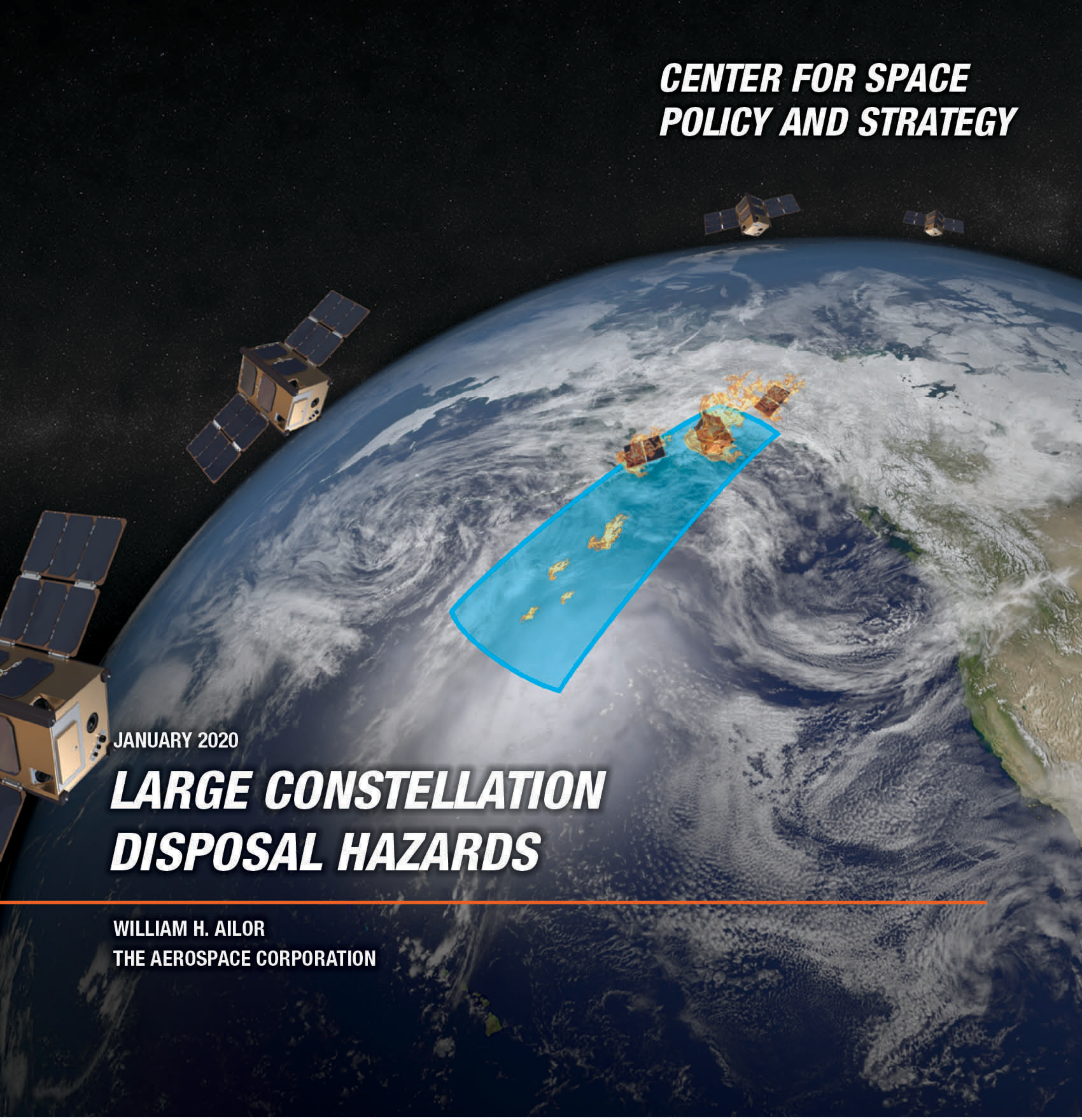

CENTER FOR SPACE POLICY AND STRATEGY

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LARGE CONSTELLATION DISPOSAL HAZARDS

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Summary

This first-order assessment of potential risks to people and aircraft from random reentries of large numbers of satellites from large constellations in low Earth orbits shows that risks to aircraft posed by small debris surviving a reentry might be a major problem facing owners of large constellations, with worldwide risk of an aircraft striking a reentering debris fragment on the order of once every 200 years. Hazards to people on the ground from larger debris objects will also be a significant problem, with expectations as high as 1 casualty every 10 years. Spacecraft components and features could be designed to have fewer large and small fragments survive, but only limited hard data on actual debris survival currently exists. Limits developed for test ranges provide some guidance relative to the acceptable yearly risks for hazards from large debris, but no such limits have been discussed for yearly reentries of satellites from large constellations. More refined hazard estimates await specific designs, lifetimes, and disposal strategies for constellation satellites. Radar observations of actual reentries could help verify mitigation approaches. Controlling reentry disposal of satellites so that all surviving fragments impact in a safe region would be an effective mitigation approach.

Introduction

At the beginning of the Space Age, there were few concerns about leaving a satellite in orbit after its end of mission. Space was vast and there were few objects orbiting the planet, so the risk of impacting another object was negligible. And many believed that a satellite would burn up when it reentered, posing no threat to people on the ground.

As the use of space increased, it was recognized that space near Earth is not so vast, that collisions of objects were possible, and the debris created could lead to more collisions. Warnings were raised that the number of objects in Earth orbit could reach a point where the population of orbiting objects would grow even if humans launched no more satellites.[1] Given those warnings and an increasing number of orbiting objects, the world community adopted guidelines that satellites should be removed from regions of space that are heavily used and disposed of in a way that limits human casualties (injuries or deaths).

For objects in low Earth orbit (LEO), orbits within 2,000 km of Earth's surface, the preferred disposal option is to send satellites back into the atmosphere, so they will pose no more threat to orbiting objects. Recognizing that some debris might survive the reentry environment, the guidelines were refined to say that if the risk of causing a casualty is less than 1 in 10,000 (i.e., if the object is reentered 10,000 times, the expected casualties would be

1 individual worldwide), an object may be allowed to simply reenter gradually as the atmosphere slowly drags its orbit down. The guidelines set a limit of 25 years for the decay process to be completed. If the casualty expectation is greater than that value, the object must be disposed of by purposefully directing reentry to occur in a region where the likelihood of debris striking a human is minimized, such as the South Pacific Ocean.

The Iridium Example

In July 2000, the *Los Angeles Times*[2] raised a new possibility when it reported that over 66 satellites in the Iridium LEO constellation might be forced to reenter due to a pending bankruptcy, noting that "Motorola now says it's moving ahead with plans to destroy the satellites." A December 2000 *Reuters* article[3] stated:

> U.S. space scientists put the odds at nearly 1 in 250 that debris from the proposed burn-up of the world's first global satellite telephone mesh would hit someone on Earth.
>
> The prospects of a casualty from the now-averted mass "de-orbiting" of the system known as Iridium were spelled out in a previously secret study by the National Aeronautics and Space Administration.
>
> The analysis was done in April as a government task force weighed fears that a hurry-up, 14-month schedule for bringing back cast-off hardware might trigger "widespread anxiety."
>
> "With the information currently available, the probability of someone being struck by surviving Iridium debris is assessed to be 1 in 18,405 per reentry and 1 in 249 for all 74 spacecraft combined," NASA calculated.
>
> The study was made available to Reuters by the Federal Communications Commission under the Freedom of Information Act.[4]
>
> It found four types of Iridium components were likely to survive a flaming reentry into the atmosphere—10-kg titanium fuel tanks, 30-kg batteries, 6.3-kg structural brackets and 116-kg electronic control panels.

To summarize, had it occurred, six items with original masses of 6.3, 9.8, 30.5, and 115.9 kg were predicted to survive each Iridium satellite's reentry.[4] Each satellite had a dry mass (no expendable liquids or gasses) of 560 kg, so 160 kg or 30% was predicted to survive as larger, potentially hazardous objects. The casualty area for surviving debris from each reentry was 6.1 m^2 and the casualty expectation was 5.4E-5—below the 1E-4 threshold for uncontrolled reentries. The probability that someone would be hit should all 74 reenter would be 1 in 249, a level the article noted that might cause "widespread anxiety." Note that as part of the upgrade to the Iridium Next system, as of November 2018, a total of 17 older Block 1 Iridium satellites have reentered, and others are gradually being lowered for disposal by random reentry over the next "20–25 years"[5]. There have been no reports of injuries; one object that survived reentry of an Iridium satellite has been discovered on the ground (see Figure 1).

The altitude of the Iridium constellation, 780 km, is well above the region where atmospheric drag would cause Iridium satellites to reenter within the required 25 years, so the satellites lower their orbits to an altitude that meets the 25-year requirement.

Figure 1: Debris hat survived reentry of Iridium satellite on October 11, 2018. *(Photo courtesy Kings County Sheriff's Office)*

Possible Large Constellations

Table 1 lists constellations used for the current study. While some constellations may not eventually be placed in orbit, these proposed constellations provide insight on the factors that will affect future hazards to people on the ground and in aircraft should some actually become operational.

Table 1: Possible Constellations

Constellation No.	Proposer	Total No. of Satellites
1	SpaceX K-band (high altitude)	4,425
2	OneWeb	720
3	LeoSat	120
4	Theia	112
5	Telestar	117
6	Boeing	2,956
7	SpaceX V-band (low altitude)	7,518
Reference	Iridium (original constellation)	74

Details on constellation designs used in this study are based on early, publicly available information.

Satellites in these LEO constellations would need to be disposed of at their end of mission. In some cases, just as with Iridium, satellites might satisfy requirements for an orbit decay reentry and, as a result, might avoid the expense of executing a controlled reentry to direct debris into a safe area. But how many of these satellites might reenter each year? Would the reentry of large numbers over a short period again raise the "widespread anxiety" expressed when reentry of Iridium's satellites was predicted?

This paper uses experience with the possible disposal of the Iridium constellation and past work related to hazards to aircraft from reentries to develop a first-order assessment of possible hazards to people on the ground and in aircraft associated with the disposal of satellites from possible large constellations.

Reentry Hazard

Figure 2 illustrates the reentry breakup process, which proceeds as follows: as a reentering object gets deeper into the atmosphere, atmospheric heating and loads gradually melt structures and release and expose major components to the heating environment. These components will each be exposed to the heating environment, melt, and come apart, releasing other components that had been previously protected, and this process will continue until much of the original object has been reduced to a cloud of fragments, some falling nearly vertically from ~30 km and possibly adding a horizontal velocity component due to winds below ~20 km altitude. This cloud can be tens of kilometers wide and hundreds of kilometers long, with each fragment falling slowly through lower altitudes at speeds defined by their aerodynamic and mass properties. Interspersed within this cloud will be a few, larger fragments, some of which could be

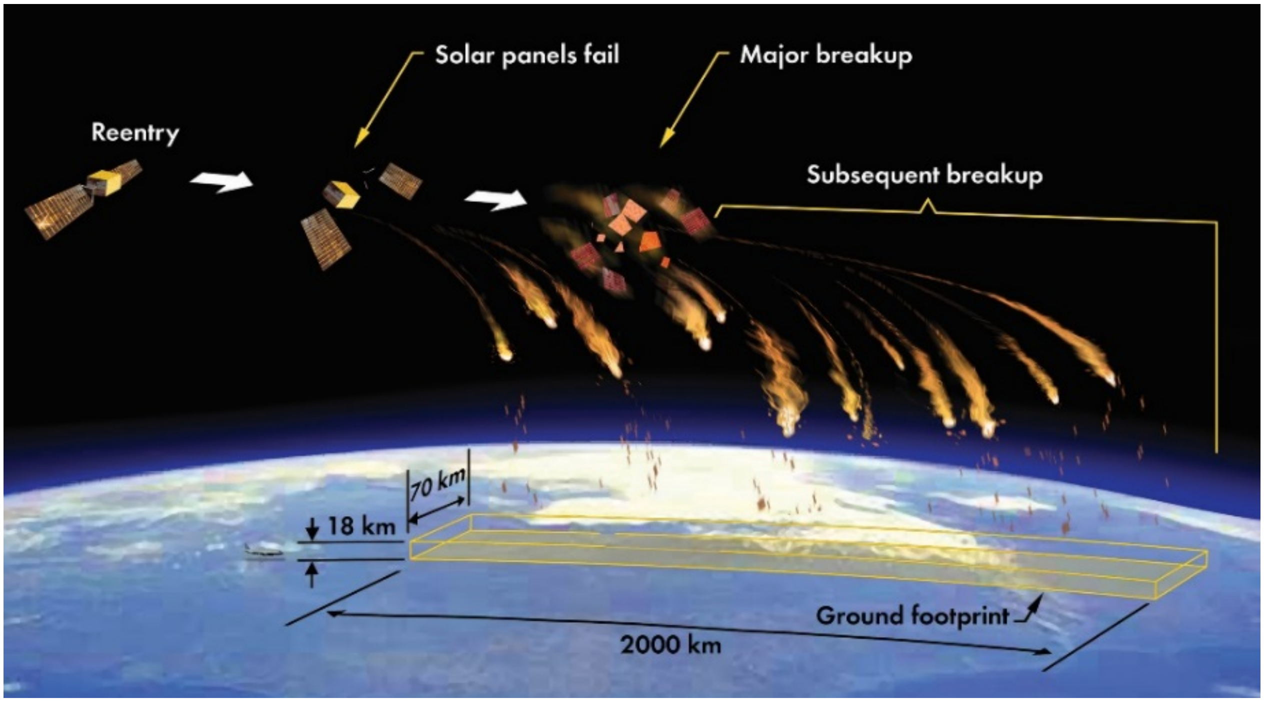

Figure 2: Illustration of reentry breakup process.

large enough to injure a human or damage an aircraft.

Casualty Expectation (E_C)

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 overwrap pressure vessels [COPVs], components made of high melting point materials such as titanium, stainless steel, and glass).

The size, shape, and mass of a surviving object can be used to estimate its aerodynamic drag and ballistic coefficient[1], 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 hazardous to a human on the ground. In these calculations, a human is defined by a 0.3-m 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.

As Figure 3 shows, for random reentries, the casualty expectation (E_C) 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.[6] Since Earth's population density varies as a function

[1] Ballistic coefficient, the ratio of the mass of an object to its drag coefficient and area, is a measure of the effect of air drag on the flight of an object. An object with a high mass will have a higher terminal velocity than an object of the same shape and area with a lower mass.

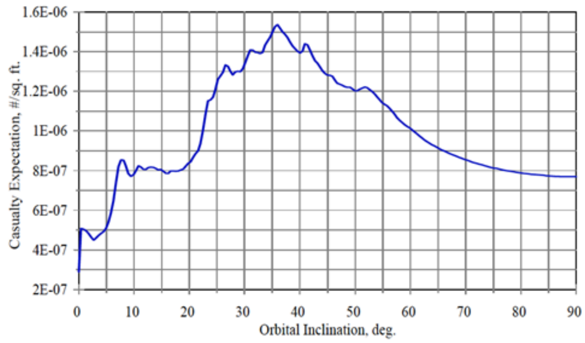

Figure 3: Casualty expectation per square foot of casualty area as a function of orbit inclination for 1995.[6]

of latitude, the inclination of an orbit defines the population that will reside beneath that orbit; e.g., if a spacecraft's orbit is inclined by 20 degrees, it will pass over only the population between 20-degree north and 20-degree south latitude, so any debris that survives a satellite's reentry will fall somewhere between those latitude bounds.

For this analysis, the E_C was computed assuming that the population affected is unsheltered, meaning that people are not indoors or otherwise protected from falling objects; this assumption is common for first estimates of the potential hazard. (NASA's technical standard, "Process for Limiting Orbital Debris" estimates that "approximately 80% of the world's population is unprotected or in lightly-sheltered structures"[7]). The E_C also neglects bounce and roll of impacting debris, both of which may increase the casualty risk to people. The effects of neglecting sheltering and neglecting bounce/roll tend to counteract each other in determination of E_C.

The casualty expectation for each surviving object is computed by multiplying the E_C/ft^2 times the casualty area for the object; the total E_C for a reentry is the sum of the E_Cs for hazardous surviving objects. R. P. Patera's "Hazard Analysis for Uncontrolled Space Vehicle Reentry"[6] provides details on this process.

The location where the debris may impact can be controlled by executing a deorbit burn that will place the debris cloud into a safe area. This is the preferred option for a single satellite or launch stage and is mandatory in some countries if the casualty expectation exceeds 1E-4. The casualty expectation for a reentry in the Southern Hemisphere is less than that for the Northern Hemisphere due to a lower population density, so in some cases the orbit decay process can be controlled to increase the likelihood of a Southern Hemisphere debris impact. Patera's "Controlled Deorbit of the Delta IV Upper Stage for the DMSP-17 Mission"[8] gives an example of how that might be done.

Recovered Debris

The debris that has been recovered to date is from reentries of large space vehicles—launch stages with large propellant tanks and rocket motors, and spacecraft containing items made of high melting point materials protected from a significant fraction of the reentry heating environment by their location within a reentering body. In addition to the debris shown in Figure 1, examples are:

- In January 1997, the debris shown in Figure 4 was recovered in the United States. The debris was from a Delta II second stage that placed an Air Force satellite in orbit, and it was noteworthy because one very light fragment from the stage brushed the shoulder of Ms. Lottie Williams in Oklahoma—the first such incident verifiably reported (she was not injured). A second much larger object (~250 kg) landed ~50 meters from a farmer's house in Texas, and other large fragments, including a spherical pressurant tank and the stage's thrust chamber, were recovered along the reentry path. That reentry event made it clear that large, hazardous fragments, as well as small fragments that might not harm a human on the ground but could be an issue for aircraft,

Figure 4: ***Delta II State 2 debris. Left: Lottie Williams holding reentered debris fragment*** *(photo courtesy Brandi Stafford, Tulsa World)****. Right: propellant tank in Texas field.*** *(Photo courtesy NASA)*

can and do survive reentry of space objects. "Test Cases for Reentry Survivability Modeling"[9] provides additional details on debris that has survived reentry.

- Several composite overwrapped pressure vessels (COPV) (see Figure 5) have been recovered. In these cases, the adhesive bonding the filaments together ablated and carried the heat away, protecting the underlying material.

Figure 5: Recovered COPVs (from left: debris from Centaur stage of Atlas V booster; SpaceX Falcon 9 Stage 2)

As noted, the surviving mass from a reentry is distributed among a number of fragments spread along a long footprint, so it is likely that more objects survived each of these reentries but were not reported or recovered.

Reentries from Proposed Constellations

For this study, it is assumed that all reentries of satellites from large constellations are orbit decay reentries; i.e., the satellites are not purposefully deorbited to control where surviving debris will land. As was discussed, to utilize a natural orbit decay strategy for disposal, a satellite's design must also limit the casualty expectation, the number of people on the ground who might be injured or killed by debris falling from the reentry, to less than one in 10,000.

Estimates on what parts of a particular spacecraft will survive can be developed given information on the materials, masses and sizes of its components. If details on a satellite's construction and materials are not available, a rule-of-thumb for the total mass of material surviving a reentry is that 10–40% of the dry mass (the mass of the spacecraft not including any onboard liquids or gasses) will survive. (Note that 30% of the Iridium satellite's dry mass was predicted to survive.)

Over the long term, designing space vehicles to have fewer and lighter surviving objects will lower these percentages. (It might be argued that the design of the first Iridium satellites did not give consideration to debris survival, because enforcement of debris policy was just beginning during their design. Per the "Iridium NEXT Orbital Debris Mitigation Plan,"[10] designs of the newer Iridium NEXT satellites have an initial mass of 659 kg and a casualty area for surviving debris of 18.8 m^2, three times that of satellites in the first constellation, which had an initial mass of 560 kg and a casualty area of 6.1 m^2.)

Ground Hazards

Reentry of a Single Satellite

Satellites in the proposed constellations will require propulsion for attitude control, stationkeeping, and disposal activities; solar panels; batteries to store power during passes through the Earth's shadow; reaction wheels to maintain prescribed orientation; communication antennas; electronics for vehicle control; and hardware associated with the payload—components similar to those used in the Iridium satellites discussed earlier. Given that the actual designs of the proposed satellites are not known, for this study it is assumed that a satellite of the same mass as an Iridium satellite (560 kg) and same orbit inclination as an Iridium satellite (86.4 degrees) reentering in the year 2030 will have the same casualty expectation as an Iridium satellite reentering that year. (In actuality, the ratio of the E_C for a constellation satellite to that of an Iridium satellite will depend on the design and materials used in a constellation's satellite; however, based on material recovered after actual reentries, the casualty expectation should be within an order of magnitude of the ratio proposed unless specific design-for-demise features are included and verified.)

As noted earlier, a satellite's orbit inclination is an important factor in estimating its casualty expectation, and Figure 3 (estimated for a 1995 population) will be used to estimate the casualty expectation per square foot for each constellation satellite given the inclination of its orbit. Each satellite's casualty expectation per square foot from that figure must be updated for a 2030 population using

$$E_C(t) = E_C(1995)\,(1+0.01099)^{(t-1995)} \qquad (1)$$

which assumes a 1.099% growth rate, and "t" is the future year. Since the Iridium E_C was estimated for the year 2000, this same relation can be used to convert to a 1995 estimate, yielding 5.1E-5 if an Iridium satellite was deorbited that year, and, for 2030, the E_C for the same Iridium satellite would be 7.5E-5.

Table 2 shows the resulting E_C estimate for each reentry of a constellation's satellite. As seen, three satellite designs look to have potential problems related to meeting the goal for allowing disposal by random reentry of a single satellite: those in Constellations 4, 5, and 6, where the dry mass for a single satellite reentry in 2030 would be 3000, 700, and 1500 kg, respectively. The highest E_C for a single satellite's reentry in those constellations would be 4.1E-4, 1.8E-4, and 3.9E-4, respectively (note the inclination effects on casualty expectations for reentries in Constellations 5 and 6). As stated earlier, these estimates are not based on actual data on the satellites in a given constellation but are intended to illustrate where possible problems might exist for disposing satellites from large constellations.

Ground Hazard due to Reentry of Multiple Satellites

The subject of this paper is the cumulative hazard for disposal of satellites in each constellation. Since no proposals have been provided for how replacements might be transitioned into and out of any of the proposed constellations, one approach might be to replace and dispose of satellites based on the design lifetime of the satellites. Table 2 includes estimates of what satellite lifetimes in these constellations might be.

It is not likely that all satellites will be disposed of at the end of their design lifetime or that each full constellation will simply be deorbited and replaced within a very short period. For this analysis, it will be assumed that after each constellation has been fully configured, the strategy will be to continuously replace a fraction of the satellites each year based on the lifetime of satellites in the constellation; e.g., once Constellation 1 is fully configured, 1/6 or about 737 of the 4,425 satellites in that constellation will be replaced, deorbited, and will reenter each year for

Table 2: Casualty Expectations for Each Satellite and Each Constellation per Year								
Constellation	Total Satellites	Orbit Altitude (km)	Orbit Inclination (deg)	Satellite Lifetime (years)	Satellite Mass (kg)	No. Reentries per year	Ec Each Satellite Reentry (2030)	Ec/year (2030)
1a	1600	1150	53.0	6	390	267	8.2E-05	2.2E-02
1b	1600	1110	53.8	6	390	267	8.2E-05	2.2E-02
1c	400	1130	74.0	6	390	67	5.5E-05	3.7E-03
1d	450	1325	70.0	6	390	75	5.9E-05	4.4E-03
1e	375	1275	81.0	6	390	63	5.4E-05	3.4E-03
1	4425		Multiple	6	390	738	Multiple	5.5E-02
2	720	1200	88.0	6	150	120	2.0E-05	2.4E-03
3	120	1400	89.0	12	700	10	9.4E-05	9.4E-04
4	112	800	98.6	5	3000	22	4.1E-04	9.3E-03
5a	72	1000	99.5	5	700	14	9.7E-05	1.4E-03
5b	45	1248	37.4	5	700	9	1.8E-04	1.6E-03
5	117		Multiple	5	700	23	Multiple	3.0E-03
6a	1120	1030	45.0	12	1500	93	3.9E-04	3.6E-02
6b	828	1082	55.0	12	1500	69	3.0E-04	2.1E-02
6c	1008	970	88.0	12	1500	84	2.0E-04	1.7E-02
6	2956		Multiple	12	1500	246	Multiple	7.4E-02
7a	2547	340	53.0	6	386	425	8.6E-05	3.7E-02
7b	2478	341	48.0	6	386	413	8.2E-05	3.4E-02
7c	2493	336	42.0	6	386	416	9.5E-05	3.9E-02
7	7518		Multiple	6	386	1253	Multiple	1.1E-01
SUM	15968					2413		2.5E-01

the life of the constellation. Of course, better estimates could be developed once the replacement and disposal cycles are defined.

While a cumulative risk limit has not been established for spacecraft reentries, "Common risk Criteria Standards for National Test Ranges"[11] provides the following guidance on how that risk might be managed. That document notes that its policies and criteria apply to "launch and reentry hazards generated by endoatmospheric and exoatmospheric range activities, including both guided and unguided missiles and missile intercepts, space launches, and reentry vehicles," and defines risk as "the product of the probability of occurrence of an event and the consequences of that event. Total risk is the combination of the products, over all possible events, of the probability of each event and its associated consequence." This definition of risk and total risk is used for this paper.

"Common Risk Criteria Standards for National Test Ranges" states:

> Collective risk for the GP [general public] must not exceed a casualty expectation of 100E−6 (1E−4) for any single mission. If annual risk is measured, collective risk for the GP should not exceed a casualty expectation of 3000E−6 (3E−3) on an annual basis.[11]

Table 2 shows what the yearly collective risk to unsheltered people on the ground would be from disposing of the yearly fraction of each constellation's members via the strategy described above.

Constellations 2, 3, and 5 have risk levels at or below the 3E-3 limit. The highest collective risk, 1.1E-1, is for Constellation 7, where 1,253 satellites, each with a mass of 386 kg would reenter yearly using the assumed disposal strategy.

While including sheltering might lower this value in many cases, in the case of a very large spacecraft, where a large, heavy surviving fragment could collapse a roof, the influence of sheltering on the casualty expectation would be minimal.[12]

Hazards to Aircraft

The hazards noted above are hazards associated with debris striking a human on the ground. But what might the hazard from a large number of random reentries be to humans riding in aircraft?

Patera's "Risk to Commercial Aircraft from Reentering Space Debris"[13] examines the risk to commercial aircraft flying domestic flights within the United States, flights leaving the United States for international destinations, and flights arriving in the United States from an international point of origin due to impacts of hazardous objects that survived reentry. That study used physical data from 17 large commercial aircraft types, including the Boeing 747, and the total number of minutes each type of aircraft was airborne in 2006. The Boeing 747 is now retired from passenger service in the United States, but other types of aircraft have replaced the 747 so there should be no net change in risk from reentry debris. That study also assumed about 100 large objects reentered per year (still a good estimate for 2019) with 100 objects hazardous to aircraft surviving each reentry, yielding a total of 1×10^4 objects per year that might threaten aircraft.

Using those assumptions, Patera notes that on average the probability of a reentering debris object impacting any aircraft in 2006 was 2.36E-9 and the weighted average casualty risk (weighted by the number density of debris objects at each orbit inclination) associated with a single debris object was 5.84E-7.[13] Following the approach given in "Risk to Commercial Aircraft from Reentering Space Debris[13], the probability of an aircraft being struck by a single debris object reentering from an orbit inclined at 35 degrees in 2006 would be 4.0E-9, as Figure 6 shows. (To reiterate, the aircraft population used for this estimate was "commercial aircraft flying domestic flights within US, flights leaving US for a foreign destination or flights arriving in US from a foreign point of origin,"[13] not for all aircraft worldwide.)

These casualty risk estimates assume that each impact would result in all occupants being seriously injured or killed without emergency actions by the pilot—a conservative assumption, perhaps excessively conservative for relatively small debris items as explained below:

- "Hazards of Falling Debris to People, Aircraft, and Watercraft"[14] notes that "A piece of debris is considered to be potentially lethal to an aircraft if it is capable of producing sufficient damage to

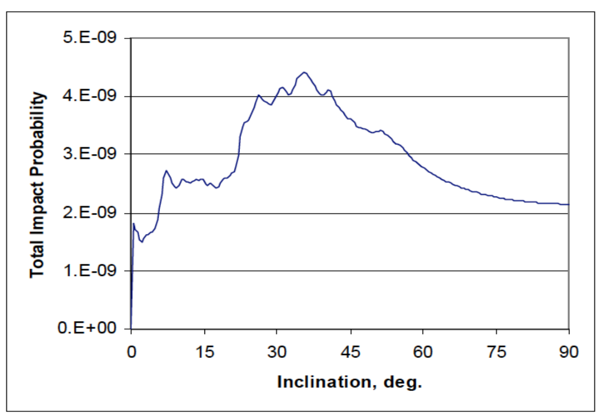

Figure 6: Total probability that a commercial aircraft will be impacted by a single debris object in 2006.[13]

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."

- "Risk Analysis Between Aircraft and Space Debris During Atmospheric Re-Entry"[15] states debris "larger than a square of 10cm x 10cm carries sufficient energy to perforate the structure of the aircraft" and 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 vulnerable surface." The reference provides no information on the mass of the impacting object. (The six objects that were predicted to survive the Iridium reentry likely exceeded this size.)

- "Impact Testing and Improvements in Aircraft Vulnerability Modeling for Range Safety"[16] estimates that the most vulnerable types of aircraft (e.g., helicopters) are vulnerable to 1-gm cubes of steel, and recent tests sponsored by the FAA demonstrated a commercial transport fuselage could be penetrated by 9-gm steel cubes. Ballistic coefficients for such a cube would be ~110 kg/m^2 (~23 psf), which is approximately the ballistic coefficient assumed in Patera's "Risk to Commercial Aircraft from Reentering Space Debris"[13]. The fall speed of the debris fragment would be about 145 mph (230 km/hr) at the aircraft's cruising altitude (30,000 ft, ~9,140 m). Patera estimated an average speed of commercial aircraft at that altitude of 450 mph (725 km/hr).[13]

- "Hazards of Falling Debris to People, Aircraft, and Watercraft"[14] notes that "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."

- "Common Risk Criteria Standards for National Test Ranges: Supplement"[12] states that a "fragment of at least 300 grams should be assumed to produce a catastrophe for any impact on an aircraft." 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 grams.

Survival of Small Debris

There are three primary sources of information on small debris that survives reentries of satellites:

1. **The space shuttle *Columbia* accident**. Extensive searches recovered over 80,000 objects with an estimate of 0.3 expected casualties on commercial aircraft.[17] Of course, that vehicle included a large number of thermal protection tiles, including 24,000 silica tiles, which would not be common on constellation satellites.

2. **The Vehicle Atmospheric Survival Test (VAST).** The ballistic coefficient range measured for debris falling from the VAST is described in R. G. Stern's "Reentry Breakup and Survivability Characteristics of the Vehicle Atmospheric Survivability Project Vehicles."[18] The reentering vehicle had a mass of 5,330 kg (11,750 lb) at reentry. The sizes and masses of the fragments falling from the VAST are not known, but a significant percentage of the objects in that debris field had ballistic coefficients greater than 125 kg/m^2, the threshold for fatal damage for a 1 cm^3 steel fragment. For that steel cube, the energy at ground impact would be ~8 Joules, below the 15 Joule hazard threshold for a human on the ground.

Based on the VAST data, "Requirements for Warning Aircraft of Reentering Debris"[19] discusses risks to humans in an aircraft from debris falling after a reentry and concludes that 27 pieces surviving a random reentry over the continental United States during a weekend morning "would correspond to a casualty expectation equal to the acceptable limit of 1x10-4 given in RCC 321-07,[11] even if only commercial air traffic is considered," and further states "accounting for Visual Flight Rule traffic may lead to at least ten times higher probability of impact on any aircraft." Visual flight rules are a set of regulations under which a pilot operates an aircraft in weather conditions generally clear enough to allow the pilot to see where the aircraft is going.

3. **The 1997 reentry of the Delta II Stage 2**, where debris was recovered in Oklahoma and Texas. The large object pictured in Figure 4 would clearly be hazardous to aircraft, but the reentering object was a rocket stage and would be expected to have fewer and larger fragments than a more complex spacecraft of the same mass. Satellites used for the commercial constellations studied here would be expected to have smaller fragments 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). Figure 4 includes a photo of a quilted material fragment that survived that reentry and brushed Williams on the shoulder while she was jogging (she was not injured). That fragment is similar to the "quilted pads," which, as noted earlier, might not be a hazard to a human but could be to an aircraft.

Given the evidence noted above, "Requirements for Warning Aircraft of Reentering Debris"[19] estimates that random reentries of satellites larger than 800 kg can yield as many as 300 fragments potentially lethal to aircraft, which are enough to "exceed the risk limit given by RCC 321-07 [the same risk level in the more recent RCC 321-17] if an aircraft is exposed to the debris field." This ratio of 300 hazardous objects per 800 kg of satellite mass will be used for the current study. Using this approach, each reentry of a 560-kg Iridium satellite would possibly produce 197 fragments potentially hazardous to aircraft, including the six large fragments that are also hazardous to people on the ground. For comparison, the ~75,000-kg space shuttle *Columbia* would be predicted to produce 28,000 fragments using this approach; as noted, over 80,000 objects were recovered after that accident.

Risk to Aircraft from Surviving Debris Fragments

For the current study, the probability of a "commercial aircraft flying domestic flights within the US., flights leaving the US for international destinations, and flights arriving in the US. from an international point of origin"[13] being impacted by a single hazardous debris object in 2030 was estimated by weighting values from Figure 6 assuming the 1.1% annual population growth rate from Eq. (1). (Note: The current FAA projected growth rate for aircraft travel is higher than this number.) "Risk to Commercial Aircraft from Reentering Space Debris"[13] used the velocities of the debris fragment and the aircraft to estimate the exposed area (risk area) of each aircraft type. The number of passengers and the number of aircraft in the air were used to estimate the cumulative casualty estimates for that aircraft type. Table 3 provides resulting estimates. Note that the estimates for the probability of striking an aircraft in 2030 range from 8.8E-6/year for reentries of satellites from Constellation 3 to 1.0E-3/year for Constellation 7.

Table 3 also shows the cumulative casualty expectation per year for disposal of a portion of each constellation's satellites in 2030 given the assumed

Table 3. Probability of Impacting an Aircraft and Cumulative Casualty Expectation Due to Aircraft Strikes										
Constellation	Total Satellites	Orbit Altitude (km)	Orbit Inclination (deg)	Satellite Lifetime (years)	Satellite Mass (kg)	No. Reentries per year	No. Haz Frag per Reentry	No. Haz Frag per Year	Probability of Striking Aircraft per Year (2030)	Cumulative Casualty Expectation per year (2030)
1a	1600	1150	53.0	6	390	267	146	39000	1.9E-04	5.0E-02
1b	1600	1110	53.8	6	390	267	146	39000	1.9E-04	4.9E-02
1c	400	1130	74.0	6	390	67	146	9750	3.6E-05	8.9E-03
1d	450	1325	70.0	6	390	75	146	10969	4.2E-05	1.0E-02
1e	375	1275	81.0	6	390	63	146	9141	3.2E-05	7.8E-03
1	4425		Multiple	6	390	738	146	107859	5.0E-04	1.3E-01
2	720	1200	88.0	6	150	120	56	6750	2.3E-05	5.5E-03
3	120	1400	89.0	12	700	10	263	2625	8.8E-06	2.1E-03
4	112	800	98.6	5	3000	22	1125	25200	8.9E-05	2.1E-02
5a	72	1000	99.5	5	700	14	263	3780	1.3E-05	3.1E-03
5b	45	1248	37.4	5	700	9	263	2363	1.6E-05	4.2E-03
5	117		Multiple	5	700	23	263	6143	2.9E-05	7.2E-03
6a	1120	1030	45.0	12	1500	93	563	52500	3.1E-04	7.5E-02
6b	828	1082	55.0	12	1500	69	563	38813	2.0E-04	4.8E-02
6c	1008	970	88.0	12	1500	84	563	47250	1.6E-04	3.9E-02
6	2956		Multiple	12	1500	246	563	138563	6.7E-04	1.6E-01
7a	2547	340	53.0	6	386	425	145	61446	3.1E-04	7.9E-02
7b	2478	341	48.0	6	386	413	145	59782	3.3E-04	8.0E-02
7c	2493	336	42.0	6	386	416	145	60144	3.8E-04	9.1E-02
7	7518		Multiple	6	386	1253	145	181372	1.0E-03	2.5E-01
SUM	15968					2413		468511	2.3E-03	5.7E-01

number of hazardous fragments created by each reentry. The casualty expectations were developed by correcting the 2006 estimates for cumulative casualty expectations at each inclination given in Figure 7 for 2030, summing the number of reentries for each constellation as noted earlier. As seen, casualty expectations for aircraft vary from 2.1E-3/year (~2 per 1,000 years) to 2.5E-1/year (~3 every 10 years), depending on the constellation.

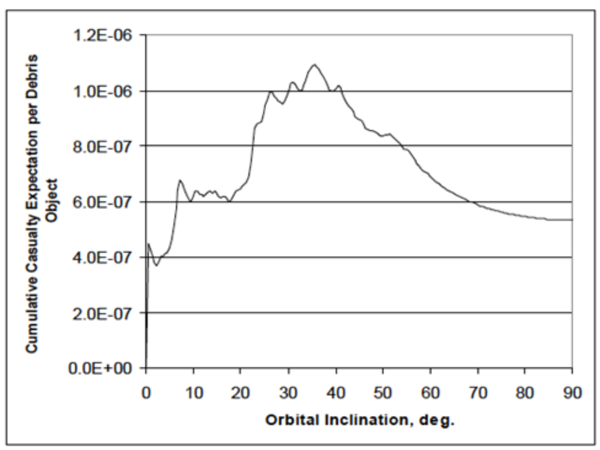

Figure 7: Cumulative casualty expectation per debris object for 17 aircraft types in 2006.[13]

These casualty expectations for aircraft are likely overstated for several reasons:

- RCC 321-07 concluded that the area of commercial transport aircraft vulnerable to casualty-producing collisions with compact metal fragments below 300 grams is far less than the size of the aircraft. Furthermore, only the engines would be vulnerable to impact by a piece of cloth, and commercial transports are designed to continue safe flight following the loss of a single engine.

- As has been noted, this study assumes that 300 objects per 800 kg of dry mass in orbit survives reentry and that each of these objects is hazardous to commercial transport aircraft. Other than the VASTs, very little information is available on the number and size of smaller objects that will survive a reentry—and the VAST data is incomplete.

It should be noted again that these estimates are based on a subset of the number of airborne aircraft worldwide. The annual worldwide risk of a commercial aircraft being struck by a piece of reentering debris is larger but "likely to be within an order of magnitude."[13] This range can be refined by comparing the average of 5,000 aircraft airborne at any given time over the United States in 2019[20] and the equivalent number of aircraft mid-flight worldwide, estimated to be between 8,000 and 20,000[21]. Using this range, the likelihood of an aircraft being struck and the corresponding casualty expectations per year for each constellation in 2030 could be at least twice that given in Table 3.

Discussion

Given the above results, it is evident that the yearly reentry of large numbers of satellites can pose a significant hazard to people, both on the ground and in aircraft. The results assume that a few objects hazardous to people on the ground survive each reentry, but hundreds can survive that might pose a hazard to aircraft. These assumptions are based on predictions of ground hazards for Iridium spacecraft, which have components likely similar to those that might be used in new satellites planned for higher LEO altitudes that require orbit lowering to satisfy reentry hazard constraints. Hazards to aircraft are based on incomplete data on observed debris fields from a very small number of past satellite reentry tests and on assumptions regarding small objects that can cause significant damage to an aircraft. Additional research to better characterize the hazards to aircraft from reentering objects (both human-made and natural) and resolve the vulnerability of aircraft to space debris collisions appears warranted.

Results show that disposal of large numbers of satellites from constellations could potentially increase the likelihood of a casualty on the ground by debris falling after reentry. For the notional constellation designs examined and using the assumed disposal rate for constellation maintenance, the casualty expectation per year for ground impacts could vary from 9.4E-4 (Constellation 3) to as high as 1.1E-1 (Constellation 7), both well above acceptable limits for a single reentry (1E-4). If all constellations were in place (perhaps not a likely eventuality), the expected casualty per year would be 2.5E-1.

These same constellations could create hazards for people in commercial aircraft as well. Based on commercial aircraft flying domestic flights within the U.S., flights leaving the US for international destinations and flights arriving in the U.S. from an international point of origin, the probability of debris striking an aircraft per year could be as high 2.3E-3 per year. Increasing the number of flights airborne by a factor of two to account for international air traffic, the probability of striking an aircraft rises to about 5E-3. The same adjustment would apply to the cumulative casualty expectation, which could be ~1 per year.

While these results are not based on actual satellite or constellation designs and were developed using simplifying assumptions, they do capture some basic realities for disposal of satellites from such constellations. These are:

- The casualty expectation for large numbers of uncontrolled reentries of satellites that individually satisfy the 1E-4 casualty limit may well exceed that limit.

- Cumulative hazards for people on the ground and in aircraft may both exceed the 3E-3 maximum annual casualty expectation limit set by RCC 321-17.

- Satellites in orbits between 30 and 50 degrees have >30% higher casualty expectations than the same satellites in orbits with higher inclinations (those in lower inclination orbits spend more time above that portion of Earth where the population is higher).

- While regulation and guidelines limit the casualty expectation for a single satellite reentering randomly, there are no formal guidelines or regulations limiting the cumulative risks associated with large numbers of reentries of satellites from a single constellation. (It should be noted that the FAA recently proposed a regulation to ensure launch or reentry vehicle disposal either target a broad ocean area or comply with collective, individual, and aircraft risk criteria[22].)

- The number of satellites in a constellation, the mass and other characteristics of those satellites, and the satellite lifetime and disposal strategy all affect hazards posed to people on the ground and in aircraft.

Some mitigation options are:

- Satellites could be directly deorbited so that all fragments impact in a safe region. This is the preferred option, since satellites would be removed from orbit quickly to minimize the possibility of on-orbit collisions and would be reentered into an area where hazards to people and aircraft were minimal.

- Satellites could be designed to minimize the number and size of fragments that survive after reentry breakup. Validation of these designs for actual reentry conditions should be considered.

- Satellites could be designed with longer lifetimes and use disposal strategies that reduce the number reentering each year.

- A warning system could be established to alert aircraft about a pending reentry. It could also warn the population to take shelter when reentry risk is high.

- Active servicing and removal of spacecraft might be included as part of constellation designs. Specialized spacecraft could collect several retiring satellites and deorbit the group into a safe area. In this case, satellites might be designed with features that facilitate collection and connection as part of a group or might self-collect and connect into a single mass and wait for removal by an active debris removal service.

Conclusions

This first-order assessment of potential risks to people and aircraft from reentries of large numbers of satellites from large constellations in LEOs shows that:

- Risks to aircraft posed by small debris surviving a reentry might be a major problem facing owners of large constellations.

- Given that hundreds of satellites per year from very large constellations could reenter, designers might find it difficult to eliminate many small fragments hazardous to aircraft and to verify whether proposed mitigation techniques perform as desired.

- Hazards to people on the ground will also be a problem, with casualty expectations for disposal of multiple satellites by random reentries likely to exceed single-satellite limits by orders of magnitude. Ground hazards result from the survival of large, hazardous fragments, and spacecraft components and features could be designed to have fewer such fragments survive. With only limited hard data on actual debris survival, it may be difficult to have confidence in proposed approaches. Radar observations of actual reentries like those conducted for VASTs could help verify mitigation approaches.

Limits developed for test ranges provide some guidance relative to the acceptable yearly risks, but no such limits have been discussed for yearly reentries of satellites from large constellations. More refined estimates await specific designs, lifetimes, and disposal plans for constellation satellites, including more measurements of small debris surviving satellite reentries and improved characterizations of aircraft vulnerability to collision with space debris.

As has been noted, several assumptions were made to develop a rough order of magnitude of the risks associated with debris from satellites from large constellations in LEO reentering randomly after disposal. Future analysis may allow better estimates given specific lifetimes and replacement strategies for these satellites, the number of satellite constellations deployed, the growth in number of daily air flights worldwide, population growth, etc. Therefore, the purpose of this analysis was not to predict the actual number of fatalities, but rather to establish whether a credible and non-trivial risk exists to humans on the ground and on aircraft. Given the results presented here, additional analyses and measurements of debris falling after reentries, and possibly new safety standards related to this subject, need to be considered going forward.

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