Comparison of predicted and observed spacecraft encounters from Russian ASAT test

Daniel L. Oltrogge, Salvatore Alfano, and Robert Hall

COMSPOC Corporation

1. ABSTRACT

This paper performs a follow-up analysis of the Russian Anti-Satellite (ASAT) intercept test conducted November 15, 2021, launching an ASAT weapon system to intercept and destroy the on-orbit COMOS 1408, a defunct Soviet Electronic Intelligence (ELINT) satellite that was launched in 1982. The original analysis had estimated how the resulting debris from the fragmentation event would adversely impact spacecraft operators, their SSA knowledge, their ability to detect and mitigate high collision threat events, and their use of maneuvering fuel within a large constellation framework. This paper compares these original predictions of encounter rates, collision risk to Low Earth Orbit (LEO) spacecraft (especially spacecraft in sun-synchronous orbits), and orbit lifetime estimates with actual conjunctions and orbit lifetimes detected by operational flight safety systems and services. Comparisons of actual fragmentation debris tracking with debris volume evolution in a continuum model and discrete breakup modeling are performed. Comparisons of our original predictions with what actually occurred identifies that original lifetime ASAT fragment orbit lifetime predictions were fairly close to what has been observed on-orbit to date, with predictions running approximately 25% longer than observed lifetimes to date. Flight safety and required avoidance maneuver predictions were also validated by observed conjunction trends, with as much as 20% reductions in flight safety and sustainability stemming from the Russian ASAT test at certain altitudes, and a doubling of collision risk for certain orbit conditions.

2. INTRODUCTION

This paper provides a follow-up of our original analysis [1] of the degradation to the global spacecraft operator community caused by the Russian ASAT intercept test conducted November 15, 2021. In that ASAT test, a direct ascent ASAT weapon was launched to intercept and destroy the on-orbit COMOS 1408, a defunct Soviet Electronic Intelligence (ELINT) satellite that was launched in 1982.

In our original paper [1], we utilized published NOTAMs and public orbit and spacecraft data to infer the likely ASAT engagement scenario employed, and that scenario was then used to predict where generated COSMOS 1408 debris fragments were likely to go, what satellites would be affected, and how operator workloads would be changed because of the test. In that study, we had predicted that increases in close approach and collision warnings, accompanied by increases in avoidance maneuvers required for flight safety, would place an undue burden on certain operators of Sun-synchronous orbiting spacecraft (largely used for Earth observing/imaging missions) for approximately 1.5 years after the intercept occurred.

In this paper, we will update our assessment of degradations to operator flight safety, as well as our comparative assessment of the Russian ASAT test with other notable fragmentation events, to include the Chinese ASAT test of 2007, USA 193 Shootdown event, India ASAT, and Iridium/COSMOS collision. Dates, altitudes, relative velocities, and debris quantities and lifetimes of these tests are assessed and provided. The time history of the number of Russian ASAT debris fragments tracked by the Space Surveillance Network is provided, including those still on orbit as of our submittal of this paper to the AMOS conference. The evolution of operator collision risk from January to August 2022 is provided as a function of altitude. And finally, the breakdown of constellation conjunction rates and collision risk are provided at three epochs in 2022.

3. OVERVIEW OF RUSSIAN ASAT TEST

3.1 Test details inferred from public data sources

On November 15, 2021, Russia conducted an ASAT test, launching an ASAT weapon system to intercept and destroy a defunct Soviet Tselina-D family of Electronic Intelligence (ELINT) satellites [2, 3, 4] that was launched on 16 September 1982 into an 82.5° inclined, roughly 540 km circular orbit. The specific weapon appears to have

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been the Nudol ASAT weapon system [5] from Plesetsk Cosmodrome. The pre-intercept mass of COSMOS 1408 was estimated to be 2108 kg [6].

Fig. 1 shows the cross-track component history for 76 cataloged debris pieces out of the initial 185 fragments published on Space-Track [7] in the first tranche released approximately two weeks after the incident. To develop a representative intercept scenario, the orbits of tracked debris fragments were then propagated backwards until they came together. As was shown in [1], compiling these distances produced a common minimum point corresponding to the impact time which as estimated using this approach to be 15 Nov 2021 at 02:47:31.5 UTC. Modeling discussed in [1] estimated a Gabbard plot of the resulting debris as shown in **Fig. 2**

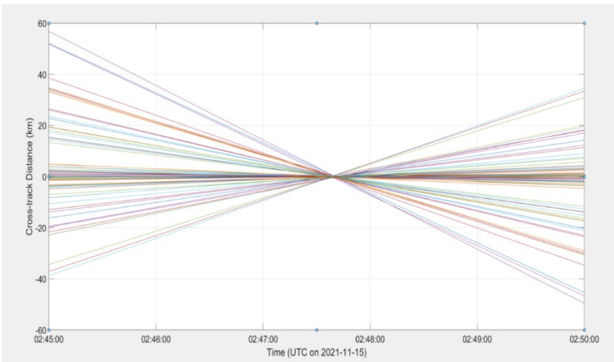

Fig. 1. Estimation of intercept time (and therefore location)

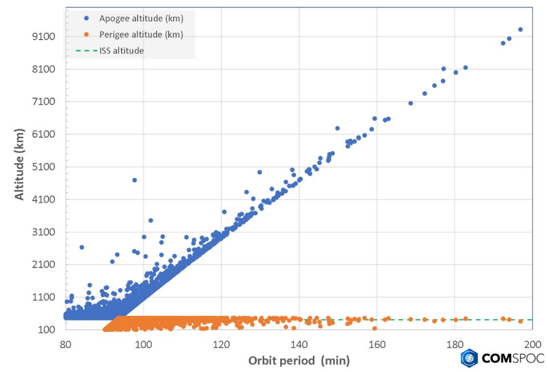

Fig. 2. Gabbard plot for all Russian ASAT debris larger than 1cm.

3.2 Predicted vs actual orbit lifetime (to date)

As was shown in [1], the corresponding orbit lifetime distributions (frequency of occurrence out of the fragment population, e.g., number of fragments) corresponding to both the discrete breakup simulation and actual tracked debris fragments is shown in **Fig. 3** and **Fig. 4**.

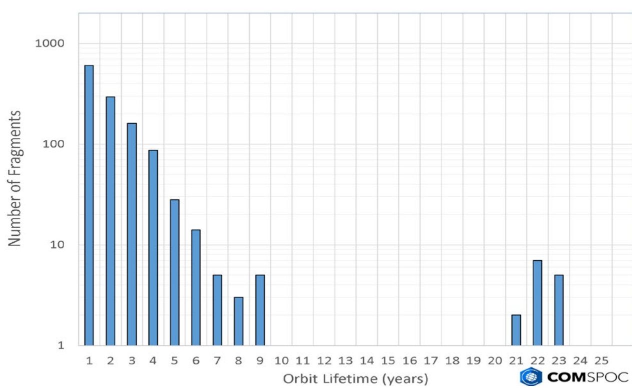

Fig. 3. Predicted orbit lifetime distribution for trackable ASAT debris > 5cm (simulation).

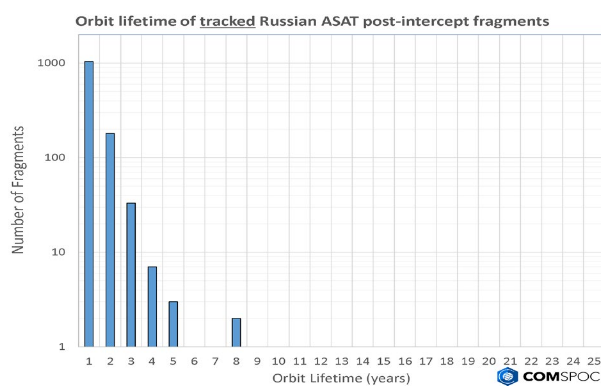

Fig. 4. Predicted orbit lifetime distribution for tracked ASAT debris (actual fragments).

Now that time has elapsed since these original predictions, we can use the number of fragments tracked in comparison to how many remain on orbit **Fig. 5** to determine how close the orbit lifetime predictions of **Fig. 4** were. **Fig. 6** provides, in the 10 months elapsed since the ASAT test was conducted, the “red bar” overlay onto predicted orbit lifetimes of tracked objects (**Fig. 5**) to illustrate that orbit lifetime predictions were within approximately 25% of original predictions.

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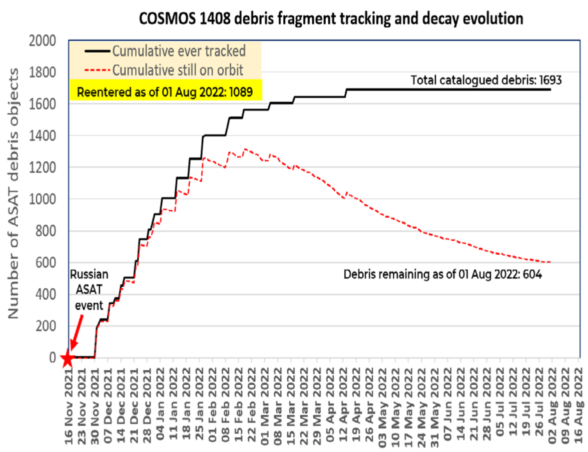


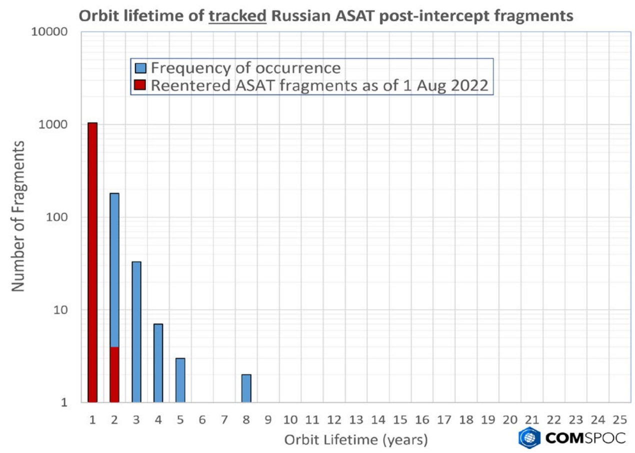
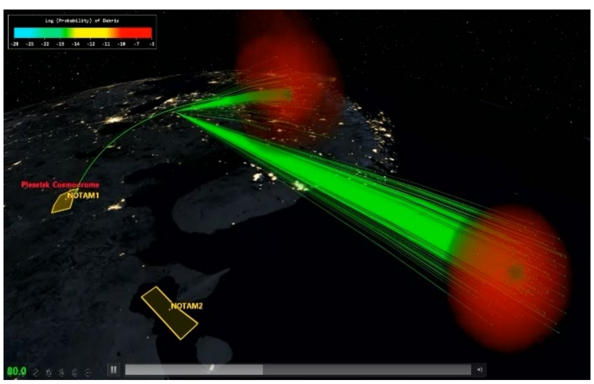


Fig. 5. Evolution of the ASAT debris fragment count, with 1089 fragments having reentered as of 1 Aug 2022.

Fig. 6. Breakdown (as of 30 Jul 2022) of collision risk for active-vs-non-COSMOS 1408 debris (orange), active-vs-active (blue) and active-vs-COSMOS 1408 debris.

3.3 Fragment cloud evolution: Volumetric spreading to date

In the first day after the ASAT test, it was estimated that fragment cloud could occupy the volumes as shown in **Fig. 7** and **Fig. 8**. Active spacecraft which traverse this volume at a time of interest are placed in harm's way at that time, and the integration of their exposure over time creates an aggregate or composite estimate of risk during that period.



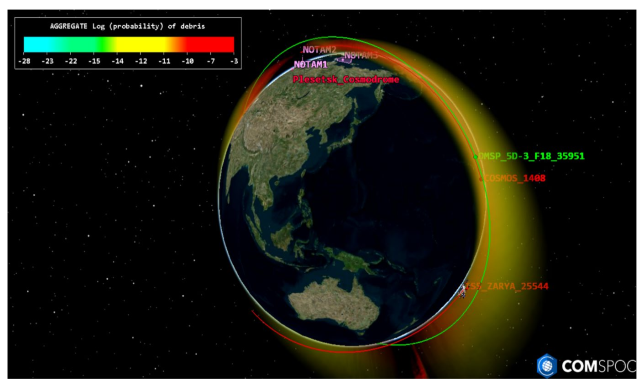


Fig. 7. Results of two breakup models (discrete and continuum) overlaid in space as a function of time since intercept.

Fig. 8. Aggregate volume debris fragments occupy during first 24 hours after intercept, colored by likelihood of a fragment's presence.

Over time, however, the ASAT fragment cloud expanded to occupy more space, at a lower spatial density, as shown by the bright red diagonal slash in **Fig. 9**. As this band moved to the left (orbit plane regressed) and Sun-synchronous orbits (thinner 'fan' of three bands at right) processed to the right, the periodic 'sharing' of orbital planes left the debris and spacecraft at times in coplanar, counter-rotating orbits, putting not only the important spacecraft and their missions at risk, but also the global space environment.

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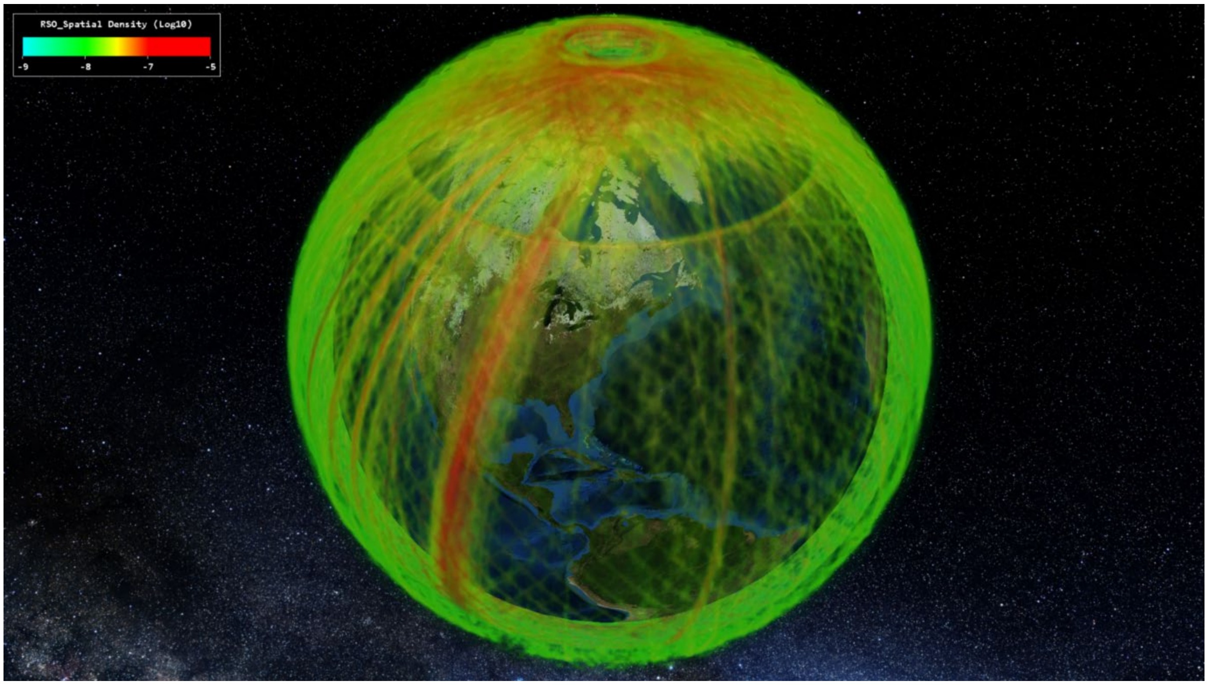

Fig. 9. Spatial density of LEO space environment based upon actual tracked objects, clearly showing COSMOS 1408 debris band (lower left to upper right).

3.4 Comparison of Russian ASAT event with other significant breakups

As described in [1], it is helpful to compare this fragmentation event with other ASAT events as shown in Table 1, where the dates, altitudes, relative velocities, catastrophic breakup metrics, and debris quantities and lifetimes are compared. The rows contain the following comparative information:

- In row 4, the relative velocity has been estimated to determine if the intercept's relative velocity exceeds the speed of sound in the material the spacecraft is constructed from (for example, steel ranges from 3.1 and 6 km/s and aluminum from 3.8 to 6.5 km/s).
- Row 5 contains the estimated energy per unit mass, which is assessed to determine if the collision can be considered as a catastrophic collision (with greater than 40 Joules per gram being considered as a rough guide) -- and all events can be seen to be catastrophic as they greatly exceed this criterion.
- Row 6 contains the number of fragments that have been tracked by the Space Surveillance Network at some point following the breakup. Rows 7 and 8 contain our simulated breakup results by comparison, where a "trackable" object is assumed to be larger than 5 cm in size with an orbit lifetime exceeding one day, and Lethal Non-Trackable objects (LNTs) are assumed to be smaller than 5 cm and larger than 1 cm. Note that the number of Russian ASAT debris fragments tracked by the SSN is still a "work in progress," as additional fragments will undoubtedly be associated with this ASAT test event for several years to come.
- Row 9 contains the 80th-percentile orbit lifetime, meaning that 80% of all fragments will have reentered before this time.
- Rows 10 and 11 serve as a proxy for overall adverse effect on the environment by summing up the estimated orbit lifetimes for all trackable and LNT objects, respectively.

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Table 1. Comparison of Russian ASAT event with other ASAT breakups.

Category	Chinese ASAT	USA 193	Indian ASAT	Russian ASAT
Date	11 Jan 2007	21 Feb 2008	27 Mar 2019	15 Nov 2021
Altitude (km)	856	246	282	461
Velocity (hypervelocity˜ > ≈ 6)	14.8 km/s	8.49 km/s	9.4 km/s	4.6 km/s
≈ kJ/kg (catastrophic ≈ >40)	15,000-35,000	1,500 – 2,500	6,000	500 – 1,000
Debris tracked by SSN	3,532	174	129	1,693
Simulated trackable* debris	3,007	452	936	1,246
Simulated Lethal Non-Track	34,733	3728	10,439	16,386
80^{th} percentile lifetime (yrs)	63	0.03	0.05	1.5
"RSO-years" (trackable)	130,347	13	65	2,098
"RSO-years" (LNT)	1,225,972	94	784	16,464

Table 1 indicates that the Chinese ASAT test was by far the most harmful to the environment, with the Russian ASAT test ranking second in terms of harmful ASAT tests. While the Iridium/Cosmos collision was an accidental event and not an ASAT test, we characterized that event in [1] and found that it was quite harmful as well, though not as much as the Chinese ASAT test.

4. Increased risk to spacecraft operators: Then versus now

4.1 Risk to operators characterized by altitude

Fig. 11 reveals average, annual, encounter rates in 25 km altitude bins that the global LEO active spacecraft population is likely to experience, as we had characterized in 24 Jan 2022. This bar chart was created using the "Probability and Frequency of Orbital Encounters" tool (U.S. Patent No 10293959) whose inner workings are explained in the paper "Volumetric Assessment of Satellite Encounter Rates." [8], and which is also used to generate the "Number of Encounters Analysis Tool" (NEAT) [9]. We separated the https://space-track.org TLE catalog on 24 Jan 2022 into active and inactive satellites. The inactive satellites were then further separated into COSMOS 1408 ASAT trackable debris and all other inactive objects, thereby representing the RSO debris prior to intercept. Three separate encounter categories were then considered: active-on-active (green bars), active-on-non-ASAT debris (orange bars), active-on-trackable COSMOS 1408 ASAT debris (red bars), and inactive-on-inactive (both including ASAT debris) depicted by the cyan bars. For the active-on-active analysis, we assumed no fratricidal encounters with respect to the same owners/operators (i.e., we excluded consideration of Starlink-v-Starlink, Iridium-v-Iridium, etc.). We also assumed no remediation or attempt at avoidance.

The combination of green and orange bars thus shows the encounter rate for the active spacecraft population prior to the Russian ASAT test. The red bars show the additional encounter burden placed on the space community by ASAT debris fragments. As the ASAT debris decays, the red bars will decrease in altitude, eventually passing through ISS altitude as updated in the subsequent categorizations for 30 July 2022 (**Fig. 12**) and 8 August 2022 (**Fig. 13**) to show in how the risk posed by the ASAT debris has evolved as the fragment population's orbits are decaying with time.

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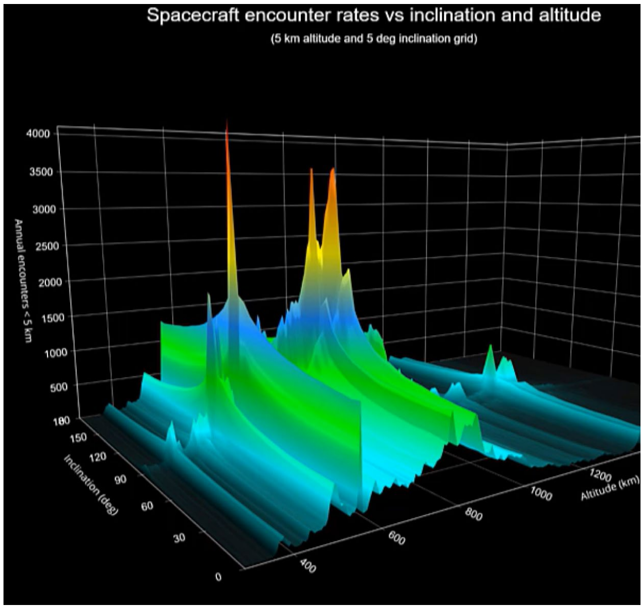

Fig. 10. Annual encounter rate for LEO spacecraft as a function of inclination and altitude, estimated by the NEAT tool.

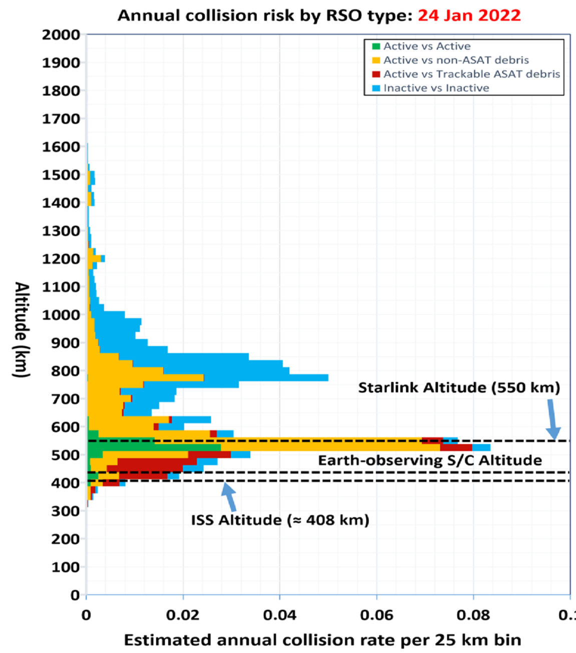

Fig. 11. Breakdown (as of 24 Jan 2022) of collision risk for active-vs-non-COSMOS 1408 debris (orange), active-vs-active (blue) and active-vs-COSMOS 1408 debris.

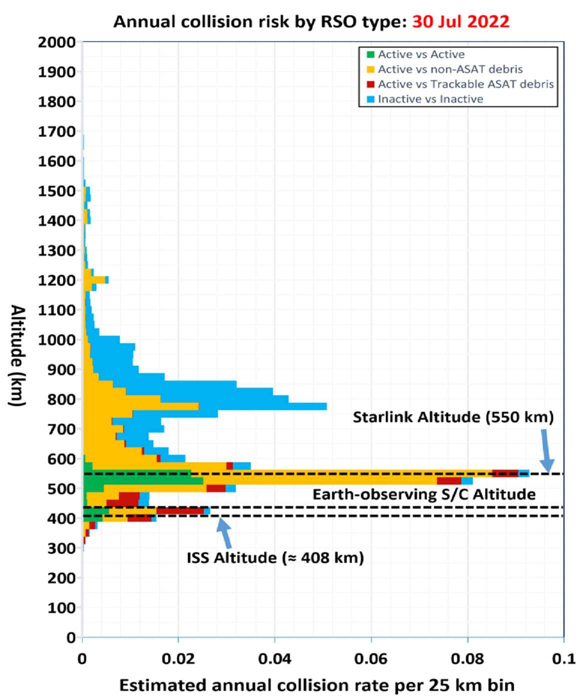

Fig. 12. Breakdown (as of 30 Jul 2022) of collision risk for active-vs-non-COSMOS 1408 debris (orange), active-vs-active (blue) and active-vs-COSMOS 1408 debris.

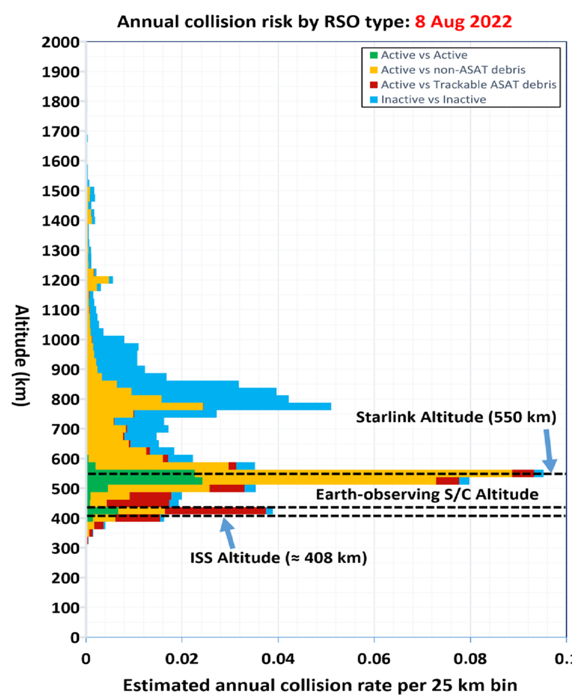

Fig. 13. Breakdown (as of 8 Aug 2022) of collision risk for active-vs-non-COSMOS 1408 debris (orange), active-vs-active (blue) and active-vs-COSMOS 1408 debris.

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4.2 Risk to operators, characterized by operator

As was predicted by **Fig. 14** earlier this year in [1], Planet's spacecraft were placed at great risk by the Russian ASAT debris, with over three orders of magnitude increase in conjunction rates. Now that half a year has elapsed, we can overlay the results of operational flight safety systems such as the Space Data Center [10] to compare the original prediction with what actually occurred as shown in **Fig. 15**. As the figure shows, the predicted trend is well validated by the observed conjunction rates for the Planet fleet of spacecraft.

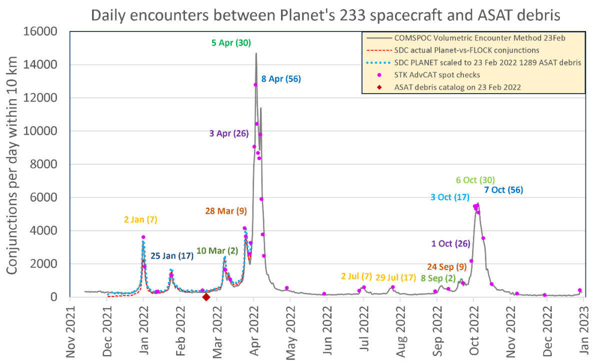

Fig. 14. 23 Feb 2022 prediction of Planet conjunction rates to end of 2022.

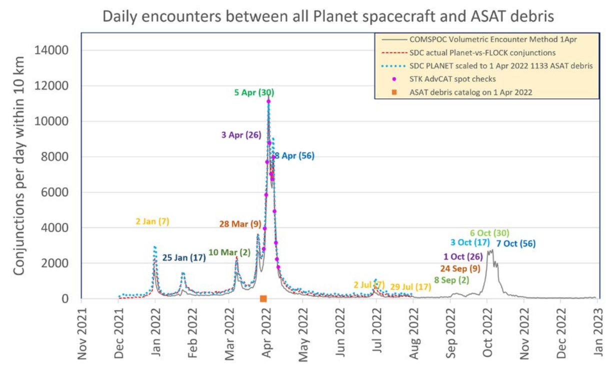

Fig. 15. Update of actual conjunctions up to 1 Aug 2022, showing very good agreement with 23 Feb prediction.

The International Space Station and the Starlink constellation have been adversely affected as well. The ISS experienced a 33% increase in number of conjunctions in summer 2022 due to ASAT fragments.

Starlink experienced large increases in conjunctions, collision risk, and automated maneuvers required by those conjunctions, as predicted from the 23 Feb 2022 space catalog (**Fig. 16**). Recent predictions for Starlink, based on a 30 Jul 2022 space object catalog, identified still further additional flight safety risks caused by the ASAT debris (**Fig. 17**), as follow-on Starlink orbit planes were launched into Sun-synchronous orbits that were occupied by the ASAT debris. As reported in [11], the Starlink constellation performed 6,873 automated collision avoidance maneuvers between December of 2021 and 31 May 2022. Starlink reported that of those 6,873 maneuvers, 1,700 were conducted to avoid Russian ASAT debris fragments.

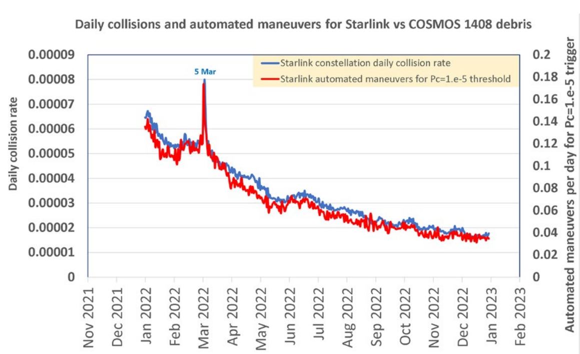

Fig. 16. Starlink flight safety degradation and resulting automated maneuvers predicted based upon a 23 Feb 2022 space object catalog.

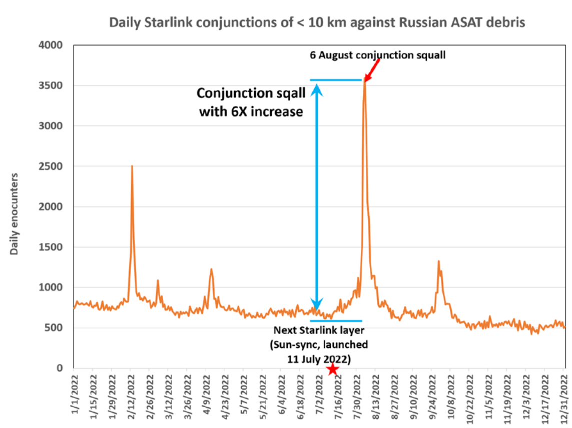

Fig. 17. Conjunction squalls (by collision probability) for active spacecraft as predicted from 30 Jul 2022.

To confirm that many of the spacecraft occupying Sun-synchronous orbits are similarly affected, the volumetric encounter algorithm was applied to the 23 Feb 2022 catalog set of all active spacecraft for the year 2022 as shown in **Fig. 18**. Many CubeSat constellations experienced close approach rate trends like those of Planet. Fortunately, the CubeSat-sized earth observing spacecraft experience a lower collision probability, as evidenced in **Fig. 19**. But larger spacecraft (e.g., ISR) and large constellation spacecraft will see elevated collision risk from this ASAT test.

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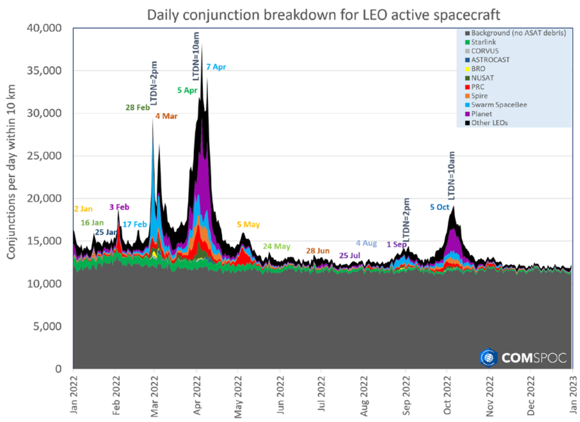


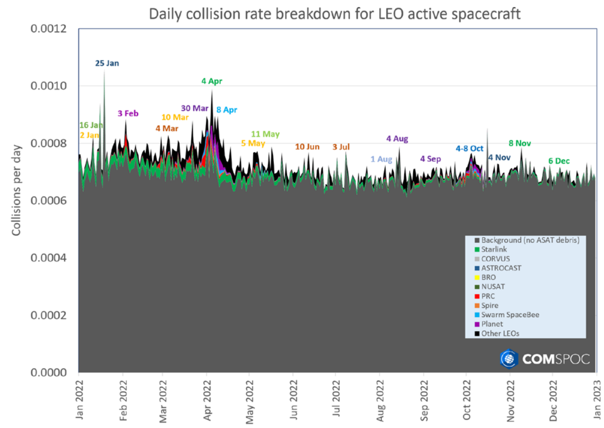
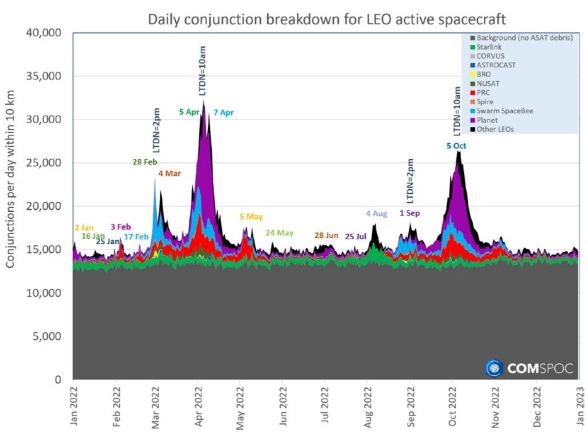


Fig. 18. Conjunction squalls (by miss distance) for active spacecraft as predicted from 23 Feb 2022.

Fig. 19. Conjunction squalls (by collision probability) for active spacecraft as predicted from 23 Feb 2022.

Now that many ASAT fragments have reentered, these two depictions were regenerated using a 30 July catatlog as shown in **Fig. 20** and **Fig. 21**. **Note that these predictions do not accurately characterize risk prior to 30 July because fragments have reentered in the meantime.**



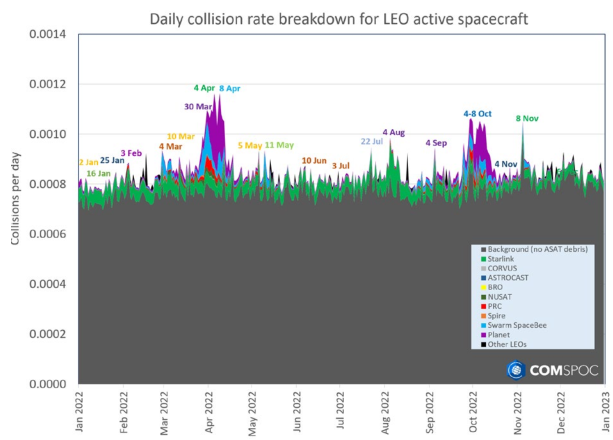


Fig. 20. Conjunction squalls (by miss distance) for active spacecraft as predicted from 30 Jul 2022.

Fig. 21. Conjunction squalls (by collision probability) for active spacecraft as predicted from 30 Jul 2022.

5. CONCLUSIONS

This paper has characterized the likely intercept scenario, debris fragment ensemble and the space it occupies, spacecraft affected, and the increased operator and SSA system workloads, maneuver fuel expenditures, and collision risk. These results indicate that operators and spacecraft have been, and will continue to be, subject to a significant increase in LEO collision risk, conjunction warnings and avoidance maneuvers, particularly so for spacecraft in Sun-synchronous orbits which are predominantly used by Earth-observing spacecraft. We identified the presence of "conjunction squalls" affecting government, commercial SSA, and commercial spacecraft operator systems. While such conjunction squalls have already taxed flight safety systems and spacecraft operators, we correctly predicted more dramatic encounter rate loading, avoidance maneuvers, and collision risk in April 2022.

The team was able to employ our volumetric encounter rate software to accurately assess how frequently active spacecraft will encounter debris (for spherical, pizza box, or ellipsoidal keep out volumes), and the tool was also able to estimate collision risk that the ASAT debris poses to all constituent spacecraft. This research provided a "trial-by-fire" opportunity for the volumetric encounter tool. Its ability to provide an accurate, forward looking,

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predictive risk assessment is a gap we've observed for not only satellite operators but also SSA and Space Domain Awareness systems. The independent verifications accomplished in this study using such operational tools as the Space Data Center, the 18 SPCS CDMs, Systems Tool Kit's Advanced CAT, and Planet's systems are noteworthy.

From a miss-distance-based conjunction perspective, it is the CubeSat Earth observing constellations that will face the greatest increase in the number of conjunction warnings. But when using collision probability or assessing collision risk, we found that the larger (costlier) Earth observing spacecraft and large constellations such as Starlink will likely face the greatest actual risk due to their spacecraft sizes.

Now that almost one year has elapsed since the Russian ASAT test occurred, we were able to validate many of the aspects of our predictions from earlier this year, to include estimated fragment orbit lifetime, the existence and severity of conjunction squalls, the safety degradation experienced by spacecraft operators (including human space stations), and the large number of collision avoidance maneuvers that ASAT fragments required to avoid mishap.

6. ACKNOWLEDGEMENT

Our thanks to the Space Data Association and Planet for allowing us to share conjunction rate data on spacecraft in Sun-synchronous orbit which initially brought this global operator and SSA Service Provider resourcing and collision risk issue to our attention.

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