A Clearer View of Orbital Debris

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ABSTRACT
DoD’s new S-band radar space fence at Kwajalein, and a new LEOLabs radar, should find and track most new LEO objects down to 2-5 cm. This may find ~20X more LEO debris than now cataloged. This raises a question: What debris detection is “good enough”? J.-C. Liou has provided a useful criterion: “The major mission-ending risks for most operational spacecraft, however, come from impacts with debris just above the threshold of the protection shields (~5-mm to 1-cm).” For each of ~10,000 >10cm LEO fragments now cataloged, there may be ~100 pieces of “cm-class shrapnel” capable of disabling most spacecraft. Ground telescope 2D fixes of sunlit LEO objects can be within meters, but predicted future positions quickly grow uncertain, particularly for small shrapnel. It has a larger area/mass ratio than satellites, so it reacts more to air drag. One must either track small debris more often, or infer future changes in debris drag area as debris spin axis, orbit plane, and perigee phase evolve. A useful telescope network may need two half-meter telescopes at each of ~50 good sites world-wide, with each telescope slewing to new sunlit objects every few seconds. This would wear out geared mounts, so agile direct-drive mounts are needed. The paper argues that telescopes can find and track not just ~1% of lethal LEO debris as we do now, or ~20% of it using S-band radar, but possibly most of it. A key question is whether that value is sufficient to support such a telescope network and the resulting conjunction analyses. The paper addresses but cannot resolve that question now.

Keywords: debris, drag prediction, telescopes, space situational awareness, actionable conjunction warning.

1. INTRODUCTION: THE IMPLICATIONS OF CM-SIZE DEBRIS
The main long-term concern about debris in LEO has been an expected slow exponential growth in tracked debris >10cm that have enough mass and impact energy to shred the ton-class intact satellites and rocket bodies that have most of the mass and area in LEO. Based on ground tests, collisions with >40J kinetic energy per gram of total mass are expected to shred the larger object, while lower energies create far less new debris [1]. The US DoD tracks space objects because its space assets are important, vulnerable, and expensive. Their focus is on maneuverable spacecraft (>10 cm). A focus >10 cm also fits since few <10 cm debris can shred most of the ton-class intact objects in LEO. Most tracked LEO fragments before the 2007 Fengyun/A-sat test and the 2009 Cosmos/Iridium collision were from sources other than collisions. But ~40% of all LEO catalog fragments are from those 2 collisions. They should be more representative of future collisional debris than other fragments. Based on orbit decay from 2009 to 2011 and an estimated median fragment Lc =14 cm, only 10-20% of those fragments may shred most large LEO objects [2]. This suggests that the Kessler syndrome may grow more slowly than expected. But debris may still cost more than we think:

1.1 The Lethality of Cm-Size Shrapnel
At LEO impacts of ~9 km/sec, shredding an object takes impact by ~1/1,000 its mass. But disabling satellites takes far less (~1E-6?). There seems to be little interest in tracking and avoiding small shrapnel. I argue here that it seems feasible, and may even pay for itself. DoD is testing a new S-band radar space fence at Kwajalein [3], and LEOLabs a radar in New Zealand [4]. They may both find objects down to 2-5 cm at close range. That raises a basic question:

What debris detection is “good enough”?

J.-C. Liou, NASA’s chief scientist on orbital debris, has suggested a useful perspective:

The major mission-ending risks for most operational spacecraft, however, come from impacts with debris just above the threshold of the protection shields (~5-mm to 1-cm. [5]

The threshold lethal impactor size for spacecraft varies with impactor mass, velocity, angle, shielding, spacecraft layout, and luck. The radar and optical detectability of “barely lethal” debris also vary. The key question is how many lethal debris impacts we can affordably avoid. Better sensors let us find, track, and avoid more debris, but cost more. And sensors that see most lethal debris will also see some less lethal debris. So it seems useful to infer the mass of tracked debris, and the likely lethality of each predicted conjunction.
DoD provides conjunction services because they have the best sensors and predictions. They were tasked to do it after the 2009 collision, but want others to do it. The US Dept. of Commerce has been tasked to manage civil needs.

1.2 Key Implications of Tracking Smaller Debris

Most cubesats might be disabled by 1 mm debris. But few cubesats can maneuver to avoid impact. My focus here is on protecting satellites that can maneuver to avoid an impact. For those larger and more valuable satellites, I assume here Liou’s estimate of mission ending risks as coming mostly from impacts just above “~5-mm to 1-cm.”

Near 1 cm, shrapnel counts above any length L scale with \( \sim L^{-1.6} \). So \( 2/3 \) of >5 mm objects are <1 cm, and \( 2/3 \) of >1 cm objects are <2 cm. Debris in this range can be called “cm-class shrapnel,” with uncertain numbers, visibility, and lethality below ~1 cm. Most lethal shrapnel will be 5-20 mm, below DoD and LeoLabs radar thresholds. Lethal shrapnel may outnumber >10 cm LEO fragments ~100 to 1. **Lethal LEO shrapnel may need a ~million-item catalog.**

Avoiding lethal debris is a different challenge from military space situational awareness. A 100X larger catalog is a big challenge, but there are other challenges as well. For example, tracking smaller objects requires more sensitive sensors. In addition, most small debris objects are also thinner. So their orbits are affected faster by drag than larger objects at the same altitude. Hence such objects require more frequent update observations, or much better drag prediction. On the other hand, unlike objects of military concern, debris cannot make sudden orbit changes, except by very infrequent small impacts. The rest of this paper explores some key implications of these differences.

1.3 What Makes Conjunction Warnings Actionable?

Current conjunction warnings have large position uncertainty, so the chances of impact are low. Consider a small object approaching a typical satellite that can maneuver to avoid debris. A satellite may have 1 m² vulnerable cross-section in the approach direction. Observations and predictions are updated before conjunctions, to reduce uncertainty. A final warning might list a 20 m predicted miss distance, but with an RMS position uncertainty of 50 m vertically and 500 m horizontally. The chance of collision is then only \( \sim 8 \) ppm. That is not a useful “actionable warning.”

Conjunction warnings are actionable if and only if it is cheaper on average for a satellite operator to act on them than to ignore them. Acting on them requires propellant, or attitude changes to change drag and/or vulnerability. This can affect satellite function or life. The total cost per active avoidance, including transient loss of function, propellant use, lifetime loss, and analysis and monitoring, may often be \( \sim 10-100 \) ppm of the cost of losing use of the satellite. Buying a warning service will add to the cost. To be actionable, a warning must be of a higher chance of satellite loss (=smaller conjunction errors) than the cost ratio of acting on a warning vs suddenly losing use of that satellite. In the case of constellations, debris from a collision breakup can also “foul the nest” for the rest of that constellation.

Tracked telescopic images of LEO objects can provide sub-arc-second fixes and few-meter alt-az errors, if we tie the target to the ends of bright star streaks in the same image. Then uncertainties will be mostly from uncertainties in orbit predictions, not a few meters of uncertainty in a 2D fix itself. Prediction errors in LEO in the most congested altitude range (\(~750-1000\) km) should be mostly from uncertainties in air density and effective drag \( C_dA \).

The DoD catalog now lists \(~3000\) intact satellites and rocket bodies in LEO [6]. Intact objects can be usefully called “cars” since most are car-sized and ton-class. The catalog also includes \(~9000\) LEO fragments, mostly 10-30 cm and <1 kg. They might be called “hubcaps.” Cars have nearly all the collision area, but hubcaps outnumber cars \( \sim 3:1 \). One might think that most debris from collisions will be from hubcap/car collisions. But car/car collisions have \( \sim 4X \) larger collision cross-sections than hubcap/car collisions. Cars also cluster more in altitude, so they collide more often. And as noted above, most hubcaps may not be heavy enough to shred most cars [2]. And car/car collisions involve twice the mass of hubcap/car collisions. And even with large CG offsets, most car/car collisions will have 10-1000X the energy of hubcap/car collisions to shred both cars. So car/car collisions will create most collisional debris, until there are enough heavy hubcaps for heavy-hubcap/collisions to dominate debris growth. That may take a century.

This leads me to focus on avoiding most shrapnel. I do not know the cost of radars or space-based telescopes that could maintain a precise ~million-item catalog. So I focus only on ground-based telescopes as a candidate for that role.

The remaining sections of the paper focus on:

2. Dynamics and implications of fast spin of LEO debris
3. Predicting changes in debris drag \( C_dA \)
4. Implications on sensor networks
5. Estimated costs of tracking and avoiding most lethal LEO debris
6. Conclusions and recommendations
2. DYNAMICS AND IMPLICATIONS OF FAST SPIN OF LEO DEBRIS

The Fengyun/A-sat and Cosmos/Iridium collisions in 2007 and 2009 created ~4200 of the ~9000 cataloged LEO fragments in orbit now [6]. They also resemble most future LEO collision-driven debris in inclination, since ~90% of the mass in LEO is at 70-100° inclination, and the altitudes of those collisions (780 and 860 km) are also relevant since 2/3 of debris from accidental collisions will be created at 750-1000 km [7]. So they are very useful test cases.

Ground tests show that impacts create fine particles that splash out at speeds similar to the impact speed. Typical collision CG offsets may let much of this “hypervelocity hailstorm” miss the rest of both objects. But even a small part of that storm can shred much of each object, without spreading fragment trajectories much. This is consistent with tracked debris from the 2007 and 2009 collisions. Most left the source orbit at only 1-2% of orbit velocity. This created 2 clouds from Cosmos/Iridium, but 1 from Fengyun. Its A-sat had a negative perigee, so its debris deoribited.

Cm-size objects created by a hailstorm should depart faster than the >10 cm catalog fragments from the 2007 and 2009 collisions. Large fragments may involve mostly intact components like batteries, electronics boxes, reaction wheels, etc. Smaller cm-class fragments may be more likely to be torn sheets from those components. As Fig. 1 suggests, impact may shred many sheet-type materials without changing the sheet thickness much:

2.1 Debris Spin and Spin Decay

Even if a 1 cm object departs from a collision at only 100 m/s, and the departure rate differs by only 5% from one edge to the other, the result is 9500 rpm spin. Most spin is likely to include both flat spin and wobble.

Fig. 2 shows eddy currents in a flat coin-shaped piece induced by spin of a conductive object in earth’s magnetic field. Currents caused by flat spin have small current loop area and low EMF. Coin-flip or wobble current loops change with rotation phase. A much larger average loop area and EMF damp wobble far faster than flat spin. In aluminum alloys, wobble should have a half-life <1 month. Flat spin may last longer by Sqr(diameter/thickness). So thin aluminum may retain a fast flat spin for decades. Fig. 3 shows wobble creation and wobble decay to flat spin:

![Fig. 2. Eddy current loops](image)

Only aluminum alloys and copper cause fast decay of wobble. Stainless steel and titanium alloys both have ~70X higher density/conductivity, so they have ~70X longer wobble and flat-spin decay times. But most lethal cm-class debris fragments created by collision or explosion are likely to be torn pieces of flat aluminum alloy sheet. They are likely to spin fast when created, and quickly transition to a long-lived fast flat spin. Note that air drag torques cannot cause damp much spin, because drag causes deorbit before much spin is lost. Magnetized debris will see spin-axis torques, but that will involve only a small fraction of most shrapnel. Table 1 and Fig. 4 below show cycle times for perigee direction and orbit plane change. If the spin axis changes more slowly than this, then drag CdA changes will occur on these timescales, and those changes can be recognized, fitted, and predicted. Most shrapnel other than torn aluminum alloy sheet may have smaller CdA changes, but those changes might still be recognized and predicted.

Table 1. LEO debris orbit cycle times: node & apside

<table>
<thead>
<tr>
<th>Debris source</th>
<th>In catalog, early 2019</th>
<th>Orbit Incl.</th>
<th>Months/Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fengyun</td>
<td>2822</td>
<td>99.1°</td>
<td>11.6</td>
</tr>
<tr>
<td>Cosmos</td>
<td>1068</td>
<td>74.0°</td>
<td>6.5</td>
</tr>
<tr>
<td>Iridium</td>
<td>326</td>
<td>86.4°</td>
<td>28.2</td>
</tr>
</tbody>
</table>

![Fig. 4. Apside and Node Motions](image)
An object whose spin axis aligns with the airspeed at perigee will have far lower drag ¼ apside cycle later, when it slices through perigee like a Frisbee. Table 1 shows that ¼ cycle of apside takes only 0.9-1.4 months, with maximum change in drag CdA. Late in orbit life, orbits are less eccentric. Then changes in node matter more than perigee phase. If a flat object now spins in the orbit plane, it will have much higher drag during most of the next ½ node cycle.

2.2 Why Does Debris Spin Axis Matter?

The DoD’s Combined Space Operations Center (CSpOC, formerly the JSpOC) uses a “High-Accuracy Satellite Drag Model” (HASDM) to infer recent 3D air density [9]. It uses frequent radar updates of ~80 catalog objects with stable CdA, to infer air density. HASDM does not predict future changes in effective drag CdA, except for a few satellites with known schedules of CdA variations. HASDM could do this for debris. It could do that by using new air density data derived from the ~80 HASDM objects, plus predicted shrapnel CdA changes since the last update. The main payoff is to allow far longer and better predictions of orbits of lethal intermittently detectable shrapnel.

Better multi-day predictions are important. Both radars and telescopes see smaller things during closer passes. Most objects are small, and detected only intermittently, when the ground track is close to the observing site, and perhaps only when perigee is also near the site. Perigee phase cycles are fairly slow (see the last column in Table 1), but ground-track offsets usually change from day to day. The challenges here are quite different from military concerns. DoD’s new S-band radar space fence can see plausibly maneuverable spacecraft throughout LEO. But to track ~cm debris, orbit updates may be feasible only when the ground track is close to the sensor, and perhaps near perigee. In the above discussion, I assume that the spin axis remains fixed inertially. But even if the spin axis does respond to environmental torques, it may be feasible to infer and correct for those changes, as discussed in the next section:

3. PREDICTING CHANGES IN DEBRIS DRAG CdA

DoD’s public catalog [6] has many thousands of Two Line Elements (TLEs) for each of 3,000 intact LEO objects, another 9,000 LEO fragments, and a similar number of objects in higher orbits, mostly in GTO and GEO. Drag history data is embedded in changes in the “B**” parameter, mean motion and ephemeris times, and often in the mean motion derivative terms. One useful group for inferring future debris trends is the ~4200 fragments now tracked from the 2007 and 2009 collisions. That is nearly half of the tracked LEO fragment population. It is probably more typical of future debris created by collisions than most of the other fragments in the catalog.

3.1 A Strategy to Infer Spin Axis

Note that here one is looking for long-term cycles of predictable wavelength for each object, but with unknown phase and amplitude. One might start by using HASDM’s 3D air density history to infer CdA for each object for each TLE. Most CdA values should be closer to maximum than minimum. Key clues are low CdA values that indicate alignment of velocity with spin plane. If an orbit is eccentric enough, low CdA indicates edge-on attitude near perigee. But if eccentricity is low, then low CdA indicates that the orbit plane aligns with the spin plane.

General-purpose graphic processing units (or “GPGPUs”) are good for parallelizable computations. One can use them to calculate CdA trends for many spin axis cases and how they fit with TLE data. The best fits can guide another iteration covering smaller steps over a smaller range of cases. The best spin axis fits may drift over time, or may even have a step change. A step change may suggest a small impact. A consistent drift may suggest an object is spinning slowly enough for its axis to respond to torques, like magnetism or solar pressure torques on the spin axis. GPGPU calculations can test the fit for different drift cases to see which make the most sense.

After testing a large ensemble, some objects will show little change in CdA over time, while others have large but predictable change, and some have changes that cannot be predicted. If the stable plus predictable subsets include most of the 4200 cataloged Fengyun and Cosmos/Iridium collision fragments, they might even allow refinement of the HASDM air density history, at least over the ~700-900 km range of most of this debris. The objects HASDM uses apparently do not have a very wide range of orbits, so a far larger test set might improve on at least part of it. ESA is funding a program to measure and model the attitude motion of passive satellites and debris [10]. Programs that focus on satellites may not be efficient in modeling simple and rigid objects with fast spin.

3.2 Effects of Spin Axis on Optical Observations

On good evening passes of the ISS or other LEO objects, they usually get brighter even well past closest approach, because you can see more sunlit surface area then. This will be even more important in observing small shrapnel, especially flat objects with flat spin. Twice each year, the sun passes through the spin plane of each object and...
illuminates only edges rather than sides. The rest of the year, the sun illuminates one side at a time. Many passes let one see first one side and then the other during a pass, but some show only one side. If one sees only an unlit side, then only the sunlit edges are visible. Changes in brightness during and between passes are spin axis clues, and sometimes clues of different finishes on opposite sides. This is most useful after a new object is found, before there is a CdA history. So new objects should be seen longer and from more sites on more passes, partly to infer spin axis.

After even a few passes, rough inferences of spin axis should allow rough predictions of brightness on future passes. Passes with ground tracks on the anti-sun side of a site allow better views of sunlit surfaces. Spin axis tilt also affects the relative brightness in dawn vs dusk passes, until node changes affect the best observing latitudes. I don’t know what one can infer from radar returns of shrapnel near the limit of visibility. But during the best passes, it may be possible to infer spin rate, with some ambiguity. Spin-related signal modulation is likely to vary with radar angle to the spin. The strongest returns will be near zenith. But orbit change changes will vary the inertial angle of the radar’s zenith over months and hence change the best view angle. Once spin rate and axis data are known for an object, they may become a useful fingerprint. They can help indicate which of several tracked objects was just observed, by either radar or telescope, by looking for spin rate and signal waveform.

4. IMPLICATIONS ON SENSOR NETWORKS

The main payoff of improving drag predictions by predicting CdA trends is to allow useful cataloging of objects that are too small to be seen often enough for useful cataloging without this aid. This lets radar or other sensor networks maintain reliable custody of a larger catalog of small but lethal debris. This lets operators protect satellites against a larger fraction of the lethal shrapnel in LEO. But realistically, not all lethal shrapnel will be seen and cataloged, and not all close conjunctions will allow actionable warnings. The goal is to allow as many of them as feasible. More accurate warnings will be issued less often, and they also allow smaller maneuvers. Higher accuracy does have actual value, but only for already actionable warnings, ie, ones accurate enough to justify a maneuver.

DoD’s new S-band space fence may track objects down to 2-5 cm, depending on altitude. Its ~$1B price suggests that finding cm-class LEO debris using radar will be costly. But radar optimized for small debris in a smaller search volume may be far cheaper. LeoLabs may be using this approach. Telescopes are also an option, as discussed below.

4.1 Telescopes to Track Most Lethal LEO Shrapnel

Telescopes are usable to track LEO objects only near dawn and dusk, when LEO objects are sunlit but the sky is dark (and also clear). Far more sensors and sites are needed than with radar. Laser illumination allows use all night, but at higher cost and with constraints. Telescope costs usually rise faster than aperture area. Larger telescopes also spend less time on each target, and more time slewing to the next one. This raises costs per observation. Telescopes should track targets because imaging is far more sensitive if photons pile up in a spot rather than on a streak.

“Balance of system” costs for mount, camera, computer, enclosure, and installation scale slower than aperture area, but mount cost may rise with telescope size, and enclosure cost with telescope length and mount type. Telescope mounts must make fast slews >1E6 times/year. Geared mounts would wear out, so direct drives are needed. The most cost-effective telescope size should have telescope costs similar to balance-of-system costs. If those system costs are of order $100K, this suggests 0.5-0.7 m diameter telescopes for consideration.

PlaneWave Instruments developed the Corrected Dahl-Kirkham (CDK) Cassegrain telescope design [11]. As the name of the company suggests, the CDK has a flat focal plane, unlike R-C telescopes. This is very useful for area targets, and also for multi-spot targets like debris in a starfield. Table 2 lists data for 0.4-1 m aperture PlaneWave observatory telescopes. Prices below include fused silica mirrors, agile direct-drive mounts, and a rotating focuser.

<table>
<thead>
<tr>
<th>Aperture, mm</th>
<th>f/ratio</th>
<th>Image dia, mm</th>
<th>Trans. area, m²</th>
<th>Price $M</th>
<th>SM/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>432</td>
<td>6.8</td>
<td>70</td>
<td>0.088</td>
<td>$46,000</td>
<td>0.523</td>
</tr>
<tr>
<td>508</td>
<td>6.8</td>
<td>52</td>
<td>0.135</td>
<td>$55,300</td>
<td>0.410</td>
</tr>
<tr>
<td>610</td>
<td>6.5</td>
<td>70</td>
<td>0.179</td>
<td>$85,500</td>
<td>0.478</td>
</tr>
<tr>
<td>700</td>
<td>6.5</td>
<td>70</td>
<td>0.212</td>
<td>$215,500</td>
<td>1.017</td>
</tr>
<tr>
<td>1000</td>
<td>6.0</td>
<td>100</td>
<td>0.433</td>
<td>$655,500</td>
<td>1.514</td>
</tr>
</tbody>
</table>

Fig. 5. PlaneWave Direct-Drive 0.5m & 1m Telescopes.
The 432 to 610mm sizes all have “L-series” mounts like the one shown at left in Fig. 5. The 432 mm telescope uses the same mount as the 508. That raises its mounted cost per square meter of effective aperture area. The 700 mm and 1000 mm telescopes both have yoke mounts. A rotating third mirror allows a dual Nasmyth focus at each side of the yoke mount. This allows fast switches between instruments. There is a minor light loss from the third mirror.

4.2 Performance in Orbit Update Fixes

I developed a spreadsheet to estimate performance vs telescope size, using high-end sCMOS and CCD cameras. Throughput per $ was best with the 508 mm aperture, paired with the $21K FLI Kepler 400 sCMOS camera [12]. Table 3 lists conditions that may be typical for an update fix of a “threshold brightness” 5 mm object at the 778 km altitude of the Iridium constellation. Sky parameters are line-of-sight values at the assumed 45° elevation angle.

<table>
<thead>
<tr>
<th>Table 3. Typical Threshold-Brightness Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target: 5mm sphere, 10% diffuse reflectance, 778 km altitude</td>
</tr>
<tr>
<td>View: 45° elevation, 45° lighting phase, 1046 km range</td>
</tr>
<tr>
<td>Sky: 0.735 transmittance; 1.5 arc-sec seeing; 500 S10- sky brightness</td>
</tr>
<tr>
<td>Telescope: 508mm aperture dia, f/6.8, 16% obstruction area, 79% transmittance</td>
</tr>
<tr>
<td>Imager: 1 e-/4.6eVsun; 1.6e- RMS read noise; 0.4 e-/s pixel dark current</td>
</tr>
<tr>
<td>Image: 19.6 magnitude; 224 eV/s; RMS blur dia=2.4 pixels</td>
</tr>
<tr>
<td>Starfield: 12 star streak ends brighter than 12th mag in typical frame</td>
</tr>
<tr>
<td>Noise: 3.2 e-/pixel/frame from sky + read + dark noise</td>
</tr>
<tr>
<td>S/N: 6.0 in 2 frames, each with 1.2 sec exposure</td>
</tr>
</tbody>
</table>

Spinning shrapnel will vary in brightness far more than diffuse spheres, so tracking should continue in a second image until the first is read out, the target is found along a predicted “line of uncertainty,” and its expected 2-frame S/N is enough higher than that of other random bright spots on the line of uncertainty. The relevant N here is the background noise, which excludes shot noise from the signal itself. This case takes 2.4 seconds for 2 frames. The average signal is 117 e- and average 2-frame S/N is 6.0. RMS blur diameter is 2.4 pixels, and FWHM is 2.8 pixels.

NASA’s Standard Breakup Model specifies a mean debris cross-section of 0.54 Sqr(Lc) for Lc=5mm, while sphere cross-sections are 0.7854 Sqr(Lc). A 10% diffuse reflective sphere should be as bright as the average brightness of tumbling same-Lc shrapnel, with NASA’s assumed 0.145 average debris diffuse reflectance. That conveniently is 10% * 0.7854/0.54. Based on the count vs size slope in NASA’s ORDEM 3.0 model of LEO debris [13], the median brightness of shrapnel above this brightness is ~2.5X brighter than this case. Such median-brightness objects will accumulate an S/N>6 in <1 second. For other object altitudes but the same view conditions, a sphere will have the same brightness if diameter scales with range (which scales nearly with altitude). With a ~million-item catalog and a mix of priority and opportunistic updates, another target will usually be within a few degrees. Priority updates may need longer slews, but average times to slew to and settle on a target should be <1 second. If typical updates take <1 to 2.4 seconds plus <1 second for slewing and settling, throughput should be ~1500/hour or ~5000 per clear night.

In the case listed in Table 3, stars will transit an image in ~1 second, but an average of 12 stars brighter than 12th magnitude (>24 e-/pixel streak signal) will have streaks that begin or end within each image. Those streak ends should fix a target alt-az position within ~1 arc-second, at a time referenced to a local GPS receiver.

4.3 Scheduling Orbit Update Fixes

Most alt-az fixes will be of small shrapnel because there is more of it, and also because its higher Cda/m requires updates more often. Unfortunately, small shrapnel is visible less often and requires longer tracking times. “Priority” and “opportunistic” describe the ends of a continuum. “Priority” fixes improve the orbit predictions for a specific upcoming conjunction, while “opportunistic” ones reduce future observing uncertainties. If small debris is at an altitude where there are no maneuverable satellites, the only reason to track it is to keep from losing it. Such an object merits higher priority if predicted visibility will be low for some time and a new update can reduce later search time for recovery when it becomes more visible again. The same situations will have even higher priority if debris crosses the orbits of maneuverable satellites. It will rise further if it crosses a satellite constellation.

The highest priorities occur once a conjunction is identified with non-trivial chance of impact. One can compute the cost of a conjunction: the chance of lethal impact times cost of losing that satellite. One can also compute the values of new fixes, since they may either eliminate a threat or trigger an actionable warning. Note that the night sky is far brighter near full moon. This requires longer exposures both morning and evening within 3 days of full moon. There may be little time for opportunistic updates then.
Based on these factors, the relative value of potential fixes can be ranked. Then one can predict brightness during each pass to estimate time required for a fix at each site. This can use an “internal market,” with software agents trying to find the most valuable use of each telescope. At a system level, other factors must be included, including the chance of clear sky at each site, and the availability of later backup fixes if a planned one does not occur.

All fixes that may trigger conjunction warnings need to be done by a “trusted organization.” Later quality-control tests of most fixes can be done by fitting a fix to earlier and later fixes. Such tests can also quantify typical fix and prediction errors. This will be needed continuously, to assure customers of prediction accuracy. Note that initial detection of new objects need not be done by trusted organizations. There might even be bounties paid for finding new objects and their orbits, once they are later verified by a trusted organization, as discussed in [7].

4.4 Building a ~Million-Item Debris Catalog

As noted in section 4.1, sensitivity is higher when an object is tracked accurately enough that photons pile up in a small spot, rather than on a long streak. But until you find a new object and its motion, you cannot track it precisely. A few tricks can help. First, most new debris is highly clustered initially. Any new debris cloud will be found by the new S-band fence within hours. It can provide tracking data for a new cloud without disclosing the fence sensitivity. Then telescopes can start tracking a new cloud whenever it is visible. New-object streak lengths will be driven more by altitude differences between two objects, more than to velocity changes themselves. Streak S/N should scale as Signal/Sqrt(StreakLen) for exposures of a given duration. For equal S/N, a 300-pixel streak needs 10X the signal of a spot with a ~3 pixel RMS diameter. But if it is only 12 or 27 pixels long, like the 2 non-star streaks in Fig. 6, it needs only 2-3X the total signal of the spot target near the top. Finding new objects in tracking updates will require objects either brighter than the faintest tracked object, or with similar altitude, to reduce streak length.

Fig. 6. Removing known star streaks from an image

A typical update observation made using a CDK500 and Kepler 400 will include 1E-7 of the volume of LEO. If there are ~1E6 detectable objects, ~10% of the updates will include a second object. But of those objects, only about 10% may be close enough in altitude, 20% of those in the same narrow inclination cluster, 50% of those moving in the right direction to put their photons in a short enough streak to be visible, and 50% of those visible on the sunlit side. Then there may be 1 new find in roughly 2000 updates. A network of 100 telescopes at good observing sites might each make ~5000 updates on each of 280 clear nights per year. Then 140E6 updates/year may find ~70,000 objects/year. Then the 1/e detection time could be of order 14 years.

This concept requires no added telescope time, just more analysis of update images. It may require fast general-purpose GPUs (Graphics Processing Units). They may add ~1% to the installed site cost per telescope. So such image analysis should be worthwhile. That work should be done on-site to preclude a need to upload megapixel imagery every second or so. The actual comlink needs for each site may be mostly for tasking, alt-az fix data, photometry curves, weather and sky data, and site security images.

We cannot predict exact target brightness for each observation, so we do not know how long we need to observe it. We can use a somewhat shorter first exposure and adjust a second exposure after we find the S/N in the first image, to improve the combined value of this plus the next fix. Using 2 images also resolves an ambiguity in a new object’s direction of motion across an imager. That lets one track a new object accurately after finishing a current fix, even if one must first do some higher-priority fixes first. Using 2 images requires slightly longer total exposure time for the same S/N of a tracked object, due to extra read noise. (That is far lower in sCMOS than in CCDs.) But using 2 frames also increases the total S/N of a new object’s streak. Sqrt(StreakLength) and sky shot noise each scale with Sqrt(Time). So they cancel out the effect of a linear signal growth over time. As a result, streak S/N asymptotes for streaks much longer than RMSBlurDia. A larger number of shorter images reduces sky shot noise and raises multi-frame streak S/N of new objects [14].
There is another issue with long faint streaks. A streak S/N may be high enough to verify that a very faint streak is real, but finding a long faint streak in random directions requires handling more pixels in more ways. Finite GPGPU throughput may miss some theoretically detectable streaks.

Debris orbits and their motions are clustered enough to justify looking for “fellow travelers” in every update image, especially after a recent collision. But we will not find objects as faint as the faintest tracked objects unless they have nearly the same orbit, or are brighter than usual when found, or justify extending a second exposure if the first exceeds a modest new-object S/N. Average update intervals for a full million-item catalog with 100 telescopes each making an average of 5000 updates an average of 280 nights/year will be ~2.6 days. This may be enough for most objects, if we do well at predicting drag CdA changes, as discussed in Section 3.

To fill a million-item catalog faster, we are now studying using a 0.7m f/2.4 prime-focus telescope with a Kepler 6060BI camera. That combination can capture 28X more sky volume in each frame, and search ~3X faster. Three such telescopes at a very good observing site in Chile might fill a catalog 2-3X faster. We are also studying a new observing strategy that should more closely approach accurate tracking sensitivity over a wider range of cases.

4.5 estimating the orbit during a discovery pass

When you find a new object, you must find its orbit well enough to find it again. Most LEO mass and debris are far closer to polar than equatorial orbits. One can alternate mostly north and south scans, looking mostly east of zenith at night and west in the morning, to see more of the sunlit side of objects. Using 3 or more well-spaced fixes during the rest of the pass of a newly-found object can quantify some gravity-induced trajectory curvature. This allows rough ranging and orbit estimates. But wide-baseline binocular ranging can do far better. Assume a “discovery site” in Chile, plus “outrigger sites” >200 km north and south. When the discovery site finds a new object, it plus the closer outrigger site can both track it. That can allow a good enough orbit estimate for recovery even several orbits later, perhaps with a few step-and-repeat search frames. When the outriggers are not ranging to new objects, they can do updates. The Atacama desert is clear enough that outrigger sites should be clear on most nights the discovery site is clear. Chance finds at other sites may often allow binocular ranging from other sites with overlapping views.

5. estimated costs of tracking and avoiding most lethal LEO debris

Actionable conjunction warnings have direct value to the owner and operator of satellites at risk. A key question is whether owner/operators will be willing to pay enough for a conjunction warning service and the sensor network needed for it. I cannot answer that, but I will estimate telescope network costs, and list key tasks I cannot yet cost.

Even if free conjunction warnings remain available, more accurate warnings can be worth paying for, since they let operators protect satellites while getting by with fewer and smaller maneuvers. That has quantifiable value.

5.1 potential hardware costs for a telescope network

To update a ~million-item catalog often enough to allow actionable warnings, I estimate a telescope network will need ~100 0.5m telescopes, spread over ~50 good sites over a wide latitude range (to see most LEO objects most of the time) and longitude (for weather and track diversity). Each telescope should cost ~$200K installed. So installing the network should cost ~$20M. These telescopes can typically track LEO objects ~1.6 hours after dusk and before dawn during clear nights. The other 7 hours of average night time may be able to partly pay for the network in other ways. One can track objects in GEO, GTO, and 12-hour navsat orbits. A network could also do satellite laser comm, also known as “free-space optical communication” [15]. But these costs may not greatly reduce LEO-tracking costs.

Besides using ~100 0.5m telescopes, one should also include several 700m f/2.4 prime-focus telescopes with Kepler 6060 cameras. Cost for each may be ~3X that of a CDK500 with Kepler 400. But each can see 28X the sky volume in each image, and can search ~3X faster. Using 3 of these may reduce 1/e detection time for a million-item shrapnel catalog from ~14 to ~4 years, while adding only ~10% to telescope network cost.

5.2 software and business tasks

There are at least 5 distinct software packages that must be developed to enable actionable conjunction warnings for much of the lethal LEO shrapnel:

1. Develop software that uses historical catalog data to find CdA variations and improve orbit predictions. (This will initially cover only the existing ~1% of an eventual million-item catalog. But it can later refine spin-axis estimates based on brightness, under the next task:)

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2. Develop software that uses optical and radar data to infer spin axis and improve predictions of the orbit and brightness of future passes. This can help tell us how many telescopes will actually be needed.

3. Develop effective new-object discovery software for GPGPUs.

4. Develop software that prioritizes and schedules all observations, possibly as discussed in section 4.3.

5. Develop software that uses later observations to verify the accuracy of prior observations and conjunction predictions, to check the predicted accuracy of conjunction warnings.

For comparison, see ref. [16] by Newman et al. It describes the evolution and the current NASA approach for conjunction analysis of unmanned spacecraft.

Besides these hardware and software investments, there will be several distinct continuing costs:

1. Manage, maintain, and upgrade a world-wide network of ~50 sites, perhaps subsidized by laser comm.

2. Operate, troubleshoot, and upgrade the 5 software packages described above.

3. Operate a business that sells actionable conjunction warnings, at prices high enough to pay for creating them and paying for all investments, but lower than the provable value provided to customers.

There are now ~1500 operating satellites in LEO. StarLink has recently proposed 42,000 new LEO comsats. That could increase the LEO total by a factor of ~30. Developers of large LEO constellations may plan to actively avoid debris that can shred their satellites, to prevent clouds of debris centered at their altitude. They may be less interested in warnings of small shrapnel that can disable but not shred their satellites, unless the warnings are rather accurate.

But chances of 2 disabled satellites colliding scale with the square of the number of disabled satellites. If there are many, a large constellation may need laser nudging to prevent close conjunctions, or capture and deboost to separate disabled satellites from each other. Reducing rates at which satellites fail at constellation altitude may have higher value than is immediately obvious, especially for constellations with many thousands of satellites.

Proactive responses like avoiding shrapnel, using laser nudging, or using “undertaker spacecraft” [17] seem prudent, especially if an operator wants to expand a constellation and needs new approvals.

5.3 Combining Radar, Telescopes, and Lasers

Actual shrapnel size is important since it plus the C_dA/m ratio (estimated from orbit decay rate plus spin axis data) allow better estimates of mass and lethality. This is not now an issue, because nearly all tracked objects are lethal to all satellites. But it becomes an issue for cm-class objects. But debris reflectance is seldom known, so we cannot infer actual size from optical brightness. So there is a recurring question:

Is an object big, dark, and lethal, or small, bright, and harmless?

NASA uses its Goldstone and Haystack radars to estimate the actual size of mm to cm LEO objects, at least on a statistical basis. The new S-band fence may allow size estimates for >2-5 cm objects, and perhaps a few <2 cm objects after close passes. Once we catalog an object, we can track it during one or more good passes over a suitable radar, to constrain debris size, particularly for debris near altitudes of constellations.

Good size and mass estimates are very useful for 5-10 mm shrapnel, since lethality will vary with size. Haystack can slew to catch optically tracked cm-class debris, first to refine small debris statistics, and eventually to size much of this population. A phased-array LeoLabs radar may be able to do this as well, without having to move the antenna.

Good size estimates are also useful for 10-30 cm debris. This should be easy to get, using the new S-band fence or LeoLabs radars. Most collision area and mass in LEO are in ton-class intact satellites and rocket bodies. Propagating the Kessler syndrome by shredding them is expected to take >40 J/gram of target mass [1]. This usually requires impactors >0.5 kg. As noted earlier, most tracked fragments from Fengyun and Cosmos/Iridium decay too fast to be that massive. Knowing which fragments can shred a satellite or just disable it may be useful to satellite operators.

Radar can also be useful for orbit updates of debris in dawn/dusk sun-synch orbits for about a month twice each year, when the terminator is nearly parallel to the orbit plane. When viewed from dark sites, objects in such orbits are backlit and hard to see. Few radars can see cm-class shrapnel in LEO, but a few observations of such objects when it is hardest to see them optically may help keep them from getting lost from the catalog. Telescopes can also direct lasers to illuminate debris during eclipse. One site may be able to handle nearly all hard cases, including dawn-dusk sun-synch objects. The team at Mt. Stromlo is working in this area [18]. Precise tracking and prediction may also enable laser nudging as proposed by NASA Ames [19], or in my other conference paper [7].
6. CONCLUSIONS AND RECOMMENDATIONS

The value of an actionable conjunction warning service should scale with how many lethal objects it can warn against. The value of each actionable warning depends on the actual chance of an impact. It appears feasible to detect, track, catalog, and avoid not just ~1% of lethal debris in LEO as we do now, but perhaps most of it.

But we do not yet know how much lethal LEO shrapnel there is, how bright it is, how often it must be seen to stay cataloged, how many telescopes and sites are needed, or how much software development will cost. We also don’t know how much a conjunction warning service will cost, or how much LEO satellite operators may pay for it.

Conjunction warnings warn not of an impact, but small chances of impact. Actionable warnings must warn of high enough chances of impact (>0.01%) that acting on them will save money on average. More accurate warnings can save operators money. But most tracked debris will be barely visible but still lethal, visible only on good passes, and more sensitive to drag than satellites. Debris orbit uncertainty will dominate satellite conjunction uncertainty.

Debris spin axis can be inferred and used to predict future changes in drag C\(_d\)A. If better C\(_d\)A predictions allow doubling average update intervals, telescope count may be cut by half, with most warnings still being actionable.

Estimated installed cost for 100 0.5m telescopes plus three 0.7m wide-field detection telescopes may be ~$22M.

Sections 3 and 5.3 discuss software tasks that may interest some students. I encourage them tackle these tasks, and to contact me at tether@cox.net. I also encourage interested companies and other organizations to contact me.

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