Potential Future Costs of Orbital Debris in Low Earth Orbit

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Introduction

I started this white paper in 2011 as an attempt to extend and generalize work by Bill Ailor and his colleagues on costs of orbital debris to future satellite programs (see paper IAC-10.A6.2.10). Such cost estimates are needed to determine the allowable costs and net payoffs of different options for dealing with debris, including business as usual, satellite hardening or replacement, better debris tracking and avoidance, and selective or wholesale removal or relocation of debris. My main goal was a spreadsheet that would let users explore the effects of different scenarios and assumptions, as a function of trends in satellite number, size, vulnerability, orbit altitude and inclination, cost of asset loss, discount rate, and time horizon.

Developing such a spreadsheet with even approximately right linkages among key parameters, combined with difficulties in quantifying threats from small debris, led to unexpected insights that may have more value than the spreadsheet itself. This led me to list my key conclusions and recommendations on the next two pages. Following that are 3 pages of graphics and text about key features of orbital debris that drive both its costs and also our uncertainties about those costs. The next 26 pages discuss in detail the conclusions and recommendations on pages 2-3. The following 9 pages are an introduction and users' guide to the spreadsheet. The last page is the spreadsheet itself. It is an embedded Excel file that can be used within Word, or separately.

This white paper is intended as an early contribution. It will be successful if it stimulates work by others along similar lines. The paper focuses on low earth orbit (LEO) because the cost of inaction appears highest there, and because the 2 most affordable wholesale removal concepts (EDDE electrodynamic vehicles and Orion ground-based pulsed lasers) are limited to LEO.

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Key Conclusions About Orbital Debris in LEO

C1. As industry practices continue to improve, explosions, coolant leaks, and most other similar traditional sources of new tracked and untracked small debris should continue to decrease.

C2. Debris orbit decay rates suggest that few tracked collision fragments have enough mass to thoroughly shred the >1 ton objects that make up ~77% of LEO mass and area. There is a slow fragment/intact collision cascade, but it will not be the main fragment source during this century.

C3. Accidental collisions between 2 intact objects like Cosmos and Iridium now have a 6%/year chance. Debris creation roughly scales with the square of mass, integrated over altitude. This is likely to be the dominant source of unintentional new debris in LEO, both tracked and untracked.

C4. On the average, future collisions of intact objects will involve more total mass and create comparable small shrapnel as the 2007 and 2009 collisions ***together***. Note that much of Iridium 33 may still be in one piece. Many future collisions will more thoroughly shred both objects.

C5. Most collisions between large objects have large enough CG offsets that only modest parts of each object try to pass through each other. Huge pressure gradients "splash" most interacting masses into fine hypervelocity sprays that spread out at roughly the original impact velocity.

C6. Most such hypervelocity spray that escapes without added collisions will deorbit within 1 orbit, some will reach escape, and some will stay in orbit. But nearly all of it is far too small to be lethal, and much of what stays in orbit will spend little time in LEO. The main impact of hypervelocity spray is its ability to shred nearby mass that missed direct impact: multiple sprays spread out, interact, and deliver far more momentum and energy to the rest of each object than shock waves or evolved vapor can. Most "lethal shrapnel" may be created by a multi-stage spray/shred process that is apparently not modeled in some hypervelocity impact simulations.

C7. Most of the mass of both rocket bodies and satellites is sheet-like, whether it is a tank wall, rocket engine, solar array, radiator, circuit board, battery, or structure. Hypervelocity sprays can shred sheets into random pieces down to a few times the sheet thickness, without changing that thickness much. Sprays may disperse shrapnel more widely than other fragmentation events, with velocities that vary more with shrapnel area than thickness. Shrapnel area/mass and even velocity distributions may be predictable in advance from the bill of materials for each object.

C8. The count, size, mass, and velocity distributions from future collisions between typical >1 ton objects should resemble those of the 2007 and 2009 events much more closely than those of other fragmentation events. Hence adequately characterizing the debris generated by the 2007 and 2009 collisions may be the main key to understanding most future collision-generated debris.

C9. The main direct debris threat, both now and in the future, is from **gram-class shrapnel that can disable expensive spacecraft, but is too small to be tracked either by the existing Space Surveillance Network or even by its planned upgrades.** The likely future cost of that shrapnel threat is not well understood, because of our very limited and mostly indirect knowledge of ~1-3 cm shrapnel, and the difficulty of collecting useful data on it.

Key Recommendations

R1. Do more realistic tests and analyses to determine the minimum shrapnel mass likely to be lethal to future high-value LEO spacecraft. Also update guidelines that may allow cost-effective improvements in spacecraft robustness, and reductions in threatening shrapnel they can generate.

R2. Directly estimate the ***mass*** of shrapnel that has impacted tracked LEO objects, by detecting infrequent small step decreases in orbit period. For example, there are 223 Russian SL-8 stages between 900 and 1800 km. Each weighs ~1434 kg and has an average cross-section of ~13 m^2. Even 0.5 gram objects will cause a ~1 km/day along-track shift and should be clearly detectable.

R3. Learn far more about the number, size, mass, and orbits of now-untracked but potentially lethal gram-class shrapnel created by the 2007 and 2009 collisions. Its area/mass may resemble that of its source object materials, and the altitude span may be larger than that of larger debris, ***but we really don't know***. This data is the key to a better understanding of future costs of debris.

R4. Study ***all*** options for protecting LEO assets from tracked and untracked shrapnel, including:

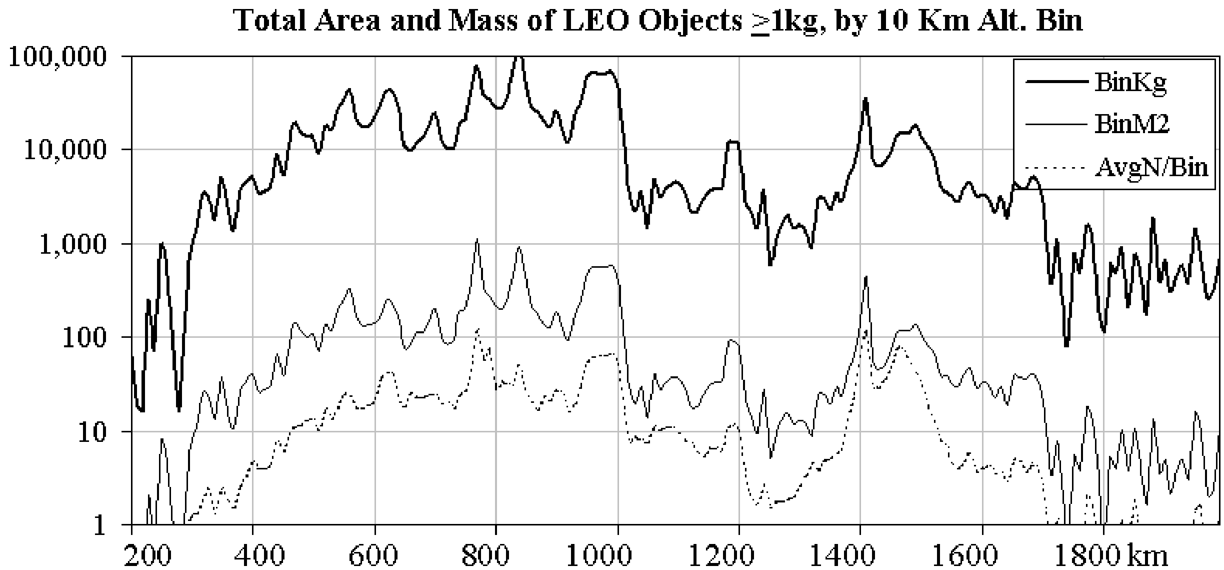
1. Upgrade tracking (radar or telescope) enough to track ***most*** probably-lethal shrapnel.
2. Actively maneuver to avoid predicted threats, by thrusting or by adjusting drag area.
3. Orient the ISS solar arrays to shield the pressurized modules as much as possible.
4. Orient spacecraft and appendages to minimize risk, as Hubble did with the Leonids.
5. Add stand-off shielding to at least some vulnerable surfaces of new spacecraft.
6. Combine #4 & #5: add selective shielding and orient that side towards predicted threats.
7. Develop the Orion pulsed laser, both to deorbit shrapnel and to prevent debris collisions.
8. Reduce the creation of new shrapnel by reducing new mass and removing existing mass.

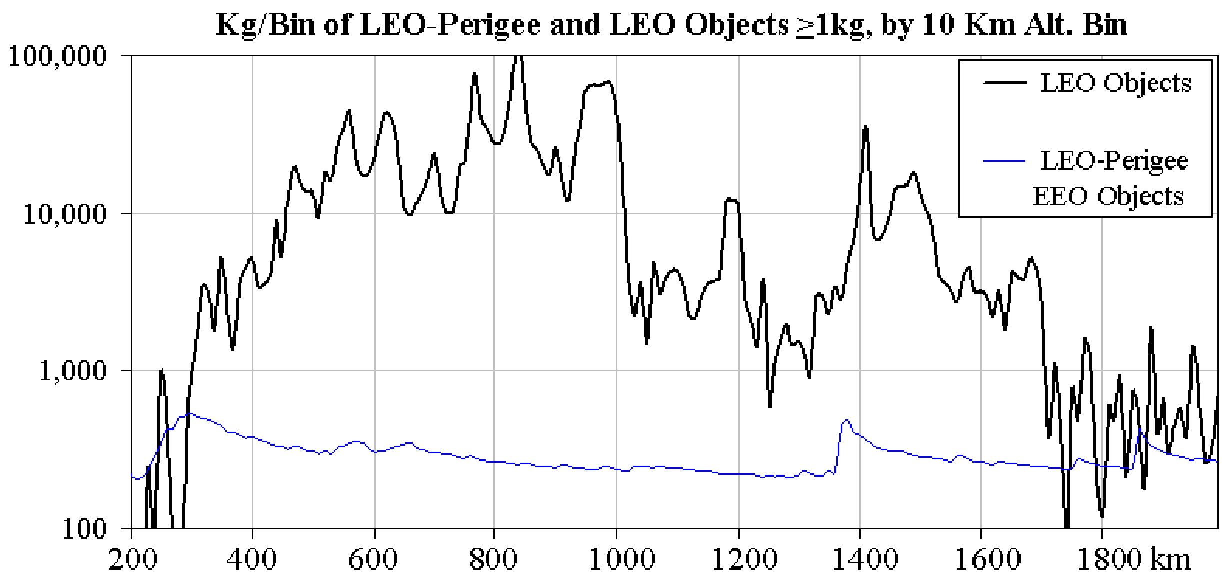
R5. Consider optical detection of sunlit objects near dawn and dusk, as well as radar upgrades. Frequent enough update for a precise catalog requires agile-tracking telescopes at dozens of sites, over a wide range of latitudes. Most discovery might be done as a background task. An optical fence should be far cheaper if commercial. But such a venture may be viable only if the USG can commit in advance to buying data, once the quality and reliability of the service are established.

R6. Work towards removing ***most*** large objects from crowded altitudes as soon as affordable. They are the main source of accidental shrapnel, from intact/intact and fragment/intact collisions and even explosions. Large objects can be deorbited, or collected into scrapyards at less-crowded altitudes. This reduces risks quickly, while allowing later decisions on deorbit vs recycling.

R7. Consider charging parking fees or requiring liability insurance for all future mass additions to crowded altitudes, and offering debris removal bounties that scale with the threat removed. LEO is an unregulated commons that is degraded by its users. If LEO users will not pay for debris removal comparable to their own future debris additions, it seems naïve to expect general funds for debris removal, especially when even key existing programs have uncertain funding.

R8. Once conclusions C1-C9 are independently verified, update debris terminology, derive and publish more accurate orbit estimates, and include more parameters and data in public databases.

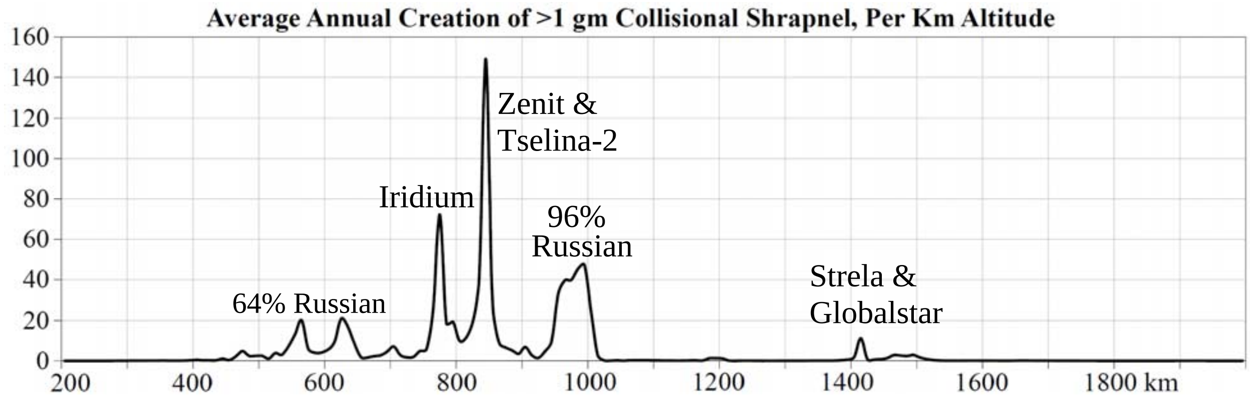




The top plot above shows the altitude dependence of key parameters that drive collisional debris creation. The collision rate roughly scales with total target area in the bin times the # of >1 kg objects in the bin, and source mass scales with average mass. Average mass times # in bin equals total mass, so the likely fragment source mass ~scales with total area times total mass in the bin.

The bottom plot shows the LEO presence of Eccentric-Earth-Orbit objects (Apo+Per>4000 km), like spent stages in GEO transfer orbits. High eccentricity makes their average mass distribution vs. altitude smooth. The steps in the blue line near 250, 1370, and 1870 km are due to objects with perigees there. They spend more time per bin right near perigee than higher up in LEO.

Typical object area nearly scales with mass, so collision rates per altitude bin nearly scale with bin mass squared. Most collisions will occur in the few bins with >50 tons. The total EEO mass with perigee<2000 km is 843 tons, 3/8 as much as the 2200 tons of LEO mass at risk of collision. But the average EEO mass in LEO is only 52 tons, and EEO objects are <1% of the mass at LEO altitudes where most of the collisions will occur. Hence EEO objects pose far lower risk to LEO than objects that spend all their time in LEO, and can be a far lower priority for removal.

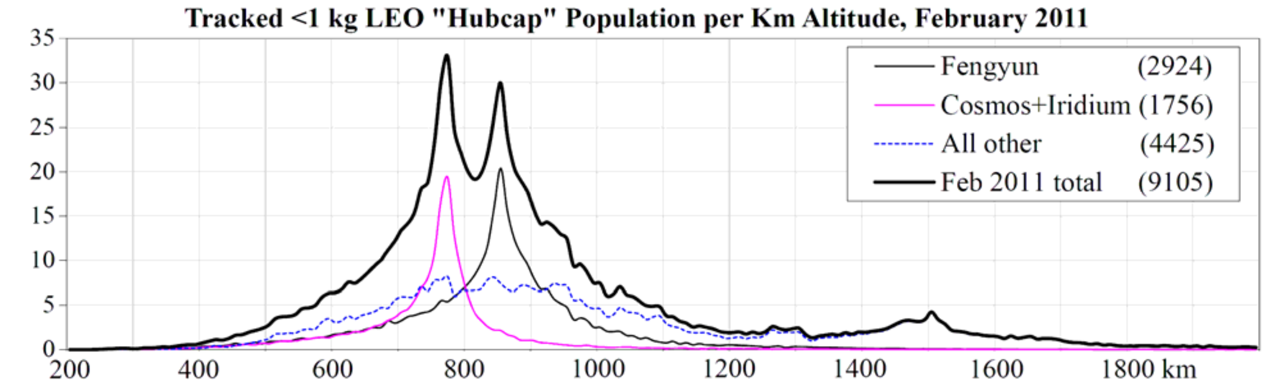


The figure above plots my estimate of mean annual creation of >1 gram shrapnel by infrequent collisions of objects ≥1 kg in LEO, vs collision altitude. The total is ~9,000/year, of which only ~3% are due to fragment/intact collisions involving the 109 fragments >1 kg. The ~9,000/year total is based on my estimate on pages 7-9 that such collisions have a 6%/year chance and should create on average as much shrapnel as the 2007 and 2009 collisions combined, plus my estimate on page 13 that those collisions together created ~151,000 >1 gram pieces. The linear plot above delivers a clearer message than do the log plots on page 4: most shrapnel created by accidental collision between intact objects will be created in a few narrow altitude bands, mostly between 750 and 1010 km, and often consisting mostly of 1-2 object types from one country.

This plot was generated from a detailed debris collision analysis spreadsheet, from a catalog for February 2011 provided by NASA JSC. The plot shows shrapnel creation vs. ***collision*** altitude. The altitude distribution after creation is far broader and smoother. It is shown on the next page.

My spreadsheet assumes that the ISS maneuvers to avoid all tracked objects, that functional LEO comsats avoid the rest of their own constellation but not other objects, and that unlisted assets avoid all tracked objects. The main threats are from Russian objects at 840-850 km and 950-1010 km. The 840-850 km cluster is mostly >8-ton Zenit stages and their >3-ton Tselina-2 payloads. The 950-1010 km cluster is heavier, but more spread out. Most shrapnel from it will have 81-83^{o} inclination. This poses disproportionate risks to sun-synch assets, as explained on pages 37 & 42.

In this paper, "altitude" is defined the same way as "apogee" and "perigee." It is the object's distance above the earth's equatorial (not local) radius, with a -7.5 km * Sin(NLat) N-S offset that is used by SGP-4 to keep eccentricity fixed through apsidal recession. That offset is common to all orbiting objects. An object in polar orbit having "zero eccentricity" in an SGP-4-compatible TLE elset is actually 15 km higher over the S pole than the N pole. The apsidal recession of all "eccentric" orbits is with respect to this offset. The offset is caused by earth oblateness plus the asymmetric J3 ("pear-shape") gravity term. My collision analysis spreadsheet assumes sinusoidal oscillation between "apogee" and "perigee" altitudes for LEO objects, but uses a better altitude-vs-time fit for EEO objects when in LEO. The spreadsheet fills 10-km-wide altitude "census" bins based on LEO object altitudes at 24 points around their orbit. It assumes that the phasing of apsidal recession and nodal regression of both the same and different objects is all uncorrelated in the long run. I use 10 km altitude bins based on tests that showed that using narrower bins or shifting bin edge altitudes had little effect on predicted collision rates even for the 2 narrowest altitude clusters (Iridium and Zenit). Note that the non-zero bin size also mimics some effects of "altitude diffusion" caused by short-term differential orbit decay of different objects.

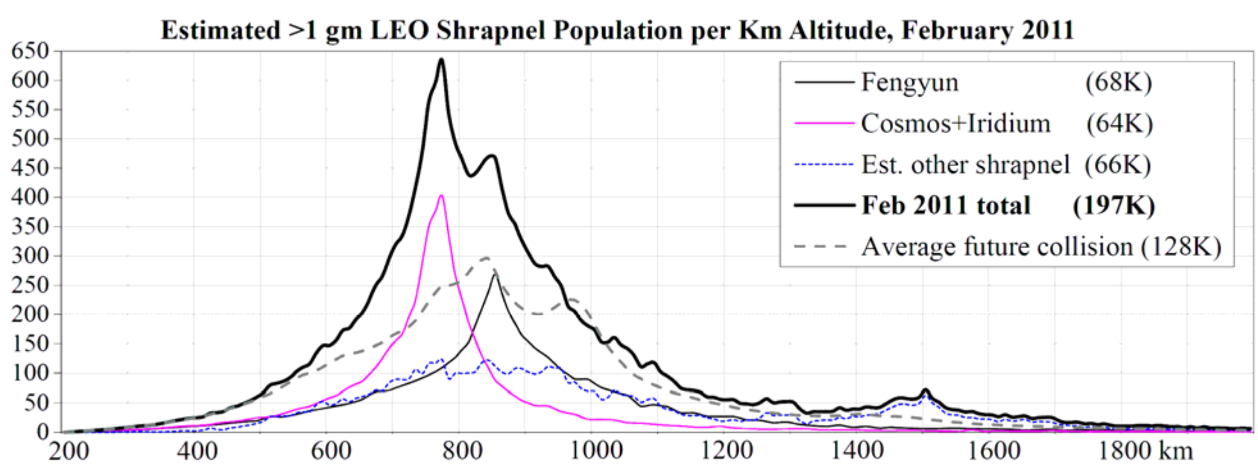


The 4 lines in the plot above show the altitude distribution (as defined on page 5) for all tracked <1 kg fragments ("hubcaps") in low earth orbit in February 2011. Fengyun did create 67% more such fragments than Cosmos + Iridium (totals for 200-2000 km are listed above in the legend), but Fengyun also spread them over a wider altitude range, so the peak values are comparable.

As discussed on page 7, most of these fragments seem far too light to cause thorough disruption of the ton-class objects that have most of the target area and mass in LEO. And the fact that they are tracked does let them be dodged by active assets. So they actually pose less direct threat than untracked "gram-class shrapnel," which appears capable of disabling most working satellites.

The plot below estimates existing and future shrapnel >1 gram, based on the counts estimated on page 13. For the 2011 altitude distributions, I start with those for the tracked hubcaps above. But I assume that the hypervelocity collisions that shredded Fengyun, Cosmos, and Iridium eject >1 gram shrapnel twice as fast as cataloged fragments. So I double the altitude spread and halve the height. I also assume that added drag on the lower tail of the stretched distributions reduces long-lived counts there. So I scale those counts down linearly, from 0 at 200 km to full count at 700 km. That drops those counts 13% from the values on page 13. Finally, I assume that shrapnel created by less energetic events than Fengyun and Cosmos/Iridium is 1/3 of the >1 gm shrapnel, vs 49% of <1 kg tracked fragments. I do not stretch its distribution, since it has many sources.

The plot below also shows my estimate of the average distribution of >1 gram shrapnel from a future intact/intact collision. It uses an average of the 2X-stretched Fengyun & Cosmos/Iridium hubcap altitude distributions, integrated over the collision altitude distribution on page 5. Then I scale down the counts for altitudes < 700 km as described above. That adjustment reduces the estimated average long-lived yield of a future collision by 15%.



Discussion of Conclusions C1-C9

C1. Improved industry practices will continue to reduce non-collision sources of debris. The US has provided long-term leadership in developing and implementing better practices and effectively encouraging other countries. Even broader collaboration may be worthwhile. As one example, more US collaboration with China may have raised their awareness of debris issues and led to use of a lower-altitude target for their 2007 A-sat test. One example is a Chinese stage that reentered 5 days before the actual test, and was at 230 km altitude a week before that.

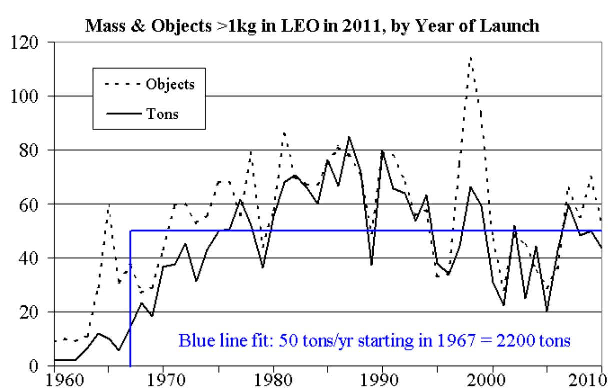
C2. Most tracked collision fragments appear too light to thoroughly disrupt large objects. The expected collision kinetic energy threshold for thorough disruption of an object is 40J per gram of total mass. (Most ground tests have used 40-60J/g.) Typical LEO collision speeds are 10-15 km/sec, so disruption requires impacts by ~1/2800 to ~1/1250 the target mass. Excluding ISS, which actively avoids all tracked objects, over half the mass and area in LEO are in 1-2.5 ton objects, and the rest is evenly split between objects <1 ton and >2.5 tons. If 1-2.5 ton objects and 10-15 km/sec velocities are typical, impactors >0.4-2 kg are needed for thorough disruption.

I studied the orbit decay of all tracked Fengyun, Cosmos, and Iridium shrapnel <1 kg in 2009-10. Median ram-area/mass is A/M=~0.09, 0.075, and 0.23 m^2/kg for the 3 groups. An A/M of 0.09 m^2/kg could be tumbling 2mm aluminum alloy sheet. The A/M distributions are all roughly log-normal, with standard deviations of factors of ~3 above and below median. So ~16% of tracked shrapnel has >3X the median mass for its L_c, and ~1.8% has 10X the median. From the plots on page 11, the median tracked L_c is ~0.14 m. For L_c>1.67 mm, NASA estimates area as $A=0.557 * L_c^{2.0047}$. Hence 0.14m ~median-L_c tracked pieces with median A/M=0.09 m^2/kg weigh ~0.12 kg. So most of the tracked collision fragments should be well below 0.4-2 kg disruption thresholds.

Fragment/intact collisions do create new shrapnel, but apparently only a small fraction of tracked collision-generated fragments can shred typical 1-3 ton objects. So collisional cascading may not become a major shrapnel source until intact/intact collisions create far more heavy fragments.

C3. Chances of a collision between two large objects in LEO are ~6%/year (and growing). A collision risk of 6%/year may seem too high, since no accidental collision between large intact objects in LEO occurred until 51.3 years into the space age. But the collision risk scales with the square of the number of objects at crowded altitudes. Heavier objects are also larger, so collision rates should nearly scale with the square of total mass, integrated over altitude.

One can roughly model historical launch data on the right by neglecting 1957-1966 and assuming a fixed net mass addition rate of 50 tons/year to long-lived orbits starting in 1967. (This excludes the 450-ton ISS. ISS dodges all tracked objects and hence cannot generate long-lived collision fragments.) Adding 50 tons/year gives the correct total of 2200 tons in 2011. With this simple fit, the 2009 collision occurred after 42 years of 50 ton/year source mass linear growth.



If that 50 ton/year linear growth continued along with previous altitude clustering, collision rates should scale with the square of time since ~1967. But since ~1995 Russia has greatly reduced its mass additions to the most crowded altitudes, so future growth in collision rates should be lower. If the change in mass addition to the most crowded altitudes since 1995 is equivalent to halving the mass addition rate since then, and one collision was likely by 2009, the risk in 2013 should be 6%/year, and another collision is >50% likely by 2024. A far more detailed debris collision analysis spreadsheet that accounts for object sizes, altitude clustering, and inclination effects also suggests a current 6%/year risk of collisions, and an average total mass of 2855 kg per collision. An independent analysis by Eugene Levin also gives similar collision rates and average masses.

I studied LEO debris removal under a NIAC grant in 2002. I thought then that most new debris created by accidental collision would come from small fragments hitting large intact objects, since tracked fragments outnumber intact objects ~4:1, but intact objects have most of the total area.

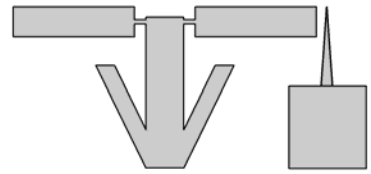
But collisions between 2 large objects involve ~4X larger collision cross-sections. This makes the collision rates comparable. Average collision cross-section is a property of a pair of objects, not of either one by itself. One can roughly estimate it by taking the square root of the cross-sectional area of each object, adding the two, and squaring the sum. This is correct for spheres and close for small/large collisions, but underestimates average collision cross-sections for pairs of similar-size objects other than spheres, especially when their aspect ratios are far from 1:1.

For example, consider typical $6m^2$ intact objects and $0.01m^2$ fragments. Collision cross-sections are $6.50m^2$ for fragment/intact collisions, and $>24m^2$ (over 3.7X larger) for collisions of two non-spherical intact objects. So intact/intact collisions should be about as frequent as fragment/intact impacts despite there being only ¼ as many impactors and N-1 targets. Further, intact objects are more tightly clustered in altitude; the mass per collision is 2X that in fragment/intact collisions; and the energy available to shred that 2X larger mass is radically higher. Hence the total shrapnel created by intact/intact collisions should still be much higher than that created by fragment/intact collisions, even if all tracked fragments could shred large objects.

C4. Average future collisions will be about as bad as the 2007+2009 events *together*.
Spacecraft fluids add to collision energy but not directly to long-lived debris mass, so I focus here on dry mass. Cosmos 2251 had ~900 kg dry mass, and Iridium 33 ~556 kg. Fengyun 1C is listed as having an initial mass of 958 kg. I assume ~900 kg dry mass. This gives ~2356 kg total. The A-sat mass that shredded Fengyun is unknown. But that appears irrelevant. As discussed on page 9, most tracked debris is dispersed from the trajectory of its source object at only a few % of orbit velocity. All tracked fragments ascribed to the A-sat test trace back to Fengyun's original trajectory. The A-sat probably had a negative perigee, so its debris would deorbit quickly. Hence the source mass for the still-orbiting 2007 and 2009 collision fragments ***together*** is ~2356 kg.

Now compare that with future collisions between two ≥1 kg objects in LEO. About 30% of the total LEO mass is in 1407-1440 kg spent Russian stages. Many are clustered at 960-1010 km, so they cause disproportionate risk. Their collisions involve 2.8-2.9 tons, vs 2.35 tons for the 2007 plus 2009 collisions. More generally, based on a detailed collision analysis spreadsheet, and an independent analysis by Eugene Levin, collisions between any two ≥1 kg objects now in LEO may average ~2855 kg of total mass, based on current populations of LEO objects ≥1 kg.

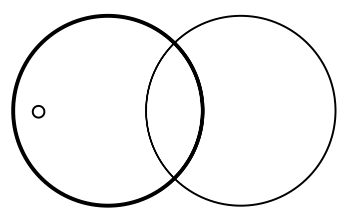
A source mass of 2855 kg from 2 objects is 21% more than the 3 source objects in the 2007-9 collisions ***combined.*** But small-mass yield is thought to scale with source object mass to the 0.75 power, so ***average*** yield may be $\sim 1.21^{0.75} * (2/3)^{0.25} = \sim 1.04$X the 2007-9 total. Averaging over a range of source masses reduces this slightly, to about the 2007-9 total. On page 13, I estimate ~151,000 >1gram objects from the 2007-9 collisions, so future collisions may average about that.



Many collisions may also release far more energy. Iridium and the smaller but heavier Cosmos are shown here at 1/200 scale. Iridium was controlled at the time, with its body vertical and its solar arrays facing the sun. Cosmos was uncontrolled. Iridium was heading north and coming into the sun, while Cosmos was heading slightly south of east. Relative to Iridium, Cosmos approached nearly from the sun direction, and hence nearly normal to Iridium's solar arrays. Impact with only a solar array may be more likely than impact with Iridium's body. There are rumors that much of Iridium may remain in one piece, and Cosmos did create 2.6X as many small tracked fragments, with ~1/3 the Iridium fragment A/M. That is ~8X the tracked small fragment mass, from ~1.6X the source mass. Many (but not all) collisions may involve more overlap and energy release, and better shredding of both objects.

One further caution is relevant. About 8% of the LEO mass is 22 Zenit second stages that weigh 8-9 tons each. These stages are also large: 3.9m diameter and 10m long. Of these 22 stages, 19 are at 800-860 km (many near 840-850 km), along with their Tselina-2 payloads and several other multi-ton objects. The Tselina-2 payloads are listed as 3250 kg. Collisions of Zenits with each other or their payloads would involve total dry source masses of 11-18 tons, or 5-8X the total source mass for the 2007 and 2009 collisions ***together***. Such a collision could occur at any time. It would immediately and drastically degrade LEO. Such collisions have a <1% chance per year, but they do make a significant contribution to the overall shrapnel-creation problem.

C5. Most intact/intact collisions directly involve only small parts of each object's mass.
It seemed very puzzling to me that the 2009 collision generated two distinct streams of debris, each ejected around the original trajectory of one object, typically at 1-2% of orbit velocity. At first it seemed as if heavy parts of each object must have passed through very light parts of the other. But that requires "bullets in foam" or "crossed-pitchfork" satellite mass distributions that are very unrealistic. There was another puzzling clue, that each debris stream spread out in all directions, not just in the direction of the other object's relative motion.



An explanation for 2 distinct debris streams appeared when I studied collision CG offsets. Consider the heavy circle at right, and impact with it by either other circle. Each light circle has the median collision offset distance, $0.7071(\mathbf{r}_1+\mathbf{r}_2)$. Hence half of all collisions have less overlap, and half have more. The small circle is totally involved, but the overlap of same-size circles is only 18% of the area of each circle.

With spheres, the median volume overlap is only 11%. With same-size squares at random angles, the median area overlap is <10%, and the median volume overlap for collisions of equal-size cubes is even lower. With "similar" but not identical sizes, the overlap is lower for the large object and higher for the small one, and when the sizes differ enough, most collisions will fully involve the smaller object.

But even if trajectory overlaps may typically directly involve only 1-10% of the total colliding mass, intact/intact collisions will release 10-100X the energy of “catastrophic” fragment/intact impacts having ~1:1000 mass ratios. Masses colliding at up to 15 km/sec see pressures so high that even solid metals become very compressible. Compression may cause enough adiabatic heating to melt solids, despite modulus and melting point increases with compression. But this may be largely reversible, as with fluids. Extreme pressures and gradients may let most solids shear nearly freely. Shear causes heating, but heating reduces shear strength, so solids may see substantial shearing without ever melting. Within microseconds, directly colliding masses will decompress and tear apart into irregular sprays of liquid, solid, and/or re-solidified material.

Hypervelocity tests on the ground show a cloud of tiny particles whose leading edge moves out at 30-50% higher speed than the original collision. The kinetic energy of a typical ~12 km/sec hypervelocity collision is sufficient to heat, melt, further heat, and vaporize aluminum, but this is not necessary: most of the collision energy can be carried away by redirected kinetic energy, without ever being thermalized. Some mass will be vaporized, but most of the vapor will expand more slowly than the hypervelocity spray, so it will carry far less momentum and energy.

C6. Hypervelocity sprays created by direct impacts can shred the rest of both objects. Some spray debris will escape without additional collisions. Its trajectory is a vector addition of random ejection at 5-20 km/sec from a ~horizontal collision CM velocity of 0-8 km/sec for the directly involved mass. Some will fall out of orbit, and some will reach escape. Much of it will have orbital energy, but with large enough vertical velocity to reenter. Only a small part may stay in orbit, and it may spend much of its time above LEO. Fine particles will pose a threat to astronauts during EVA, but may not do much else. The main effect is that concentrated sprays can shred the adjacent mass that misses direct impact. Masses in the direct trajectory overlap of a collision may see several collisions in parallel and in series. The sprays will interact and fan out over large solid angles that may include most of the mass of either or both source objects. The greater mass and speed and irregular timing and distribution of hypervelocity sprays should make them far better at shredding the rest of an object than shock or expanding vapor can be. Hence such shredding may create far more small shrapnel than explosions can. Such spray/shred sequences are apparently not modeled in some hypervelocity impact computer simulations.

C7. Shrapnel area/mass and dispersal velocities may be predictable from bills of materials. Most of the solid mass of both satellites and rocket bodies is in sheet-like materials, and most of it (other than deployed solar arrays) has two or more well-separated layers. Hypervelocity spray will spread in all directions, so it should be less effective at completely disrupting a large object than a similar-mass small object that directly punches into it. But the spray may usually involve 10-100X as much directly interacting mass and energy as typical “catastrophic” fragment/intact collisions having mass ratios of order 1:1000. Hence hypervelocity spray should overcome the “directionality disadvantage” and CG offset, and shred most source objects more thoroughly.

Pictures of debris from ground hypervelocity tests of simulated multi-layer satellite structures show that most of the fragment mass remains sheet-like, like shrapnel, with apparent thicknesses near the original ones. This suggests that one may be able to predict the area/mass distribution of shrapnel from a bill of materials for its source object. Correlation with relevant ground tests may even allow useful estimates of typical shrapnel dispersal velocities.

C8. The 2007 and 2009 events are far more relevant than older data, analyses, and models. The largest fragments created by intact/intact collisions may vary more with the object design, orientation, and CG offset than smaller fragments do. And large fragments are less thoroughly shredded than small fragments, so some multi-layer items like electronics boxes may stay largely intact. This may create the bi-modal area/mass distribution seen in drag data for large fragments. Hence to extrapolate the statistics of 1-10 cm shrapnel from larger shrapnel, it may make more sense to extrapolate down from the many 10-30 cm objects, than to include the objects >30 cm in each stream, which are only a few % of tracked fragments and may have less relevant statistics.

This suggestion has significant implications, as can be seen by studying the 3 plots below. The first two are taken from NASA JSC's Orbital Debris Newsletter of April 2010, which is available at http://orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv14i2.pdf.

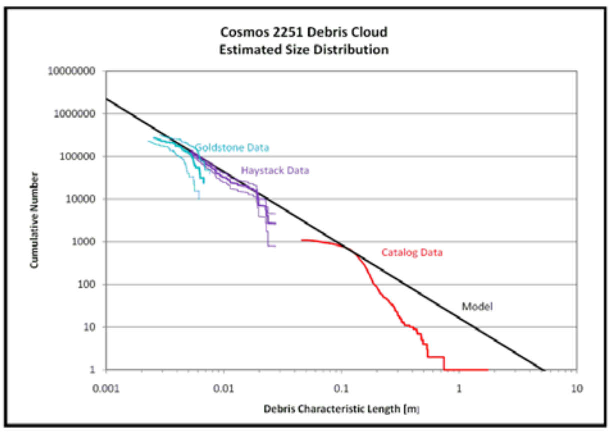


Figure 3. This is a composite size distribution of the Cosmos 2251 debris cloud based on Goldstone, Haystack, and SSN data compared to the model size distribution. The Goldstone and Haystack populations also show a +/- one sigma uncertainty on the inferred population.

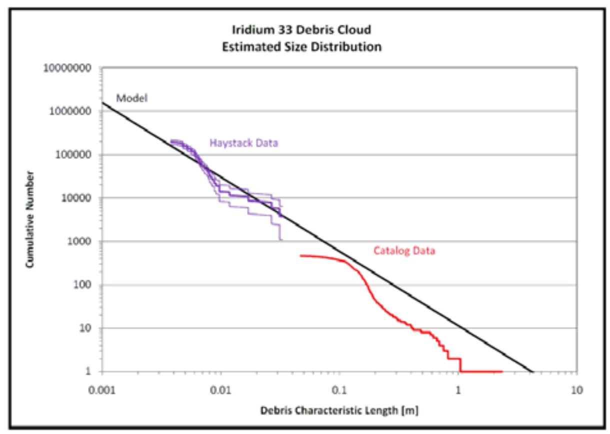


Figure 4. This is a composite size distribution of the Iridium 33 debris cloud based on Haystack and SSN data compared to the model size distribution. The Haystack population also shows a +/- one sigma uncertainty on the inferred population.

The straight "Model" lines above represent the "NASA Standard Breakup Model" for collisions, which is documented at www.sciencedirect.com/science/article/pii/S0273117701004239. This model is based on data from ground tests with kinetic energy/mass of 40-60 J/g, plus high-energy A-sat flight tests in 1985 and 1986 that could not detect fragments <10 cm. So the accuracy of predicted gram-class shrapnel counts for intact/intact collisions with 10-100 $*$ 40J/g energy is an empirical question. A 2008 AMOS paper describes that model, and shows its fit to Fengyun A-sat shrapnel (see www.amostech.com/TechnicalPapers/2008/Orbital_Debris/Stansbery.pdf):

The actual NASA collision model formula is:

$$N_{\geq Lc} = 0.1 * KgMass^{0.75} * L_c^{-1.71}$$

where $N_{\geq Lc}$ is # pieces exceeding a characteristic size L_c (in meters), and L_c is the average of the 3 longest orthogonal dimensions of a fragment. The model focuses on fragment/intact collisions, in which the intact object provides nearly all the mass. The lines plotted above are consistent with finding $N_{\geq Lc}$ separately for each source mass and its debris stream. (This increases $N_{\geq Lc}$ by $2^{0.25}$, or 1.19.)

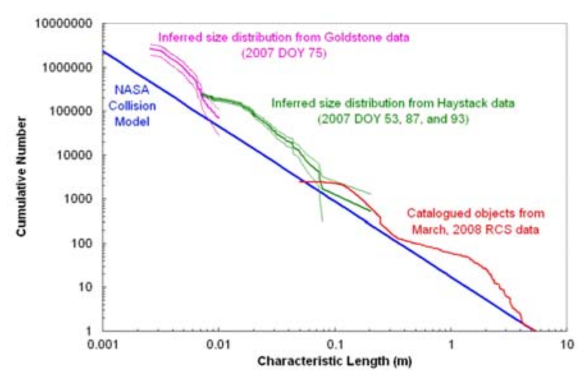


Figure 1. Size distribution from Fengyun-1C collision. Data from SSN catalog and Haystack and Goldstone compared with NASA Standard Breakup Model for collisions.

The most pronounced features of the Cosmos and Iridium plots on the previous page are steeper slopes and large shortfalls in large fragments compared to the NASA Model. This is important, because most of the source mass is expected to end up in the large fragments. If more of the total mass ends up in smaller fragments, which the standard model says have only a small part of the total mass, then one must carefully study Haystack and Goldstone data and analyses to find where the “missing” mass ends up. In contrast, Fengyun data track the slope of the NASA Model better, but exceed the model by a factor of ~4 over most of the range of solid data, except for the few largest fragments. For all 3 streams, the catalog curves start to asymptote (ie, be incomplete) below ~12.5-14 cm. But the total counts do fit a soft ***average*** size threshold near 10 cm.

If interpreted well, Haystack may allow the best constraints on estimates of populations of small but lethal shrapnel. But there are problems. First, the stairstep curves are inferred from small numbers of objects that passed through a ~1 km wide radar beam. If I am interpreting the data correctly, the stairstep curves on the previous page suggest that the total number of detections judged related is ~50 each for Cosmos and Iridium. Each object represents ~3,000 objects that did not pass through the sample volume during the observations. The staring angle used by Haystack (75^o elevation, looking east), causes a Doppler shift that varies with the target’s orbit inclination. Near 800 km altitude, the Doppler is 97% of the target’s vertical velocity, plus 0.90 km/sec for 65^o inclination, or 0.55 km/sec for Cosmos (at 74^o orbit inclination), or -0.45 km/sec for 99^o sun-synch orbit. Since Doppler is affected by both orbit inclination and vertical velocity, it is hard to be sure which objects were from Cosmos. Figure 1 in the Orbital Debris Newsletter article shows that they discarded 89 of the 112 detections made in one day:

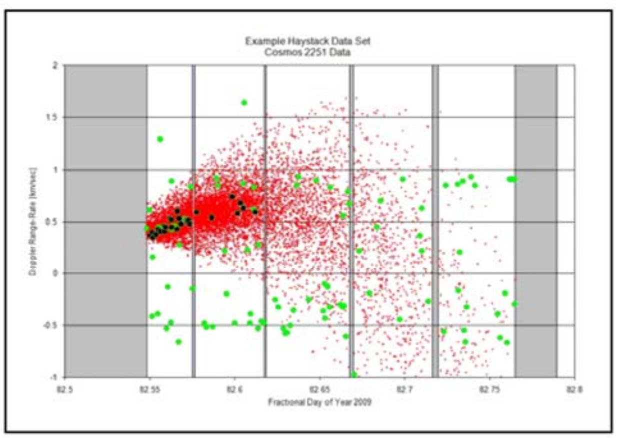


Figure 1. This is a sample of Haystack data taken on day 82 of year 2009, at a time when the Cosmos 2251 cloud was passing through the beam. Time is on the x-axis, the grey gaps represent periods when the radar was not taking data, and the y-axis represents the Doppler range-rate measurements. The green dots represent objects detected that are not believed to be part of the collision cloud, and the black dots represent those that have been assigned to the collision cloud. The cloud of red dots are predicted values for the model cloud.

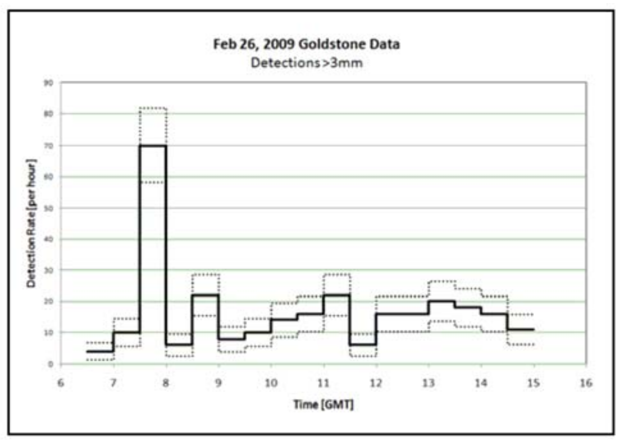


Figure 2. This chart shows the detection rate in the Goldstone radar data from 26 February 2009. The Cosmos 2251 cloud shows up as a noticeable spike in the detection rate between 07:30 and 08:00. Dotted lines are one sigma error bars in the detection rate.

The red cloud was generated by Monte Carlo simulations using shrapnel dispersion assumptions from NASA’s Standard Breakup Model. That cloud was used to judge whether detected objects were related (23 black points) or unrelated (89 green points). Hence only 23/112 or 20.5% of the points were judged to be from Cosmos. Most of the rejected points are in two distinct bands, one near –0.5 km/sec (probably Fengyun and other sun-synch debris), and a thin band at +0.9 km/sec (65^o inclination) which may be mostly NaK coolant droplets leaked by Soviet reactors decades ago. But even if we exclude points with Doppler below +0.2 km/sec or above 0.75 km/sec, there are still 20 green points, many of which may actually be from Cosmos. NASA accepted only 23 of the points as being from Cosmos, but the actual Cosmos count may be well above that.

Most lethal shrapnel will be "gram-class" and will have L_c=1-3 cm. It may make sense to re-analyze existing Haystack and test data with a specific focus on that size and mass range, and with looser dispersal velocity and Doppler constraints than NASA used on the previous page.

The NASA Standard Breakup Model for collisions also includes a statistical model for A/M and hence fragment mass. The log of A/M is normally distributed and both the mean and standard deviation change with L_c. "A" is the average cross-sectional (or ram drag) area. For randomly tumbling objects, that is 1/4 the non-concave area, or just over half the area of one side of thin flat shrapnel. For shrapnel with L_c=2 cm, the NASA model estimates median and mean masses of 0.51 and 0.86 gram. This is equivalent to aluminum alloy shrapnel ~0.46 and ~0.78 mm thick.

The standard model's estimates of A/M for objects with L_c<8 cm are based on correlation with fragment/intact ground impact tests. The model says that as L_c drops by a factor of 3.1, from 5.6 to 1.8 cm, median A/M increases by 5.0, and a growing standard deviation increases mean A/M by 5.6. Hence in this range estimated shrapnel thickness drops much faster than the transverse dimensions. In contrast, for ***all*** larger and smaller L_c values, estimated median and mean A/M change far slower than L_c, rather than faster. This local change may be due to ground test target design, such as material changes with thickness. Whether such drastic A/M changes are likely in shrapnel from the 2007, 2009, or future collisions is a critical unknown. Comparing test target materials and thicknesses with resulting fragment thicknesses may tell us whether A/M can be estimated better from NASA's correlation, or from the actual bill of materials for each target.

Rather than using ground-test data to infer A/M vs L_c, it may be better to use a direct mass correlation of ground test data: scale the count of fragments of mass>M with $M^{-0.75}$. More ductile materials may create fewer fragments of each L_c, but they may be thicker, so correlating count with mass rather than L_c may fit a wider range of source objects. As with the standard breakup model, a $M^{-0.75}$ distribution puts most of the mass into the heavy pieces. To minimize extrapolation errors, it seems best to derive a scale factor for gram-class counts from the closest observable part of the distribution. The plots on page 11 suggest that the counts >14 cm may be nearly complete. And 14 cm is near the median size of the <1 kg fragments I estimated A/M for (see page 7). Those estimates give median masses of 120, 144, and 47 grams for 14 cm Fengyun, Cosmos, and Iridium fragments. Ignoring the asymptote that starts below 14 cm, Fengyun has a count vs L_c power law of -2.2 near 14 cm. That plus a ~3:1 log-normal standard deviation in A/M mean that for each of the ~1500 Fengyun fragments with L_c>14 cm, there are 1.43 (mostly smaller but thicker) objects heavier than the median-mass 120 gram L_c=14 cm fragment. So the Fengyun count >1 gram should be $\sim 1500 * 1.43 * (1/120)^{-0.75} = \sim 78{,}000$. For Cosmos and Iridium, the L_c slope just above 14 cm is -4.0. That steeper slope gives a ~3.29 count multiplier, which is over twice that for Fengyun. So Cosmos should have $\sim 440 * 3.29 * (1/142)^{-0.75} = \sim 60{,}000$ >1 gram fragments, and Iridium $\sim 220 * 3.29 * (1/47)^{-0.75} = \sim 13{,}000$. The total shrapnel yield from these 3 objects may hence include ~151,000 "probably lethal" fragments >1 gram.

It should be feasible to improve the above mass-based extrapolation from the catalog data by using current counts plus object-specific L_c and drag-based A/M estimates. This allows better estimates of count vs mass near L_c=14 cm, for extrapolation down to ~1 gram. Updated counts also represent a more "aged" (ie, heavier) population that is more representative of longer-term risks. Radically better estimates are possible if we find, track, and catalog many 1-3 cm objects and directly estimate their size, A/M, and mass. Pages 22-25 discuss a way to do this.

C9. The main threat is untracked gram-class shrapnel, which we know far too little about. Large expensive spacecraft with affordable levels of shielding may be able to tolerate impact by shrapnel up to "of order" 1 gram. The lethal mass threshold will be lower for thick or edge-on impactors than for larger thin pieces that do not hit close to edge-on. This suggests a lethal size threshold <1 cm for aluminum alloy spheres, and 1-2 cm for more typical sheet-like shrapnel.

For each >10 cm tracked collision fragment that ISS or other high-value satellites actively avoid, the NASA model's $L_c^{-1.71}$ correlation suggests there are comparably close conjunctions with ~2 fragments >5 cm that are not now tracked but should be by the planned S-band fence, plus ~13 pieces 2-5 cm that may be missed by an S-band fence but are still very likely to be lethal, and another ~35 that are 1-2 cm and may be lethal. Potentially lethal conjunctions may occur even more often than this, depending on shrapnel A/M and on interpretation of the plots on page 11.

The threat to spacecraft scales with the product of target area and cost of asset loss, and high-cost assets are also larger and often have longer-duration missions (which also increases the chance of loss). As a result, the threat to unmanned LEO spacecraft turns out to be dominated by the threat to high-value satellites like Hubble and NRO assets, as shown on the spreadsheet on page 43. Shrapnel effects are necessarily highly variable, because each piece is different, and even the same piece can hit assets in many locations at many speeds, angles, and attitudes. The low rate of such high-value losses also adds statistical uncertainties. Hence even if we can eliminate our existing ignorance about shrapnel count as a function of size, mass, and altitude, the future costs of disabling impacts will still involve substantial uncertainties.

The ISS merits special concern, and not just because it is manned. If you compare it to all other operating spacecraft in LEO combined, ISS has ~50% higher mass (450 tons), probably higher cost, and a non-trivial fraction of their combined vulnerable cross-section. High air drag at ISS altitude does clear debris quickly, but the large shrapnel inventory above ISS will keep raining shrapnel down through ISS altitude for decades. Shrapnel threats to ISS will jump after each significant collision and then gradually decay, on a timescale that varies with collision altitude. (So much of that shrapnel may last much longer than that from Fengyun and Cosmos/Iridium.) Damage to ISS by pressure-shell breaches will vary with the size of the breach, but the required responses and impacts on ISS operations may be similar for most such breaches.

Many spacecraft have particularly vulnerable exposed items like antennas, sensors, mechanisms, or cables, and even interior items right next to an outer wall can be vulnerable. But a study of impact vulnerability of the Canadian RadarSat showed that shielding adding only 0.6% to the total mass could eliminate most "excess" vulnerability. As shielding becomes more common, most of the threat may come from shrapnel large enough that impact at most body locations would disable the asset. So using a single lethal threshold for each asset may be reasonable.

The work by Ailor et al. considered not just total losses, but also loss of usable satellite life, from impact-induced solar array damage adding to normal solar array degradation. The net effect was a very small fractional increase in expected overall program cost. The actual relative impacts of fractional losses may be even less than they estimated, since adding small losses to an expected gradual power loss allows time for programs to adjust replacement launch schedules. This poses fewer problems than dislocations caused by sudden full loss of an asset. So the spreadsheet at the end of this paper ignores small shrapnel impacts that cause less than full asset loss.

The Excel shrapnel-cost analysis spreadsheet on the last page of this paper lets one choose a different lethal shrapnel mass threshold, asset vulnerable area, and orbit for each of 5 classes of spacecraft, ranging from ISS to cubesats. The shrapnel lethal threshold is specified as mass rather than size, because mass is more relevant than the more directly observable "L_c" parameter. If we can use optical or other survey techniques to find and track some shrapnel down to 1-2 cm, and determine its orbit decay and hence mass, we can determine actual lethal shrapnel populations as a function of altitude and mass, and radically improve our knowledge of actual impact threats.

Even if the "likely loss" threshold for high-value spacecraft is as large as median-thickness 2 cm shrapnel, that is far less important than the facts that the threshold is ***far*** below 10 cm, and that there are no current plans to track most such shrapnel. Reducing the tracking threshold to ~5 cm allows detection and avoidance of only a small fraction of the probably lethal shrapnel exceeding 1-2 cm in size. Whatever the size threshold and population of such shrapnel, the problem will get worse until we actively reverse trends. Otherwise even currently-pessimistic projections of asset losses to shrapnel will eventually become too optimistic.

Most of the mass of most rocket bodies (tanks and engines) is in two well-separated layers with a few different thicknesses, materials, and separation distances. By contrast, most satellite mass is in many-layered objects with a wider range of thicknesses, materials, and sheet separations. It is essential to consider both, since LEO contains ~1100 tons of each. Shrapnel from many-layer objects may resemble conventional explosion shrapnel more than shrapnel from two-layer rocket bodies does. But Iridium appendages that missed the direct impact may shred more like the far wall of a rocket tank, than like many-layer satellite bodies like Fengyun or Cosmos.

One other key issue is that whatever the "likely loss" size threshold is, most of the threat will come from shrapnel not far above that threshold. If the power law for count vs L_c in this region is close to -1.71, as estimated by NASA's collision model, half of the >1cm shrapnel will be <1.5 cm, and half of the >2cm shrapnel will be <3cm. So rather than referring to 1-10 cm shrapnel, it really makes sense to refer to and focus on 1-3 cm shrapnel. We can't deal with most of this problem if we can't deal with that part of it. Reducing the SSN threshold from 10 to 5 cm will let satellites dodge only a small fraction of the now-untracked lethal shrapnel.

At present, we can guess that the dispersal velocity and hence altitude range of "probably lethal" shrapnel are probably somewhat larger than those of tracked debris, and we can guess that such shrapnel may have average A/M not drastically higher than that of the smallest tracked fragments created by intact/intact hypervelocity collisions, ***if*** both are made mostly by shredding the same source sheet material. But those are guesses, not knowledge. What we don't know includes:

1. The minimum shrapnel mass likely to be lethal to current & future high-value LEO assets;
2. The accuracy of NASA's Breakup Model for gram-class shrapnel creation & distribution;
3. The typical radar cross-section or visual brightness of such "barely-lethal" shrapnel;
4. Differences in properties of small but lethal shrapnel generated from rockets vs. satellites;
5. Current and likely future populations and altitude distributions of such lethal shrapnel;
6. The cost and effectiveness of ruggedizing future LEO satellites against such shrapnel;
7. Or the costs of either preventing or removing, or tracking & avoiding, most such shrapnel.

Discussion of Recommendations R1-R7

R1. Do more realistic ground tests and analyses to estimate lethal shrapnel mass threshold. Hypervelocity impact tests are done on the ground to compare impact shield designs, find impact energy thresholds for large-scale shrapnel creation, study impactor deceleration in aerogels, and test military offensive and defensive performance and models. These tests are expensive, and usually limited to 7-8 km/sec. But an expendable "implosion gun" (see IAF Congress paper IAC-11.A6.3.12 by J. Huneault et al.) may allow controlled tests at up to 15 km/sec or more. Computer simulation models I have seen discussed disregard fragment secondary collisions, but the discussion of collision CG offsets and effects on pages 9-10 suggests that it may be necessary to explicitly model multi-stage spray/shred processes to be at all realistic.

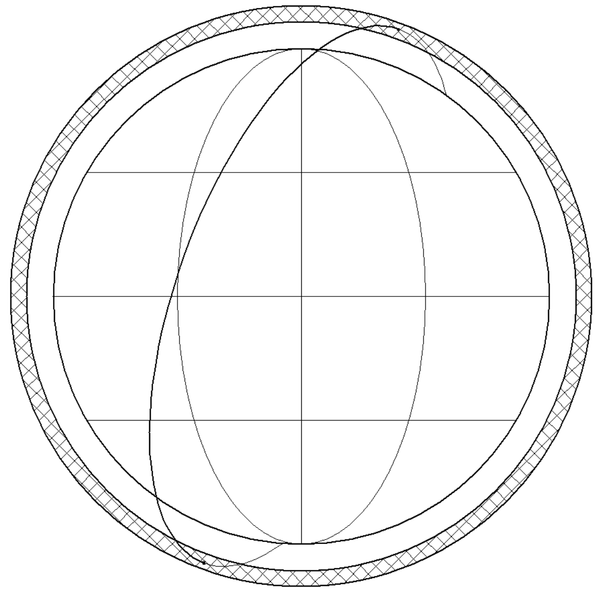
Whether or not new tests are needed, or just better analysis of existing data, it is worth ensuring that we understand the probably lethal mass threshold for small shrapnel, typically aluminum alloy, ~1-2 cm across and 1-3 mm thick. The main issues are breaching of pressurized modules on ISS, and disabling of shielded or unshielded unmanned spacecraft. The best use of ground tests may be validating better simulations or analytical techniques, perhaps using implosion guns, and using representative impactors and targets to generate multi-stage impacts. Tests and/or analyses are needed to understand shrapnel generation and dispersal by hypervelocity spray into rocket bodies, satellite bodies, and appendages. Single or sequenced sprays into 1-, 2-, or many-layer structures may generate significantly different shrapnel populations.

R2. Directly estimate the *mass* of shrapnel that has impacted tracked LEO objects.
One way to estimate count vs. mass of small shrapnel in LEO is to see if shrapnel has already detectably changed the orbits of objects it impacts. Two-line-element ("TLE") data lists mean motion (=orbits/day) with 8 digits to the right of the decimal. Velocity changes <<1ppm and impactor masses <<1 gram may conceivably be detectable, for passive objects in high enough orbits that drag variations don't cause excessive "mean motion noise." A sudden change in the orbit and spin of the Russian BLITS laser-ranging satellite in early 2013 is a possible example. (See www.amostech.com/TechnicalPapers/2013/Orbital_Debris/KELSO.pdf for more details.)

Spent stages seem like useful observation targets, since they have at least two well-separated walls over nearly all their area and hence should usually absorb all the momentum of impactors that penetrate the first wall. They also have simple shapes with reasonably predictable average collision cross-section and drag. The single most common object type in LEO is the SL-8 or Kosmos-3M Russian stage. There were 296 SL-8 stages in LEO in February 2011, and 223 of them had perigees >900 km. This is a high enough altitude for drag to not be too large a source of mean motion noise. In addition, SL-8 stages have much larger average target area (~13m^2) than two other types of similar-mass Russian stages, so they make better impact detectors.

Before pursuing this very far, it is worth estimating how many collisions might be detectable. The plot at the bottom of page 6 suggests that there might be ~210 pieces of shrapnel >1 gram per km altitude near 970 km after the Cosmos/Iridium collision in 2009, ~180 after Fengyun but before Cosmos/Iridium, and ~90 before Fengyun. (This ignores possible concentrations of NaK reactor coolant droplets right near 970 km.) Lighter shrapnel might have counts in accordance with a -0.75 power law on mass, but such a power law may not apply to NaK droplets.

The figure at right shows one way to estimate collision rates. All objects in different orbit planes cross each other's orbit plane twice per orbit. Collision occurs if objects in the plane of the cross-hatched ring are at the crossing point when the other object crosses. That chance scales with the annual number of crossings and collision area divided by ring area. The cross-hatched ring area from 960-980 km altitude is 923E9 m^2. Another object at ~970 km altitude passes through the ring 10068 times/year. The messiest part of the problem is an "arc length multiplier." This is explained on page 42. This parameter accounts for the effects of varying approach angles. Its average value is 1 for near-coplanar orbits, ~2 for typical LEO inclinations, and even higher when $\mathbf{i_1}+\mathbf{i_2}$=~180°. For objects in 74° and 86.4° orbits, the average value is 2.02.



If an object is in an eccentric orbit, you can use average shrapnel densities or explicitly model densities and collision rates vs. altitude around the orbit. If an SL-8 stage has an average impact cross-section of $13m^2$ for 1cm debris, chances of collision per year near 970 km altitude are:

10068 passes * 210 fragments/km * 2.02 {=ArcLenMult} * $13m^2$ / $46E9m^2$ orbit plane area/km alt.

This gives 1 impact by >1 gm shrapnel every 845 years on each SL-8. There are 151 SL-8 stages in near-circular orbits with average altitudes of 960-1000 km, so the expected number of >1gm impacts should be ~0.8 from the 2009 collision through September 2013, another ~0.3 between the 2007 and 2009 collisions, and <0.1/year before 2007, due to lower shrapnel counts then.

These low rates seem discouraging for this concept. But if the actual >1gm population is higher (particularly from NaK droplets), or if one can detect impacts by masses much less than 1 gram, then the number of detectable impacts may be statistically useful.

This analysis made it seem very unlikely that I would find any clear impact signals on one stage, but it still seemed useful to do a first-order reality check on this concept by determining actual "mean motion noise" in historical TLE elsets. I downloaded from www.space-track.org all 10,792 TLEs for one SL-8 stage that has been in orbit since December 1970. I chose catalog object number 4800. It is the 17th oldest SL-8 still in orbit, and the closest to a circular orbit at an altitude high enough to keep drag small (962x976 km). That altitude is the most crowded one for SL-8 stages, and it is also of specific interest because of NaK coolant droplets released near there by Soviet nuclear reactors in the 1980s. If impact rates increase after 2007 or 2009, it suggests those events may be dominant, while steady impacts over time might indicate that NaK impacts are dominant. Note that there are also 67 SL-8 stages between 1140 and 1800 km. They can be used to check altitude sensitivity.

My analysis was very simple: I subtracted mean motion values in adjacent elsets. There were many big gaps in the first 22 years but since 1992 the TLEs have usually been 12-24 hours apart. It turned out that even at 970 km altitude, the largest ΔMM values were all associated with large solar flares or multi-day gaps in data. The next step was to subtract mean trends just before and after a step of interest. For that, I computed the mean ΔMM/rev over the 4 TLE intervals before and 4 after that step, and multiplied that mean slope by the interval of interest. I then subtracted that change from the gross change, to get an estimate of drag-compensated ΔMM at that step.

To make the resulting ΔMM noise intelligible, I converted the ΔMM values into equivalent masses of impactors capable of causing those ΔMM values. Small shrapnel hitting a large spent stage will generally transfer all its momentum to the stage, probably punching through the first wall but being absorbed by the other wall some distance away. In addition, there will be some "splashback" momentum at the first wall. Impact angle is a larger source of momentum transfer variations. As shown with the "drunk driver model" on page 42, objects in near-polar orbit (as most LEO satellites and debris are) are more likely to have near-head-on collisions than low-velocity "side-swipes." So the fractional loss in orbit velocity will usually be 1-2X the mass ratio. Hence if a 1 gram object hits a 1 ton object, the orbit velocity will usually drop by 1-2 ppm. I assume an average multiplier of 1.5 including splashback and impact direction variations. The actual mass of a nominal 1-gram impactor capable of causing a 1.5ppm loss of orbit velocity is then ~3/4 gram for head-on collisions without splashback, less than that with splashback, and up to several grams for smaller-angle impacts.

In near-circular orbits, a 1 ppm loss of horizontal orbit velocity causes a 3 ppm increase in mean motion. So an average momentum multiplier of 1.5 and an orbit mechanics multiplier of 3 give a built-in gain of ~4.5. With these multipliers and MM=13.77 revs/day, 1 gram impacting a 1434 kg SL-8 stage should cause a ΔMM of $1.5 * 3 * 13.77 * 0.001/1434$, or 43E-6 rev/day. This causes a 2.0 km/day change in along-track stage position. This should be clearly observable.

My analysis showed an RMS noise in drag-compensated ΔMM for SL-8 stage #4800 equivalent to 0.5-2 grams in the 1970s, 0.1-0.2 gram in the 1980s, <0.1 gram from 1992-2002, <0.05 gram from 2002-2005, and an extremely low 0.005 gram since late 2005. I repeated this test with a second SL-8 in very similar orbit, SatCat# 4784. Its noise was nearly as low, except that it "bottomed out" at 0.03 gram over the last 8 years, perhaps due to different attitude motion.

After I did this analysis, a colleague told me that the mean-motion noise appeared low because reported values are based on a running average of all observations within the previous 10 days. This led me to consider 2 other TLE parameters: time of epoch and rev #. The time of epoch is listed to the nearest 1E-8 day (<1 millisecond, or ~6m along-track motion), for the estimated time of the ascending node closest to the most recent observation (before or after). But the actual accuracy may be far worse. Dividing time between epochs by #revs may give an unfiltered mean motion estimate. This estimate includes a 193-day periodic term due to changing phase operating on the difference between mean and true anomaly, plus a small difference due to the definition of mean motion used in TLE data. Most of the noise is in updates less than a few revs apart. This causes paired comparable opposed changes. Even with this filterable noise, the RMS noise is <0.3 gram over nearly all of the last 17 years. More sophisticated analysis of this data may allow enough noise reduction to make fairly small real step-changes clearly visible.

If more detailed analysis of the already-filtered ΔMM or epoch time series data can reduce the noise enough, it appears useful to do this for the 222 other SL-8 stages between 900 and 1800 km altitude, and other common stage types in orbits high enough for drag noise to be tolerable. Even with just 223 SL-8 stages >900 km, there is an average area of ~3000m^2 exposed to impact. That is ~80X the area of LDEF, with an average exposure time ~4X longer. The sensitivity threshold may be far below 1 gram when there aren't solar flares, data gaps, or other problems. We may be able to determine count vs mass of small shrapnel directly, and perhaps its variations with altitude and time. (This may be a good student thesis topic.) It may also be worth testing whether any satellite failures correlate with small step increases in mean motion, as with BLITS.

R3. Learn far more about the lethal shrapnel created by the 2007 and 2009 collisions.
As of February 2011, 51.4% of the tracked <1 kg fragments in LEO are ascribed to the 2007 and 2009 collisions. And future $\geq$1 kg collisions may create on average as many tracked fragments as those 2 collisions ***together***. Intact/intact collisions may also generate an even larger fraction of smaller but still lethal untracked 1-10 cm shrapnel. If the characteristics and statistics of such shrapnel do differ from those of most prior fragmentation events, then we should pay far more attention to this debris than to previous debris, in inferring the likely future population, altitudes, mass, and other characteristics of potentially lethal shrapnel in LEO.

It should also be feasible to use cumulative decay data on already-tracked fragments to correlate area/mass distributions with those of the source-object construction, for Fengyun, Cosmos, and Iridium. Even if Russia and China will not provide detailed design data for their satellites, they may be willing to provide information on materials and A/M ratios. Deriving and providing that data will itself raise consciousness in this area, which is useful. And the data should be useful to anyone who is considering adding affordable levels of shielding to future satellites.

Re-analysis of existing data from hypervelocity impact tests on the ground may also allow more insight, if focused specifically on shredding of sheet-like materials by hypervelocity sprays, and on likely shrapnel mass and velocity distributions for few- and many-layer targets and impactors.

High-resolution AMOS or other images of the few largest Cosmos and Iridium fragments may tell us more about what and how much of Cosmos and Iridium were directly involved in impact. This may let us improve predictions of shrapnel generation in future collisions. But collisions between intact objects may have inherently more variable effects than fragment/intact collisions, since variations in overlap and energy release can be far larger, as the figures on page 9 suggest.

The key question is: **What are the counts of gram-class shrapnel vs altitude, inclination, etc?**

Existing sensors and analytical tools may not help much in answering this question, but careful re-analysis of Haystack data from just after the 2009 collision could be useful. And as described on pages 22-25, ~0.5m aperture telescopes may be able to detect, track, and derive single-pass orbit solutions for most shrapnel down to 1-2 cm. Periodic later optical tracking can update the orbits and allow decay and hence A/M estimates. Orbit data can also be used to task Haystack to estimate actual size (which Haystack is apparently good at for ~cm objects), and hence the actual mass of the optically-tracked shrapnel. Even tasking one 0.5m telescope for several hours/day for a few months can let us better quantify the actual populations and threats posed by shrapnel from Fengyun, Cosmos/Iridium, NaK droplets, and other major sources.

R4. Study *all* options for protecting LEO assets from tracked or untracked shrapnel:

1. Upgrade tracking (radar or telescope) enough to track ***most*** probably-lethal shrapnel.
2. Actively maneuver to avoid predicted threats, by thrusting or by adjusting drag area.
3. Orient the ISS solar arrays to shield the pressurized modules as much as possible.
4. Orient spacecraft and appendages to minimize risk, as Hubble did with the Leonids.
5. Add stand-off shielding to at least some vulnerable surfaces of new spacecraft.
6. Combine #4 & #5: add selective shielding and orient that side towards predicted threats.
7. Develop the Orion pulsed laser, both to deorbit shrapnel and to prevent debris collisions.
8. Reduce the creation of new shrapnel by reducing new mass and removing existing mass.

Option #1, upgrading tracking, seems likely to require driving detection thresholds down to 1-1.5 cm to allow tracking and avoidance of ***most*** shrapnel likely to be lethal to high-value LEO assets with affordable shielding. Less substantial upgrades may serve other needs, but they can't allow avoidance of most "probably-lethal" shrapnel. It is unclear whether this is affordable, but there should be a serious attempt to estimate costs. The exact threshold needed depends on tests and analysis done under R1, to determine lethal mass and size thresholds. On pages 22-25, I describe an "optical fence" that may allow affordable tracking down to ~1 cm.

Option #2, active maneuvering, is already done several times/year by ISS, and may be needed far more often if ISS wants to dodge far more small shrapnel. There is now no marginal propellant cost, just the work of re-scheduling reboosts needed anyway, and re-predicting conjunctions for the new orbit. But if far more maneuvers must be done, they may exceed reboost needs and this option will get very costly. That increases the value of more accurate orbit predictions: they can reduce both the number of worrisome conjunctions ***and*** the deltaVs required to avoid them.

With accurate enough predictions, even many non-thrusting spacecraft may be able to do useful active avoidance, by changing attitude and hence drag enough to avoid a predicted conjunction days later. This may let even cubesats actively avoid Hubble, ISS, and other high-value assets.

Option #3 is orienting the ISS solar arrays to shield the pressurized modules. The main threat to ISS from untracked shrapnel is the possibility of breaching the pressure vessels. Most debris at ISS altitude travels nearly horizontally and approaches ISS 30-60^o away from the ISS velocity vector. As a result, most of the vulnerable area is along each side of the modules. With proper orientation, the solar arrays can shield much of that vulnerable module area from most small shrapnel, even if it is not tracked. This can be done all the time in eclipse, using a modified low-drag "night-glider" solar array attitude. It can even be done in the sun whenever the sun is far from the ISS orbit plane. Then power penalties from not tracking the sun accurately are lower, and eclipses are shorter so ISS is more likely to have surplus power. The thin ISS arrays should be able to disrupt small untracked shrapnel, so modules get sand-blasted rather than breached.

Option #4 is orienting spacecraft and their appendages to reduce risk. This is like option #3, but the main goal is not providing shielding, but reducing collision cross-section. I understand that this was done with Hubble during the peak Leonid meteor showers in the late 1990s. It can be done to minimize threats coming from a known direction, by any spacecraft with attitude control, even if it has no thrusters.

Option #5 is adding standoff shielding where feasible. In general, the most weight-effective shielding is a "Whipple shield" or thin outer layer spaced some distance from the structural shell. Effectiveness apparently scales with shield mass times standoff distance squared, so a large standoff allows a fairly light but effective shield. It may often not be feasible to cover all of a spacecraft, but any surfaces usually covered with MLI and/or Kapton might often be covered with a heavier outer layer. But multi-layer structures can delay heating of the spacecraft interior during reentry, increasing the amount of mass likely to survive reentry and cause hazards on the ground. So Whipple shields should be designed with reentry burnup in mind, not just impact shielding. A heavy metal screen may be preferable to solid aluminum sheet, especially if the local variations in mass help cause wider angular dispersal of thin sheet-type shrapnel hitting it.

Option #6 is adding selective shielding ***and*** orienting the spacecraft as needed. Many spacecraft are prolate, and the face that mates to the booster is usually free of deployable appendages and sensors. This face may be easy to harden with either fixed or deployable debris shielding. Then that face can be oriented towards occasional threats coming from known directions. This option can reduce both impact area and the likelihood that impact will cause damage. Even satellites that require specific attitudes might be able to change attitude sometimes. For example, Iridium satellites might change solar array and/or body attitude on demand near the poles, where impacts are most likely, if data traffic is low there and other Iridium satellites nearby can carry it.

Option #7 is developing and using the Orion laser. If a large telescope focuses a powerful laser pulse on a LEO object, it can vaporize material and cause an impulse on the surface. The impulse is ~10,000X that of the laser pulse light pressure, but only if the pulse is intense enough to cause surface ablation. Impulses will usually also induce tumbling. The average effect of many pulses is repulsion from the laser. If this is done while an object approaches, it will drop into a lower orbit. Most lethal shrapnel and larger "disruptive" kg-class fragments might be removed within a few years. In addition, any Orion laser that can deorbit small shrapnel can also nudge multi-ton debris objects enough to prevent shrapnel-generating intact/intact collisions.

Orion cannot be done on a small scale: triggering ablation at ~1000 km range may require ~10m adaptive optics and ~10 kJ laser pulses. Claude Phipps proposed Orion in the mid-1990s. It received ~$1M funding then, but little thereafter. Orion may be a good complement to EDDE (see below), since Orion can prevent debris/debris collisions until EDDE can remove or collect most large debris. For more on Orion, see http://arxiv.org/ftp/arxiv/papers/1110/1110.3835.pdf.

Option #8 is reducing future shrapnel generation, by using electrodynamic or ion-engine vehicles to move bulk mass from crowded long-lived orbits either to short-lived orbits below ISS, or to weakly maneuverable "tethered scrapyards" in longer-lived orbits. Objects likely to burn up during reentry can be dragged down to orbits below ISS, from which they will reenter within months. Most mass in the major inclination clusters (see the list on page 27) might be collected at tethered scrapyards in the fairly uncrowded ~660-720 km altitude band. This is high enough to allow decades for any decisions on recycling vs. reentry. Collection must be done at "nodal coincidence." Larger altitude differences increase differential nodal regression and allow faster collection. Dragging objects down is preferable for EDDE, since it can descend ~5X faster than it can climb. But if problems preclude EDDE development or use, ion-engine vehicles might be used. Then boosting some debris now above 900 km to uncrowded altitudes near 1050 km may make sense. To learn more about EDDE, go to www.star-tech-inc.com/id121.html.

R5. Consider optical tracking near dawn and dusk, as well as radar upgrades.
The high-precision tracking done to test and refine models of the orbits of early satellites was optical. There were few objects in orbit, so it was easy to determine which object was in each image. But if there are ~500,000 now-untracked 1-10 cm objects, mostly clustered tightly in inclination, this becomes more difficult. It seems preferable to try for one-pass orbit solutions.

Optical imaging allows extremely good angle measurements relative to bright stars in the same images. Even if one tracks the object, so star images become streaks, one can still find centroids for each end of each bright star streak. Good hardware and software may limit uncertainty in each direction normal to the range vector to <3m RMS for objects <1000 km away. But images of sunlit targets give no direct range data, except rough values derived from when an object goes into eclipse. Lasers can allow sub-meter ranging, but high power is needed if targets have no retroreflectors. (EOS in Australia has done this, and hopes to do pulsed-laser ablation as well. See www.eos-aus.com/?pid=21 to learn more.) Note that such lasers are expensive, and they are not welcome at existing dark-sky observatory sites.

An alternative is capturing multiple images during one pass, from either one or two sites.

Binocular vision with a baseline of half the target distance should allow range estimation with an RMS error of ~3X a <3m RMS along-track error, or <10m. Two fixes >1 minute apart should allow accurate enough predictions to allow recovery within a few images, up to 1-2 days later. Most LEO debris is in near-polar orbit, because most debris stays near its source object orbit inclination, and most of that is near-polar: 56% of non-ISS mass is 7-9^{o} from polar, and <9% is >26^{o} from polar orbit. So most debris travels roughly N-S or S-N except near the poles. Objects usually appear brightest when you look away from the sun towards their sunlit side. A pair of observing sites along a roughly N-S baseline may allow the best binocular viewing, both because such pairs have the largest overlap in twilight viewing times, and because their baseline is nearly normal to the view direction when the objects appear brightest. Ranging uncertainties should be lowest then. The baseline need not be exactly N-S, since the earth's terminator moves >23^{o} to either side of N-S during each year, and some debris will travel >30^{o} away from N-S.

Binocular tests need telescopes at two sites having a suitable baseline. Once either finds a target, it tracks it. The angular rate allows a rough range estimate. This reduces pointing uncertainty for the other telescope to a short moving line in the sky. It can step along that line until it finds an object with compatible motion. Once both have it, they can track it until it disappears.

Even one-site, one-pass imaging should be enough to allow later recovery of the same object, if one tracks objects that do not pass too close to overhead. Paths well off to either side are visibly curved, by an amount that varies nearly inversely with range. If one takes 3 or more images at ~2 minute intervals, one should be able to derive an orbit solution accurate enough to allow recovery of the object up to at least several orbits later, by searching along the predicted path.

Once an object is recovered on a later pass, the orbit period can be determined well enough that most later updates should require only one image. Monocular views are enough for updates, since the key issue is along-track uncertainty. The much slower growth of uncertainty in the other two directions can be limited by the varying view angles of a series of updates.

Such a system has 3 main limitations. First, brightness data cannot be directly translated into radar cross-section or other size estimates. But once there is a good orbit estimate, one can task the Haystack radar to detect the object during any good pass. Haystack is apparently good at estimating the size of cm-class LEO objects. (Thermal imaging may also allow size estimation.)

A second limitation is more serious: except at high latitudes, each site can be used for a total of only 3-4 hours/day, when the sky is dark enough but the sun illuminates objects over enough of the LEO altitude range. Usable time per site is further reduced by a need for enough clear sky. The 350-1000 km altitude range will be of highest concern for tracking of potentially lethal small debris that could impact the ISS or disable other operating satellites. Sites at high latitudes have longer twilight and greater concentrations of potential viewing targets, but they usually also have worse weather, poorer "seeing," and more expensive support logistics.

A third limitation is probably the most serious of all for any operational system: objects can only be seen when they are near eclipse. This generally requires use of a observing site in one latitude band before dawn, or another latitude band after dusk. Those bands move north and south on a regular but slow basis. A full cycle takes ~4 months for objects in 70^o orbit, ~6 months in ~82^o orbit, and years if close to a ~99^o sun-synch orbit. Prompt detection of shrapnel near a noon-midnight polar orbit near equinox may require viewing from a site near the arctic or antarctic.

Even more challenging than noon-midnight polar orbits are orbits nearly normal to the sun: then objects may never get close enough to eclipse to be easily viewed from a dark enough site, which typically requires the sun to be >12^o below the horizon. Such objects can be viewed around a large arc of their orbit, but only nearly back-lit. This greatly reduces object brightness. This condition occurs a few % of the time for most high-inclination objects, and often lasts 1-2 weeks. It poses the most problem for faint objects at low altitude. Low altitudes make the lighting closer to backlit, and higher drag makes objects harder to find again once the lighting improves enough.

Demands on an operational fence may be dominated by near-daily catalog updates of >300,000 objects, to limit drag-induced along-track orbit uncertainties. More frequent updates are desired during solar flares. Some flares will occur with full moon night sky glare, and worse than usual weather. To avoid "losing the catalog" then, we may need several ~0.5m telescopes with agile tracking at each of dozens of observatory-type sites, spanning from ~70^oN to >50^oS latitude.

Most of the time such a network will have large surplus capacity. Within a day after a collision, new shrapnel will spread into two rings, each visible from one latitude band at dawn and another at dusk. The telescopes in those 4 bands can be tasked mainly to find the new fragments when they have good views of each ring. It may be feasible to find most new >1 cm debris within a few months. This is comparable to the existing SSN response in finding 10-20 cm objects.

The key question for such an optical fence is sensitivity. Fairchild, Andor, and PCO collaborated on a new imaging technology called scientific CMOS (see www.sCMOS.com). Each now sells sCMOS cameras using the same imaging chip for ~$20K, mostly for biotech. Hamamatsu has a similar camera. sCMOS offers a unique combination of pixel count, fast readout, and low read noise. For example, Andor's Neo camera has 2160x2560 pixels, a 1e- median-pixel RMS read noise at 200 Mpixel/s read rates, and 57% peak quantum efficiency, at 560nm.

With a good view geometry, the Andor Neo plus a 0.5m aperture f/3.5 Newtonian Astrograph telescope may be able to detect most 1 cm sunlit shrapnel up to ~700 km altitude, with exposures well under 1 second. The detection threshold diameter should nearly scale with altitude, so 1 cm at 700 km corresponds to 5-6 mm at ISS altitudes, and 14mm at 1000 km. According to a paper at the 2011 AMOS conference, www.amostech.com/technicalpapers/2011/Poster/Levesque.pdf, tracking a faint object rather than the starfield raises sensitivity: accumulating a faint signal in fewer imager pixels seems better than reducing the number of pixels blinded by bright stars. Hence telescopes in an optical fence should slew back and forth nearly continuously, to track and update the orbits of objects heading in different directions.

Most debris after a major collision will be in a narrow band around the inclination of each source object. The RMS inclination dispersion of tracked fragments is 0.8^o for Fengyun, but only 0.1^o for Cosmos and Iridium. Most accidental collisions will be at high latitude, like Cosmos/Iridium. This reduces inclination dispersion. But the spray/shred mechanism should disperse gram-class shrapnel more widely than current catalog debris is dispersed. As with the existing radar-based Space Surveillance Network, smaller shrapnel will take longer to find. But the sensitivity may be good enough to allow detection and tracking of most of the probably lethal shrapnel in LEO.

Haystack could be used as a weather-insensitive update site. But it cannot steer fast enough to do updates on more than a tiny fraction of the >300,000 objects that may be optically detectable. Haystack's main value may be allowing estimates of the actual size of a good statistical sampling of objects that are found and tracked optically. This plus decay data allow decent mass estimates.

If a many-site "optical fence" is built and operated as a set of classified-operation government facilities like the existing SSN, it will probably be limited to this use. Typical costs for such facilities may apply to this new network. This network appears to require dozens of sites with good astronomical viewing, distributed around the world from ~70^{o}N to >50^{o}S. Such a network may not work well if it is constrained to sites with existing secure US facilities.

Such an optical fence might be far cheaper if done commercially. A commercial entity will want to sell the same services to US and other customers, and to negotiate use of foreign sites, which may be mostly existing observatory sites. An additional advantage of a commercial entity is that it may be able to profitably sell other services when LEO objects cannot be seen. It might receive high-rate laser comm data from earth imagers, or look for high-orbit debris or Near Earth Objects.

There is an existing organization called "Global Rent-A-Scope." It is a boutique service that requires membership and has only a few sites. With many sites having identical equipment, it may be feasible to directly sell real-time astronomical viewing over the Internet using PayPal. Customers might include astronomy teachers and planetarium operations around the world, and comet-hunters and other hobbyists with their own telescopes but poor local viewing conditions. Telescopes well into the southern hemisphere may be particularly popular, since many amateur astronomers never see much of the southern sky very well.

There is also an existing Russian-led network that might capture the business opportunity for optical tracking of LEO objects. It is the International Scientific Optical Network (ISON; see http://lfvn.astronomer.ru/main/english.htm). Vladimir Agapov of the Keldysh Institute for Applied Mathematics in Moscow leads this group. ISON uses telescopes at 19 existing observatories around the world to track GEO objects for commercial and government customers. Agapov has said that ISON wants to offer services to LEO customers. Agapov presented at the AMOS conference in 2009, and had one paper each (on GEO topics) at the 2011, 2012, and 2013 IAF Congresses. It is unclear what if any progress ISON has made on LEO objects.

It is not clear how a commercial optical fence would be viewed by existing US government users of LEO tracking data. It could allow active avoidance or other protective responses by the ISS and all other high-value assets against ***most*** potentially lethal shrapnel, not just the largest ~2-5% of the lethal fragments. This could be of great value to all US and foreign operators of high-value assets in LEO. On the other hand, it seems likely that USG agencies would not like to become dependent on a commercial entity that needs a many-country viewing site footprint and customer base. This is true even for a US-based business, and far more the case for Moscow-based ISON. Imposing ITAR controls on a US business may be counterproductive. Only 1 of the 4 sCMOS camera vendors is US-based, and suitable telescopes and agile computer-controlled tracking mounts are also made and sold outside the US. Imposing ITAR controls on US entities could make "ITAR-free" non-US options attractive to non-US clients. This would handicap any US-based entities competing against ISON or other non-US entities.

Over a century ago, the Army Signal Corps wanted to see the Wright Flyer in operation before committing to buy it, while the Wright brothers didn't want them to see it until they committed to buy it. After years of impasse, the result was creation of the "acceptance flight": the customer commits in advance to buy the product if it works as specified in the contract. If the performance and price of an "optical fence" for LEO objects down to ~1 cm can be determined, and detailed specs can be agreed on for performance and reliability, a contract may be feasible between some USG agency and a US business, under terms favorable enough to let the business raise money, build a network that includes dozens of foreign observing sites, and develop a global customer base for LEO tracking and possibly other services like LEO laser comm. If something like this is not done, more limited LEO services may still be offered by ISON or other non-US entities.

R6. Work towards removing *most* large objects from crowded altitudes as soon as feasible. Mark Twain said that everybody talks about the weather, but nobody ***does*** anything about it. The same is true about existing orbital debris. This population will persist in generating new shrapnel until we remove the large objects at crowded altitudes, whose collisions will create most future shrapnel. To stop the population growth of tracked >10cm objects, it may be enough to remove 5-20 high-threat objects/year more than we now add. But that will not stop the occasional much larger step increases in lethal gram-class shrapnel. Stopping those more lethal increases requires that we both stop adding mass to crowded altitudes, ***and*** remove ***much*** of the mass now there.

The USSR and Russia, which owns all USSR objects, launched 71% of the mass now in LEO, including nearly all of the highest-threat objects at most of the crowded altitudes. Excluding ISS, which is in a low orbit and avoids all tracked objects and hence cannot generate much long-lived shrapnel, ownership of mass in LEO that can generate lethal untracked shrapnel is as follows:

USSR:	52% (through 1991); now owned by Russia
Russia:	19% (launched after 1991)
US:	16%
Other:	13%

The above masses include active satellites as well as debris. Many satellites at crowded altitudes seem more likely to fail and become long-lived debris than to be deorbited before failure. And even most operating satellites are not actively maneuvered to avoid collisions, except with other members in a constellation. So it seems reasonable to consider nearly all satellites other than ISS as potential sources of lethal shrapnel, even while they still operate. Note that future shrapnel is likely to be well over 71% Russian, since Russian-owned objects are not just 71% of the total mass and area, but are also clustered in altitude far more tightly than most other objects.

It is necessary to discuss ownership because under the 1967 Outer Space Treaty, space object ownership is not affected by location or condition. Maritime salvage rules do not apply here. Further, the 1972 Convention on International Liability for Damage Caused by Space Objects says that launching states retain a strict and unlimited liability for any damage their space objects cause on the surface of the earth or to aircraft. (They also have liability for damage caused in orbit if they are "at fault," but "fault" is not defined.) The 1967 treaty, the 1972 convention, and related documents are all available at www.oosa.unvienna.org/oosa/en/SpaceLaw/treaties.html.

The 1972 convention also appears to state that when several countries collaborate, e.g., with one owning the satellite, another the rocket, and a third the launch site, all 3 are launching states of ***both*** satellite and rocket. They are all jointly and severally liable, and any can be sued under the treaty for the full loss. Another key point is that no distinction is made between intentional and "natural" reentries: they both impose the same strict liability. The convention also states that if one space object damages another, any liability for subsequent damage by the second object is shared by the launching states of both objects. Reentry, recycling, and even nudging by laser ablation all damage space objects, so a state that handles another state's objects seems to acquire liability. The overall liability regime might be summarized as "fingerprints are indelible." Once a state is involved with an object, it cannot escape later liability under the 1972 convention, even if object ownership, operation, and/or registration are transferred to another state.

Another clause in the 1972 convention may be essential. It lets collaborating states negotiate indemnification agreements to assign financial responsibility among themselves for different losses (eg, X will pay for launch-related damage, Y for satellite-reentry damage, etc.), within the context of joint and several liability under the treaty. Hence it seems essential for any state that plans to deorbit, relocate, or recycle foreign objects to negotiate indemnification agreements with the launching states**. It also seems possible that no other agreements will be needed.** Many Russian objects also involve Kazakhstan as a launch state, but even a 3-way indemnification agreement should be far easier to negotiate than a new UN-level treaty.

The US has more assets in LEO and more government and commercial dependence on them than any other country, so it makes sense that the US has taken the lead in improving debris practices. But I cannot imagine Congress agreeing to pay Russia for the privilege of "taking out Russian trash," and it may even object to paying a US company to do it even if Russia allows it at no cost. In addition, I have trouble believing that Russia would allow the US to deorbit Russian debris without the US accepting reentry liability, and I have trouble seeing the US doing that.

These difficulties may steer efforts in a direction that increases technical challenges but may still make sense. Instead of deorbiting most large debris, one can gather it into "tethered scrapyards" at 660-720 km altitude. Such scrapyards can be maneuvered to avoid collisions, and later either recycled or deorbited in a controlled manner. This can radically reduce the chance of collisions between large objects, while requiring less deltaV than deorbit. Delivering debris to an orbiting scrapyard also lets one delay decisions and investments in recycling or deorbit, while quickly reducing shrapnel-creation rates. Scrapyards may allow later Mir-like controlled deorbit from low altitude, using one rocket per scrapyard. And even selective recycling can ventilate objects, so they burn up more thoroughly during reentry and cause less damage on the ground.

The US may be willing to accept indemnification responsibility for non-US objects once a US operator contacts them, if the launching states agree to accept it back once objects are attached to a scrapyard. A US business might even be allowed to retain ownership of some scrapyards for later recycling, as in-kind payment for gathering most Russian LEO debris into scrapyards. The mass available for recycling includes >1000 tons of aluminum alloys. At current world launch rates, that would take decades to launch. It may be in Russia's interest to let a US entity own some of Russia's collected debris, since that could stimulate a market for the rest of their debris.

What makes debris collection feasible is that most LEO mass is tightly clustered in inclination. Objects with nearly the same inclination but different ascending nodes can be collected at low deltaV if you have enough time, since nodal regression rates vary with altitude. The ascending node of a scrapyard passes by that of one object after another over a period of years. Collection can even be done using ion-engine vehicles rather than EDDE. EDDE should be far lighter and cheaper, but if problems block EDDE development, large-scale collection should still be viable.

Below are the 6 most crowded narrow inclination clusters. These clusters also include a few non-Russian objects, but they are neglected since they total only 0.1% of the mass in these 6 clusters:

Cluster mass	Inclination	Width	Avg km alt (by mass)	
337 tons	82.83-82.99^o	0.16^o	981 km	
319 tons	82.46-82.62^o	0.16^o	941 km	
169 tons	81.08-81.30^o	0.22^o	741 km	6 Russian clusters = 62% of LEO mass
229 tons	73.96-74.08^o	0.12^o	1091 km	
220 tons	70.84-71.11^o	0.27^o	843 km	
+ 94 tons	64.69-65.86^o	1.17^o	937 km	
1367 tons	= total for the 6 clusters above			

Of the total LEO mass ***not*** in these 6 clusters, 56% is in a highly international cluster: 473 tons in 96.42-102^o sun-synchronous orbits. This mass can be gathered into several scrapyards, to avoid any need for several-degree inclination changes that would dominate maneuver needs and time.

It is also useful to list the potential debris source mass in LEO under the categories listed below:

1367 tons	total for the 6 clusters above
+209 tons	Russian mass in all other inclinations, including 113 tons in sun-synch
1576 tons	total Russian-owned LEO mass (=680 tons satellites + 896 tons spent stages)
348 tons	US-owned LEO mass (excluding the ISS)
+283 tons	all non-US, non-Russian LEO mass
2207 tons	all LEO mass (excluding ~450 ton ISS mass)
+ 52 tons	average mass in LEO of 843 tons of objects in GTO and other eccentric orbits
2259 tons	total average potential shrapnel source mass in LEO (excluding the ISS)

Shrapnel creation by collision nearly scales with the square of the mass at crowded altitudes, so collecting the inclination-clustered 62% of LEO mass could reduce shrapnel generation to ~14% of the current rate. The actual reduction should be even larger, because the 6 Russian inclination clusters also include much of the densest altitude clustering, particularly near 845 km and 950-1010 km. Note that GTO and other eccentric-orbit objects move faster than LEO objects but are in lower-inclination orbits, with lower angle-driven collision arc-length enhancement (see page 42). The threat they add when in LEO is similar to that of LEO objects at the same altitudes.

Russian ownership of most LEO mass makes negotiations on bulk removal of non-US objects a challenge. But there is a silver lining: negotiations with Russia can cover everything owned by Russia plus the US. That is 87% of LEO mass (85% including EEO mass in LEO). Removing all that can reduce collisional shrapnel creation by ~98%. Hence we do not need any changes in UN treaties; just US/Russia negotiations. Finally, much of the 283 tons non-Russian non-US debris is owned by US allies like Europe and Japan. Hence it may be feasible to get agreements that let source mass be driven down by >90%, and collisional shrapnel creation by >99%.

R7. Consider parking fees or liability insurance requirements to limit degradation of LEO.
Current US National Space Policy directs NASA and DoD to:

> Pursue research and development of technologies and techniques, through the Administrator of the National Aeronautics and Space Administration (NASA) and the Secretary of Defense, to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment. (see www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf)

Recommendations R1-R6 focus on ways to do much of what is required by this directive. This recommendation, R7, focuses on the future, once cost-effective technologies and techniques are ready for operational use, probably under a future administration. Wholesale debris removal or collection (for later recycling or removal) are not the most exciting or politically rewarding ways to spend federal funds. So a key question is how to raise the chances of removal funding, once cost-effective technologies have been developed and adequately tested.

A key clue to this may be that the only entities that will directly suffer from LEO orbital debris in the future are also nearly the only ones contributing to the LEO debris problem by adding mass to LEO. This is a classic "tragedy of an unregulated commons." Garrett Hardin has argued that this often has no technical solution, and requires "mutual coercion mutually agreed upon." If LEO users object to paying to remove at least as much debris threat as they add, it seems naïve to expect allocation of general funds for cleanup. On the other hand, I don't think that LEO users should have to pay to remove more threat than their future additions: they shouldn't be penalized relative to new players by liability for objects already launched under existing groundrules.

Cap-and-trade has been proposed, but that works only when natural cleaning mechanisms allow non-trivial levels of continued new pollution. Here the sustainable cap is negative. Starting out with a negative cap is equivalent to starting out with a retroactive liability.

Another scenario may follow naturally if a good optical fence comes into use. Such a fence and supporting analyses can let operators actively avoid most potentially lethal shrapnel. Raising the tracked LEO object count from 12,000 to >300,000 will require far more accurate orbit data and predictions. That can reduce both the number of conjunction notifications and also the deltaVs required to prevent collisions. An optical fence with dozens of observing sites may allow this.

Continuing avoidance costs will be real, and they will be traceable to individual pieces of small shrapnel and the collisions that generated them. Recovery of the continuing costs of monitoring, planning, and actively avoiding debris will become the basis of lawsuits. The early lawsuits will probably be mostly within various countries rather than between them. Early suits may fail, but others may eventually succeed. This will drive the evolution of perspectives on liability.

If one state's object damages another's object and that results in damage to a third state, the first two states are ***both*** liable to the third state, "based on the fault of either." So even if each stream of shrapnel created by a collision is traced to one object and its launch state, the launch states for both objects in a collision may share in any treaty liability for later damage done by any piece in ***either*** stream. This might include not just asset loss costs, but even shrapnel avoidance costs.

A key turning point may come once many countries start arguing that the undefined term "fault" in the 1972 UN liability convention should start applying to some previously-accepted practices, like leaving objects at crowded altitudes and not maneuvering them to prevent collisions. Then operators and their governments could become liable not just for later asset losses, but even for shrapnel-avoidance costs, even those from another stream of shrapnel created by a collision with their object. Hence the owner of a cubesat could become liable for the costs of avoiding a ton or more of shrapnel. This could drive requirements and markets for debris liability insurance.

Eventual issues may include whether, when, and how much "fault" may be deemed to apply to:

1. Leaving new rocket stages or satellites at crowded altitudes once their mission is done;
2. Launching objects to crowded altitudes and not maneuvering them to avoid collisions;
3. Continuing to leave dead satellites and stages in long-lived orbits at crowded altitudes;
4. Not letting a foreign entity move objects from crowded altitudes under reasonable terms;
5. Not allowing spacecraft operators timely access to data needed to prevent a collision;
6. Not letting a foreign entity nudge an object by laser ablation under reasonable terms;
7. Not using an Orion laser to prevent a predicted collision, when offered reasonable terms.

The liability convention governs only state-to-state liabilities between treaty signatories. What happens within a state is a matter of that state's laws, precedents, and procedures. But if better fences, catalogs, and orbit predictions let most threats from existing shrapnel be traced to Russia, China, and the US, these issues may arise as soon as operators start dodging shrapnel routinely. This is a difficult issue, but we must deal with it if we want LEO to remain sustainably usable. A November 2011 meeting at McGill University in Montreal focused on orbital debris legal issues. Its report is available at www.oosa.unvienna.org/pdf/limited/c1/AC105_C1_2012_CRP16E.pdf.

Whatever the international outcome, it seems useful to start discussions about future liability scenarios under existing or changed US laws, even before an optical fence is built. A fence will raise the visibility and urgency of these issues. A transition from the current regime where there is no presumption of fault for shrapnel generation to a regime with clear liabilities, insurance requirements, and competitive debris liability insurance suppliers will not occur overnight.

As an early step during a probably extended transition to a new liability regime, it may make sense for countries to charge their operators "congestion-based parking fees" as an alternative to requiring liability insurance against collision. This can encourage more responsible practices in LEO use, as well as collecting funds for removal. Taxes intended to improve decisions by "internalizing negative externalities" are called "Pigovian taxes," after the English economist Arthur Pigou. There is a "Pigou Club" that favors such taxes. Its members span a surprisingly wide political spectrum, as can be seen at http://en.wikipedia.org/wiki/Pigou_Club.

Existing US rules allow equal 25-year after-mission orbit life for both cubesats and comsats. This is like "2 hours free parking." But parking downtown generally costs money starting at arrival, costs more in congested areas, and costs more for motor homes than cars. Congestion-based parking fees intended to scale with threat may make sense in LEO as well. They can be assessed before launch and mostly refunded after objects are deorbited or moved to low-threat orbits. Such fees plus general funds could go into a removal fund to pay for net threat reduction. Payments to and from the fund should not be fixed $/object or $/ton, but should use consensus formulas for threat change, both positive and negative. Early debris additions and removals will involve larger changes in threat, and hence higher fees and bounties. This can encourage a race to remove debris before bounties drop. If removal attempts create rather than removing debris, operators might be penalized, or required to remove an equal threat without receiving payment.

Getting general funds allocated for cleanup may require that industry fund some of the removal or accept congestion-based parking fees. Similar strategies may make sense for both LEO and GEO, but program timing and funding should be separate, because the key players are mostly different. Operators should be more willing to pay for debris removal if the program is targeted specifically to the orbit region they operate in, rather than being spread out over all of earth orbit.

Congestion-based parking fees might initially be set too low to balance even optimistic estimates of debris removal costs, since this may be enough to shift practices toward sustainability, such as deboosting spent stages, using lower mission altitudes, and taking more propellant for avoidance and end-of-mission deorbit. Fees that start low and then ramp up towards a balance with mature removal costs may also reduce concerns about a tilted playing field between the US and other countries. This gives time for other countries to cooperate by establishing similar rules, as many countries have already done in response to US leadership on earlier debris-reduction measures.

There may be objections to such fees being used to pay for removal by foreign entities or of foreign objects, analogous to US restrictions against using federal funds to launch USG payloads on foreign launchers. And there may be strong objections if Russia tries to make money from removal of Russian debris, however they may try to do that.

But if Russia starts to remove, relocate, nudge, collect, and/or recycle much of its debris, or let others do such things under reasonable terms, then it may make sense to help Russia with at least its USSR-era debris, which is 73% of the Russian mass in LEO. Objections may be raised on a basis of fairness, national competitiveness, or simple resentment of past Russian practices, but the most serious issue may simply be that government and industry entities in most countries will not want to constrain or tax their future space operations if they can avoid that. But eventually most countries may agree to restrict launch of their payloads by countries that do not follow prudent practices in this area. That could greatly enhance compliance by most major players.

Developing and adequately testing debris removal technologies and techniques will take years. Those tests will probably have to be done under government contract, partly for the funding and partly to take advantage of the government's liability umbrella for its contractors. Past practice suggests that Congress may not assign statutory authority to the FAA or another regulatory agency to regulate removal operations until commercial entities are planning operation, and then it will take additional time to draft regulations, hold hearings attended by this fledgling industry, and settle on final regulations governing removal operations involving US entities and/or objects. This will also require setting of reasonable liability limits and indemnification rules for removal operations. As a signatory to the 1972 UN liability convention, the US government already has ultimate liability for all damage caused to other countries and their non-government entities by any US objects and operations, either government or commercial.

Making debris removal both politically and commercially viable in the US probably requires all the above steps, plus mandates that users of LEO (first US, but eventually also Russian and many others) do things like pay parking fees, contract for removal services, and/or buy debris liability insurance. Requiring liability insurance could make insurers become wholesale customers for removal services. They could become savvy customers, since they will need to frequently revise their liability estimates and adjust policy premiums, if they want to stay both competitive and profitable. The rules should allow LEO users to directly contract for removal services. This can help force any "parking fee fund" to keep payout and overhead rates low. For example, Iridium should be allowed to pay a removal operator directly, to remove its failed satellites and/or other objects, rather than paying parking fees. Iridium should be motivated to do this, both because it should be able to get a bulk discount, and because clearing out large objects near its constellation altitude would preferentially reduce future collision-generated debris at that altitude.

By the time all the above steps have been taken, there may be another collision. It may create more new shrapnel than the 2007 and 2009 collisions together. And it may have effects and implications that are by then better understood and more clearly quantifiable, especially with the aid of an optical fence. Such a collision may be needed to raise both industrial and political consciousness and enough resolve to trigger adequate action in the US and other nations.

A more optimistic but possibly realistic scenario is that evolving perspectives on liability, plus gradual restrictions on launch of US payloads by non-cooperating states, may encourage Russian cooperation. A full solution may include accurate enough optical tracking of most lethal shrapnel to allow avoidance until shrapnel can be deorbited by an Orion laser, plus Orion nudging of large debris to keep it from colliding until it can be affordably removed or collected by EDDE or other vehicles. Key issues for lasers, EDDE, optical fences, and even most satellite servicing include liability for errors, and paranoia about A-sat capabilities. It may be better if all such activities are licensed, regulated, and insured commercial operations rather than government operations, either military or civil. Provisions for government indemnification above some limit (as is now provided to US commercial launch services) seem essential to enable prudent investment in any of these areas. Governments must oversee these activities not just to limit their indemnification exposure, but also to comply with an Outer Space Treaty clause that requires signatory states to "authorize and continuously supervise" the space activities of their non-government entities.

It is said that in the rocket business, "Amateurs talk about performance, but professionals talk about insurance." That may apply even more to orbital debris.

R8. Once conclusions C1-C9 are independently verified, update debris terminology & data. Conclusion C1 is probably uncontroversial, but C2-C9 and most of the recommendations may be unobvious enough to need significant independent checking and verification by acknowledged experts before wide acceptance. Those experts have suitable tools; it is just a matter of deciding whether such checks should displace some work on other tasks. That is their call; not mine.

If enough of these items are verified, then the debris analysis community should update some of its standard terminology. For example, it may make sense to retire the existing term "catastrophic breakup" since its categorical nature suggests equal severity for drastically different events. In addition, it now describes thorough shredding of a large object (usually already debris), but it might better fit loss of a working satellite (usually to gram-class shrapnel). To prevent confusion, it may be better to retire it rather than continue use with either the old definition or a new one.

Several terms used in this paper, particularly "spray," "shred," and "shrapnel," seem generally useful. In addition, in 2009 I suggested "cars, hubcaps, and bullets" respectively as labels for intact large objects, a ~4X larger tracked fragment count, and untracked but lethal small debris. "Car" and "hubcap" are still useful, but "shrapnel" seems better than "bullets," because it better describes the shapes of fragments created in hypervelocity tests, and their random dispersal from their source object. Once we can detect, track, and avoid most shrapnel, then "hubcap" might be reserved for kg-class fragments that can shred ton-class cars by hypervelocity impact.

It may also be generally useful for many purposes to report average LEO object counts per km altitude, as defined on page 5 and used on pages 5-6 (with typical values of 1-1000/km), rather than objects/km^3, which gives values of 1E-9 to 1E-6 that are far less memorable or intuitively useful. In addition, the average "ArcLenMultiplier" presented on page 42 should allow far better combinations of simplicity and accuracy in debris analyses that span a wide range of complexity.

Many years ago, NASA shifted its focus from debris fragment mass to size, because L_c is more directly observable. But once we can detect, accurately track, and estimate the L_c of 1-10 cm shrapnel, we can determine orbit decay and estimate individual masses. Such estimates are now made for tracked objects including debris, but not published. It is worth publishing estimated mass in both statistical studies and catalogs. It is particularly useful for masses of order either 1 gram (since that affects lethality to satellites) or 1 kilogram (since that affects whether an object can shred typical ton-class intact objects). Such estimates can help satellite operators and can also help raise awareness of potential future liabilities. Mass (or at least A/M) estimates can also aid Orion laser scheduling, by indicating how many pulses or passes each object may need.

An updated TLE-like orbit-reporting format also seems timely. I suggest 1 line rather than 2, with 1 rather than 3 drag parameters. Adding 1 digit more resolution for all parameters other than eccentricity and mean motion should let it capture the full orbit prediction accuracy available from optical tracking. Even if precise propagators use special perturbations rather than SGP-4, a TLE-like format can specify a precisely-defined mean orbit propagators should be able to use.

An object catalog might list fixed data like name & object type, ownership, launch date, original mass, and size with and without appendages. A separate "recent trends" catalog might list radar and optical data, apparent current mass and drag area, attitude dynamics, and recent maneuvers.

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As always, the author alone is responsible for mistakes. I am interested in feedback on mistakes or items that may seem wrong, misleading, ambiguous, unjustified, or just unclear. This effort started as an attempt to extend work by Ailor and his colleagues. I would like this to be pursued further by others, and would like to stay aware of such work. Please email me at tether@cox.net with all feedback, questions, and indications of interest in pursuing any aspects of this work.

Bibliography

Web-links are included in the body of the paper for reader convenience. Listed below are some key links for those interested in further pursuing issues considered in this paper:

UN Treaties on space: www.oosa.unvienna.org/oosa/en/SpaceLaw/treaties.html.

US Space Policy: www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf

NASA's orbital debris program website: http://orbitaldebris.jsc.nasa.gov/

2011 NRC review of NASA's debris program: www.nap.edu/catalog.php?record_id=13244

Website for Aerospace Corp. Center for Debris Studies: www.aerospace.org/cords/

ESA debris website: www.esa.int/Our_Activities/Operations/Space_Debris

AMOS Conference proceedings (optical tracking, etc.): http://amostech.com/?page_id=20

Papers on EDDE and debris, and cost estimates by Levin et al: www.star-tech-inc.com/id27.html

Orion laser for debris removal: http://arxiv.org/ftp/arxiv/papers/1110/1110.3835.pdf

Secure World Foundation (focuses on sustainability of space usage): http://swfound.org/

Detailed analyses of Cosmos/Iridium collision & other debris issues: http://wangting.org/pages/

Klinkrad, Heiner, **Space Debris: Models and Risk Analysis**, Springer/Praxis, 2006.

Space Junk 3D, 37 minute "edutainment" movie in Blu-Ray, available from Amazon, 2011.

Introduction to LEO Shrapnel Cost Estimator Spreadsheet

Introduction

The last page of this paper is a one-page Excel spreadsheet that allows estimation of the expected future cost of small shrapnel in LEO. It does not attempt to estimate existing or potential future costs for space situational awareness or avoidance, or costs of debris removal by different means, or losses due to partial loss of solar array output or other function, or losses from shredding large objects that might otherwise be affordably recycled. It just estimates the expected total present cost of a string of future total asset losses caused by hypervelocity impact, nearly all by 1-10 cm shrapnel that is too small for the SSN to track, but potentially lethal to most assets in LEO.

The spreadsheet logic is simple: estimate this-year costs, then annual cost trends, and then the net present cost of those trends. It starts with estimates of the number and typical characteristics of LEO assets of 5 different classes. With that data, plus formulas that estimate shrapnel count vs. mass and altitude, it computes the current expected rates of asset losses for each class of assets.

Other inputs quantify expected trends in debris mass and changes in asset count, size, and cost for each class. They let the spreadsheet estimate discounted annual cost for each class of assets for 5 different years at uniform intervals, and then overall costs for that whole period.

The next 9 pages march down the spreadsheet, discussing input and output parameters and their values and the calculations line by line. Input values are listed in blue both here and also in the spreadsheet. Derived values are in black. As suggested on the spreadsheet page:

Users can change all inputs they disagree with, and should explore the effects of changes. The value of the spreadsheet may be far more in its quantitative linkages between key parameters, than in the specific inputs used.

Current LEO Asset Data

At some level of detail, all spacecraft are unique, but to make this effort manageable, one must lump existing assets at risk into a few categories. The main focus here is on cost, so I group the assets by cost category. This cannot get everything right, but it does let one test the implications of coincident variations of parameters like cost, size, and lethal impactor size, which affect both cost and likelihood of loss. The unusually high cost and area and low altitude of manned assets make them differ enough from other assets to merit a distinct class, despite ISS being the only one in use now. For user convenience I also added a Test Case at the right, with 3U cubesats as an example. Users can change any inputs in that or any of the other classes to see the effects of those changes. (The “Test Case” values are included in the totals column on the right.)

Number of assets now operating in LEO

Rather than estimating annual launch rates and actual lifetimes (which seldom agree with plans), it seems better to focus on the number of currently operating spacecraft, since those are the assets actually now at risk. In general there are fewer “High$” than “Low$” spacecraft. I don’t know the breakdown, but I tried to get the total number right (~400 active spacecraft in LEO), while making number * avg-cost-of-impact the same for high, medium, and low-cost spacecraft. That gives the same total cost-of-loss for each of these classes, and eases comparison of trends.

Est. avg net cost of "lethal" impact, $M

Manned assets are the only ones that can suffer literally lethal impacts, since crewmembers can be killed as a direct or indirect result of such an impact. Many impacts that do breach a pressure wall may be unlikely to kill an astronaut, but they will have serious implications on facility use, as was seen from the leaks caused by the low-velocity impact of Progress with Mir in 1997. That caused loss of the use of one module. Effects on ISS may be worse due to its mostly linear pressurized module layout. I understand that there are repair plans, but don't know the details.

Effects on normal operations and potential permanent loss of hard-to-replace equipment leads me to estimate $4B (roughly 1 year of ISS ops costs) for breaches of the pressure shell, but to ignore other impacts. That is tiny compared to overall ISS cost, but may be reasonable as an average for repair launch and ops costs, loss of use of hardware, dislocation and replanning costs, etc.

For unmanned assets the cost of lethal debris impact is the cost of unexpectedly and permanently losing the remaining use of that asset, due to accident rather than hostile action. It may seem that the cost of loss of a fairly new spacecraft should exceed the cost of building and launching it, or it would not have been worth doing. But that may not always be the case, especially with novel designs: simply getting a new design built and qualified has substantial value that is not lost with the spacecraft. In addition, most impact losses of new designs will occur after checkout and use, and discovery of any design problems. So cost-of-loss may often be much less than full cost.

On the average, impact-induced loss should cut asset useful life by ~half. In some cases the cost-of-loss may decrease ~linearly over time, but in others it may drop much faster at first. In other cases, any loss of use before a replacement is launched may impose service interruption costs. Because impact-induced losses are unexpected, they also impose operational dislocation costs that do not occur when life ends due to gradual power degradation or propellant exhaustion.

I do not know of any rigorous way to estimate the average net cost (including dislocations) of suddenly but randomly losing the use of operating spacecraft. It may typically be of order 1/2 the recurring cost of building and launching an asset, plus a small part of the cost of designing it. This led me to assign estimated cost-of-loss values of $1,000M, $200M, and $40M respectively for typical currently operating high, medium, and low-cost unmanned LEO spacecraft.

What is far more important than each number is the total estimated cost of loss integrated over all LEO assets. My inputs give a ~$40B total "cost of random sudden loss" for all operating LEO assets. (Total costs for random loss of all GEO assets may be far higher, but such losses are also far less likely.) For 3U-cubesat loss, $1M may be high, but total losses for this class are so low that "being generous" has little effect. The numbers used are intended to cover both US and foreign assets. But world costs may be only moderately higher than US costs, since many other leading countries and consortia have space-related budgets of order 10-20% of US budgets.

Grams shrapnel mass for ~50% lethality

This input specifies the estimated average mass of a piece of shrapnel with ~50% lethality for a strike anywhere on the vulnerable body area, for each asset class. I assume non-lethal impacts by heavier shrapnel will be about as common as lethal impacts by lighter shrapnel, so one can get the right overall risk by assuming all heavier impacts are lethal and no lighter impacts are lethal.

Average vulnerable normal area, m^2

For objects with near-random LVLH attitude like Hubble, average vulnerable "target area" can be estimated as ¼ of the total exposed "non-concave" (or "shrinkwrapped") body area, excluding solar arrays and other appendages. The 45m^2 value used for the High$ class is approximately right for Hubble and may be roughly representative of other High$ LEO spacecraft as well. The 3U-cubesat area was calculated the same way: ¼ the total exposed non-concave area.

For spacecraft with fixed LVLH orientation like ISS, most shrapnel will approach from the front to sides. The main vulnerability of ISS is to the sides of its pressurized modules. Shrapnel can hit only one side per approach, so the effective target area is the average module diameter times the backbone length, with cosine foreshortening. The Japanese and ESA modules on either side of the backbone shield part of the backbone behind them, so they add little to the total vulnerable area. So I estimate a 200m^2 average lethally vulnerable target area for shrapnel approaching ISS.

My estimate of vulnerable target areas for Med$ and Low$ spacecraft scale down slightly slower than cost. I don't know how accurate that is.

Typical asset orbit altitude, km

This input drives shrapnel populations (#/km) at the spacecraft altitude, and also has a modest effect on collision frequency via changes in orbit circumference and number of orbits/year. (The study by Ailor et al placed all 3 constellations at 850 km, where Fengyun fragments are densest.)

Typical asset orbit inclination, deg.

This input affects the estimated collision frequency through its effect on the ArcLenMultiplier. That parameter is explained in more detail on pages 37 and 42, and used on page 17.

Current LEO asset values at risk, $M

This is simply the number of objects in each class times the estimated average cost of sudden accidental loss of a class asset. Selection of baseline inputs that give equal values for the High$, Med$, and Low$ assets was intentional, to give equal granularity in the analysis, and to ease side-by-side comparisons of the current and long-term effects of differences in class properties.

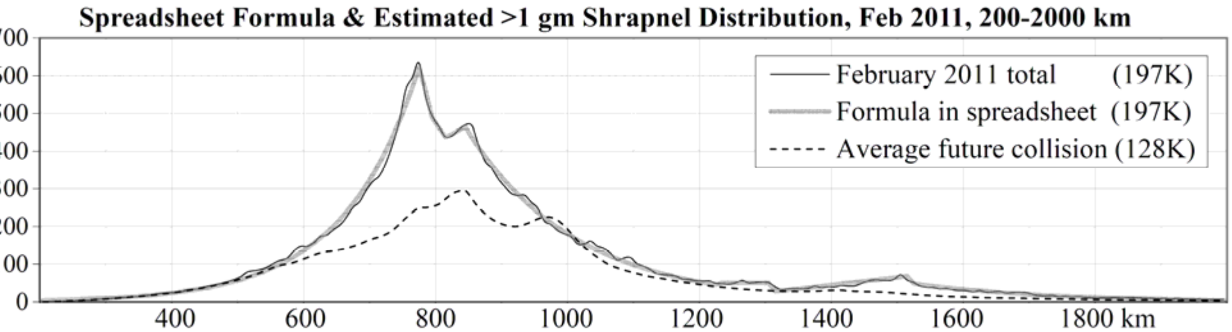
Current Debris Population and Threat

This part of the spreadsheet estimates current collision rates from the above inputs plus this item:

Est. total # LEO fragments >1 gram (ie, from 200 to 2000 km)

This is the single most important parameter in the whole spreadsheet, since all costs scale with it. As discussed on pages 11-13, it is poorly known. Future changes may also scale with this value, since both are driven mostly by intact/intact collision yield. A value of 200,000 is derived from my estimate of ~151,000 >1 gram fragments from Fengyun, Cosmos, and Iridium, decreased to 132,000 as described on page 6, increased by 50% to include all other sources (fragment/intact collisions, explosions, NaK coolant leaks, etc.), and rounded off as a reminder of the estimate's roughness. Other sources provide 95% as many ***tracked*** fragments as the 2007-9 collisions, but the lower energy of those sources should reduce their relative yield of smaller fragments. (Small NaK coolant droplets will partly make up for that.) In the future, improved practices may reduce some of these contributions, but growing fragment/intact collisions will decrease the net benefit.

Estimated #/km of >1g shrapnel at typical asset altitude
This line estimates the current population density of >1 gram shrapnel, in #/km altitude, at the "typical asset altitude" for each asset class. It uses the following altitude distribution of existing >1 gram shrapnel (from page 6), scaled by the total number of fragments (from the line above):



The thin black line and the dashed line above are copied from the plot on the bottom of page 6. The heavy gray line is a piecewise Excel formula fit to the black line. The spreadsheet uses that formula. The dashed line is included for comparison, but is not used by the spreadsheet. It is my mean expectation of the distribution of new shrapnel from a collision of 2 LEO objects > 1 kg.

Estimated #/km *lethal* shrapnel at typical asset altitude
This line takes the altitude-driven shrapnel population (#/km) from the previous line, and scales it by $\text{Grams50\%LethalMass}^{-0.75}$. This assumes a -0.75 power law for fragment count vs mass in the vicinity of 1 gram, based on the SOCIT4 and other ground tests.

Average Shrapnel-Asset ArcLenMultiplier
This line calculates the parameter described on page 42 and used on page 17. Most shrapnel is within ~1° of one of 4 inclinations, and most of the rest is within ~4°. The spreadsheet estimates the average ArcLengthMultiplier as a weighted average for those 4 clusters, based on shrapnel count estimates listed on page 6. The cluster weights and inclinations used are: 49% near 99.0°, 28% near 74.0°, 16% near 86.4°, and 7% near 65.5°. The 7% weight for 65.5° includes ~1% that is not clustered, and mostly <60°. To limit artificial enhancement when AvgA+B= ~180° but A is actually spread out, the calculation of the Ln(Cos) term for each cluster limits A+B to 179°. It would be more accurate to compute the altitude distribution, ArcLenMult, and asset threat from each shrapnel inclination cluster separately, but that seems infeasible in a one-page spreadsheet.

Objects at 81-83° and objects in sun-synch orbits (at 96-102°) pose enhanced collision threats to each other, since A+B= ~180°. As a result, any future shrapnel generated from objects in 81-83° inclination orbits will put sun-synch assets at disproportionate risk. And sun-synch is the main "international" inclination cluster. It includes 57% of the non-Russian, non-ISS mass in LEO, and perhaps an even higher fraction of operating satellite value. One item of good news here is that other than a small overlap near 620 km, most of the mass at 81-83° is at different altitudes from that at 96-102°. This reduces near-term intact/intact collision risks. But even one collision will have more serious effects than elsewhere. So please remember that tight altitude clustering and the high total mass at 81-83° (3 Russian clusters totaling 3/8 of the LEO mass) should make these objects of high priority for early wholesale removal or relocation. Shredding of ***any*** large object at 81-83° inclination will greatly increase risks to ***all*** sun-synchronous spacecraft.

AltitudeRateAdjust relative to 1000 km
This line calculates the effect of operating altitude on orbit circumference and orbit period, both of which affect collision rates. The actual Excel calculation is very simple:

Adjust = (AssetKmAlt+6378)/7378)^-2.5

Lethal Impacts/Yr/Km2NormalTargetArea
This line calculates the average chance of hitting a 1 km^2 area normal to the shrapnel approach path at the asset orbit altitude and inclination. It simply multiplies the last 3 lines above (# lethal shrapnel/km altitude * ArcLenMultiplier * AltitudeRateAdjust) times twice the # of orbits/year at 1000 km altitude (10007), and divides by the orbit path length at 1000 km altitude (46357 km).

Vulnerable normal area for class assets, m2
This line is simply the product of the number of assets in the class by their average vulnerable area normal to approaching shrapnel.

Lethal impacts/year (total for class assets)
This line is the product of the two lines above, divided by 1E6 to adjust from rate/km^2 to rate/m^2. Note that it is the total number of collisions for all assets in that class.

Current Actuarial Cost to Class, $M/Yr
This line is simply the product of LethalImpacts/Year and the EstAvgNetCostOfImpact input. It is the estimated cost per year, for this year's asset and shrapnel populations.

Expected Annual Trends Affecting Costs

This part of the spreadsheet consists of inputs estimating annual trends that affect future costs. Objects in orbit will add to future threats until they and shrapnel they create are removed, so one must estimate trends to estimate the future cost impacts of leaving debris in place. The inputs are necessarily guesses, but what matters is not so much individual entries as their combined effect, because that is what drives the overall expected annual change in cost. Note that the shrapnel population trends have linear and quadratic terms, but the costs are compounded and are hence exponential. The spreadsheet calculations handle these differences properly.

Net shrapnel Δ/year w/current LEO mass
This input specifies the expected net average annual increase in shrapnel count, given the current population of intact objects that can collide and generate new shrapnel. (The next input adjusts this for an expected future trend in large-object population.) I suggest using 3.35%, based on the following analysis. First, separate analyses by Eugene Levin and me both suggest a ~6% annual chance of a collision between 2 large objects now in LEO, with an average shrapnel yield equal to that of the Fengyun/A-sat plus Cosmos/Iridium collisions together. On page 36 I suggest assuming that all other shrapnel sources together increase the current shrapnel population 50%. If so, then a 6%/year collision rate with an average yield equal to Fengyun plus Cosmos+Iridium is a 4%/year increase in the 50% larger total shrapnel count. I also assume that all sources other than intact/intact collisions (including fragment/intact collisions) currently add 50% as much as intact/intact collisions. This brings the total increase back to 6%/year.

But this input requires estimating the ***net*** annual increase in shrapnel, despite shrapnel decay. Many estimates of debris cleanout use prior solar cycle drag trends, and do not adjust for the current low cycle or predictions of reduced average future exosphere temperatures. The actual cleanout of tracked fragments through 2012 is 1.5%/year for Fengyun, 4% for Cosmos, and 5% for Iridium. Also, the plot on page 5 indicates that much of the future shrapnel will come from collisions at 950-1010 km altitude. That shrapnel will stay in orbit significantly longer than shrapnel from Fengyun, Cosmos, and Iridium. Overall I suggest 2.5% average annual cleanout.

A 6% shrapnel increase with 2.5% average cleanout gives a net increase of 3.35%/year (=106% * 97.5% - 100%) for the current source population, for collisions plus all other sources. One can argue about components and still agree on net annual change, or disagree on both components and net annual change. Users can substitute any other net change trend they think more likely.

Annual ΔMass at crowded LEO altitudes

This input increases the predicted shrapnel growth rate with mass in orbit. Page 7 of this paper showed historical contributions to the mass in LEO in 2011. One can model that as a fixed 50 tons/year added since 1967. Continuing that trend forward suggests a ~2.27%/year linear mass addition. But since 1995 Russia has greatly reduced launches to the most crowded altitudes, 840-850 and 950-1010 km. In addition, many LEO users may shift away from those altitudes, and they may also deorbit more objects. Overall, I suggest using 1%/year as an effective net mass addition rate to crowded altitudes. The spreadsheet uses this as a linear (not compounded) annual mass increase. It has a quadratic effect on intact/intact collision rates and a linear effect on other shrapnel sources, which I assume now produce ~1/3 of the expected new shrapnel.

Change in (Asset# * Cost * Vulnerability)

This input estimates the combined annual effect of trends affecting assets of each class, including asset count, cost, and vulnerability. Since all LEO assets are lumped into 5 classes, covering ISS to Cubesats, it is critical to model all assumed trends using those classes, rather than envisioning new classes that are not included. The Totals column at right shows the overall current trend (+1.1%/yr). It is weighted by the Current LEO Asset Values At Risk values computed on line 13. For manned assets, rather than considering only ISS depreciation, one should estimate future trends in the number, area, vulnerability, and cost-of-loss of all manned assets. Hence Bigelow, Chinese, and other possible facilities may justify a zero or even positive input for this class, even if ISS may depreciate and not be replaced. But the high cost-at-risk and likely long life of ISS should limit the size of any cost-weighted estimates of trends in vulnerability of manned assets.

For unmanned assets, the inputs used assume a slow shift in focus towards lower-cost LEO satellites: -4%/year changes for High$ assets, +1% for Med$ assets, +6% for Low$ assets, and +20% for Cubesat programs. (Current cubesat annual increases are much larger, but they are unlikely to persist at such rates for the 20-year time horizon used in the later calculations.)

Future-Cost Real Annual Discount Rate

This input is the standard parameter used to compare current and future costs. A 5% discount rate means $100 of next-year cost is worth $95 of this-year cost. Longer-term discounts are compounded annually. So a 5% discount rate makes a $100 cost 20 years from now equal to a present cost of only $\$100 * (1-0.05)^{20} = \$35.85$.

The spreadsheet allows different annual discount rates for different asset classes, because large programs usually have a longer-term perspective and proportionately less funding uncertainty. Hence they (and any parent programs that may also fund removal) can probably justify spending more to reduce expected future costs than smaller programs can. So I have used discount rates of 5% for ISS and High$ programs, 6% for Med$, 7% for Low$, and 8% for Cubesat programs. Users are free to change these and all other parameters as desired, to explore the effects of changes in input assumptions.

The asset cost trend and annual discount values used in the spreadsheet can be specified either as including or excluding inflation, as long as one is consistent. I think it is far cleaner to use "constant value" dollars so one can avoid having to guess at long-term average inflation rates.

5 Year Interval Shrapnel Data

The "5" value is actually an input. It specifies the timestep used for the 5 sample years used below (years 0, 5, 10, 15, and 20 when the input is "5"). This value is used not just to show sample intervals, but also to set the overall time horizon (=4X the selected interval) over which future costs are discounted and accumulated. So if you change the interval, the trends and total discounted present-value costs do adjust properly to the change.

The spreadsheet uses a finite time horizon because unlimited horizons become very sensitive to small differences between asset + shrapnel trends and discount rate, and can even show infinite present cost. Railroads and utilities may be able to justify horizons well over 20 years, but since the space age is only 56 years old, it seems relevant to limit the horizon to well under 56 years.

Open extrapolation is also unrealistic in neglecting the likelihood of future changes in policy, technology, or other trends. If the chance of large collisions remains ~6%/year, another collision is >70% likely within 20 years. That may trigger changes, so far longer extrapolations may have little basis. And 20 years is a plausible investment horizon at least for High$ programs. So 5-year intervals and a 20-year time horizon may be reasonable. But one can change the time interval (and resulting time horizon) to any other value of interest.

EffMass is the projected mass at crowded LEO altitudes, relative to the current value. It is calculated from the Annual ΔLEO mass at crowded altitudes and the time interval used. It is assumed to change linearly over time. (The plot on page 7 supports a "noisy" linear trend.)

Incr/Yr is the annual increase in shrapnel populations at the 5 sample years. It is 2/3 of the assumed net annual shrapnel increase at the current LEO mass, times the square of **EffMass** on the left (to represent trends in intact/intact collision rates), plus 1/3 of the current net annual shrapnel increase, times **EffMass**, to represent trends in all other shrapnel sources.

Rel#Shrapnel is the relative shrapnel count in the 5 years sampled. It multiplies the average of previous and current Incr/Yr times the interval and adds that to the previous Rel#Shrapnel. This is used to compute discounted costs for each asset class, in the columns over on the right.

Discounted Annual Future Costs by Year, $M

This array of cells calculates discounted annual costs for five different years for each asset class. It multiplies current-year costs (from line 24) by the relative shrapnel population for that year (in column D), times the compounded effects of annual changes in asset cost and discount rates. The High$ class has higher costs despite an assumed higher lethal shrapnel mass threshold, because the total vulnerable area is comparable that of the smaller classes, but the cost of each impact is far higher. Both High$ and Med$ risks decrease over time, because their discount rates exceed the trends in shrapnel count and class asset cost-at-risk. For Manned assets, cost trends are roughly flat, since other trends balance discount effects. The Low$ risks increase slowly. And for Cubesats, a 20%/year assumed growth rate increases costs rapidly over time, but the costs remain very low compared to the other classes, due to very small cubesat area and cost and their modest altitude and inclination. (Note that if you use time horizons >20 years, annual Cubesat growth rates <20% may be more realistic.)

20 Year Discounted Costs, $M

This is the bottom line: estimated present costs of a series of future losses of assets in different classes, as a function of all the inputs on the page. It is calculated from the 5 sample years listed above, using Simpson's rule weighting (1-4-2-4-1) for those 5 sample years. The 20-year time horizon can be changed by changing the blue "5" year interval input on spreadsheet line 31.

The reasonableness of the bottom-line costs depends on the accuracy of the inputs, most of which necessarily involve guesswork. It is easy to change the inputs used, and I encourage readers to do so. Playing with the spreadsheet, and even fighting with it, can be enlightening.

If the discounted 20-year costs-of-loss are indeed highest for High$ and Med$ programs, then optical fence and debris removal concepts may get the most support from such programs.

Note that this finite-horizon approach includes only the losses due to increasing shrapnel count that occur within the selected horizon. The fact that the year beyond that horizon may start with ~1.79X the current shrapnel population is not included in finite-horizon costs. Increasing the intervals and resulting horizon allows inclusion of later losses, but the accuracy depends on the accuracy of the further extrapolation of all inputs and trend assumptions. For example, doubling the interval from 5 to 10 years changes the horizon from 20 to 40 years, adds 66% to the present-value discounted cost, and predicts a 2.84X larger shrapnel population at the end of year 40. It seems likely that substantial progress may be made to prevent or greatly reduce such increases well before then, so such 40-year "business as usual" extrapolations may be unjustified.

This spreadsheet can clearly be improved, at the cost of more complexity. For example, rather than using current shrapnel altitude & inclination distributions in future years, it could separately keep track of expected collisions, evolving counts and altitude distributions, varying drag effects, and specific AvgArcLenMultiplier values for each major shrapnel inclination cluster.

But the most important improvement may be not to the spreadsheet structure or calculations, but better input values. I encourage readers who may have better values for any inputs to use them. This will give them results that they will have reason to take more seriously.

Calculation of the Average Collision Arc Length Multiplier

There are various ways to calculate orbital collision rates. The method shown and explained on page 17 is straightforward, but requires a factor that accounts for how collision rates vary with approach geometry. Most objects at a given altitude in LEO have horizontal velocities within a few percent of each other and low vertical velocities. Hence the collision geometry, speed, and frequency are mostly affected by variations in the direction of relative motion in the plane of the local horizontal. So the problem can largely be reduced to coasting horizontal motion.

Consider a drunk driver on an uncrowded freeway, who is "slaloming" back and forth through several lanes at nearly the same speed as the other traffic. If he passes between two cars in one lane, the minimum clearance needed to prevent collision (if he is lucky) is little more than his car length. This resembles the case of an impactor in low-inclination orbit "slaloming" between objects distributed along another low-inclination orbit. The common velocities can be ignored, and what is left is transverse oscillation about the nearly common orbital motion.

If the same driver is driving against the flow of traffic, far larger clearances are needed between adjacent cars in one lane, because of the distances traveled in opposite directions during the time it takes to traverse that lane. And if head-on traffic involves a total slalom amplitude less than the combined widths of the cars, collision is inevitable. This would occur to objects in 0^o and 180^o orbits: only altitude differences and perturbations can keep them from colliding every half orbit.

Actual orbit geometries can range between these cases. Differences in the along-track clearance needed between spherical or randomly-oriented objects are differences in "ArcLengthMultiplier" along an orbit. Near-equatorial orbits have nearly parallel motion, so impactor relative motion is normal to the target orbit plane. Then there is no enhancement of the orbit arc length along which a target can be positioned and be hit by an impactor. Objects in inclined orbits always approach objects in 0^o orbit at the same angle, so the enhancement is fixed, at 1/Cos(Inclination/2). This goes to infinity at 180^o but saturates shortly before that, when the enhanced arc reaches ½ orbit.

In the general case of 2 inclined orbits with varying relative nodal phasing, the approach angles and enhancement vary over time. The average enhancement equals the average reciprocal of the straight-line distance between 2 points on a unit-diameter sphere. One point has fixed longitude and a distance from the north pole equal to the orbit inclination of one object. The other point moves uniformly through all longitudes at a distance from the south pole equal to the inclination of the second object. Study of limiting cases and their combinations led to the empirical formula below. It gives an average ArcLengthMultiplier to be used as shown on page 17, for two objects (either spherical or randomly oriented) in orbit inclinations A and B, provided $A+B<180^o$. (If $A+B>180^o$, subtract each inclination from 180^o and use those values, which now sum to $<180^o$.)

AvgArcLenMult = Sqrt[1+Sqr{0.347 * Ln(Cos{A/2+B/2})}] / [Cos(A/2) * Cos(B/2)]

The Ln(Cos) term handles effects that cause large periodic spikes in risk if A+B is near 180^o, and the Cos * Cos divisor handles other effects. This formula is within 2% for inclination pairs that sum to $175\text{-}179.9^o$, and within 1% for all sums $<175^o$ or $>179.9^o$. For oriented non-spherical objects like the cars in the above freeway model, object length is relevant when ArcLenMult is near 1, and width is more relevant for high values. The average relative approach angle should be close to ArcSin(1/AvgArcLenMult) away from a head-on approach.

LEO Shrapnel Cost Estimator   Joe Carroll   **10/31/2013**

Blue represents input data; black indicates derived values.

Asset Classes:	**Manned**	**Unmanned Assets**			**TestCase**	
Current LEO Asset Data:		**High$**	**Med$**	**Low$**	**3U-Cube**	**Totals**
Number of assets now operating in LEO	**1**	**12**	**60**	**300**	**20**	393
Est. avg. net cost of "lethal" impact, $M	**4000**	**1000**	**200**	**40**	**1**	
Grams shrapnel mass for ~50% lethality	**1.5**	**1**	**0.5**	**0.25**	**0.01**	
Average vulnerable normal area, m2	**200**	**45**	**12**	**3**	**0.040**	2361
Typical asset orbit altitude, km	**400**	**650**	**700**	**750**	**600**	
Typical asset orbit inclination, deg.	**51.6**	**98**	**75**	**60**	**51.6**	
Current LEO asset values at risk, $M	4000	12000	12000	12000	20	40020

Current Debris Population & Threat:	**Est. total # LEO fragments >1 gram:**					**200000**
Est. #/km of >1g shrapnel at typ. asset alt.	24	213	329	508	138	
Est. #/km ***lethal*** shrapnel at typ. asset alt.	18	213	553	1437	4358	
Average Shrapnel-Asset ArcLenMultiplier	1.68	2.37	2.29	1.81	1.68	
AltitudeRateAdjust relative to 1000 km	1.24	1.13	1.11	1.09	1.15	
Lethal Impacts/Yr/Km2NormalTargetArea	8.0	123	303	613	1822	
Vulnerable normal area for class assets, m2	200	540	720	900	0.8	
Lethal impacts/year (total for class assets)	0.002	0.066	0.218	0.552	0.001	
Current Actuarial Cost to Class, $M/Yr	**6**	**66**	**44**	**22**	**0.001**	**139**

Expected Annual Trends Affecting Costs:						
Net shrapnel Δ/year w/current LEO mass	<average over all congested orbits>					**3.35%**
Annual Δmass at crowded LEO altitudes			"			**1.0%**
Change in (Asset# * Cost * Vulnerability)	**2%**	**-4%**	**1%**	**6%**	**20%**	1.1%
Future-Cost Real Annual Discount Rate	**5.0%**	**5.0%**	**6.0%**	**7.0%**	**8.0%**	5.9%

5 Year Interval Shrapnel Data:				**Discounted Annual Future Costs by Year, $M:**					
Year#	EffMass	Incr/Yr	Rel#Shrapnel	Manned	High$	Med$	Low$	3U-Cube	Totals
0	1.00	3.4%	1.000	6.4	66.5	43.6	22.1	0.001	139
5	1.05	3.6%	1.175	6.4	49.3	39.5	24.1	0.003	119
10	1.10	3.9%	1.364	6.4	36.1	35.4	26.1	0.005	104
15	1.15	4.2%	1.568	6.3	26.2	31.4	27.9	0.010	92
20	1.20	4.6%	1.788	6.1	18.8	27.6	29.6	0.019	82
20 Year Discounted Costs, $M:				**127**	**765**	**709**	**520**	**0.138**	**2121**

Users can change all inputs they disagree with, and can easily explore the effects of changes. The value of the spreadsheet may be far more in its linkages between key parameters, than in the specific inputs used. If you copy the blue inputs for a case of interest to the "3U-Cube" test case, and then change that, you can see the effects of your changes side by side.