish whether all required licenses, authorizations, and permits required for a payload have been obtained. If no license, authorization, or permit is required, the Secretary may prevent the launch or reentry if the Secretary decides the launch or reentry would jeopardize the public health and safety, safety of property, or national security or foreign policy interest of the United States.").

[2] 14 CFR § 450.43(a).

Since over 85 percent of the expected risk to people on the ground and aviation from reentering debris in 2035, as predicted in the Aerospace technical report, is a result of FAA-licensed Space Exploration Technologies Corporation (SpaceX) launches of Starlink satellites, it would be worthwhile to definitively evaluate if any debris from random atmospheric reentry of Starlink spacecraft survives reentry. If SpaceX is correct in reporting zero surviving debris, as SpaceX reports in FCC filings, and Starlink is a fully-demisable spacecraft, the rise in reentry risk is minimal over the current risk.

By 2035, if the expected large constellation growth is realized and debris from Starlink satellites survive reentry, the total number of hazardous fragments surviving reentries each year is expected to reach 28,000, and the casualty expectation, the number of individuals on the ground predicted to be injured or killed by debris surviving the reentries of satellites being disposed from these constellations, would be 0.6 per year, which means that one person on the planet would be expected to be injured or killed every two years.

Some debris fragments would also be a hazard to people in aircraft. Projecting 2019 global air traffic to 2035 and assuming that a fragment that would injure or kill a person on the ground also would be capable of fatally damaging an aircraft, the probability of an aircraft downing accident (defined in the Aerospace report as a collision with an aircraft downing object) in 2035 would be 0.0007 per year.

The FAA will continue to work with other government agencies and industry to improve the management of large constellations of non-geostationary satellites, particularly those in LEO, that pose an increased risk due to reentering debris. The FAA will continue to improve the launch and reentry licensing process to address this risk where appropriate.

1. Report Request

Congress enacted the Consolidated Appropriations Act of 2021 (The Act), Public Law No. 116-260, on December 27, 2020. The 2021 Transportation Housing and Urban Development explanatory statement for the Act asks the FAA to provide Congress with an assessment of how the FAA's launch and reentry licensing process may be leveraged to address the risk from reentering space debris. Specifically, the task states:

> *"…the Committee observes that the exponential rise of non-geostationary satellites, particularly those in low Earth orbit, poses an increased risk due to reentering debris. Therefore, the Committee directs the FAA to provide a report to the House and Senate Committees on Appropriations within 270 days of enactment of this act assessing how the FAA launch and reentry licensing process can be leveraged to address this risk."*

This report provides the results of the FAA analysis, pursuant to the 2021 Transportation Housing and Urban Development explanatory statement for the 2021 Consolidated Appropriations Act.

The Commercial Space Launch Act of 1984, as amended and codified at 51 U.S.C. §§ 50901–50923, authorizes the Secretary of Transportation to oversee, license, and regulate commercial launch and reentry activities and the operation of launch and reentry sites within the United States or as carried out by U.S. citizens. Section 50905 directs the Secretary to exercise this responsibility consistent with public health and safety, safety of property, and the national security and foreign policy interests of the United States. In addition, § 50903 requires the Secretary to encourage, facilitate, and promote commercial space launches and reentries by the private sector. As codified in Title 49 of the Code of Federal Regulations (49 CFR) § 1.83(b), the Secretary has delegated authority to carry out these functions to the FAA Administrator.

This report evaluates the potential risk to people on the ground and in aircraft due to debris from random and controlled (targeted) reentries of non-geostationary satellites located in LEO and assesses how the FAA launch and reentry licensing process can be leveraged to address this risk. The report bases its estimates on the assumption that 12 large constellations proposed in applications to the FCC as of March 2021 will be fully constituted and functioning in orbit in 2035 and will deorbit satellites for disposal according to the design lifetime of their satellites.

2. Risks Associated with Reentering Space Objects

Space objects impose two safety hazards that concern the welfare of people and spacefaring activities: risks to people and property in space while the space object is in orbit and risks to people and property when the space object reenters the Earth's atmosphere. Roughly 12 countries have the ability to launch objects into space, and those countries have responsibilities to ensure that the exploration and use of outer space are carried out for the benefit and in the interests of all countries.[3] Even non-spacefaring nations benefit greatly from space activities, including weather forecasting, communication, remote sensing, navigation, climate monitoring, national security, and banking.

With the increasing use of space, it has become abundantly clear that simply abandoning space objects in orbit is detrimental to the current and future use of space for the United States as well as for all spacefaring nations. The primary orbital safety risk posed by objects in orbit is collision or close approaches where collision is possible. The number of collision warnings (conjunctions) of passes within 5 km of another space object in 2014 was 210 in a single week.[4] The Center of Space Standards & Innovation reported in August 2021 that the number of conjunctions within 5 km was roughly 60,000 per week.[5] Of that number, nearly 40 percent of all conjunctions were with SpaceX Starlink payloads. Managing the ever-increasing safety risks on orbit will necessitate removing defunct payloads and rocket bodies from congested LEO as soon as possible when their mission is completed; this is an imperative for orbital safety.

However, the removal of objects from space translates a perpetual orbital risk into a finite and transitory risk to people on the ground and in every mode of transportation. The risk associated with reentry is primarily physical impact (i.e., collision) risk. There are instances where either contamination or toxic chemical releases could provide additional terrestrial risk. Those instances are very rare and are best handled on a case-by-case basis. The dominant risk that governments address is the reentry of large space objects (e.g., upper stages of launch vehicles) posing significant hazard risks to people on the ground. In 2001, the U.S. Government established a guideline for the reentry of large objects stating the risk of a casualty[6] on the ground should be no greater than 1 in 10,000.

> *"If a space structure is to be disposed of by reentry into the Earth's atmosphere, the risk of human casualty will be less than 1 in 10,000."*[7]

The international community followed the United States' example, and in 2002, the United Nations endorsed the Inter-Agency Space Debris Coordination Committee space debris mitigation guidelines.

> *"If a space system is to be disposed of by re-entry into the atmosphere, debris that*

[3] Outer Space Treaty [Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies], Article 1.
[4] Room Space Journal of Asgardia, "Beware the situation: how JSpOC tracks space debris", Col John W Wagner, 460th Space Wing Commander, 2014.
[5] Data Centre Dynamics Ltd, "SpaceX's Starlink accounts for 'half of all satellite near misses'", Dan Swinhoe, Aug 2021.
[6] The 2001 U.S. Government Orbital Debris Mitigation Standard Practices (USG ODMSP) states that casualty risk is defined as the risk to humans from surviving components with impact kinetic energies greater than 15 joules.
[7] 2001 USG ODMSP

survives to reach the surface of the Earth should not pose an undue risk to people or property. This may be accomplished by limiting the amount of surviving debris or confining the debris to uninhabited regions, such as broad ocean areas."[8]

On March 25, 2021, a highly visible space object reentered the atmosphere. The object was a Falcon 9 launch vehicle upper stage launched on March 4 from Cape Canaveral and tracked by the U.S. Space Surveillance Network as space surveillance network object number 47782 (SSN# 47782). Despite guidelines recommending purposeful reentry, large space objects reenter the Earth's atmosphere roughly once a week. Some are recently launched, and many more were launched prior to any agreed-upon disposal strategies. These objects can reenter anywhere on Earth with a latitude between north and south points of the orbital ground trace. The Falcon 9 upper stage that reentered in March 2021 could have landed anywhere from 53 degrees south to 53 degrees north latitude. Given that seventy percent of the Earth is covered with water, most random reentries occur over water. However unlikely, large objects still can reenter over populated areas and may cause injury or casualty to people on the ground.

In May 2021, a Chinese rocket body reentered through random atmospheric reentry. The rocket was launched on April 29, 2021, from the Wenchang Space Launch Center in south China's Hainan province. It measured 98 feet long and 16.5 feet wide, and it weighed 21 metric tons.[9] Fortunately, the debris landed near the Maldives, and no injuries were reported. The reentry was covered widely by U.S. and international media and received even wider criticism as an irresponsible space disposal.[10]

While the U.S. Government tracks and predicts reentering objects, the accuracy of those predictions varies greatly over time, and currently, the precise location of a reentry cannot be predicted with enough accuracy to provide meaningful warnings. As a rule of thumb, a reentry time can be off by ten percent of the orbital time remaining. This means that 10 hours before reentry, the predicted reentry time can be off by one hour. Given that an object in LEO circles the globe in just 90 minutes at over 27,000 kilometers per hour, at 10 hours before reentry, the likely reentry area is 27,000 kilometers long. Even 60 minutes prior to reentry, the potential area over which debris may fall is still over 2,000 kilometers long. The public does have access to reentry predictions, and a number of space entities provide information on upcoming reentries. For instance, Aerospace provides reentry predictions of large objects on its public webpage. However, these potential reentry areas are too broad to provide realistic or actionable public warnings.

In addition to the reentry of large space objects, it is becoming apparent that a large

[8] A/AC.105/C.1/L.260, Committee on the Peaceful Uses of Outer Space Scientific and Technical Subcommittee Fortieth session, Vienna, 17-28 February 2003.

[9] http://cnbc.com/ China says its rocket debris landed in the Indian Ocean, Matt Clinch, 5/9/2021.

[10] https://www.cnbc.com/2022/07/31/chinese-rocket-falls-to-earth-nasa-says-beijing-did-not-share-information.html

number of small objects reentering may also pose an unacceptable risk to people on the ground and in the air. The FAA commissioned a study by Aerospace that found Starlink and OneWeb comprise roughly 90 percent of expected large satellite constellations.[11] As of August 2021, the Space-Track.org orbital object space catalog indicates that SpaceX has launched 1738 Starlink satellites and OneWeb 288 satellites. It also indicates that 96 Starlink payloads have reentered, while none of the OneWeb payloads have reentered. By March 2022, the number of Starlink spacecraft launched reached 2,137, with 1,542 presumed operational.[12]

There is an important distinction in the terrestrial risks imposed by reentering objects. Specifically, the characteristics (e.g., size, density, and mass) of a reentering object that may cause a casualty on the ground are different than the characteristics of debris that may cause an aircraft downing incident. A ground hazard area is the area of the reentering debris that would impact with enough energy to cause a casualty. The casualty area of roughly 7 square meters equates to a risk of casualty of 1 in 10,000 for most inclinations.[13] The orbital inclination defines the amount of the world population at risk from random reentries. Orbits that have high inclinations pass over the polar regions of the Earth where few people live, whereas objects in lower inclination orbits spend more time over populated regions. The populations that drive the risk associated with these operations are China, India, the United States, and Indonesia.

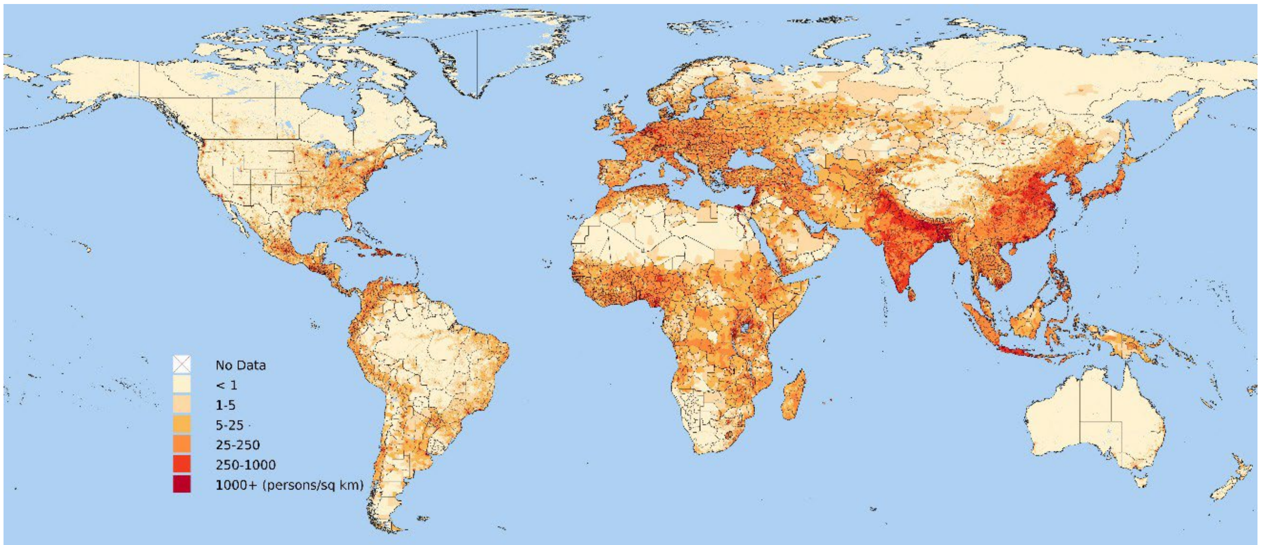

Figure 1. World Population Density[14]

[11] Risks Associated with Reentry Disposal from Proposed Large Constellations in Low Earth Orbit provided under FAA contract, Aug 2021.
[12] SpaceX launches 46 more Starlink internet satellites in 7th flight this year, William Harwood. https://www.cbsnews.com/news/spacex-launch-46-starlink-internet-satellites-7th-flight-this-year/
[13] 1 in 10,000 is the acceptable risk identified in FCC, NASA, DoD and international standards.
[14] Map source: https://mapstor.com/data/images/news/digital-catography-and-gps-navigation/2016-11-planet-population.jpg

3. Quantitative Risk Summary

Because the primary risk to people on the ground is orders of magnitude greater than the risk to people in aviation activities, the internationally accepted safety approach is to regulate to the ground safety standards only. The FAA commissioned Aerospace to provide a technical assessment of the rise of non-geostationary satellites (launched by the United States under FAA licenses and otherwise) and the risks associated with random and controlled (targeted) reentries of the satellites and upper stages to people on the ground and aviation. The FAA limited its review to the reentry of satellites from LEO since the current disposal practice for satellites launched into MEO and above is not reentry. Additionally, while the launch and disposal of individual non-geostationary satellites present risk from debris (from both the satellite and any launch vehicle components), for the reasons discussed in this report, it is the launch and disposal of large satellite constellations that poses the most significant risk to people on the ground and in aircraft. Since large constellations are responsible for the "exponential rise of non-geostationary satellites," the FAA focused on the debris risks associated with debris reentering from large satellite constellations in LEO. The full Aerospace report is attached to this report.

The Aerospace report on reentry risk summarizes the risks to both people on the ground and people in aircraft in 2021:

- Total annual Casualty Expectation in 2021 to people on the ground was 7.2E-2, or 72 out of 1,000 of a single casualty.
    - Therefore, in 2021 there was about a seven percent chance of at least one person on the planet being seriously injured or killed by the debris from space vehicles (inclusive of vehicle components and payloads) falling out of orbit.
- Annual expected human casualty due to impact of Aircraft Downing Object is 1.0E-3, or one out of 1,000 of a single casualty.
    - Therefore, in 2021 there was, conservatively at most, about a 0.1 percent chance that falling space debris would result in a single global injury or death during an aviation activity. This number is useful in comparison with the ground risk.
    - Although an aircraft mishap would be less likely than a ground mishap because there are far fewer planes than people, an aircraft mishap would likely be a multi-casualty event, unlike a ground mishap. The combined impact, with fewer aircraft with many people aboard, results in the 0.1 percent referenced.

At the present time, the annual risk to people on the ground significantly exceeds the risk to people in aircraft. These risks are the probability that someone, anyone in the world, may become a casualty. For space operations, it is also common practice to address a specific individual risk, which can be defined as a person's probability of dying (or receiving a serious injury) as a result of the activity undertaken. The rarity of a casualty caused by space activities implies that individual risk is a better assessment than collective risk or societal casualty risk, which includes the probability of many casualties caused by the same event. The Aerospace report on 2021 reentry risk states:

- Probability of an individual being seriously injured or killed on the ground is 7.5E-11, or 75 out of a trillion.
    - Therefore, in 2021 any single person's risk of injury or death was over 13 billion to one.
- Probability of an aircraft collision event producing a serious injury or worse to an individual passenger is 3.6E-13, or 0.36 out of a trillion.
    - Therefore, the individual risk from falling space debris to an individual passenger in an aircraft is below a trillion to one and is statistically insignificant.

The risks provided in the Aerospace report are the 2021 risks. As large constellations grow, the number of satellites and launch vehicle stages that will reenter will increase significantly. The risk to people on the ground is expected to increase from 7.2E-2 in 2021 to 6.1E-1 (61 out of 100) in 2035. That is an order of magnitude increase in the risk to people on the ground associated with the increase in the number of reentries from large constellations.

The risk to aircraft also increases by over an order of magnitude in 2035 from 1.0E-3 to 8.4E-2 (84 out of 1,000). The rise in aviation risk is due to the increased number of reentering objects. The number of worldwide objects hazardous to aviation is projected to increase by 40 times the number from 2021.

4. Current Practices

There are two U.S. Government agencies that regulate the reentry of objects from space. The FAA regulates the launch and reentry of commercial launch and reentry vehicles,[15] as well as the controlled disposal of launch vehicle stages or components from Earth orbit to Earth.[16] The FAA also executes a policy and payload review as part of the FAA-licensed activities.[17] The

[15] The term "reentry" as used in the FAA's governing statute and regulations means "to return or attempt to return, purposefully, a reentry vehicle and its payload or human beings, if any, from Earth orbit or from outer space to Earth." 51 U.S.C. § 50902(16). Furthermore, "reentry vehicle" means a vehicle designed to return from Earth orbit or outer space to Earth, or a reusable launch vehicle designed to return from Earth orbit or outer space to Earth, substantially intact." 51 U.S.C. § 50902(19). Because satellites are not vehicles designed to return to Earth "substantially intact," the FAA's statutory and regulatory requirements pertaining to reentry do not apply to these satellites.

[16] § 450.101 (d) Disposal safety criteria.

[17] § 450.41 Policy review and approval and § 450.43 Payload review and determination.

FCC regulates the reentry of U.S. commercial satellites. Under both agencies, reentries may be controlled (also called targeted reentries) or uncontrolled (also called random reentries).

With regards to large satellite constellations, the FAA regulates commercial launches, including those of SpaceX's Falcon 9, Falcon Heavy, and Starship; ULA's Atlas V and Vulcan; and Blue Origin's New Glenn launch vehicles. Aerospace predicts that over 90 percent of large satellite constellations will be launched on these FAA-licensed vehicles.

U.S. commercial launch vehicles launching large satellite constellations typically place both upper stages and multiple spacecraft in orbit. The upper stage generally contains more mass than individual satellites and therefore poses a greater reentry risk to people on the ground. The National Space Transportation Policy (NTSP) of 2013 states that the Secretary of Transportation shall "[e]xecute exclusive authority, consistent with existing statutes and executive orders, to address orbital debris mitigation practices for U.S.-licensed commercial launches, to include launch vehicle components such as upper stages, through its licensing procedures." Pursuant to this, the FAA oversees the orbital debris mitigation requirements for launch vehicle upper stages and is undertaking a rulemaking activity that would limit the growth of orbital debris.

The FAA participated in the update to the USG ODMSP. The ODMSP provides guidance for federal space activities and consensus advice for the three federal regulators of space activities (FAA, FCC, and National Oceanic and Atmospheric Administration [NOAA]), each of which has, or is currently undertaking, rulemaking action to consider the appropriate implementation of orbital debris mitigation activities. The Department of Commerce (specifically NOAA) eliminated all NOAA regulatory requirements regarding orbital debris and spacecraft disposal in a final rule in 2020—deferring orbital safety and debris mitigation requirements for the remote sensing spacecraft to FCC authority.

The ODMSP was updated in 2019 to address the rapid changes in the space environment. It states:

> *"The United States Government (USG) Orbital Debris Mitigation Standard Practices (ODMSP) were established in 2001 to address the increase in orbital debris in the near-Earth space environment. The goal of the ODMSP was to limit the generation of new, long-lived debris by the control of debris released during normal operations, minimizing debris generated by accidental explosions, the selection of safe flight profile and operational configuration to minimize accidental collisions, and postmission disposal of space structures. While the original ODMSP adequately protected the space environment at the time, the USG recognizes that it is in the interest of all nations to minimize new debris and mitigate effects of existing debris. This fact, along with increasing numbers of space missions, highlights the need to update the ODMSP and to establish standards that can inform development of international practices."*

The reentry risk criteria developed in the 2001 ODMSP was retained in the 2019 update (one in 10,000 risk of casualty on the ground). For large constellations, direct reentry is the preferred postmission disposal option. In developing the mission profile, the program should limit the cumulative reentry human casualty risk from the constellation.[18]

The Space Safety Coalition is a group of space industry stakeholders that collaborated in 2019 to develop a "Best Practices for the Sustainability of Space Operations," and published an updated document in April 2023. The coalition recognized that the standard reentry criteria established by the international community, which was based on the ODMSP, was not established with a consideration of the size and composition of today's large spacecraft constellations. The coalition stated:

> *"The IADC [Inter-Agency Space Debris Coordination Committee] and UN guidelines and ISO-24113 standardized practices were formulated on the basis of future space-traffic envisaged at the time they were created. As such, they are not necessarily sufficient in light of recent scenarios that incorporate step increases in commercial space activities, such as the deployment of NGSO [non-geostationary satellite orbit] constellations with larger numbers of spacecraft than those deployed in previous decades."*[19]

The coalition provided a clear recommendation for individual spacecraft disposal but did not address risks to aviation on a singular or cumulative basis. The coalition noted that the cumulative casualty risk to people on the ground should be reviewed on an annual basis:

> *"Designers of spacecraft disposed of through atmospheric re-entry should reduce residual casualty risk to less than 0.0001 per spacecraft and additionally should evaluate casualty risk on a system-wide, annual basis."*[20]

The FCC regulates the reentry risk of U.S. commercial satellites under its jurisdiction to people on the ground. The FCC recently updated its regulations in 47 CFR part 25 to address debris mitigation changes, including incorporating the applicable practices included in the 2019 ODMSP update. The FCC adopted, in clearer language, the requirement for a casualty risk of less than 1 in 10,000.[21] The FCC requested comments in its notice on the need to regulate cumulative casualty risk versus individual casualty risk:

> *"In the Further Notice we seek additional comment on how the additional*

[18] Map source: https://mapstor.com/data/images/news/digital-catography-and-gps-navigation/2016-11-planet-population.jpg
[19] Space Safety Coalition, "Best Practices for the Sustainability of Space Operations", Page 7.
[20] Space Safety Coalition, "Best Practices for the Sustainability of Space Operations", Page 11.
[21] § 25.114 Applications for space station authorizations. (d)(14): (2) If planned disposal is by atmospheric re-entry, the statement must also include:

(i) A disclosure indicating whether the atmospheric re-entry will be an uncontrolled re-entry or a controlled targeted reentry.

(ii) An assessment as to whether portions of any individual spacecraft will survive atmospheric re-entry and impact the surface of the Earth with a kinetic energy in excess of 15 joules, and demonstration that the calculated casualty risk for an individual spacecraft using the NASA Debris Assessment Software or a higher fidelity assessment tool is less than 0.0001 (1 in 10,000).

> *ODMSP guidance related to design-for-demise and other measures such as targeted reentry to further reduce human casualty risk should be addressed in our rules, as well as the guidance for large constellations that such constellations limit cumulative reentry human casualty risk. Thus, to the extent that some commenters suggest that we should apply a more stringent standard than 1 in 10,000 and consider total casualty risk on a system-wide basis, we address those topics in the Further Notice.”*[22]

Comments received after the FCC proposed its amendment to 47 CFR part 25 indicate a common trend: Space operators who operate or may operate large constellations prefer individual spacecraft risk assessment, whereas commenters not operating large constellations prefer assessing cumulative risks. In amending part 25, the FCC solicited information on the cumulative risk of reentry of large constellations, but to date, the FCC does not regulate collective reentry risk from such constellations. There are practical difficulties and a number of considerations in regulating to an annual risk limit. For example, would the risk budget be on a first-come, first-served basis, or would multiple license seekers in a given year split the allowable risk budget equally (if so, then applicants would need to have the application in at the beginning of the year), or would there be a rolling average, and would these risks be based on the year launched or the year of the forecasted reentries (which could be highly uncertain)?

5. Launch Licensing and Payload Approval

It is worthwhile to note that the single most effective mitigation to risks to people on the ground and in the air is to use a direct, targeted reentry instead of a random atmospheric reentry.

As part of its review of an application for a launch or reentry license, the FAA conducts a payload and policy review for each proposed launch or reentry involving a payload. Additionally, a satellite operator may request a payload review from the FAA independent of a license application. The policy review focuses on the policy implications of a launch or reentry, while the payload review is broader and incorporates both policy and safety elements.[23] For each review, space launch operators provide information on the launch or reentry vehicle and payload to the FAA (as directed in the part 400 regulations), and the FAA shares that information through interagency consultation with the U.S. space interagency partners to gather advice for the Secretary of Transportation’s license decision. Interagency consultation gives federal agencies the opportunity to review a proposed operation and address any potential impacts to ongoing operations, as well as U.S. national security and foreign policy interests, prior to launch. Interagency partners, including the Department of Defense, Department of State, National Aeronautics and Space Administration (NASA), and FCC, routinely request information about

[22] Federal Register / Vol. 85, No. 165 / Tuesday, August 25, 2020 / Rules and Regulations, p 52441.
[23] § 450.41 Policy review and approval and § 450.43 Payload review and determination.

the orbital debris mitigation plans of U.S. commercial launch operators.

The FAA issues a favorable payload determination if it determines that the applicant or payload operator has obtained all required authorizations and the launch or reentry of the proposed payload "would not jeopardize public health and safety, safety of property, U.S. national security or foreign policy interests, or international obligations of the United States."[24]

The FAA issues a policy approval to an applicant if the FAA determines that a proposed launch or reentry "would not jeopardize U.S. national security or foreign policy interests, or international obligations of the United States."[25] Unlike the payload review determination, the policy review and approval does not address public safety.

Some launch operators still operate under the older Part 417 regulation, which contains similar requirements for a policy review and payload determination.[26]

With regards to the reentry, or disposal, of satellites from large constellations launched on FAA-licensed launch vehicles, the FAA payload review includes an assessment of safety risks associated with licensed missions.[27] Three points must be clarified:

1) FAA licenses often authorize multiple launches under a single license.
2) The FAA "does not make a payload determination for those aspects of payloads that are subject to regulation by the FCC or Department of Commerce, or payloads owned or operated by the U.S. Government."[28]
3) U.S. commercial payloads launched abroad by a foreign launch operator or entity (foreign-launched operations such as European Space Agency, Russia, India, Japan, or China) do not require FAA authorization. However, the FCC does leverage debris as well as orbital safety if a satellite will be licensed by the FCC and when foreign communication satellites apply to access the U.S. market.

While the FAA authorizes each individual launch, a launch operator may obtain a license for multiple launches using the same vehicle or family of vehicles under a single license. The public safety aspects of a multi-launch license are evaluated on a per-launch basis. Meaning each launch must meet the same safety criteria, and the number of launches does not matter. However, a multi-launch license does evaluate the cumulative impacts of the launch activities under the National Environmental Policy Act (NEPA) for environmental consideration.

[24] § 450.43 Payload review and determination.
[25] § 450.41 Policy review and approval.
[26] § 415.23 Policy review and § 415.57 Payload review.
[27] § 450.43(a)(2) Its launch or reentry would not jeopardize public health and safety, safety of property, U.S. national security or foreign policy interests, or international obligations of the United States.
[28] § 450.43(b) Relationship to other executive agencies.

While space launch and reentry environmental reviews address cumulative impacts, the FAA payload review is typically done on an individual basis. For the FAA to cover the cumulative reentry safety of a single or series of launch licenses for a related large constellation, the FAA would explore if that aspect was already regulated by another federal agency. The FAA would need to explore whether cumulative risk differs from individual risk enough to justify a separate regulatory threshold. If so, any new regulatory threshold could only be implemented through notice and comment rulemaking consistent with FAA's statutory authority, taking into account public comments and industry impact, as well as discussions with the FCC regarding the FCC-licensed U.S. satellite individual reentry risk assessments.

The FAA would not pursue such a rulemaking if the FCC were to begin regulating the cumulative impacts of reentering satellite constellations. To ensure that the FAA's payload review does not interfere with any requirement that the FCC or Department of Commerce might impose on payload operators under their respective authorities, the FAA does not make a payload determination over those aspects of payloads subject to regulation by those agencies.[29] The FAA must evaluate the effect of any payload on the integrity of a proposed launch or reentry in order to issue a license. However, since Title 51 requires the FAA to verify that a payload received all necessary approvals,[30] in consultation with the heads of other executive agencies as appropriate,[31] and 51 U.S.C. § 50919(b) states that Title 51 does not affect the authorities of the FCC or Department of Commerce, the FAA elected to clarify in 14 CFR § 450.43 that it will exclude from its payload review aspects of payloads regulated by those agencies.[32]

In addition, the FAA currently does not link launch licenses by payload. For example, a license to launch polar orbit satellites may be conducted under multiple launch licenses or under a single operator's license. Unlike the FCC treatment of constellations of satellites, space launches, even launches of identical payloads, are not treated as systems or constellations. Another complicating factor is that the FAA would likely need to exclude spacecraft launched on foreign launch systems. For example, if 50 payloads are launched on FAA-licensed launches and 50 payloads are launched on foreign launch systems, the FAA would not be able to address all 100 payloads.

6. Random Reentry Hazard to Aviation

Aircraft are afforded special protections over other modes of transportation because of the high vulnerability of aircraft to damage and the number of individuals potentially impacted in a single aviation event. Debris fragments of 300 grams or larger are conservatively assumed to be able to cause at least one serious injury or worse to an aircraft occupant and could lead to an

[29] See Streamlined Launch and Reentry License Requirements, 85 FR 79566, 79590-91 (Dec. 10, 2020).
[30] 51 U.S.C. § 50904(c).
[31] 51 U.S.C. § 50918(c).
[32] See Streamlined Launch and Reentry License Requirements (NPRM), 84 FR 15296, 15370 (April 15, 2019).

uncontrolled aircraft landing with catastrophic loss of life to many or all people on board.[33, 34] It is noteworthy to recognize that the imposed risks to people on the ground and in aircraft are not equal. Additionally, the impacted population of ground and airborne people are also not equal. In fact, the difficulty in predicting the outcome of a collision between an aircraft and a debris fragment necessitates the use of different metrics to characterize the risks to people on the ground and aircraft occupants.

The risks associated with aviation activities are different than the risks associated with space activities. The risk to people on the ground with respect to reentering debris is a 'first order' or direct risk. There is a significant amount of research that indicates that an object that directly impacts a person with the energy of 15 joules (or about 11 foot-pounds) may result in a fatality or possibly a serious injury. Furthermore, the ground casualty analysis in this report is conservative in nature because sheltering protections are not incorporated into the analysis.

The primary reentry risk with respect to aviation activities is in the 'second order' or indirect risk. Unlike the reentry risk to people on the ground, analysis of reentry risk to people in aircraft must be accomplished with many highly variable assumptions. Based on conservative assumptions, a fragment of 300 grams or greater may cause casualties to aircraft occupants. This assumption produces what should be considered a worst-case scenario under a very conservative analysis. Commercial aircraft are large complex systems, and the risk analysis is complex. Previous analyses compared the risks to aircraft as similar to extremely high population density events, such as athletic events or outdoor concerts. "Analysis has shown that while the possibility of multiple casualties is high for such situations, the probability of occurrence (i.e., impact in such an area) is so low that it does not significantly affect the overall risk."[35]

Space activities occur in low numbers compared to aviation activities. Risks to humans as a result of these activities are most often considered as third-party (uninvolved public) risks, except for relatively rare human spaceflights. Space risks typically are described in terms of "expected casualty" or E_C. Expected casualties per year means the mean number of casualties expected to occur every year given the predicted number of uncontrolled reentries; because the probability of a multi-casualty event is much smaller than a single-casualty event, the E_C is approximately equal to the risk of one casualty.

The ODMSP, IADC guidance, and FCC regulations each address the casualty risk of random reentry to people on the ground. The FAA regulations include evaluations of risk to people on the ground as well as people in aircraft. Under a controlled reentry regulated by the FAA, the standard for aircraft risk is captured in 14 CFR § 450.101(b)(3), *Aircraft risk*. "A

[33] Range Commanders Council 321-20 Common Risk Criteria for National Test Ranges Supplement provides common USG standards on aircraft vulnerability to space vehicle debris impacts.
[34] FAA/AST and others have continued to sponsor research to improve the ability to predict the outcome of a collision between an aircraft and space vehicle debris. A recent report is: ARCTOS Technical Report No.21-1128/14.1, Aircraft Vulnerability: Modeling and Quasi-static Testing, November 2021
[35] Review of Orbital Reentry Risk Predictions, 15 July 1992, The Aerospace Corporation (ATR-92(2835)-1

reentry operator must establish any aircraft hazard areas necessary to ensure the probability of impact with debris capable of causing a casualty for aircraft does not exceed 1×10^{-6} [1 in a million]."[36] This standard applies to reentry vehicles and controlled upper stage disposals.

The Aerospace report on Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in LEO evaluates the risk to commercial aviation from random reentering objects associated with large satellite constellations. Similar to the risks to people on the ground, the hazard to aviation arises from large objects reentering or many small objects reentering.

Two facts characterize reentering debris aviation risks: first, aircraft have a larger area that is susceptible to a fatal debris strike than a single person on the ground, and second, there are far fewer people in the air than on the ground. On average, there are 5,500 commercial passenger aircraft, as well as many cargo, private, and military aircraft, in the air at any given time. Assuming 300 people per aircraft is quite conservative and places a cap of roughly 1.65 million people in the air around the globe. Aircrews are likely to be the people most impacted by reentering debris, given that aircrews likely spend more time aloft than any other class of people. The FAA allows air carrier crews to log 1,000 hours in a year. Excluding personal travel, these flights would account for 1,000 hours of 8,760 hours in a year, or 11.4 percent of a year.

The Aerospace technical report used a similar methodology to determine airborne risks as the standard approach to determining ground risks from random reentries; it assumed an average of 120 persons/aircraft. This is because many of the planes aloft are commuter-type aircraft with < 50 passengers. However, during the busiest hours of the day, there could be well over 1 million people aloft. Aerospace created an aviation density chart (figure 2). Aviation density is heavily biased to the northern latitudes.

Ground hazard risk from reentry is derived from an analysis of debris area that reaches the ground versus the area on the ground that if a single person were there, they would likely become a casualty. This area, for conservative analysis, is usually a minimum of 0.36 m^2 per hazardous fragment. However, people in aircraft derive their vulnerability from debris that either penetrates the fuselage and directly impacts an occupant or causes an uncontrolled landing of the aircraft. This debris can be fairly small, and the area of aircraft vulnerability is much larger than a single person's ground area. Even for the direct impact, the volume of the region where a single person on an aircraft could be hit is much larger than for someone on the ground due to the velocity of the person in the aircraft. A good analogy is getting wet from raindrops: if you run fast through a rainstorm, you will hit many more raindrops per unit of time than if you stand still. A conservative value of aircraft area for vulnerability of 1,000 m^2 was used in the Aerospace technical report.

[36] 14 CFP § 450.101(b)(3)

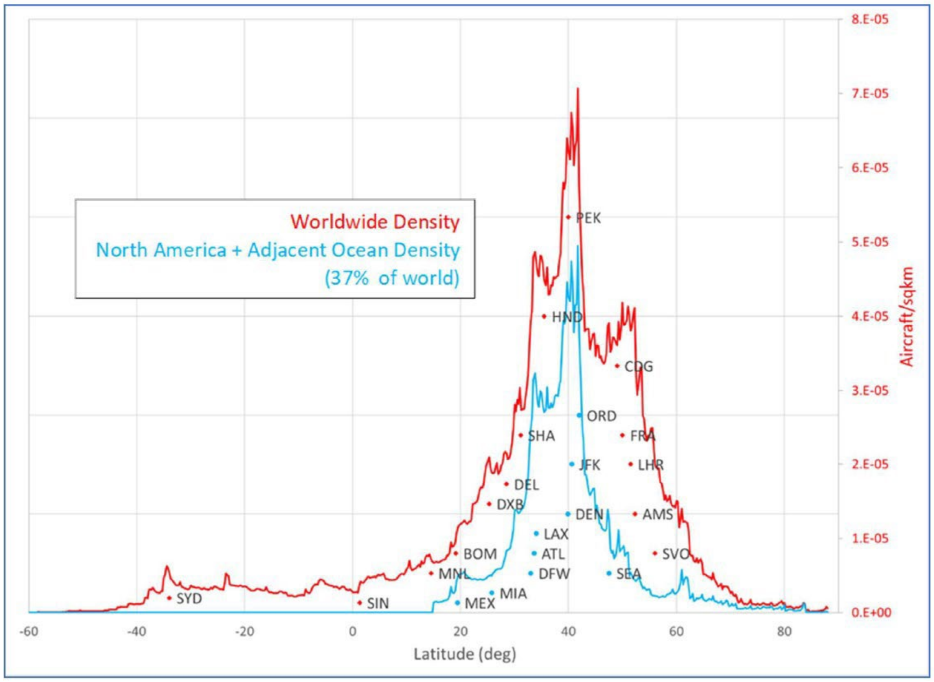

Figure 2. Density of Commercial Aircraft and Latitude Locations of Some of the World's Busiest Airports.

The Aerospace technical report assumed a threshold for aircraft downing objects is roughly 300 grams. The characteristics of debris that could cause a casualty in commercial aviation are very complicated. For example, a relatively small metal object, such as one gram of steel, could be ingested and choke some aircraft engines but would not be expected to hurt an adult on the ground. In other cases, heavier debris could cause a ground casualty that would not be expected to hurt people on some types of aircraft. A similar piece of debris could have enough energy to cause a casualty on the ground, depending on its shape and density. For example, a 300-gram piece of debris traveling at a terminal velocity of 32 m/s will exceed the 15 joules of energy (mass times velocity) used as the safety threshold for ground safety.

According to the Aerospace technical report, the annual probability of one or more people on an aircraft being hurt or killed due to a collision with space vehicle debris in 2021 was 0.1 percent. This is highly dependent on the amount of reentering debris. The largest constellation of satellites is the SpaceX Starlink constellation. SpaceX states its spacecraft are fully demisable, meaning zero surviving pieces. The FCC accepted the SpaceX orbital debris mitigation representation of zero debris. Aerospace assessed that the SpaceX spacecraft could each produce three pieces of debris of 300 grams. For purposes of this report, the FAA uses the more conservative approach.

The future risk associated with the reentry of large constellation spacecraft is influenced by the magnitude of the individual satellite debris that may survive reentry. The Aerospace technical report states the risks to aircraft would increase by well over 10 times the current risks. If SpaceX Starlink does produce surviving debris as estimated by Aerospace, the Aerospace technical report states the probability of an aircraft impacted by a piece of reentry debris large enough to take down a single plane in a year worldwide would rise to 7 in 10,000 in 2035. The corresponding expected casualty within an aircraft would be 8.4 out of 100. These are high numbers compared to today's 1 in 1000 expected aircraft casualty probability.

However, the risk to aviation remains below the expected ground casualty risks in 2035: a 6.1 out of 10. The Aerospace report indicates the annual chance of someone being killed as a result of space debris in 2035 would be 61 percent for a single death on the ground and a 0.07 percent chance of an aircraft downing event. Figure 3 illustrates why the ground risk is the only risk assessed for random reentries: The number of people per square kilometer is roughly a million times greater than the number of aircraft per square kilometer.

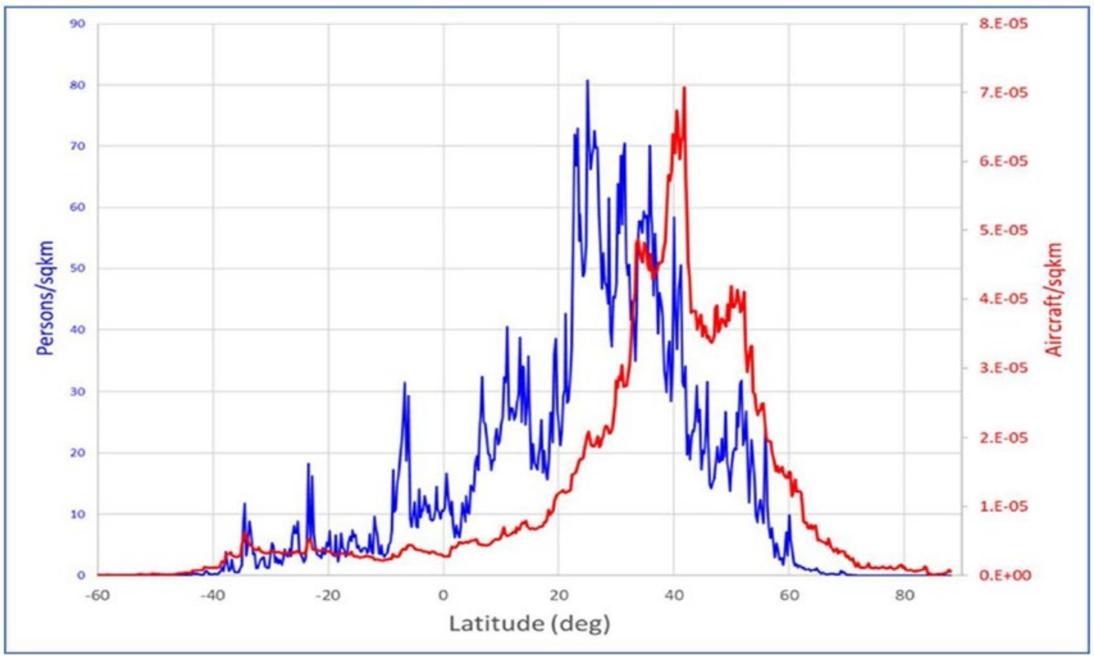

Figure 3. Population and Aircraft Densities vs. Latitude, 2021

7. Risk Mitigations

The growth of large constellations in LEO is occurring at a rapid pace. The risks on orbit have greatly increased, and the risks to people on the ground and in the air will continue to rise as more objects reenter the atmosphere during disposal. The FAA has the authority to address the safety of the likely 119 launches per year that are needed to continuously replenish the planned large constellations. Since over 90 percent of all large constellation launches will likely be FAA-licensed, the FAA's upcoming orbital debris mitigation rules can directly impact risks associated with launch vehicle upper stage reentries.

Payload reentries are expected to continue to grow to roughly ten thousand per year if the Starlink constellation's operational lifetime follows the announced operational lifetimes of 5 years.[37] Risks to people on the ground and in the air will continue to grow accordingly. There are only three feasible mitigation strategies to reduce the risk of reentering objects:

1) Reduce the number of reentering objects;
2) Reduce the amount of mass that survives reentry; or
3) Control the location of reentering objects.

Reduce the Number of Reentering Objects

A reduction in the number of reentering objects is unlikely. Satellites on orbit pose a continuous risk to other space systems and need to be removed from orbit to ensure a sustainable space environment. Some satellites will inevitably fail in orbit and will eventually reenter. The ODMSP recommends a 90 percent success rate for post-mission disposal. The space industry has not yet collectively met the 90 percent success rate for satellite post-mission disposal, and even at the 90 percent rate, over 5,000 satellites could fail in orbit and randomly reenter.

Reentry debris from random reentering objects has differing ballistic coefficients and masses. This causes the reentering debris to fall in a very long reentry footprint. Even a controlled disposal, which results in a breakup, spreads debris over a wide path. The Aerospace technical report describes the spread of debris generated in a reentry survivability test program conducted in the early 1970s. The four VAST (Vehicle Atmospheric Survivability Tests) conducted in 1971 and 1972 produced the scientific information and recommendations relevant to risks produced through reentry. The debris footprint for the VAST reentries ranged up to 1,000 nautical miles (1,852 kilometers); however, it is unclear if the debris that spans the entire footprint would be hazardous to aircraft.[38] Larger, heavier objects travel farther downrange in the footprint, while smaller, lighter pieces fall in the 'heel' of the footprint. Therefore, the threat to commercial aircraft is not homogenous throughout the footprint. The technical report provided the distance from the first point of the expected impact zone for pieces that were tracked with radar and optical trackers. Figure 4 shows the wide range of space covered by reentering debris. Because the risk to the population was understood, the VAST tests were conducted far from populated areas in the Western Pacific.[39]

[37] Risks Associated with Reentry Disposal from Proposed Large Constellations in Low Earth Orbit provided under FAA contract, Aug 2021.
[38] Stern, R.G., "Reentry Breakup and Survivability Characteristics of the Vehicle Atmospheric Survivability Project Vehicles," Report No. TR-2008(8506)-3, The Aerospace Corporation, 5 August 2008.
[39] Ibid.

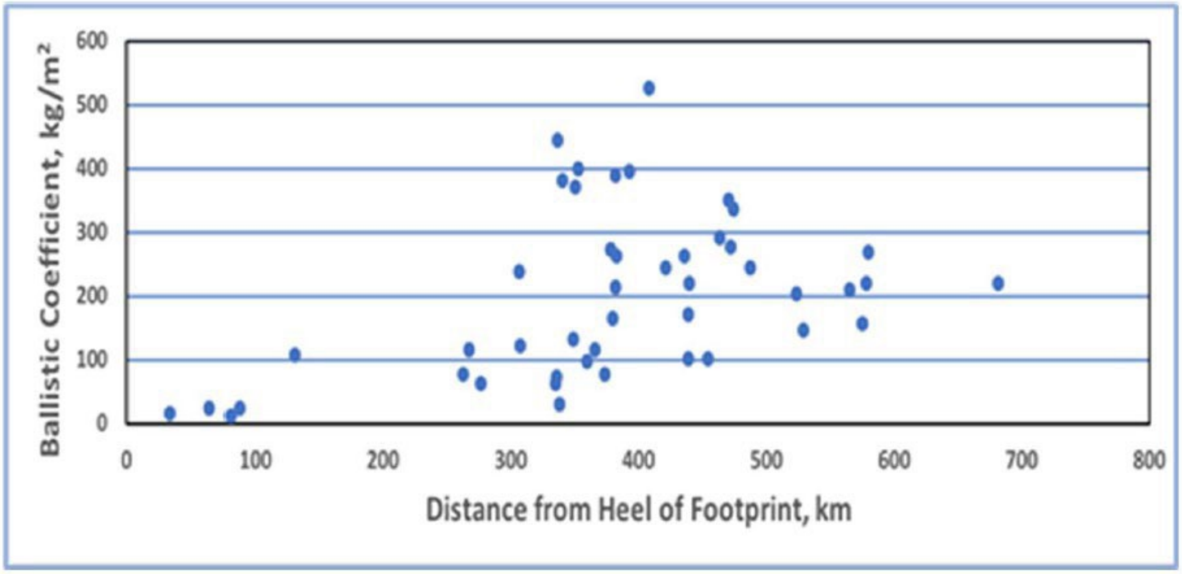

Figure 4. Impact Distance from Heel of Footprint in Kilometers

Reduce the Amount of Mass that Survives Reentry

To reduce the amount of mass that survives reentry would necessitate a design criterion that is typically called a 'design for demise.' This criterion is currently impractical for launch vehicle upper stages. Upper stages are purposely built to be robust enough to contain high -pressure systems and handle the extreme stress and temperatures required for high-thrust operations. Evidence of upper stage reentry survival is readily available.

Spacecraft, on the other hand, can be more easily designed to demise on reentry. SpaceX states that the Starlink payloads fully demise. In an August 10, 2021 letter to the FCC, SpaceX stated that "v1.0 Starlink satellites are designed to be fully demisable" and "[p]ose zero Risk of Human Casualty."[40] SpaceX used the NASA program Debris Assessment Software (DAS). DAS is the standard evaluation tool used to assess the ground risk of reentry. A more sophisticated analysis tool is also available from NASA. The Object Reentry Survival Analysis Tool (ORSAT) provides a higher fidelity modeling software to evaluate demisability.[41] Both programs focus on the implications of ground-impacting objects. Most reentry breakup events occur between 80 kilometers and 70 kilometers in altitude. Fairly quickly after a violent breakup, pieces cool down and the trajectory becomes nearly vertical as the objects' forward velocity rapidly decreases. There is no difference in the size of debris that passes through navigable airspace and debris that strikes the ground. The Aerospace reentry

[40] SpaceX letter to FCC, David Goldman, Director of Satellite Policy, 10 Aug 2021, https://ecfsapi.fcc.gov/file/1081071029897/SpaceX%20Orbital%20Debris%20Meeting%20Ex%20Parte%20(8-10-21).pdf

[41] FCC regulations do not require the use of ORSAT or DAS – CFR 47 § 25.114 Applications for space station authorizations.

report assumed a small amount of debris for each Starlink satellite: ~3 meters squared casualty area. This small area would easily meet the 1 in 10,000 reentry casualty restriction. However, with the thousands of satellites expected to reenter, even a small amount of debris can impose a significant risk over time.

The risk to people on the ground exceeds the risk to people in aircraft by well over a magnitude of 10 times. Historically, it has been appropriate to use ground casualty risk as the driving factor in regulating random reentry risk. A targeted reentry affords the opportunity to predict higher fidelity risks for both ground and aircraft risks.

Control the Location of Reentering Objects

The logical question that arises from overly large impact footprint predictions and the variability of the impact locations within that area is one of usability. Given current logistical constraints in terms of information processing and communication, it is impractical to close very large swaths of airspace or evacuate large, populated areas globally. Therefore, random reentry predictions are viewed as non-actionable warnings. At best, reentry predictions can be viewed as safety advisories. An increase in the number of random atmospheric reentries, which is the issue at hand for large constellations of satellites, does not help in defining where those reentries will occur. The Aerospace technical report estimated that Starlink spacecraft could create three objects each that could cause an aircraft downing incident. Unlike the VAST spacecraft, which were over 5,300 kilograms and produced a debris field as described in figure 4, Starlinks have a mass of just 286 kilograms and may produce three objects spread over 600 kilometers. Or, if the SpaceX analysis is correct, no measurable debris could be produced by fully demisable Starlinks. Other constellations are proposed with spacecraft of much larger sizes, but the number of spacecraft envisioned would be less than 2000 spacecraft compared to the over 40,000 proposed Starlink satellites.

The best mitigation to rising safety risks is avoiding random reentries in favor of targeted, controlled reentries. Controlled reentry is the third mitigation strategy to reduce reentry debris risks. Direct, targeted reentries are recommended for large reentering space objects, such as launch vehicle stages and space stations. A reentry into the broad ocean area renders the risk to people on the ground to effectively zero. The risk to aviation can be mitigated somewhat through advisory notifications.

8. Conclusions

Although the FAA's current regulations address risks posed by the controlled reentry of vehicles and their components, the FAA would need to pursue notice and comment rulemaking to adequately address the risks associated with satellite constellations reentering from LEO. The FAA could amend its payload review to address the reentry risk of large constellations through a rulemaking activity. In order to maintain a streamlined approach across U.S. federal regulations, this would ideally be limited to risks- not regulated by another U.S. federal regulator. However, the FAA's authority does not extend to payloads launched from outside the United States by a person who is not a U.S. citizen or an entity organized under the laws of the United States. At this time, the FCC does regulate the reentry risk of spacecraft within its jurisdiction, which can include large constellation spacecraft. The FAA regulates the launch vehicle and upper stages, placing those spacecraft in orbit.

There is no debate on the risks produced by an upper stage reentering the Earth's atmosphere, and it is generally accepted that disposing of large upper stages through controlled disposal is preferable to allowing large upper stages to reenter Earth's atmosphere randomly. The FAA currently regulates controlled disposal of upper stages at the end of a launch operation (yet controlled disposal is not a mandatory action and operators may abandon upper stages in orbit if they choose to do so). The FAA is pursuing rulemaking to limit the growth of orbital debris.

Since over 85 percent of the expected 2035 risk to people on the ground and aviation from reentering debris is a result of FAA~~CC~~ -licensed launches of Starlink satellites, it would be worthwhile to definitively evaluate if any debris from random atmospheric reentry of Starlink spacecraft survives reentry. If SpaceX is correct in reporting zero surviving debris and a fully demisable spacecraft, the rise in reentry risk is minimal over the current risk.

The FAA will continue to work with other government agencies and industry to improve the management of the non-geostationary satellites, particularly those in LEO, that pose an increased risk due to reentering debris. The FAA will continue to improve the launch and reentry licensing process to address this risk where appropriate and consistent with its statutory authority.

Appendix: Aerospace Corporation Technical Report: Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbits

Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbits

Executive Summary

This report estimates the risk to people on the ground and in aircraft due to debris from random and controlled (targeted) reentries of non-geostationary satellites located in low Earth orbits (LEO). The report bases its estimates on the assumption that 12 large constellations proposed in applications to the U.S. Federal Communications Commission (FCC) as of March 2021 are fully constituted and functioning in orbit in 2035 and are deorbiting satellites for disposal according to the design lifetime of their satellites. Disposed satellites are entering the atmosphere at random locations along their orbit track. A total of 54,902 constellation satellites would be in orbit, well above the ~3,000 satellites operating in LEO in 2021. The assumed replacement strategy would lead to reentry and replacement of 9,800 (approximately 18%) of the constellation satellites each year.

The total number of hazardous fragments surviving reentries each year would be 28,000 and the casualty expectation, the number of individuals on the ground that might be injured or killed by debris surviving the reentries of satellites being disposed from these constellations, would be 0.6 per year, which means that one person on the planet might be injured or killed every two years.

Some debris fragments would also be a hazard to people in aircraft. Projecting 2019 global air traffic to 2035 and assuming that a fragment that would injure or kill a person on the ground would also be capable of fatally damaging an aircraft, the probability of an aircraft downing accident in 2035 would be 0.0007 per year. Of course, an aircraft downing accident would likely kill all passengers on that aircraft.

A larger number of small objects that are not hazardous to a human on the ground would likely survive each reentry, and impact of a small fragment on a critical part of an aircraft (e.g., cockpit window) might cause emergency action by the crew to avoid a disaster. The probability of such an event in 2035 would be 0.03 per year.

Replacing the 9,800 satellites being disposed each year will require an estimated 119 launches per year, with each launch carrying multiple replacement satellites. After the satellites have been deployed, each launch stage will be disposed into the atmosphere, and based on debris recovered from stage reentries, each stage may have six objects that survive reentry and are hazardous to humans on the ground and to aircraft. The stage reentries add a small number of hazardous fragments to the total for a year in 2035, increasing the hazard to people in aircraft by ~2%.

Controlling or targeting reentries so that surviving debris lands in remote, uninhabited regions would reduce the casualty expectations for people on the ground to near zero. If these same regions are crossed by few aircraft and notices of possible hazards are sent to aircraft that might be affected, risks to aircraft could also be moved toward zero.

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1 Problem Statement

Congressional language

"…the Committee observes that the exponential rise of non-geostationary satellites, particularly those in low Earth orbit, poses an increased risk due to reentering debris. Therefore, the Committee directs the FAA to provide a report to the House and Senate Committees on Appropriations within 270 days of enactment of this act assessing how the FAA launch and reentry licensing process can be leveraged to address this risk."

2 FAA Task statement

a. The 2021 Transportation Housing and Urban Development explanatory statement for the 2021 appropriation bill contains a requirement that AST respond to Congress regarding ways to mitigate risk from reentering space objects. Specifically, the task states:

i. "…the Committee observes that the exponential rise of non-geostationary satellites, particularly those in low Earth orbit, poses an increased risk due to reentering debris. Therefore, the Committee directs the FAA to provide a report to the House and Senate Committees on Appropriations within 270 days of enactment of this act assessing how the FAA launch and reentry licensing process can be leveraged to address this risk."

b. In support of AST, Aerospace will:

i. Provide an assessment of the rise of non-geostationary satellites (launched by the U.S. under FAA licenses and otherwise)

ii. Provide an assessment of the risks associated with random and controlled (targeted) reentries of the satellites identified in (i).

iii. Support AST development of a draft report for AST Associate Administrator approval that assesses current licensing processes that may be applicable to addressing reentry risks identified in (ii).

3 Objective

Develop reasonable projections of the possible increase in the risk to both people on the ground and in aircraft due to debris from non-geostationary satellites, particularly those in (low Earth orbit) LEO, that survive both random reentries (debris impact region unknown prior to reentry) and controlled or targeted reentries (debris impact region directed to uninhabited area). This information will be used by the AST Associate Administrator to assess the applicability of current licensing processes for mitigating risk from reentering space objects.

4 Summary of Standard Practices for Satellites and Constellations

4.1 Inter-Agency (Space) Debris Coordinating Committee (IADC)

The March 2020 IADC Guidelines[1] provide the following recommendations for satellites being disposed by reentry into the atmosphere:

> Spacecraft or orbital stages that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be deorbited (direct re-entry is preferred) or where appropriate maneuvered into an orbit with an expected residual orbital lifetime of 25 years or shorter. The probability of success of the disposal should be at least 90%. For specific operations such as large constellations, a shorter residual orbital lifetime and/or a higher probability of success may be necessary. Retrieval is also a disposal option.
>
> If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property. This may be accomplished by limiting the amount of surviving debris or confining the debris to uninhabited regions, such as broad ocean areas. Also, ground environmental pollution, caused by radioactive substances, toxic substances or any other environmental pollutants resulting from on-board articles, should be prevented or minimized in order to be accepted as permissible.
>
> In the case of a controlled re-entry of a spacecraft or orbital stage, the operator of the system should inform the relevant air traffic and maritime traffic authorities of the re-entry time and trajectory and the associated ground area.

4.2 U.S. Government Orbital Debris Mitigation Standard Practices

Section 4-1 of the 2019 revision of the U.S. Government Orbital Debris Mitigation Standard Practices[2] (ODMSP) states:

> Programs and projects will plan for disposal procedures for a structure (i.e., launch vehicle components, upper stages, spacecraft, and other payloads) at the end of mission life to minimize impact on future space operation,

and gives two preferred options:

> Maneuver to remove the structure from Earth orbit at the end of mission into (1) a reentry trajectory or (2) a heliocentric, Earth-escape orbit.

The focus of this report is on disposal of satellites in LEO, and these satellites will be disposed via reentry into Earth's atmosphere.

The ODMSP goes on to say:

> For direct reentry, the risk of human casualty from surviving components with impact kinetic energies greater than 15 joules should be less than 0.0001 (1 in 10,000). Design-for-demise and

[1] "IADC Space Debris Mitigation Guidelines," IADC-02-01, Revision 2, Inter-Agency Space Debris Coordinating Committee, March 2020 (https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf).

[2] "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)

other measures, including reusability and targeted reentry away from landmasses, to further reduce reentry human casualty risk should be considered.

The ODMSP notes: “The USG [United States Government] will follow the ODMSP, consistent with mission requirements and cost effectiveness, in the procurement and operation of spacecraft, launch services, and the conduct of tests and experiments in space.” Thus, the standard practices specified in the ODMSP do not specifically apply to satellites acquired and operated by commercial companies, but the Federal Aviation Administration (FAA) and Federal Communications Commission (FCC) have incorporated similar practices into their regulations for satellites built, launched, operated and disposed by U.S. commercial companies.

This report looks at the effects on risks to humans on the ground and in commercial aircraft from two of the postmission reentry disposal options defined in the ODMSP:

- Direct reentry [also known as controlled or targeted reentry] from orbit at end of mission life (the preferred option), where a satellite or rocket stage uses onboard propulsion to place the vehicle on a reentry trajectory that will control the debris impact region and limit the hazards of surviving debris, and

- Atmospheric reentry [also known as uncontrolled or random reentry], where a satellite or rocket stage uses atmospheric drag, with or without drag enhancement devices, or low-thrust propulsion to slowly lower the vehicle’s orbit for final capture by the atmosphere. In this case, the vehicle will reenter somewhere along the orbital path, and the debris impact region will have unknown location somewhere along the orbital ground track.

For both direct and atmospheric reentry, the “risk of human casualty from surviving components with impact kinetic energies greater than 15 joules should be less than 0.0001 (1 in 10,000).” For atmospheric reentry, the orbital lifetime should be limited “to as short as practicable but no more than 25 years after completion of mission.” The ODMSP encourages consideration of “design-for-demise and other measures, including reusability and targeted reentry away from landmasses, to further reduce reentry human casualty risk.” The term design-for-demise refers to use of structures and features that maximize destruction of the space vehicle during reentry to minimize the hazards associated with debris that survives reentry.

A long-term reentry option is also available for structures in Medium Earth Orbits (MEO) and other orbits, where atmospheric reentry results in orbital lifetimes well beyond 25 years. For long-term reentry, the orbital lifetime should be limited “to as short as practicable but no more than 200 years.” In addition, a 7 m^2 total casualty area limit for debris exceeding 15 joules of kinetic energy may be used as a relaxed alternative to the 1 in 10,000 human casualty risk limit. It is a relaxed risk limit, because casualty risk corresponding to 7 m^2 exceeds the 1 in 10,000 limit for some or all orbital inclinations, depending on year. For example, in year 2021, corresponding casualty risk can be as low as 0.6 in 10,000 and as high as 1.7 in 10,000; in year 2060 corresponding casualty risk will exceed 1 in 10,000 for all inclinations. Given the infrequent nature of these disposals, these objects will not be considered in the current study, which looks at reentries of large numbers of satellites from the LEO region.

Large Constellations

The ODMSP defines a large constellation (LC) as having "100 or more operational spacecraft cumulative" and states that "the program should limit the cumulative reentry human casualty risk from the constellation," but provides no limit on cumulative human casualty risk and no guidance on how the cumulative hazard should be measured (i.e., is the cumulative hazard the sum of the hazards for each satellite in the constellation when it becomes operational? does it include operational spares? is it measured on a per year basis or at the end of the constellation's operational life?). The ODMSP definition of a constellation with 100 or more satellites as a "large constellation" will be used in this analysis.

4.3 ISO Standards

The International Organization for Standardization (ISO) does not specify a specific level of risk for debris that survives a reentry, noting only that "Specific re-entry safety requirements imposed contractually, voluntarily or by national or international authorities shall be identified and applied on hazards from debris that survives reentries."[3] The standard does note that the 1 in 10,000 hazard threshold is set in a number of existing guidelines and regulations.

4.4 National Space Transportation Policy

The National Space Transportation Policy[4] (NTSP) of 2013 states that:

> The Secretary of Transportation is responsible for authorizing and providing safety oversight for nonfederal launch and reentry operations and for the operation of non-federal launch and reentry sites. In performing these responsibilities, the Secretary of Transportation shall:
>
> - Coordinate with the Secretary of Defense, the Administrator of NASA, and other appropriate heads of departments and agencies. Such coordination shall include work to establish and/ or refine common public safety requirements and other common standards, as applicable, for launches from or reentries to Federal, state, and commercial sites;
> - Develop, in coordination with the Administrator of NASA, a comprehensive, efficient approach to the regulatory oversight of commercial spaceflight capabilities transporting United States Government and United States Government-sponsored crews safely to and from orbit — these coordination efforts shall strive to avoid unnecessary overlap or undue burden; and
> - Execute exclusive authority, consistent with existing statutes and executive orders, to address orbital debris mitigation practices for U.S.-licensed commercial launches, to include launch vehicle components such as upper stages, through its licensing procedures.
>
> In addition, the Secretary of Transportation and other appropriate department and agency heads, shall:

[3] "Space systems – Space debris mitigation requirements," ISO 24113:2019,, July 2019 (https://www.iso.org/obp/ui/#iso:std:iso:24113:ed-3:v1:en).

[4] "National Space Transportation Policy," Executive Office of the President, November 2013 (https://www.nasa.gov/sites/default/files/files/national_space_transportation_policy_11212013.pdf).

- Seek to ensure that the regulatory environment for licensing commercial space transportation activities is timely and responsive, and addresses current market and industry developments;
- Support continuation of the current liability risk-sharing regime for U.S. commercial space transportation activities, including provisions for the conditional payment of excess third-party claims by the United States Government; and
- Advocate internationally for the adoption of United States Government safety regulations, standards, and licensing measures to enhance global interoperability and safety of international commercial space transportation activities.

The Federal Communications Commission has recently approved new rules that “improve the specificity and clarity of rules that require disclosure of debris mitigation plans by satellite companies. The changes include requiring that satellite applicants assign numerical values to collision risk, probability of successful postmission disposal, and casualty risk associated with those satellites that will re-enter Earth’s atmosphere.” [5]

5 Summary of FAA and FCC Information Requests for Satellites and Constellations

5.1 Information Requested by FAA for Satellite Launches, Reentries and Constellations

The FAA issued a new rule in Title 14 (Aeronautics and Space) of the Code of Federal Regulations (CFR) on December 10, 2020, which “streamlines the FAA’s commercial space launch and reentry regulations and removes obsolete requirements.”[6] The rule went into effect on March 10, 2021. 14 CFR Part 450 of the new rule covers the requirements for obtaining and maintaining a license for a launch vehicle or reentry vehicle.[7] The FAA defines a reentry vehicle as “a vehicle designed to return from Earth orbit or outer space to Earth substantially intact.”[8] This definition is intended to only cover vehicles that are designed to return safely to the ground, and therefore does not apply to satellite reentry.

5.2 Information Requested by FCC for Satellites and Constellations

The FCC regulations for satellite reentry are included in Title 47 (Telecommunications) of the CFR. Satellite reentry is specifically mentioned in three sections of Title 47: Part 5 (Experimental Radio Service), Part 25 (Satellite Communications), and Part 97 (Amateur Radio Service). Each of these parts provide details on each specific type of system, and all three parts provide a statement for a requirement for a postmission disposal plan of the satellites that involves atmospheric reentry: “The [postmission disposal plan] shall . . . include a casualty risk assessment if planned postmission disposal

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[5] “FCC UPDATES SATELLITE ORBITAL DEBRIS MITIGATION RULES,” FCC NEWS from the Federal Communications Commission, April 23, 2020 (https://www.fcc.gov/document/fcc-updates-orbital-debris-mitigation-rules-new-space-age-0).

[6] “Streamlined Launch and Reentry License Requirements” A Rule by the Federal Aviation Administration, 12/10/2020 (https://www.federalregister.gov/documents/2020/12/10/2020-22042/streamlined-launch-and-reentry-license-requirements).

[7] 14 CFR Part 450 – Launch and Reentry Requirements, Section 450.1

[8] “Streamlined Launch and Reentry License Requirements” A Rule by the Federal Aviation Administration, 12/10/2020 (https://www.federalregister.gov/documents/2020/12/10/2020-22042/streamlined-launch-and-reentry-license-requirements).

involves atmospheric re-entry of the [spacecraft]. An assessment shall include a statement as to the likelihood that portions of the spacecraft will survive re-entry and reach the surface of the Earth, and the probability of human casualty as a result."[9] This statement is taken from Part 5, Section 64; with similar statements in Part 25, Section 114 and Part 97, Section 207. Presently this is the only requirement, to include a casualty risk assessment to provide an estimate of the likelihood of reaching the surface and an estimate of the probability of casualty. But an amendment was published on August 25, 2020, to revise these sections to mitigate the growth of orbital debris.[10] The effective date of the amendment is still pending and will be published in the Federal Register once accepted. As with the current regulations, the amendment includes very similar statements in Part 5 (Experimental Radio Service), Part 25 (Satellite Communications), and Part 97 (Amateur Radio Service). This text (taken from Part 5, Section 64) states:

"If planned disposal is by atmospheric re-entry, the [postmission disposal plan] must also include:

1. A disclosure indicating whether the atmospheric re-entry will be an uncontrolled re-entry or a controlled targeted reentry.
2. An assessment as to whether portions of any individual spacecraft will survive atmospheric re-entry and impact the surface of the Earth with a kinetic energy in excess of 15 joules, and demonstration that the calculated casualty risk for an individual spacecraft using the NASA Debris Assessment Software or a higher fidelity assessment tool is less than 0.0001 (1 in 10,000)."[11]

This new proposed rule is more specific and requires a casualty risk assessment to be performed for all objects that would have a kinetic energy at impact of 15 joules or greater. The proposed rule also requires the calculation of risk of casualty from surviving debris, and providing the assumptions used in the calculation, with a requirement of a likelihood of casualty less than 1 in 10,000. This is the same value that is in the most recent version of the U.S. Government Orbital Debris Mitigation Standard Practices[2] (ODMSP), as described in Section 4.2.

6 Summary of Current FCC Applications for Large Constellations of LEO and LEO-crossing Satellites as of April 1, 2021

Our focus in this report is on the constellations shown in Table 1, which is an accumulation of estimates based on analysis of filings of applications to the Federal Communications Commission (FCC) as of March 2021. The FCC does not publish these types of statistics, nor do they require launch plans. Included in the table are estimates on launch rates, type of launcher (medium or heavy), and possible launch vehicles. In some cases, applicants include additional detail on satellite mass design lifetime. When details are not available, estimates were made based on public records or from various publicly available sources such as *SpaceNews* and *SpaceflightNow*.

Given that this study is focused on the hazards associated with debris that might survive reentry, we have limited our study to FCC filings for LEO constellations with at least 50 satellites of mass 150 kg and higher in and passing through the LEO protected region (perigee altitudes less than 2000 km). Satellites

[9] 47 CFR Part 5 – Experimental Radio Service, Section 5.64.
[10] Federal Register, Vol. 85, No. 165, August 25, 2020
[11] Ibid

highlighted in the table are judged to have individual masses of less than 150 kg, and their reentry would not add significantly to hazards predicted for the constellations of larger satellites used for this study.

Table 1. Applications to the Federal Communications Commission for non-geosynchronous satellite orbit (NGSO) constellations as of March 2021.

Call Signs	Constellations	Proposed LEO Satellites	Approved	Deployed	Annual Launch Rates (Sustainment)	Launcher Category	Certain or Likely	Possible
S3069	SpaceX Starlink Gen2	30,000	0	0	15	Heavy or Medium	Starship	Falcon 9
S2992	SpaceX Starlink VLEO	7,518	7,518	0	25	Medium or Heavy	Falcon 9	Starship
S2963	OneWeb LEO	7,088	720	182	20	Medium or Heavy	Soyuz	Any available
S2983 & S3018	SpaceX Starlink LEO	4,408	4,409	1,443	15	Medium or Heavy	Falcon 9	Starship
S3051	Amazon Kuiper	3,236	3,236	0	14	Medium or Heavy	Atlas V; New Glenn	Any available
S2976	Telesat	1,671	117	0	9	Medium or Heavy	New Glenn; Terran	Any available
S2994	Oneweb MEO (720 satellites in LEO)	720	720	0	6	Medium or Heavy	Any Available	
S3068	Mangata**	791	0	0	6	Medium or Heavy	Any Available	
S2985	Viasat	288	20	0	2	Medium or Heavy	Any Available	
S3065	AST	243	0	0	1	Medium or Heavy	Any Available	
S2993	Boeing (132 satellites in LEO)	132	0	0	1	Medium or Heavy	Vulcan	Any available
S2986	Theia Holdings A	120	120	0	1	Medium or Heavy	Any Available	
S2991	Telesat Vband	117	117	0	1	Medium or Heavy	New Glenn; Terran	Any available
S2935	O3b (36 satellites in LEO)**	112	38	20	2	Medium or Heavy	Soyuz; Ariane 6	Any available
S2110	Iridium NEXT (none in LEO	81	81	75	2	Medium or Heavy	Falcon 9	Any available
S3019	New Spectrum Satellite**	18	0	0	1	Medium or Heavy	Any Available	
S2982	Audacy (none in LEO)**	3	3	0	0	Medium or Heavy	Any Available	
S2978	Space Norway (none in LEO)**	2	2	0	0	Medium or Heavy	Falcon 9	
S2912	Planet Labs Flocks of Doves	1,156	1,156	424		Small or Rideshare	Any Available	
S2946	Spire Global	1,000	1,000	84		Small or Rideshare	Any Available	
S3045	Spire Global MINAS	872	636	12		Small or Rideshare	Any Available	
S3064	SWARM Astrobiene	450	0	0		Small or Rideshare	Any Available	
S3070	Kepler	360	0	0		Small or Rideshare	Any Available	
S3041	SWARM	300	150	81		Small or Rideshare	Any Available	
S2981	Kepler	140	140	8		Small or Rideshare	Any Available	
S3042	Hawkeye	80	80	3		Small or Rideshare	Any Available	
S3014	Astro Digital U.S.	30	5	1		Small or Rideshare	Any Available	
S3047	Myriota	26	26	0		Small or Rideshare	Any Available	
S3054	Keneis	25	0	0		Small or Rideshare	Any Available	
S3038	Hiber	24	24	0		Small or Rideshare	Any Available	
S2862	Planet Labs Skysat	21	21	21		Small or Rideshare	Any Available	
S3032	Blacksky Global	16	16	7		Small or Rideshare	Any Available	
S2980	Karousel	12	12	0		Small or Rideshare	Any Available	
S3073	Capella Space	3	3	2		Small or Rideshare	Electron; Falcon 9	
S3067	R2 Space	8	0	0		Small or Rideshare	Any Available	
S3052	LOFT	1	0	0		Small or Rideshare	Any Available	
36		61072	20370	2363	122			
Subtotals for satellites likely to use medium/heavy		56548	17101	1720	122			
Subtotals for satellites likely to use small or ride share		4524	3269	643				

These numbers are estimates based upon analysis of FCC filings and public records of launches from various sources such as SpaceNews and SpaceflightNow. The FCC does not publish these types of summary statistics. Nor do they require launch plans. **Constellation not included in study (see text).

The 50-satellite lower limit, which is less than the 100-satellite threshold set by the 2019 ODMSP, primarily assures that the Iridium NEXT constellation of 75 satellites of mass 676 kg, with the final constellation possibly including 81 satellites, is included in the analysis. The 720 OneWeb MEO satellites were included in the total for the OneWeb LEO constellation. The O3b (36 LEO satellites), New Spectrum (18 satellites), Audacy (3 satellites) and Space Norway (2 satellites) constellations will not be included in the study, nor will reentries from constellations of small satellites (those highlighted in "green" in the table), which will not contribute significantly either to the total number of reentering satellites (4,500 vs. 57,007) or to total mass of reentering satellites. Mass is a key indicator of the associated hazards, and most of these satellites are very low mass and are carried to orbit by small launch vehicles or via ride-share on larger vehicles (i.e., take advantage of space-available on launches carrying larger payloads).

The Mangata Networks constellation includes 112 satellites with perigee altitudes less than 2,000 km and apogee altitudes above 11,000 km. In this case, Mangata proposes an “active” disposal of their satellites, and disposal options include raising satellite perigees to above 2,000 km for disposal or directed reentry into the atmosphere. Since this study is concerned with uncontrolled reentries from circular orbits, disposal of the Mangata constellation was not considered in this study.

In April 2021, China announced plans to place a large constellation (13,000 satellites) in LEO. At present, there is insufficient information on the satellites or details on the constellation’s design to add to the study. The constellation will be added if details arise before delivery of the final report.

Since the goal is to identify possible FAA regulatory requirements to reduce reentry hazards, the study identifies those constellations that currently are being or may be placed in orbit by FAA authorized launches and considers the case where each constellation is operating in a steady-state manner in the year 2025; i.e., the constellation is fully configured and is disposing and replacing satellites on a yearly schedule according to the mission lifetime of constellation satellites.

Table 2 includes details on the configuration of each constellation derived from FCC filings noted in Table 1. (Note: there are cases where mass is not provided in filings, and mass estimates provided for these cases are derived from public sources or educated guesses). Included in Table 2 are details on orbit altitudes and inclinations of orbit planes and the number of satellites in orbit at each inclination. As will be seen, the inclination of orbits is important to estimate the people on the ground and commercial aircraft that might be exposed to risk by debris surviving reentry.

The FCC does not require applicants to identify the launch vehicles that will be used to deploy or sustain the constellation. Information on launch contracts typically becomes available well after an FCC filing has been made and approved. Table 1 identifies, to the extent presently known, the launch vehicles certain, likely, or possibly to be used for the deployment of each of the constellations. It is known that the approved OneWeb LEO constellation of 720 satellites are being deployed by Soyuz launchers. These launches would be outside the control of the FAA. Similarly, the other constellations that show “any available” for the launcher could use non-FAA licensed launches as well. They could also choose to use FAA licensed launchers and even the additional 6,368 OneWeb LEO satellites could be deployed using a mixture of U.S. and foreign launchers.

Another important factor in determining the risk from reentries is the number of satellites to be disposed by reentry as a function of time, i.e., each satellite has a design lifetime, but will it be disposed when that lifetime expires or will operators wait until its mission is degraded by equipment failure or other factors and then send it to disposal and replace it with a new satellite? While the 2019 ODMSP does recommend that programs should “limit the cumulative reentry human casualty risk from the constellation” for government systems, there is currently no requirement that applications to the FCC or FAA provide information on the projected number of or the cumulative hazard for satellites reentering in any fixed period of time (e.g., the number of satellites reentering per year or the maximum number of satellites that might reenter in one year).

Since the filings do not provide information on the overall disposal strategy for constellation satellites, this report assumes that the number of satellites to be disposed each year is the total number of satellites in the constellation divided by the mission lifetime of each satellite. It is recognized that in actuality, disposals may occur at a different rate and, potentially, fewer satellites might be disposed in one year and many more in the next. Table 2 estimates the number of satellites reentering per year for each constellation and the total number if all constellations are active. Eventually all satellites will need to be replaced within the constellation's lifetime or all disposed at end of the constellation's life, so a yearly rate based on design lifetime of satellites should yield a reasonable average for the risk that might be expected.

Table 2. Constellation satellite mass and number reentering per year.

Proposer	System	Call-Sign	Total Proposed by Call Sign in LEO	Estimated Satellite Mass (kg)	Satellite Design Life (years)	Currently Proposed	Orbital Planes	Satellites Per Plane	Approximate Altitude (km)	Orbital Inclinations (Deg.)	Number Reentering per Year
SpaceX	Gen2 NG SO Satellite System	S3069	30,000	286	5	7,178	1	7,178	328	30	1436
						7,178	1	7,178	334	40	1436
						7,178	1	7,178	345	53	1436
						2,000	40	50	360	97	400
						1,998	1	1,998	373	75	400
						4,000	1	4,000	499	53	800
						144	12	12	604	148	29
						324	18	18	614	116	65
						30,000					**6000**
SpaceX	VLEO (V-Band)	S2992	7,518	286	5	2,493	1	2,493	336	42	499
						2,478	1	2,478	341	48	496
						2,547	1	2,547	346	53	509
						7,518					**1504**
OneWeb	LEO Phase 1	S2963	7,088	150	10	588	12	49	1,200	87.9	59
						128	8	16	1,200	55	13
	LEO Phase 2					1,764	36	49	1,200	87.9	176
						2,304	32	72	1,200	40	230
						2,304	32	72	1,200	55	230
						7,088					**709**
SpaceX	LEO	S2983 & S3018	4,408	286	5	1,584	72	22	550	53	317
						1,584	72	22	540	53.2	317
						720	36	20	570	70	144
						348	6	58	560	97.6	70
						172	4	43	560	97.6	34
						4,408					**882**
Amazon	Kuiper System	S3051	3,236	150	7	784	28	28	590	33	112
						1,296	36	36	610	42	185
						1,156	34	34	630	52	165
						3,236					**462**
Telesat	Phase 1	S2976	1,671	700	10	220	20	11	1,325	50.88	22
						78	6	13	1,015	98.98	8
	Phase 2					440	20	22	1,325	50.88	44
						660	20	33	1,325	50.88	66
						273	21	13	1,015	98.98	27
						1,671					**167**
Viasat		S2985	288	700	15	288	8	36	1,300	45	19
AST (AST &Science LLC)	SpaceMobile	S3065	243	1,500	7	18	1	18	725 to 730	0	3
						165	11	15	725 to 740	40	24
						60	4	15	735 to 740	55	9
						243					**35**
Boeing	V-band LEO / ~GSO	S2993	132	1,500	10	132	11	12	1,056	54	13
Theia Holdings A		S2986	120	3,000	12	8	8	1	750	98	1
						112	8	14	791 to 809	99	9
						120					**10**
Telesat	Vband	S2991	117	700	10	45	5	9	1,248	37.4	5
						72	6	12	1,000	99.5	7
						117					**12**
Iridium	Iridium NEXT	S2110	81	676	15	81	6	11	781	86	5
		TOTAL	54,902							TOTAL	9818

The information in Table 2 is the primary data used for each constellation: the number and mass of satellites in each constellation, the number of orbit planes and the number of satellites in each plane, and finally, the inclination of each orbit plane. As will be seen, the number of people and the number of airborne aircraft at risk from debris surviving reentry of a satellite is a function of that satellite orbit inclination.

7 Assumptions and Analysis Approach

Where possible, the study will generate an estimate for hazards associated with satellites being disposed from large constellations on a yearly basis. The estimate will use the assumption that, in steady-state operations in the year 2035, constellations will dispose of satellites at the end of their mission lifetime (e.g., a constellation with 1,000 satellites, each with a lifetime of 10 years, would continuously deorbit 1/10 of its satellites or 100 satellites every year on average). Of course, this would likely vary from year to year, with some years possibly having several times that number reentering. The number deorbited at the end of the constellation's lifetime could be significantly higher (e.g., all 74 satellites in the original Iridium constellation were proposed to be reentered in approximately one year when that operator neared bankruptcy).

Hazard estimates will be based on evidence from debris recovered after satellite and launch stage reentries, predictions of hazards associated with reentries of satellites and launch stages, and data collected by radar observation of satellite reentries.

Hazards to people on the ground for each satellite and launch stage will be compared to the 1-in-10,000 (1E-4) casualty expectation (E_C) threshold; the cumulative hazard per year will be the single satellite hazard multiplied by the average number of satellites reentering per year when the constellations are in steady-state operations.

NASA predicted[12] that ~6 m^2 of casualty area would result from reentry of a 560 kg Iridium satellite. Based on this estimate it is assumed here that 6/560 or 1.07 square meters of debris casualty area exists per 100 kg of satellite mass in 2035.

Hazards to aircraft will include:

- Hazard associated with aircraft impacting objects with mass >300 gm that are deemed fatal to aircraft (see Section 8.3.2) and
- Hazards associated with aircraft impacting objects with mass >1 gm that are deemed to require emergency action by the pilot (see Section 8.3.3).

The fatal hazard estimated for objects > 300 gm will be based on the estimated number of those objects that might survive each satellite's reentry, and on large components that have survived reentries of launch stages. Hazards associated with smaller debris will be based on radar measurements of debris falling after a spacecraft reentry.

Aircraft that might be affected will be based on commercial aircraft that would be in flight on routes shown in Figure 1. Figure 2 compares the number of people and aircraft per square kilometer as a function of latitude. Figure 3 compares the E_C for people and the probability of an aircraft being struck as a function of latitude in 2021.

[12] "Exhibit E: Orbital Debris Mitigation and Casualty Risk Assessment," FCC Form 312, Schedule A, https://transition.fcc.gov/transaction/iridium-motorola/iridumconstel_exhe.pdf

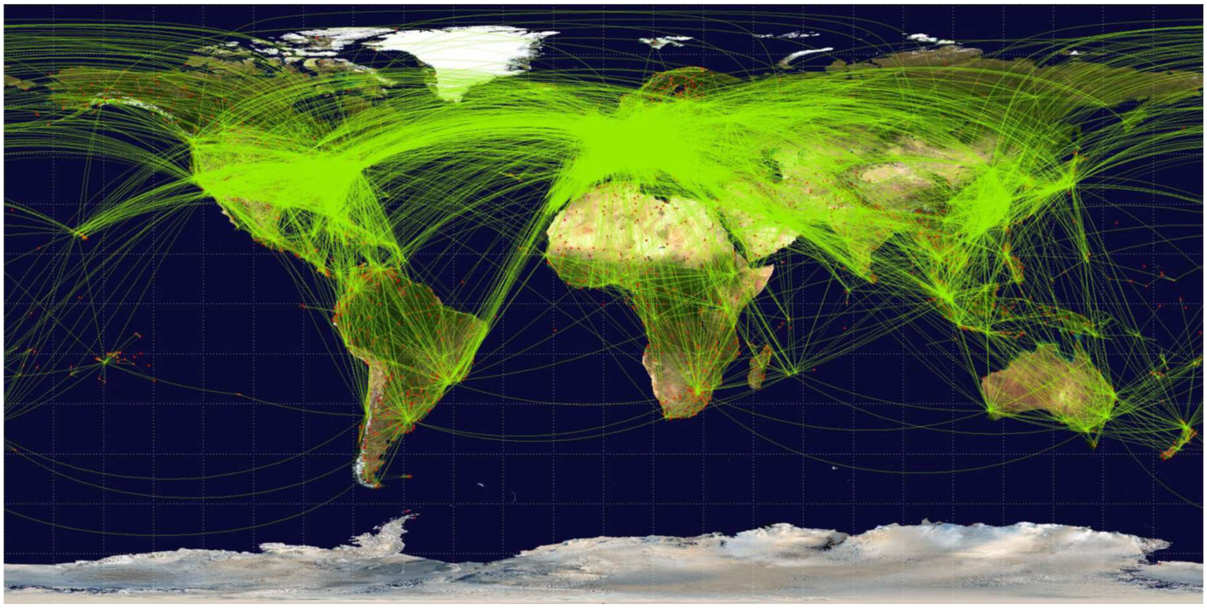

Figure 1. World airline traffic routes, 2021.[13]

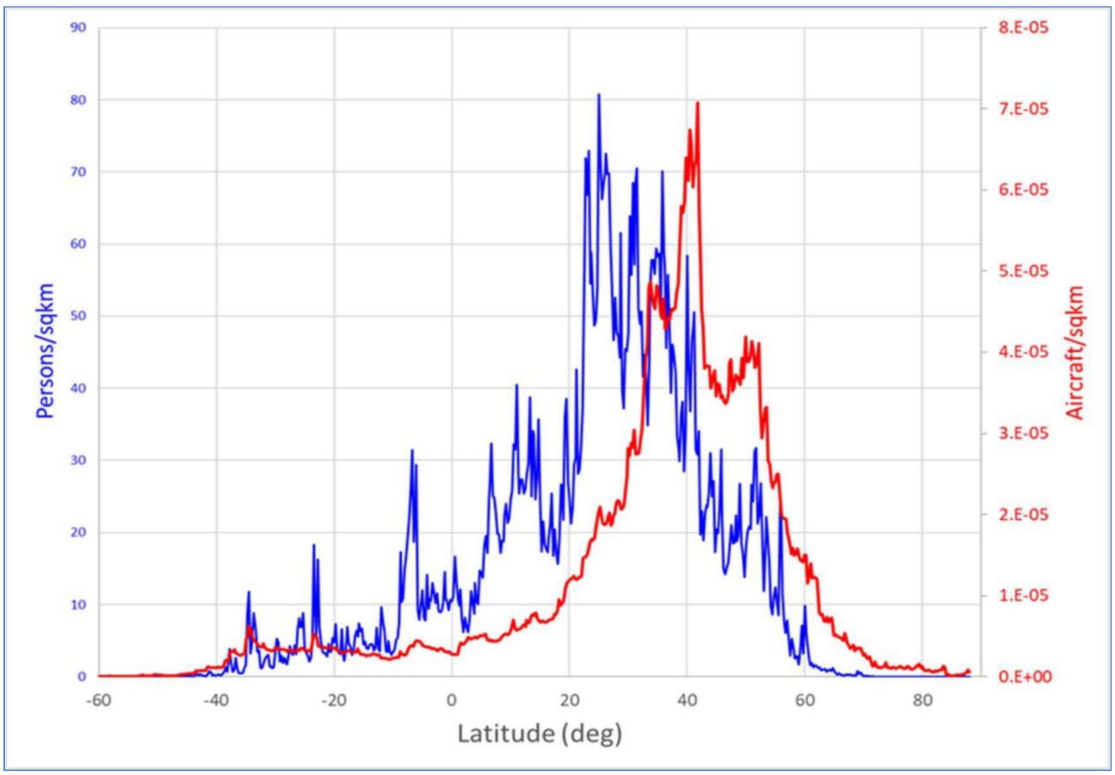

Figure 2: Population and aircraft densities vs latitude, 2021[14]*.*

[13] Source: https://en.wikipedia.org/wiki/Civil_aviation#/media/File:World-airline-routemap-2009.png

[14] *Based on Gridded Population of the World (GPW) v4; and Official Aviation Guide (OAG) airline schedules data.*

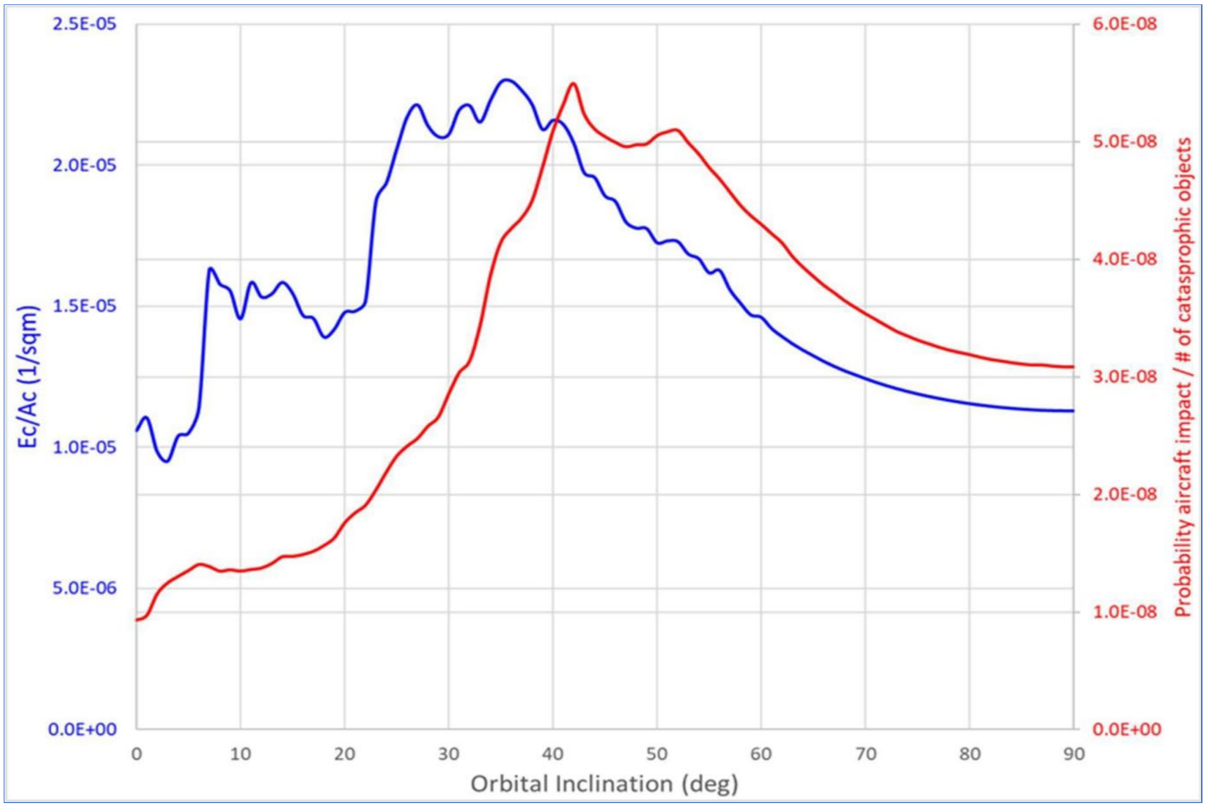

Figure 3. Population and aircraft risk model for 2021.

Additional areas of investigation include case examples of E_C (ground) vs E_C (aircraft) and comparisons for both current and future projections of P_E vs. P_i, where P_E is the probability of casualty (same as collective probability of human impact on the ground without sheltering), and P_i is the collective probability of aircraft impact.

Regional dependencies, (e.g., North America only, without North America, etc.) will also be investigated.

7.1 Basic assumptions

This study assumes that in the year 2035:

- All satellites proposed in FCC applications posted by April 1, 2021 (see Table 1) with mass of 150 kg or larger are in orbit and operating in their constellations.
- Each constellation is being maintained with all slots filled – satellites that have reached the end of their mission life are being removed and sent toward reentry disposal[15] and disposed satellites are being actively replaced, so the number of satellites in a given constellation is that given in the table.
- The percentage of a constellation's satellites disposed and replaced in 2035 will be based on the mission lifetime of that constellation's satellites provided in the FCC application. Specifically, it is

[15] From the perspective of space hazards, satellites being disposed from constellations remain threats of possible collisions with other objects in orbit as they move toward reentry, so the time from end of mission to final reentry is important from that perspective, but this study considers only hazards to people on the ground and in aircraft from debris surviving from satellites that are reentering.

assumed that if a mission life for satellites in a constellation is 5 years and the constellation has 1,000 active satellites, on average 20% of that constellation's satellites or 200 satellites must be replaced each year (of course, the actual disposal schedule might be different, with some years having more reentries and some less, but the average should be a reasonable first estimate).

- All disposed satellites will reenter in an uncontrolled manner, i.e., the final location of debris surviving reentry will not be controlled and debris surviving reentry would fall through the airspace and impact the Earth's surface somewhere along a satellite's orbital ground track. Of course, some may choose to control the final reentry point and place debris in an uninhabited area. That approach should be encouraged.
- Satellite dry mass (mass of the satellite without consumables and propellant) used for reentry hazard estimation is based on information in the FCC application or estimated based on publicly available information.

7.2 Analysis Approach

The information on satellite mass and constellation design given in Table 2, combined with projections of Earth's population and the number and types of airborne aircraft will be used to estimate the hazards to people and aircraft in 2035 associated with each proposed large constellation and a total assuming all constellations are fully constituted and operating. Specifically, information in the FCC applications will be used to estimate the:

- Number of satellites in each constellation, based on those currently proposed in the FCC applications,
- Number of orbital launch stages reentering on a yearly basis, based on "Annual Launch Rates (sustainment)" given in Table 1,
- Number of satellites being disposed in 2035 when constellations are assumed to be fully constituted and operating in steady-state conditions (i.e., with a percentage of constellation satellites being disposed and replaced each year).

This information will be combined with:

- Predictions of debris that might survive and be a hazard to people and aircraft from each reentry and cumulative reentries each year,
- The casualty expectation, E_C (the number of people somewhere on the planet that might be injured or killed by falling debris), and
- The probability that a commercial aircraft flying somewhere on Earth might strike an object that would be fatal to the aircraft or might cause emergency action by the pilot.

8 Hazards Associated with Constellation Satellite Disposal

8.1 Overview of Reentry Breakup

Figure 5 illustrates the reentry breakup process, which proceeds as follows. As a reentering object gets deeper into the atmosphere below about 120 km, aerodynamic heating gradually raises the temperature of primary structures, until widespread melting suddenly releases and exposes other major components to continued heating and to increasing aerodynamic loads. This significant disassembly is referred to as major breakup, usually occurring around 80 km for satellites and around 70 km for larger stages, and taking place 15 to 20 minutes after passing through 120 km.

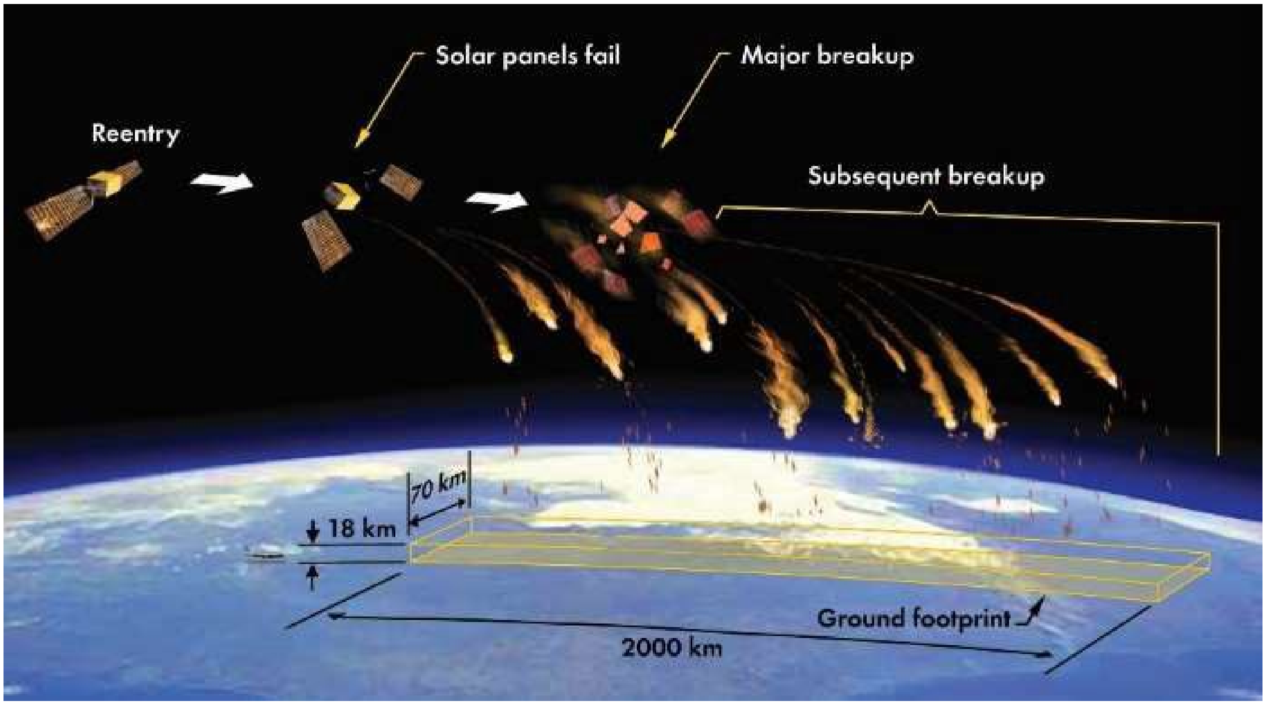

Figure 5. Illustration of reentry breakup process.

The released components will, in turn, each be heated, melt, and disassemble, releasing other previously protected components, with this process continuing until much of the original object has been reduced to a cloud of debris varying in size from particulates to large fragments. This more prolonged disassembly is referred to as subsequent breakup, lasting from major breakup to about 50 km.

The original object and early released components continue to travel nearly horizontally to the Earth's surface, but steadily steepen with time and experience progressive disassembly until the surviving debris are falling nearly vertically from around 30 km, possibly with a horizontal velocity component due to winds below 20 km. This debris cloud can be tens of kilometers wide and hundreds of kilometers long, with each element falling through lower altitudes at speeds defined by their aerodynamic and mass properties. Particulates settle slowly, while larger objects, perhaps even a few mostly intact components, fall with enough momentum to injure a human or damage an aircraft.

Figure 6 and 7 show photographs of objects that have been recovered on the ground after satellite or launch stage reentries. To date, there has been only one person on the ground who is known to have been "touched" by a reentered debris fragment: Ms. Lottie Williams of Tulsa, Oklahoma was brushed on the shoulder by the small, lightweight fragment. She was not injured. The other objects shown in Figures 6 and 7 would surely be hazards to people and aircraft and represent the types of objects considered as hazardous debris in this study. Note that finding debris on the ground is not common today given the relatively few reentries of large objects per year (less than 100) and the fact that many land in water (71% of the Earth's surface is covered with water). Since 1960, there have been fewer than 90 reentry events that have resulted in recovered debris.

Figure 6. Photos of debris that survived satellite reentries – Left: Titanium alloy propellant tank from Iridium satellite in October 2018 (Kings County Sherriff's Office, Hanford, California). Center: Metal bulkhead from Cosmos 2267 satellite in December 1994 (Sinaloa Science Center, Culiacan Rosales, Mexico); Right: Titanium alloy propellant tank from Foton 4 satellite in April 1988 (Space.com, February 2000).

Figure 7. Photos of launch stage debris that survived reentries – Left: Composite overwrapped pressure vessel (COPV) from Falcon Stage 2 in March 2021 (Grant County Sherriff's Office, Ephrata, Washington); Center: Metal ring from engine of Falcon Stage 2 in December 2014 (The Aerospace Corporation); Right: COPV from Atlas V Centaur in March 2008 (The Aerospace Corporation).

8.2 Hazards to People on the Ground

The hazard posed to people on the ground by the reentry of any satellite or launch stage depends on how much of the object will survive reentry, the location where the debris is likely to land, the number of people in the area, and how many of these people are sheltered (in this study, people are assumed to be unsheltered). The number and size of major surviving fragments can be estimated knowing the mass, shape, construction material and dimensions of the reentering object and its major components (e.g., propellant tanks, composite overwrapped pressure vessels (COPVs), components made of high melting point materials such as titanium, stainless steel and glass).

The size, shape and mass of each surviving object can be used to estimate its aerodynamic drag and ballistic coefficient, which can be used to predict the object's velocity and kinetic energy at impact. If the kinetic energy of a fragment exceeds 15 Joules at impact, it is judged to be hazardous to a human on the ground. In these calculations, a human is defined by a 0.34 m (1 ft) radius circle, and a casualty is said to occur if any part of a falling object with an energy level exceeding 15 Joules intersects this circle.

The sum of the human area plus the area of the intersection of the debris fragment with that circle is the casualty area (A_C) for the object.

For random reentries, the casualty expectation for each surviving fragment is a function of the original inclination of the parent object's orbit, meaning that the only population at risk lies along the orbit track, whose maximum latitude equals the orbit's inclination. With Earth's population density expressed as a function of latitude only (because longitude is unconstrained for a random reentry), the inclination of an orbit defines the population that will reside beneath that orbit, i.e., if a spacecraft's orbit is inclined by 20 degrees, it will pass over only the population between 20-degrees North and 20-degrees South latitude, so any debris that survives a satellite's reentry will fall somewhere between those latitude bounds.

Figure 8 shows the casualty expectation, E_C, per square meter of casualty area for estimated populations in 2021 and 2035 as a function of orbit inclination, and Figure 9 shows the number of satellite reentries estimated for each latitude. The casualty expectation for each surviving object is computed by multiplying the E_C/A_C times the casualty area for that object, and the E_C for the reentry is the sum of the E_C values for all hazardous surviving objects.

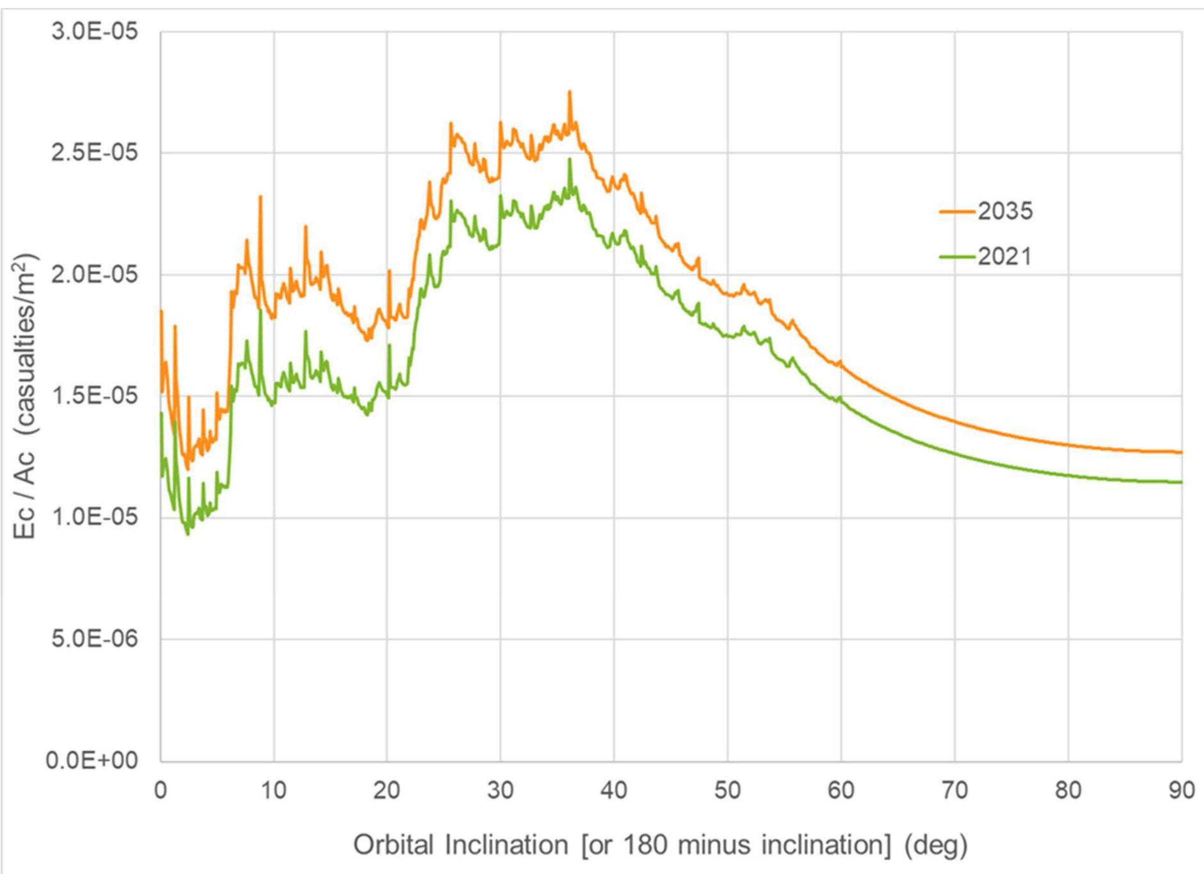

Figure 8. Casualty expectation per square meter of casualty area as a function of orbit inclination for 2021 and 2035.

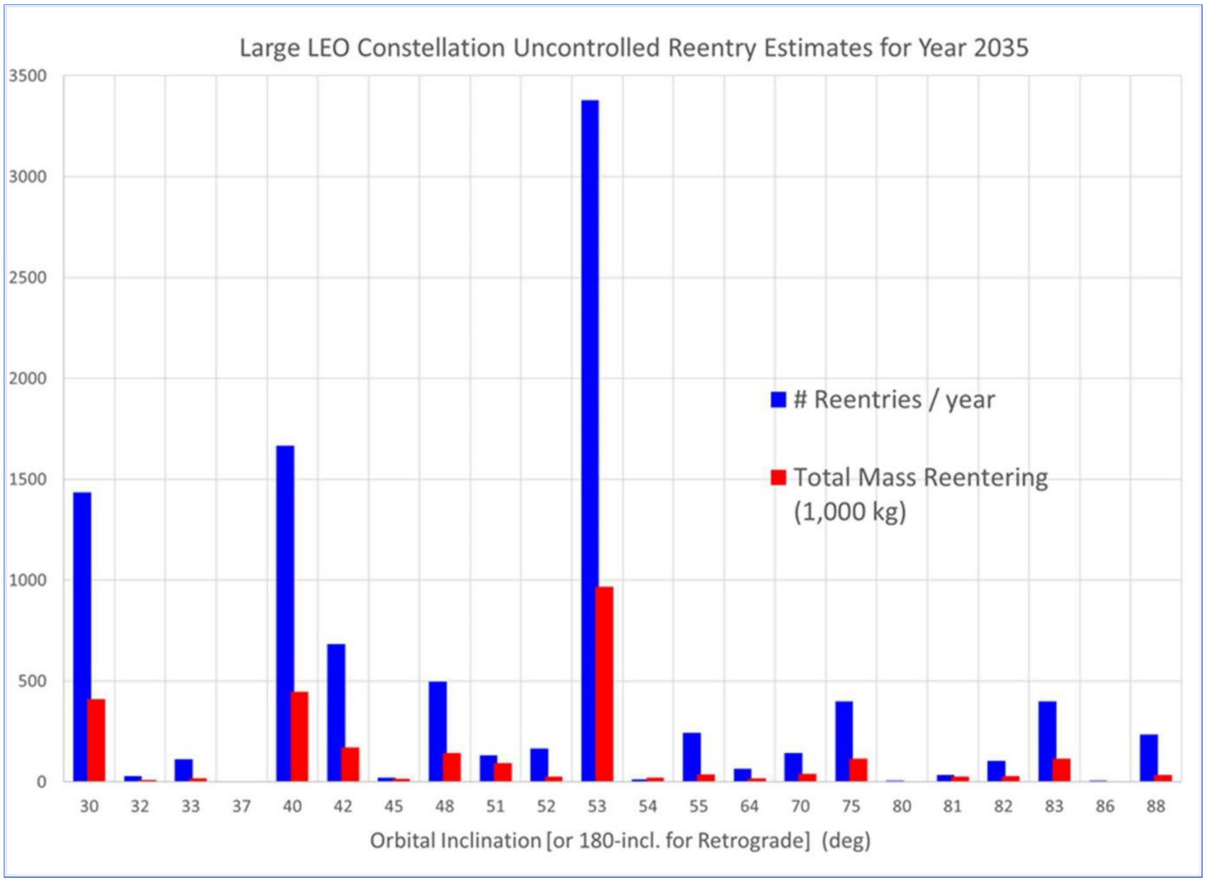

Figure 9. Number of Satellites from Large LEO Constellations reentering in 2035 as a function of Orbit Inclination.

Table 3 shows the estimated casualty expectation in 2035 for each of the proposed large constellations assuming that each constellation is active and disposing of satellites according to its advertised mission lifetime. The total casualty expectation should all be active would be ~0.6, meaning that as many as one person somewhere on the planet might be a casualty every two years. The largest contributors to that hazard are the three SpaceX constellations, with a total casualty expectation of ~0.5.

Table 3: Ground Casualty Expectation of satellites being disposed from proposed large constellations in 2035.

Proposer	System	Call-Sign	Total Proposed by Call Sign in LEO	Estimated Satellite Mass (kg)	Satellite Design Life (years)	Satellites per Plane	Orbital Inclinations (deg)	Number Reentering per Year	Total Casualty Area (m2/year)	Ground Casualty Expectation per m2 in 2035	Casualty Expectation in 2035
SpaceX	Gen2 NGSO Satellite System	S3069	30,000	286	5	7,178	30	1436	4393	2.6E-05	1.2E-01
						7,178	40	1436	4393	2.4E-05	1.0E-01
						7,178	53	1436	4393	1.9E-05	8.3E-02
						2,000	97	400	1224	1.3E-05	1.6E-02
						1,998	75	400	1223	1.3E-05	1.6E-02
						4,000	53	800	2448	1.9E-05	4.6E-02
						144	148	29	88	2.5E-05	2.2E-03
						324	116	65	198	1.5E-05	3.0E-03
						30,000		6000			3.9E-01
SpaceX	VLEO (V-Band)	S2992	7,518	286	5	2,493	42	499	1526	2.3E-05	3.5E-02
						2,478	48	496	1517	2.0E-05	3.0E-02
						2,547	53	509	1559	1.9E-05	2.9E-02
						7,518		1504			9.4E-02
OneWeb	LEO Phase 1	S2963	7,088	150	10	588	87.9	59	94	1.3E-05	1.2E-03
						128	55	13	21	1.8E-05	3.7E-04
	LEO Phase 2					1,764	87.9	176	283	1.3E-05	3.6E-03
						2,304	40	230	370	2.4E-05	8.8E-03
						2,304	55	230	370	1.8E-05	6.6E-03
						7,088		709			2.1E-02
SpaceX	LEO	S2983 & S3018	4,408	286	5	1,584	53	317	969	1.9E-05	1.8E-02
						1,584	53.2	317	969	1.9E-05	1.8E-02
						720	70	144	441	1.4E-05	6.1E-03
						348	97.6	70	213	1.3E-05	2.7E-03
						172	97.6	34	105	1.3E-05	1.4E-03
						4,408		882			4.7E-02
Amazon	Kuiper System	S3051	3,236	150	7	784	33	112	180	2.5E-05	4.4E-03
						1,296	42	185	297	2.3E-05	6.8E-03
						1,156	52	165	265	1.9E-05	5.1E-03
						3,236		462			1.6E-02
Telesat	Phase 1	S2976	1,671	700	10	220	50.88	22	165	1.9E-05	3.2E-03
						78	98.98	8	58	1.3E-05	7.6E-04
	Phase 2					440	50.88	44	330	1.9E-05	6.3E-03
						660	50.88	66	494	1.9E-05	9.5E-03
						273	98.98	27	204	1.3E-05	2.6E-03
						1,671		167			2.2E-02
Viasat		S2985	288	700	15	288	45	19	144	2.1E-05	3.0E-03
AST (AST&Science LLC)	SpaceMobile	S3065	243	1,500	7	18	0	3	41	1.9E-05	7.6E-04
						165	40	24	378	2.4E-05	9.0E-03
						60	55	9	138	1.8E-05	2.5E-03
						243		35			1.2E-02
Boeing	V-band LEO / ~GSO	S2993	132	1,500	10	132	54	13	212	1.8E-05	3.9E-03
Theia Holdings A		S2986	120	3,000	12	8	98	1	21	1.3E-05	2.8E-04
						112	99	9	300	1.3E-05	3.9E-03
						120		10			4.1E-03
Telesat	Vband	S2991	117	700	10	45	37.4	5	34	2.5E-05	8.5E-04
						72	99.5	7	54	1.3E-05	7.0E-04
						117		12			1.6E-03
Iridium	Iridium NEXT	S2110	81	676	15	81	86	5	39	1.3E-05	5.0E-04
		TOTAL	54,902				TOTAL	9818	30152		6.1E-01

8.3 Hazards to People in Aircraft

For this study, hazards to people in aircraft will be considered for the case where a commercial aircraft flying worldwide would be downed immediately by a strike by a large fragment from a reentering spacecraft or launch vehicle stage. There is the additional possibility that a commercial aircraft flying worldwide might impact a smaller surviving object that would require an emergency action by the pilot to avoid a catastrophe.

The next sections discuss the number of commercial aircraft in air at a given time, the assumption of the number of “aircraft downing objects” (ADOs) that might be created by a given reentry, and the methodology for determining the number of aircraft that might be affected by an ADO.

8.3.1 Airborne Aircraft vs. Latitude

In the last decade worldwide air travel has grown at a higher rate than population. World population in 2011 was 7.0 billion, in 2021 it is almost 7.9 billion--a~1.2% per year growth rate. Over the same period, the number of airline passengers grew from 2.8 billion in 2011 to 4.4 billion in 2019--a~5.4% per year increase. Even with the downturn in 2020 due to the pandemic, the International Air Transport Association (IATA) estimates future continued growth in passengers over the next twenty years at an average rate of 3.7% per year, and IATA expects nearly 7 billion airline passengers to travel in year 2035.

Current flight statistics show that while the numbers vary according to time of day, on average, there are about 5,500 commercial aircraft aloft at any moment. This is likely to increase 70% by 2035. Utilizing worldwide airline travel data, then converting flight routes with assumed travel time, a dynamic aircraft aloft system is transformed into a static model of aircraft density. This model can then be used in the same standard practice manner as the global population models.

To gain insight into regional effects to the global aircraft density model, an additional model was developed that isolated the commercial air traffic over North America and the adjacent airspace in the Atlantic Ocean and Pacific Ocean. Figures 10 and 11 quantify this North America contribution to the global air traffic system. The latitude locations of some of the world’s busiest airports shown in Figure 11 provide an intuitive understanding of the lines plotted in Figure 10.

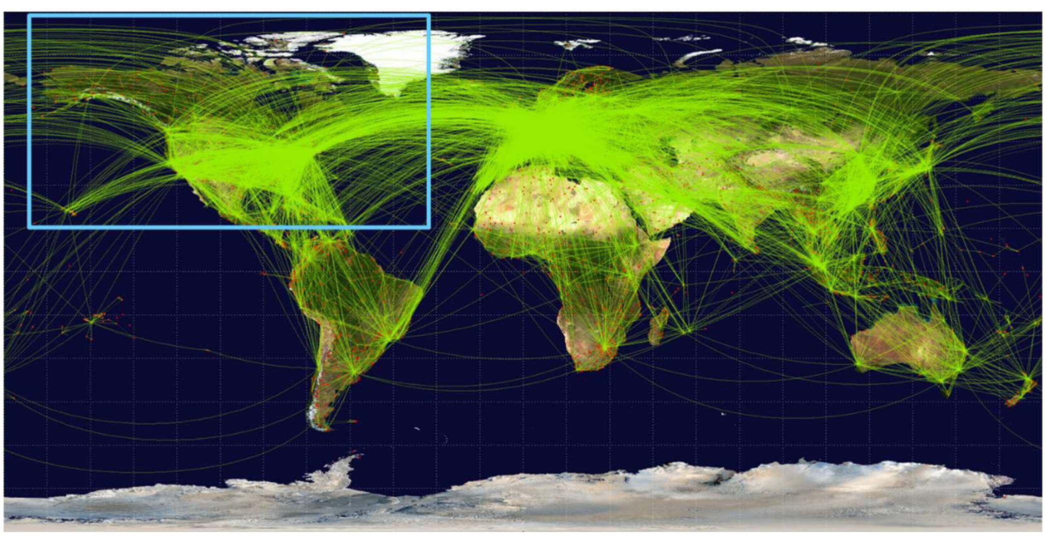

Figure 10. Commercial aircraft entering, flying within, and leaving the United States.

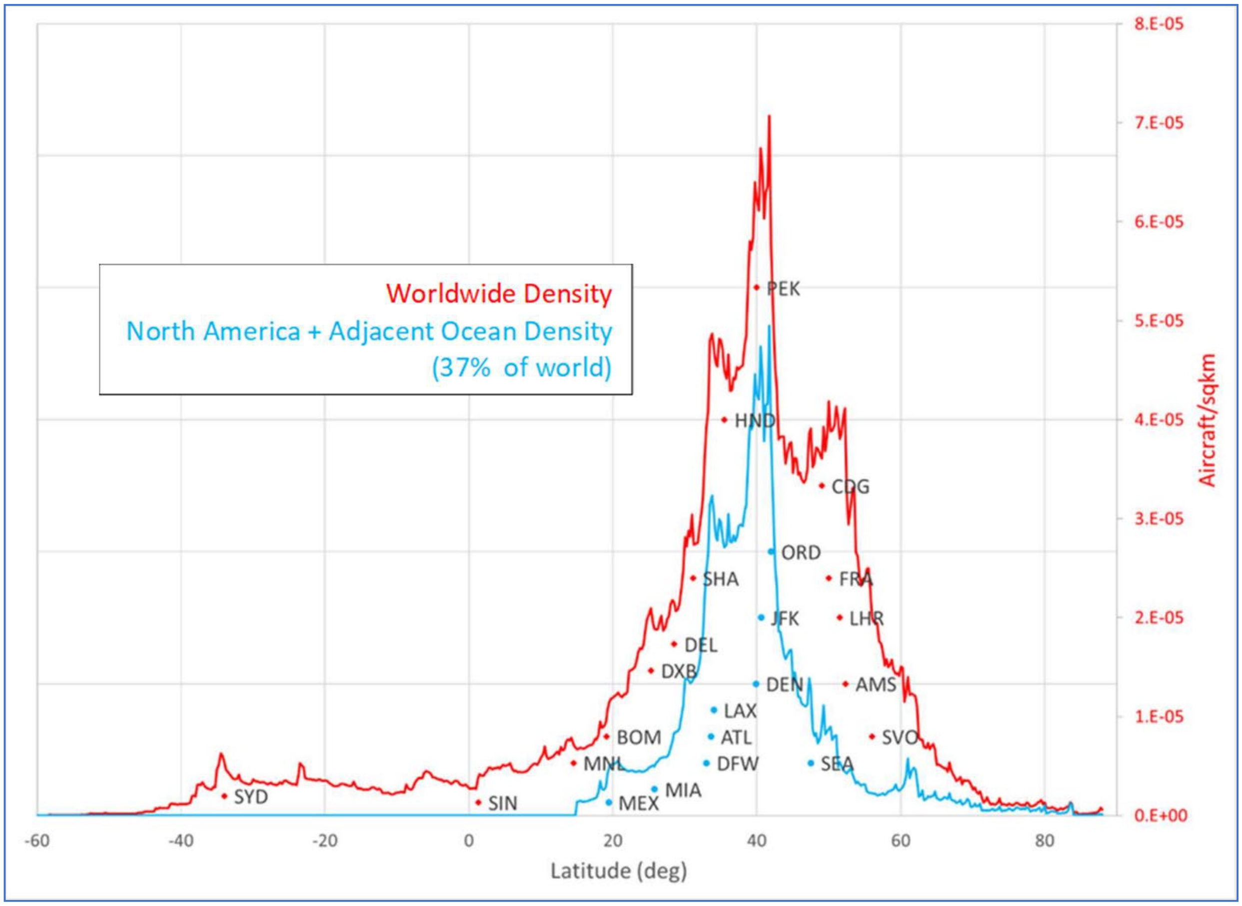

Figure 11. Density of commercial aircraft and latitude locations of some of the world's busiest airports.

8.3.2 Aircraft Downing Objects (ADOs)

"A piece of debris is considered to be potentially lethal to an aircraft if it is capable of producing sufficient damage to cause loss of life or necessitate emergency response by the crew to avoid a catastrophic consequence. The two principal ways that debris can be hazardous to aircraft are: (a) fragment penetration of a critical aircraft structure or the windshield and (b) fragment ingestion by an engine."[16]

It is known that even very small objects can be a hazard to an aircraft in flight due to the high relative velocities at impact. Possible threats include:

- Debris "larger than a square of 10cm x 10cm carries sufficient energy to perforate the structure of the aircraft." The reference concludes that impact of a reentering object bigger than 100 cm^2 might lead to the loss of at least one passenger/crew member should impact occur within "79% of the

[16] Cole, J.K., Young, L.W., Jordan-Culler, T, "Hazards of Falling Debris to People, Aircraft, and Watercraft," Sandia Report SAND-97-0805, April 1997.

vulnerable surface."[17] The reference provides no information on the mass of the impacting object. Note that six objects that likely exceeded this size were predicted to survive reentry of an older Iridium satellite.[18]

- Recent tests sponsored by the FAA demonstrated that a commercial transport fuselage could be penetrated by 9-gm steel cubes.[19] The fall speed of such a fragment would be about 145 mi/hr (230 km/hr) at an aircraft's cruising altitude (30,000 ft, ~9,140 m). The average speed of commercial aircraft at that altitude is approximately 450 mph (725 km/hr).

- A "fragment of at least 300 grams should be assumed to produce a catastrophe for any impact on an aircraft."[20] The six large objects predicted to be hazardous to humans on the ground for the reentry of the Iridium satellite all had masses exceeding 300 gm.

- "One of the worst objects an engine can ingest is a piece of cloth, e.g., a shop rag," and "thin plastic sheets and quilted pads sometimes used on missile and space vehicles for thermal protection could become part of the falling debris and act somewhat like a rag if ingested."[17] Experience shows that such ingestions are unlikely to cause casualties.

Reference 21 provides estimates of impact consequences of "compact steel fragments with penetration characteristics reasonably represented by a solid cube impacting face-on" on three types of jet-propelled aircraft: Business Jets (BJs), Commercial Transport (CT) jets and Jumbo Commercial Transport (JCT) jets (this study is concerned with Business Jets and Commercial Transport jets), and Figure 12 shows aircraft vulnerability model results for impacts that are catastrophic for these aircraft. While these model-based results are for "compact steel fragments", they illustrate the sensitivity levels that might be expected for larger fragments surviving reentry (note that fragments larger than 300 grams can cause catastrophic damage to Business, Commercial Transport, and Jumbo Commercial Transport jet aircraft).

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[17] Bellucci A., Fuentes N., Guerra-Algaba A., Cointe-Fourrier M., Goester J.F., "Risk Analysis Between Aircraft and Space Debris During Atmospheric Re-Entry," 9th IAASS Safety Conference, Toulouse, France, October 2017.

[18] "Exhibit E: Orbital Debris Mitigation and Casualty Risk Assessment," FCC Form 312, Schedule A, https://transition.fcc.gov/transaction/iridium-motorola/iridumconstel_exhe.pdf

[19] Wilde, P., "Impact Testing and Improvements in Aircraft Vulnerability Modeling for Range Safety," 7th IAASS Conference, Friedfrichsafen, Germany, October 2014.

[20] "Common Risk Criteria Standards for National Test Ranges: Supplement," Range Commanders Council, Range Safety Group, RCC 321-07, June 2007.

[21] "Common Risk Criteria Standards for National Test Ranges: Supplement," RCC 321-20 Supplement, May 2020.

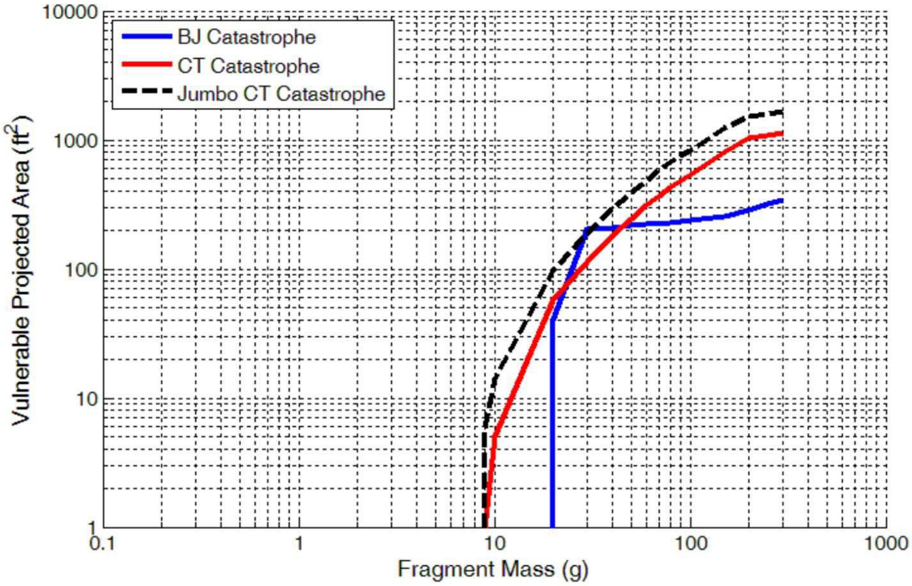

Figure 12. Fragment masses for impacts causing catastrophic damage to three classes of jet aircraft (from Ref. 21).

Given the uncertainty in the number and size of large objects surviving reentry of a constellation satellite in 2035, it is assumed here that the ratio of 6 objects per 560 kg of satellite mass found to cause ground casualties for the Iridium satellite would be used to estimate both number of objects hazardous to aircraft for reentries of constellation satellites, e.g., reentry of a 1,000 kg satellite would generate 1000* 6/560 = 11 aircraft downing objects.

As noted earlier, objects smaller than those that might be hazards to unprotected people on the ground can also cause events that require action by pilots to avoid a catastrophe. These types of events are discussed in Section 8.3.3 of this report.

The risk to aircraft from reentries of constellation satellites depends on the latitude density of air traffic (see Figure 11), the number of ADOs that might be falling through air traffic at those latitudes, and the hit area of aircraft in flight. The hit area includes both the object fall speed and speed of aircraft and is determined as follows[22]:

- If the aircraft were stationary, the top view area would be the area exposed to a debris impact.
- If the debris were stationary, the front view area would be the area exposed to debris impact.

The actual situation involves the aircraft moving horizontally and the debris moving vertically. Even for a ballistic coefficient of 250 kg/m^2, the flight path angle of a reentering object at 40,000 feet is -86.6 degrees, which corresponds to nearly vertical descent. Since most debris objects have ballistic

[22] Patera, R.P., "Risk to Commercial Aircraft from Reentering Space Debris," AIAA Atmospheric Flight Mechanics Conference and Exhibit, August 18-21, 2006, Honolulu, Hawaii.

coefficients[23] equal to or less than 250 kg/m^2, the vertical descent assumption is a very accurate approximation. In this case, the effective risk area for each aircraft is given by the equation,

$$\varepsilon_i = \frac{(s_{ac} * a_{hi} + s_d * a_{vi})}{\sqrt{s_{ac}^2 + s_d^2}}$$

where s_{ac} is the average aircraft speed, s_d is the average debris object fall speed, a_{vi} is the area as viewed from above the aircraft and a_{hi} is the area as viewed from the front of the aircraft.

The risk area for various commercial aircraft types have been calculated assuming aircraft airspeed of 450 mph and a debris fall speed of 145 mph. This corresponds to an aircraft at 30,000 ft encountering debris having a ballistic coefficient of 100 kg/m^2. A reference area of 1,000 m^2 was used as an average across all commercial passenger aircraft that are typically inflight. Then multiplying the aircraft reference area by the aircraft density per latitude and the probability of object reentry per latitude gives the probability of aircraft impact per object as a function of orbital reentry inclination. This is analogous to the widely accepted method for calculating ground casualty risk based on casualty area and latitude population density. Combining the number of ADOs with the probability of aircraft impact per object, a probability of an aircraft downing incident can be determined.

Table 4 shows the probability of an aircraft downing incident in 2035 due to fragments generated during reentries of satellites from each constellation. Assuming constellations are all operating in 2035 and all dispose of their satellites according to design lifetime, the total number of ADOs created by these reentries would be over 28,000. As with reentries hazardous to people on the ground, the probability of striking an aircraft varies as a function of the orbit inclination, and the 8,300 satellites disposed from the SpaceX constellations per year poses the highest probability of downing an aircraft, 6E-4 per year.

The total probability if all constellations are disposing satellites in an uncontrolled manner would be 7E-4 per year. Of course, the risk would be reduced if the mass of each satellite is lower than that shown in the table or if operators use design-for-demise principles to lower the number of hazardous objects surviving reentry. Finally, these risks assume the reentry locations of satellites (and the regions where debris will fall) are not controlled. Directing satellites into a remote location such as the South Pacific Ocean would reduce the risk to aircraft (and to people on the ground) substantially.

[23] Ballistic coefficient of an object is the ratio of mass to the product of the drag coefficient and drag reference area and is a measure of how an object's motion is affected by the atmosphere. A ping-pong ball has a very low ballistic coefficient; a metal ball bearing of the same size has a high ballistic coefficient.

Table 4. Probability of Aircraft Downing Incident resulting from reentries of satellites in 2035.

Proposer	System	Call-Sign	Total Proposed by Call Sign in LEO	Estimated Satellite Mass (kg)	Satellite Design Life (years)	Satellites per Plane	Satellites Per Plane	Orbital Inclinations (deg)	Number Reentering per Year	Total ADOs in 2035	Probability of Aircraft Impact per ADO in 2035	Probability of Aircraft Downing Incident in 2035
SpaceX	Gen2 NGSO Satellite System	S3069	30,000	286	5	7,178	7,178	30	1436	4106	1.6E-08	6.5E-05
						7,178	7,178	40	1436	4106	2.8E-08	1.2E-04
						7,178	7,178	53	1436	4106	2.8E-08	1.1E-04
						2,000	50	97	400	1144	1.8E-08	2.0E-05
						1,998	1,998	75	400	1143	1.9E-08	2.1E-05
						4,000	4,000	53	800	2288	2.8E-08	6.4E-05
						144	12	148	29	82	1.8E-08	1.4E-06
						324	18	116	65	185	2.2E-08	4.1E-06
						30,000			6000			4.1E-04
SpaceX	VLEO (V-Band)	S2992	7,518	286	5	2,493	2,493	42	499	1426	3.1E-08	4.4E-05
						2,478	2,478	48	496	1417	2.8E-08	3.9E-05
						2,547	2,547	53	509	1457	2.8E-08	4.1E-05
						7,518			1504			1.2E-04
OneWeb	LEO Phase 1	S2963	7,088	150	10	588	49	87.9	59	88	1.7E-08	1.5E-06
						128	16	55	13	19	2.7E-08	5.1E-07
	LEO Phase 2					1,764	49	87.9	176	265	1.7E-08	4.6E-06
						2,304	72	40	230	346	2.8E-08	9.8E-06
						2,304	72	55	230	346	2.7E-08	9.2E-06
						7,088			709			2.6E-05
SpaceX	LEO	S2983 & S3018	4,408	286	5	1,584	22	53	317	906	2.8E-08	2.5E-05
						1,584	22	53.2	317	906	2.8E-08	2.5E-05
						720	20	70	144	412	2.0E-08	8.1E-06
						348	58	97.6	70	199	1.8E-08	3.5E-06
						172	43	97.6	34	98	1.8E-08	1.7E-06
						4,408			882			6.4E-05
Amazon	Kuiper System	S3051	3,236	150	7	784	28	33	112	168	1.9E-08	3.2E-06
						1,296	36	42	185	278	3.1E-08	8.5E-06
						1,156	34	52	165	248	2.8E-08	7.0E-06
						3,236			462			1.9E-05
Telesat	Phase 1	S2976	1,671	700	10	220	11	50.88	22	154	2.8E-08	4.4E-06
						78	13	98.98	8	55	1.8E-08	9.7E-07
	Phase 2					440	22	50.88	44	308	2.8E-08	8.7E-06
						660	33	50.88	66	462	2.8E-08	1.3E-05
						273	13	98.98	27	191	1.8E-08	3.4E-06
						1,671			167			3.1E-05
Viasat		S2985	288	700	15	288	36	45	19	134	2.8E-08	3.8E-06
AST (AST&Science LLC)	SpaceMobile	S3065	243	1,500	7	18	18	0	3	39	5.4E-09	2.1E-07
						165	15	40	24	354	2.8E-08	1.0E-05
						60	15	55	9	129	2.7E-08	3.4E-06
						243			35			1.4E-05
Boeing	V-band LEO / ~GSO	S2993	132	1,500	10	132	12	54	13	198	2.7E-08	5.4E-06
Theia Holdings A		S2986	120	3,000	12	8	1	98	1	20	1.8E-08	3.5E-07
						112	14	99	9	280	1.8E-08	5.0E-06
						120			10			5.3E-06
Telesat	Vband	S2991	117	700	10	45	9	37.4	5	32	2.4E-08	7.7E-07
						72	12	99.5	7	50	1.8E-08	9.0E-07
						117			12			1.7E-06
Iridium	Iridium NEXT	S2110	81	676	15	81	11	86	5	37	1.7E-08	6.3E-07
		TOTAL	54,902					TOTAL	9818	28180		7.0E-04

8.3.3 Risks of Impacts Requiring Emergency Actions by Pilots

The figure below shows model-based results of impact fragment masses that could cause casualties, but not catastrophic damage to Business Jets, Commercial Transport jets and Jumbo Commercial Transport jets.

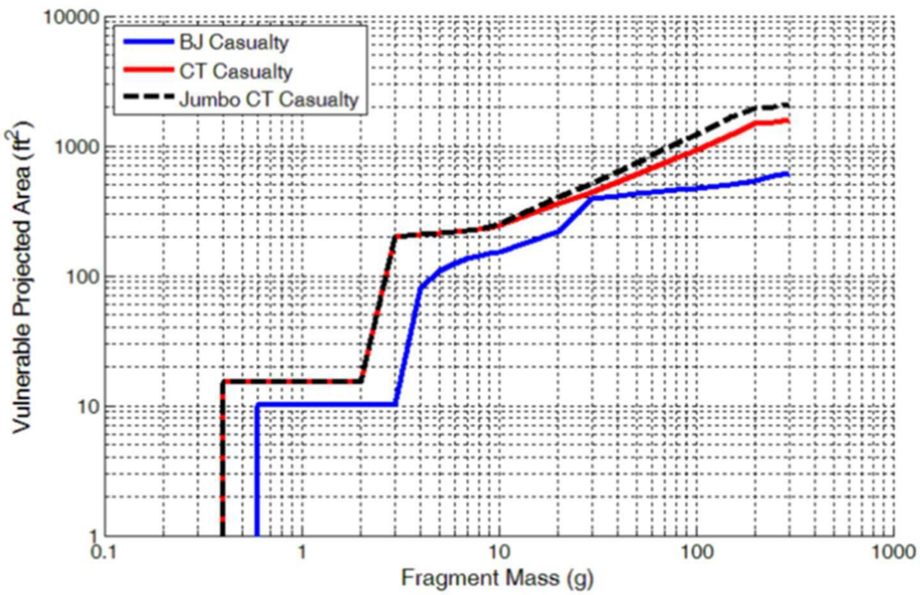

Figure 13. Fragment masses for impacts causing casualties but not catastrophic damage to three classes of jet aircraft (from Ref. 21).

There are two primary sources of information on small debris that might survive reentry and, should it impact an aircraft, cause the crew to take action to avoid a catastrophic outcome:

1. The Space Shuttle Columbia accident. Extensive searches recovered over 80,000 objects that produced an estimated 0.3 expected casualties on commercial aircraft only.[24] Of course, that vehicle included large number of thermal protection tiles that would not be common on constellation satellites.

2. The Vehicle Atmospheric Survival Test (VAST). Figure 14 shows the ballistic coefficient[23] range (and the debris footprint length) measured for debris falling from the VAST test[25] (the report notes that the objects included in the figure were only a fraction of those observed due to sensor limitations). That vehicle had a mass of 5,330 kg (11,750 lb) at reentry. The sizes and masses of the fragments falling from the VAST test are not known, but a significant percentage of the objects in that debris field had ballistic coefficients greater than 50 kg/m^2, the threshold for fatal damage for stainless steel or aluminum fragments. Note that for 1-gm cubes of these materials, the energy at impact would be 0.4 to 0.8 Joules, well below the 15 Joule hazard threshold for a human on the ground.

[24] Columbia Accident Investigation Board, CAIB Report, GPO, Washington, D.C., August 2003.

[25] Stern, R.G., "Reentry Breakup and Survivability Characteristics of the Vehicle Atmospheric Survivability Project Vehicles," Report No. TR-2008(8506)-3, The Aerospace Corporation, 5 August 2008.

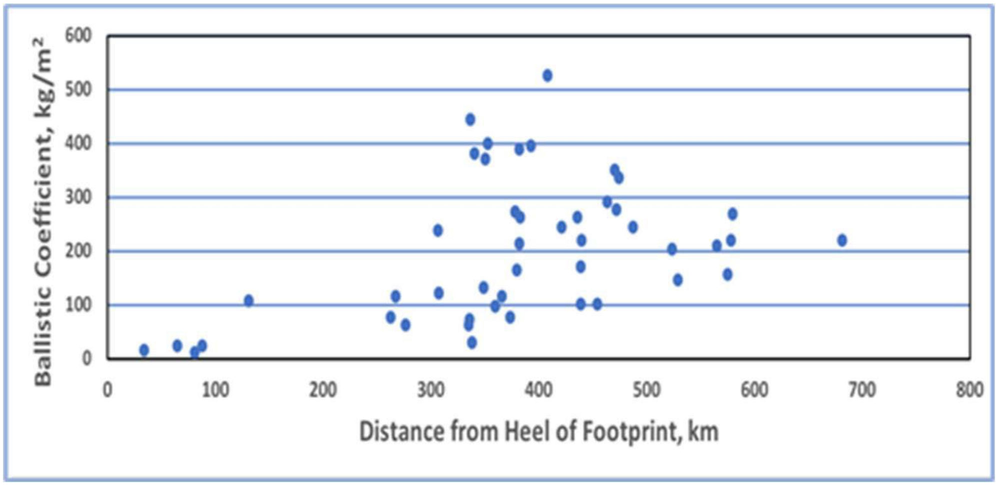

Figure 14. Ballistic coefficient for debris falling from VAST test.

Based on these estimates, satellites used for the commercial constellations studied here would be expected to have more smaller fragments than launch stages due to the greater number and type of internal components, many of which might be shielded from a significant fraction of reentry heating by surrounding structure (potentially, spacecraft could be designed to minimize this effect, but work is required in this area). Unfortunately, the fragment of woven glass fabric[26] shown in Figure 15, which survived reentry of a rocket stage and brushed Ms. Williams on the shoulder while she was walking (she was not injured), is the only small fragment known to have been recovered after uncontrolled, shallow reentry of a satellite or launch stage (the Shuttle Columbia accident occurred during a maneuvering, controlled reentry). That fragment is an example of a "woven fabric" which might not be a hazard to a human but could be if ingested by an aircraft's engine.

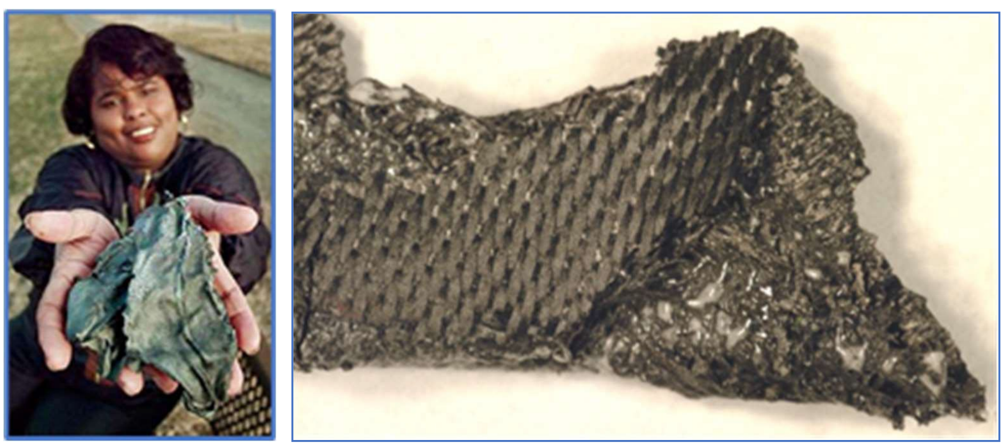

Figure 15. Left: Ms. Lottie Williams holding woven glass fabric that survived rocket stage reentry (photo courtesy Brandi Stafford, Tulsa World). Right: closeup photo of fabric[26].

[26] Adams, P. M., and Kao, W. H., "Examination of Suspected Delta II Second-Stage Reentry Debris," TR-2001(1494)-1, The Aerospace Corporation, 15 July 2001.

Given the evidence provided by the VAST tests, Ref. 27 predicted that random reentries of satellites larger than 800 kg could yield as many as 300 fragments potentially lethal to aircraft. The ADOs discussed earlier would be included in that estimate.

Table 4 provides the probability than an aircraft will be impacted by larger debris, which are assumed to be created at a rate of 1 fragment per 100 kg of satellite mass and gives an overall probability of impact of an object large enough to down an aircraft of 7E-4. The smaller debris would be created at a rate ~38 times larger, or 38 fragments per 100 kg of satellite mass. As a result, the probability that a small object would strike an aircraft and force the crew to take emergency action would be ~0.03 per year.

8.4 Hazards Associated with both Satellite and Launch Stage Reentries

Given the relatively simple design of launch stages (i.e., one or two very large tanks plus two or more COPVs containing pressurized gas used to expel fluids from the tanks and one or more thrust chambers and rocket nozzles), and evidence on the ground after stage reentries that shows that COPVs and thrust chambers survive, it is reasonable to assume that independent of the stage mass, six objects hazardous both to humans on the ground and in aircraft might survive each stage reentry. Also, a stage breakup results in about 80 m^2 of debris casualty area. That information and the number of launches per year given in Table 1 can be used in similar fashion as with satellite debris to estimate the potential hazards to people and aircraft that stages might pose.

Estimates were made for the risks that are currently experienced by both the general population and commercial air travel passengers due to uncontrolled reentries of space objects—both satellites and launch stages. The number of reentries for 2021 was determined by using 2019 data and including anticipated satellite and launch stage disposals for this year. The result is 125 large object reentries of which 40% are rocket bodies. Figure 16 shows the number of ADOs and the probability of impacting an aircraft in 2021 as a function of latitude.

[27] Ailor, W., Wilde, P., "Requirements for Warning Aircraft of Reentering Debris," 3rd International Association for the Advancement of Space Safety Conference, Rome, Italy, October 21-23, 2008.

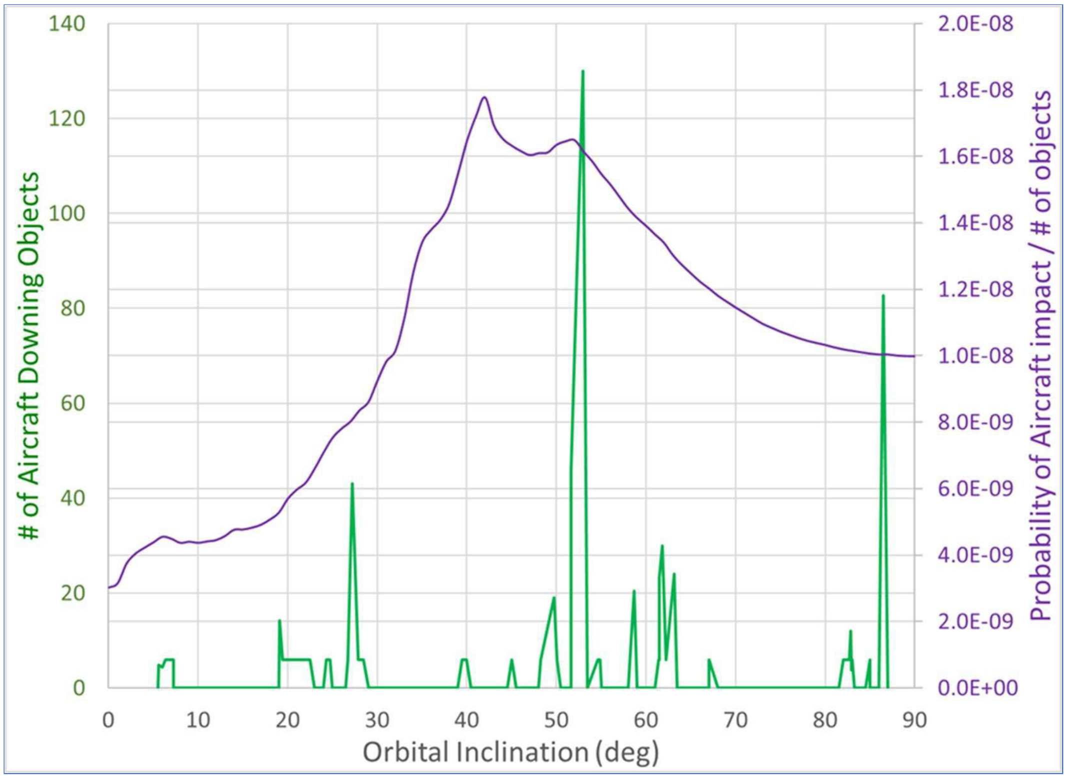

Figure 16. Year 2021 estimated number of aircraft downing objects falling after breakup of rocket bodies or satellites (green) and probability of aircraft impact per debris object as a function of latitude (purple).

Collective risk and individual risk for both ground population (every human) and the flying public were calculated and are shown in Tables 5 and 6, respectively, using the nomenclature shown below. Both collective risk measures in 2021 exceed the typical tolerable levels of 1E-4. However, the risk to any individual, whether on the ground or in an aircraft (P_{IND} and P_{AIND}), is extremely low. In fact, the risk to a passenger perishing from random reentries of disposed satellites and launch stages is orders of magnitude lower than the odds of dying on a commercial flight due to some other incident such as weather, mechanical failure, etc.

E_C = expected human casualty for world population
P_{IND} = probability of casualty to any individual on the ground
P_{ADI} = probability of an aircraft downing incident (ADI)
E_{AC} = expected human casualty from an aircraft downing incident
P_{AIND} = probability of ADI to any individual passenger
DCA: debris casualty area (causes serious injury to an unsheltered person)
ADO: aircraft downing object (causes airplane crash with 100% fatalities)

*Table 5. Risk to **people on the ground** due to reentries of satellites and launch stages in **2021**.*

Total Casualty Expectation in 2021 (E_C)	Probability of an Individual being Affected (P_{IND})	Total Casualty Area (m^2)	Distribution of Risk by Country of Origin (% of total)			
			USA	China	Russia	Others
7.2E-2	**9.1E-12**	**4400**	**19**	**28**	**25**	**28**

*Table 6. Risk to **people in aircraft** due to reentries of satellites and launch stages in 2021.*

Probability of Aircraft being impacted by ADO in 2021 (P_{ADI})	Expected human casualty due to Impact of ADO (E_{AC})	Probability of Aircraft Downing Event to any Individual Passenger (P_{AIND})	Number of ADOs	Distribution of Risk by Country of Origin (% of total)			
				USA	China	Russia	Others
8.4E-6	**1.0E-3**	**3.6E-13**	**700**	**38**	**15**	**30**	**17**

Not surprisingly, the major spacefaring nations are responsible for most of the risk. Somewhat counterintuitive is that a person is at greater risk on the ground than in an airplane. This is because ground population assumes a person is always in one location and is always at risk of being hit. Whereas for aircraft modeling, it is known that an airplane is aloft only a fraction of the time. Thus, an individual is at risk only a fraction of the time. Since P_{AIND} is a per-flight measure, if a person is on more than 25 flights per year, then their individual risk aloft exceeds their ground risk. Since a person cannot simultaneously be aloft and on the ground, to be precise the ground population should be reduced by the population aloft. However, on average less than 1 million people are aloft compared to nearly 8 billion total persons. Hence the effect to ground collective risk is negligible.

The risk estimates associated with satellite reentries in year 2035 are given in Tables 7 and 8, respectively, and Figure 17 shows the corresponding number of aircraft downing objects falling and the variation of the probability of an aircraft impact as a function of latitude. The uncontrolled reentries of satellites and launch stages associated with large LEO constellations cause dramatic increases in debris casualty area and especially in the number of aircraft downing objects in 2035. Reentries of the estimated 113 launch stages per year, each adding six objects to the estimated 28,000 ADOs generated by satellite reentries, increases the total probability of an ADO event by ~2%.

While the collective risks become rather concerning, the individual risks are still extremely low. Due to the extraordinary numbers of anticipated SpaceX satellites, satellites being disposed from the SpaceX constellations dominate the total risk consideration.

*Table 7. Risk to **people on the ground** due to reentries of satellites and launch stages in **2035**.*

Total Casualty Expectation in 2035 (E_C)	Probability of an Individual being Affected (P_{IND})	Total Casualty Area (m^2)	Distribution of Risk by Country of Origin (% of total)			
			USA	China	Russia	Others
6.1E-1	7.5E-11	30000	88	4	4	4

*Table 8. Risk to people in aircraft due to reentries of satellites and launch stages in **2035**.*

Probability of Aircraft being impacted by ADO in 2035 (P_{ADI})	Expected human casualty due to Impact of ADO in 2035 (E_{AC})	Probability of Aircraft Downing Event to any Individual Passenger (P_{AIND})	Number of ADOs	Distribution of Risk by Country of Origin (% of total)			
				USA	China	Russia	Others
7.0E-4	8.4E-2	1.7E-11	28000	88	4	5	3

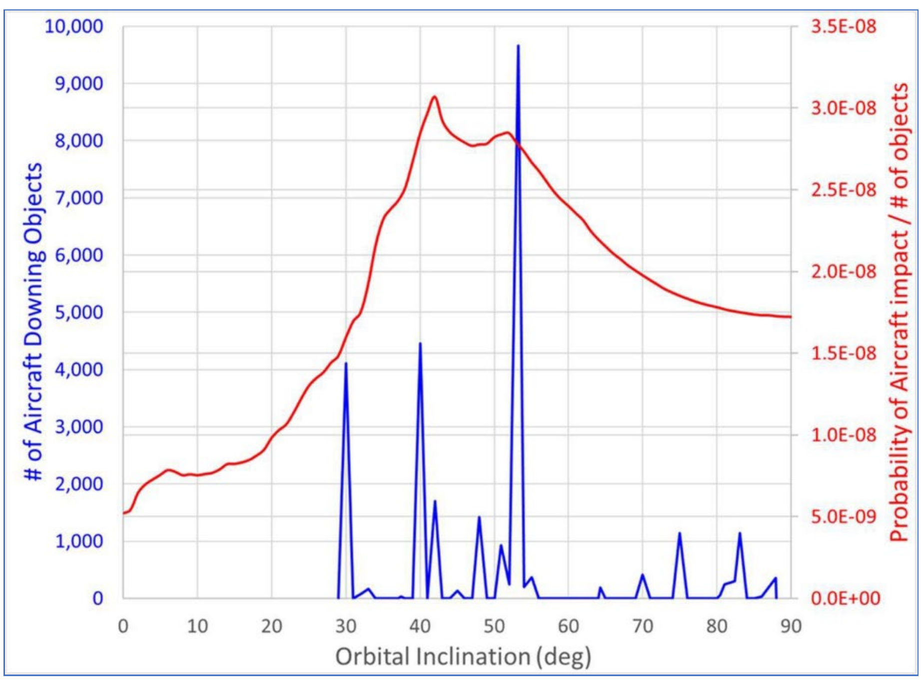

Figure 17. Estimated number of aircraft downing objects falling after breakup of constellation satellites (blue) and probability of aircraft impact per debris object in Year 2035 as a function of latitude (red).

8.5 Risks Associated with Controlled (Targeted) Reentries

When reentry hazards predicted for a space vehicle are less than 1E-4 (1 in 10,000), it is acceptable to allow that vehicle to reenter in an uncontrolled fashion, where the final impact locations of surviving debris are not known beforehand. Many of the individual satellites in the proposed large constellations meet this requirement.

The issue is that 100 reentries of satellites that meet that requirement could have a cumulative hazard within a prescribed time frame (e.g., yearly) that exceeds the acceptable per-reentry threshold. For example, one SpaceX constellation could have as many as 6,000 relatively small satellites reentering yearly. In this case, the cumulative hazard for a year from these satellites would be 0.38/year, much higher than the 0.0001 limit for a single satellite.

A way to minimize the risks to people and aircraft associated with reentries is to control where the surviving debris will land. This approach is currently used to assure that debris from large vehicles used to deliver supplies to the International Space Station lands in the South Pacific Ocean, well away from populated land masses.

Controlling a space vehicle's reentry location requires that the vehicle be maneuvered with precise timing and location in its orbit, where an onboard engine is used to "slow the vehicle down" so that it will enter the atmosphere at a prescribed location and flight-path angle designed to assure its debris lands within a pre-designated area. Executing a deorbit maneuver requires that the vehicle:

- Maintain attitude control until the deorbit engine burn has been executed,
- Maintain sufficient thrust and propellant to apply the necessary velocity change,
- Fire the engine at precisely the correct location and time, most likely under control of ground operators or possibly by automated control, and
- Have a highly reliable deorbit system.

Including these capabilities on a spacecraft add mass and complexity to a satellite and increases the costs associated with its mission. However, including a reliable deorbit system on constellation satellites could dramatically reduce the cumulative hazards posed to humans on the ground and in aircraft. If all constellation satellites included a deorbit system that targeted debris to a remote area, the cumulative casualty expectation for people on the ground and in aircraft could be orders of magnitude lower than for uncontrolled reentries even if some deorbit systems fail.

9 Results and Discussion

To summarize, the expected human casualty (E_C) and probability of an aircraft downing incident (P_{ADI}) in 2035 are shown in Table 9. Both risk measures exceed what are typical tolerable levels by orders of magnitude. Note that a vast majority of the risk is from spacecraft constellations under United States Government regulatory authority.

Table 9. Casualty Expectation (E_{CSAT}) for world population and probability of an Aircraft Downing Accident (P_{ADIS}) in 2035 resulting from possible reentries of satellites from proposed large constellations.

Year 2035	Risk	USA Administration Authority	Likely Launched on USA Launch Vehicle
E_{CSAT}	0.61	91%	95%
P_{ADIS}	0.0007		

As discussed earlier, a key to the risk of an aircraft downing accident is the number of satellites being disposed per year and the number of hazardous fragments generated by each reentry. This analysis assumes roughly 1 object per 100 kg of reentering satellite mass, and the number reentering assumes that constellations are disposing a fraction of their satellites each year based on the mission lifetime of those satellites.

The expected human casualty (E_{CLV}) and probability of an aircraft downing impact (P_{ADILV}) due to launch vehicle stage reentries are shown in the following tables. Table 10 conservatively assumes that all launches result in an uncontrolled reentry of a launch stage. Should that occur, the total E_C including both uncontrolled launch stage and satellite reentries totals 0.78 for people on the ground.

It is hopeful that current trends of responsible stage disposal, as well as possible SpaceX use of the reusable Starship system to launch its satellites, will continue and at least ninety percent of launch missions will result in controlled launch stage reentry. Table 11 reflects the corresponding order of magnitude reduction in risk if that goal is realized.

*Table 10. Casualty Expectation for world population (E_{CLV}) and Probability of an Aircraft Downing Impact (P_{ADILV}) resulting from **100% uncontrolled reentries** of launch vehicle stages associated with proposed large constellations in 2035.*

Ground Casualty Expectation (E_{CLV})	Probability of Aircraft Downing Impact (P_{ADILV})	USA Administration Authority	Likely Launched on USA Launch Vehicle
0.17	1.8E-5	62%	73%

*Table 11. Casualty Expectation for world population and Probability of an Aircraft Downing Impact resulting from **10% uncontrolled reentries** of launch vehicle stages associated with proposed large constellations in 2035.*

Ground Casualty Expectation (E_{CLV})	Probability of Aircraft Downing Impact (P_{ADILV})	USA Administration Authority	Likely Launched on USA Launch Vehicle
0.017	1.8E-6	62%	73%

Factors that might affect the risk level are:

• Satellite designers incorporate "design-for-demise" features that significantly lower the number of large hazardous surviving objects. The success of these designs should be verified by independent testing. Note that design-for-demise might reduce the hazard posed by large objects but could increase the number of smaller fragments. As noted above, small fragments can also be a hazard to aircraft.

• Constellation operators extend the life of constellation satellites and have fewer reentering per year, although operators might choose to dispose much larger numbers when their constellations are decommissioned.

• Satellite end-of-life disposal maneuvers adjust orbit parameters to enhance risk mitigation. A satellite with insufficient thrust to execute a controlled reentry may still have capability to shape the disposal orbit in a desirable manner. By lowering the perigee altitude to as low as possible while simultaneously maintaining that low point near the descending node, the likelihood of a rapid decay and breakup in the southern hemisphere increases significantly and decreases the risk to both population and aircraft. Studies have shown up to a 50% decrease in expected casualty for reentries in which the disposal orbit argument of perigee was set near the descending node. Adjusting disposal orbit inclination could also mitigate risk; however, orbit plane change is generally impractical for LEO satellites.

• Satellite designers include controlled (targeted) reentry capabilities on each satellite to assure that debris that survives reentry lands in an uninhabited area.

10 Limitations of Data Provided in FAA (and FCC) Applications

At present, applicants for approval of large constellations are not required to provide the following information, which is judged to be critical in understanding the hazards associated with large constellations:

- Estimates of the dry mass of their proposed satellites (dry mass is the mass of a satellite without consumables and propellant),
- Constellation deployment and sustainment plans including planned launch vehicles to be used and number of satellites to be launched at a time,
- A disposal strategy for their satellites that includes the estimated number of satellites to be disposed each year and the cumulative hazard per year for the life of the constellation,
- The method of satellite disposal (i.e., direct reentry, orbit lowering, and uncontrolled reentry) and the number of satellite to be in transit toward reentry each year (e.g., if a constellation has 1,000 operating satellites and disposes 10% (100 satellites) per year and each disposed satellite takes 5 years to finally reenter, that constellation actually could have 1000 satellites operating in the constellation (assuming disposed satellites are replaced) plus 100*5 or 1,500 satellites continuously in orbit per year). The actual number of satellites owned by the operator is important for managing the space environment.

- The predicted casualty expectation for each satellite, the software tool used to predict the casualty expectation, and the input data for the tool, including a listing of masses, shapes, dimensions, and materials for each modeled component.
- A list and total number of small objects fabricated of materials that might survive reentry (e.g., glass, titanium), especially if not included in modeling for casualty expectation.

11 Recommendations

Based on this analysis, recommendations for “how the FAA launch and reentry licensing process can be leveraged to address” launch stage reentry risk are that applicants should provide:

- Number of launch stages forecast for use each year for constellation buildup and ongoing replenishment activities
- Orbital inclination at end of mission and number of launch stage reentries at each inclination per year
- The predicted casualty expectation for each launch stage, the software tool used to predict the casualty expectation, and the input data for the tool, including a listing of masses, shapes, dimensions, wall thickness, and materials for each modeled component.
- Type of reentry planned (e.g., controlled, uncontrolled). If controlled, location of planned disposal area, propellant reserve required, probability of successful stage disposal, and evidence of reliability of disposal maneuver

Given that FCC authorization is required for constellations and related on-orbit activities, it is recommended that FCC applications include:

- Details on short and long-term strategies for disposing satellites, including projected number of satellite reentries per year and per orbit inclination
- Type of end of mission disposal (direct reentry into pre-designated area, orbit reduction, active removal, and orbit decay with uncontrolled reentry, etc.),
- Maximum number of satellites in orbit each year, including operational satellites, spares, satellites being disposed,
- Estimated satellite reliability and probability of successful disposal,
- Information on spacecraft design and any special features to reduce reentry hazards (e.g., design-for-demise, features to enhance active removal),
- Details on hazard prediction models and inputs to those models,
- Mass, materials, physical dimensions of basic satellite components, and
- Mass, number, dimensions of components fabricated from high melting point materials (e.g., glass, titanium).

It is clear from this analysis that uncontrolled deorbit and reentry of constellations of satellites and launch stages may pose higher than desired risk to both people on the ground and in aircraft. Constellation operators should be encouraged to use the ODMSP’s preferred disposal option, direct targeted reentry, for disposing of constellation-related hardware.