An Analysis of the Impact of the Russian DA-ASAT Event on Space Domain Awareness

Christian Ramos
Omitron, Inc.

Deshaun Hutchinson
18th Space Defense Squadron

Brent Skrehart
Omitron, Inc.

David Gillespie
Omitron, Inc.

Diana McKissock
18th Space Defense Squadron

ABSTRACT

On November 15, 2021, at 0247 UTC, Russia's direct ascent Anti-Satellite Weapon (DA-ASAT) conducted a destructive test against COSMOS 1408 (SCC# 13552) in Low Earth Orbit (LEO). We will assess the impacts of the Russian debris-causing event on the Space Domain Awareness (SDA) mission and the technological advancements made to meet the growing challenges of the congested environment. Beginning with initial candidate nomination, new tools were implemented to merge system capabilities, leverage the manning of 18th Space Defense Squadron (18 SDS), and expedite the new object nomination process. During the candidate formation and debris separation phase, new event management tools were developed, and senior analyst expertise was grown to better delineate high drag objects at a mass scale. Lastly, the increase in debris density in LEO has resulted in increased reporting to NASA's Trajectory Operations Officer (TOPO) at Johnson Space Center's Mission Control. The International Space Station (ISS) will consistently travel through the densest part of the debris plane (~400-550km) due to its orbital altitude (~420km). Likewise, any LEO high-value assets in an orbit similar to that of the ISS will pass through the densest part of the debris plane and will also be at increased risk. We will break down the exponential increase in number of conjunctions reported to NASA and satellite operators globally, debris avoidance maneuvers performed, and how 18 SDS has continued to maintain spaceflight safety in the space domain.

1. INTRODUCTION

The primary organization tasked with performing United States Space Command's (USSPACECOM) Space Domain Awareness (SDA) mission is the United States Space Force's (USSF) 18th Space Defense Squadron (18 SDS), whose objective is to provide a continuous, comprehensive, and combat-relevant understanding of the space situation. The contested nature of the space environment and number of satellites operating in Low Earth Orbit (LEO) has grown exponentially in recent years. This accelerated proliferation in LEO has drastically accentuated the need for improvements across all levels of SDA operations in order for the 18 SDS to continue to meet their mission objectives. A collective effort between 18 SDS senior analysts and NASA-funded Subject Matter Experts (SMEs) was required to develop tactics, techniques, and software enhancements to manage the observation-based tracking of the COSMOS 1408 debris-causing event, leveraging automation to ensure the provision of timely SDA despite the dramatic increase in congestion.

2. ASSESSING SDA IMPACT

The COSMOS 1408 direct-ascent anti-satellite (DA-ASAT) event is currently the third largest debris event in the history of spaceflight. Estimated to have created over 2000 total pieces of debris, it falls behind only two events: the Fengyun 1C ASAT event and the Cosmos-Iridium hypervelocity collision, at 3500+ and 2300+ currently cataloged pieces, respectively. Massive debris events and the sudden creation of thousands of debris pieces require redistribution of SDA resources to properly obtain and maintain custody. Months after it occurred, even with the current pace of mega-constellation launches, the COSMOS 1408 event accounted for half of the objects cataloged by 18 SDS. At 1777 total cataloged pieces as of June 27, 2022, this event has and will continue to require analysis and intervention for decades to come. Its long-lasting effects continue to be felt by 18 SDS, the SDA community as a whole, and the space community at large.

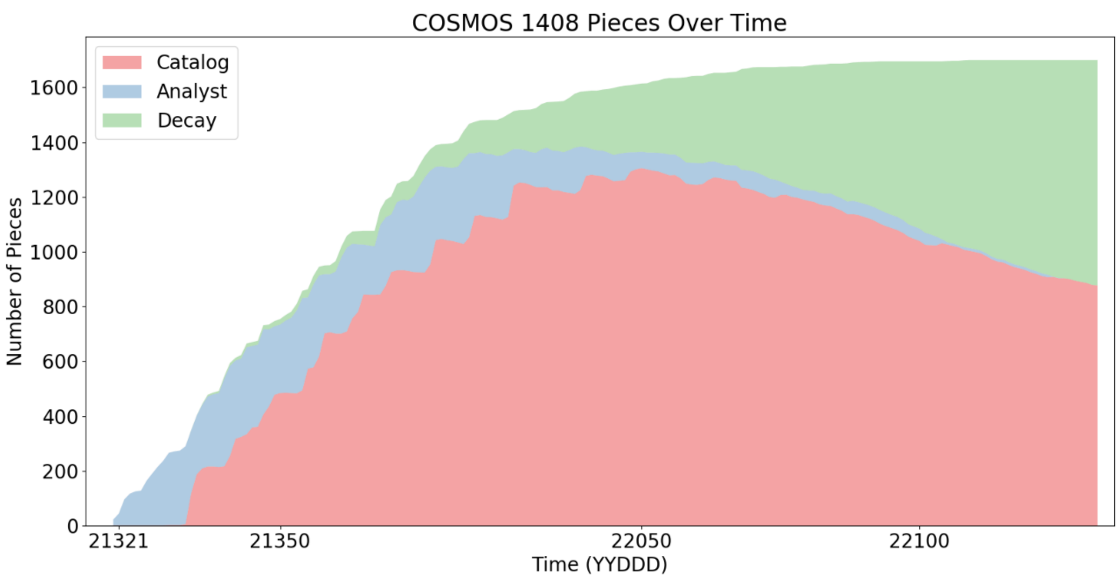

Fig. 1: COSMOS 1408 Analyst, Cataloged, and Decayed Objects Over Time

Fig. 1 shows the evolution of identified objects from the COSMOS 1408 event over time, with portions of the total height representing analyst, cataloged, and decayed catalog states. The initial analyst object creation phase, in blue, shows a first wave of analyst objects created at event start, transferring into the red cataloged section once they were consistently tracked and promoted to the public catalog. The number of analyst objects at any given time stayed mostly consistent, with pieces being cataloged and new analysts being created as the event processing progressed. Decayed pieces occur on Fig. 1 quickly after the start of cataloging. The green section shows a steady increase over time as the pieces more affected by drag decay reenter Earth’s atmosphere.

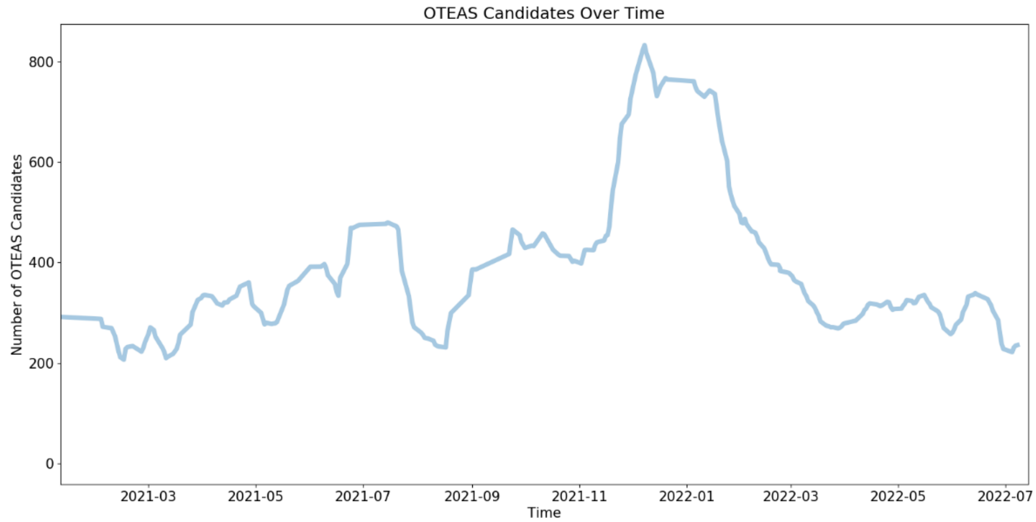

Fig. 2: Analyst Object Candidate Counts Over Time

From Fig. 1, a significant decrease in analyst object creation and cataloging can be seen at approximately 100 days after the event. As seen in Fig. 2, the number of analyst object candidates created during the initial 100 days of the COSMOS 1408 event stayed steady at around 800 per day, and at the same time as analyst object creation slowed, the number of candidates created decreased. The reduced number of unassociated observations being seen by sensor sites indicated that the majority of the pieces from the event had been made into analyst objects or catalogued by the 18 SDS. With over 1500 objects created in 100 days, the addition of maintenance support from the 18 SDS Mega-Constellation Analysis (MECA) Cell helped a great deal. The skills and toolsets developed for maintaining custody of mega-constellation launches translated well to a massive debris event. Significant efforts were made to catalog and maintain consistent custody of all debris as quickly as possible to ensure Human Spaceflight (HSF) safety, as well as provide accurate Conjunction Assessment (CA) for all satellite owner/operators.

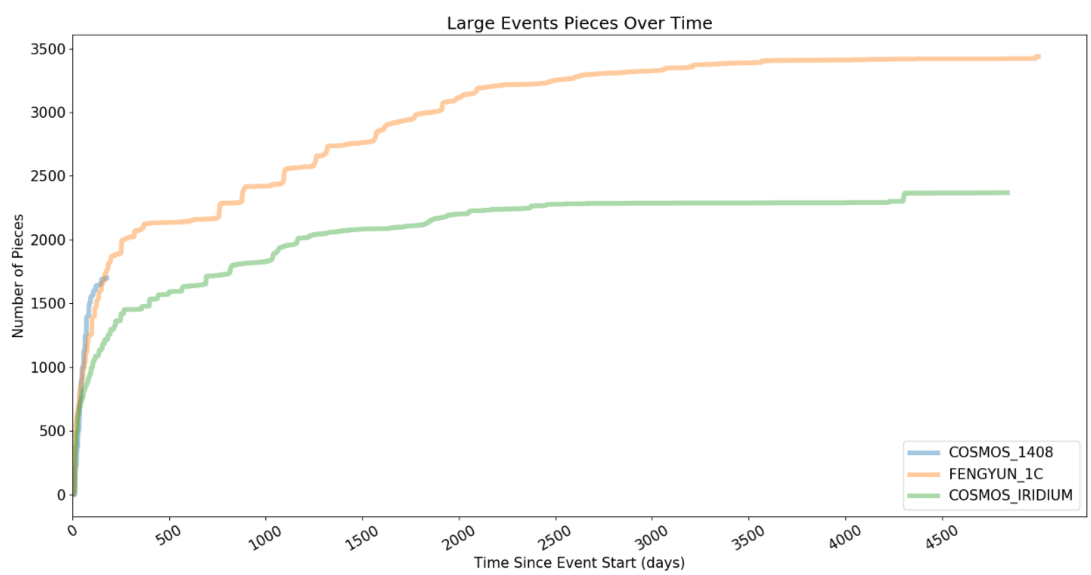

Fig. 3. Catalog Pieces Over Time, Full Timelines

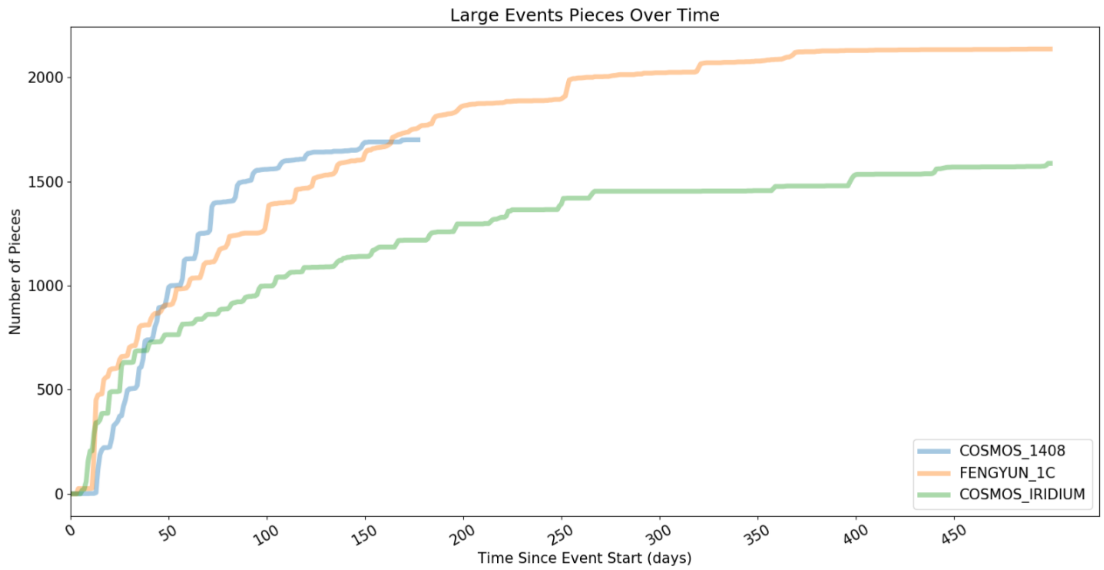

Fig. 4. Cataloged Pieces Over Time, First 500 Days

Fig. 3 shows the total number of cataloged pieces from event start to current state for Fengyun 1C, COSMOS-Iridium, and COSMOS 1408. The three events show the same trend as most debris events, with a slow growth over years after the initial rapid cataloging. Full cataloging of an event of this size can take decades to accomplish. All three events have a similar rapid cataloging stage, and in Fig. 4, a closer look can be taken at the initial cataloging stage, where COSMOS 1408 has a steeper curve of initial cataloging than the other events.

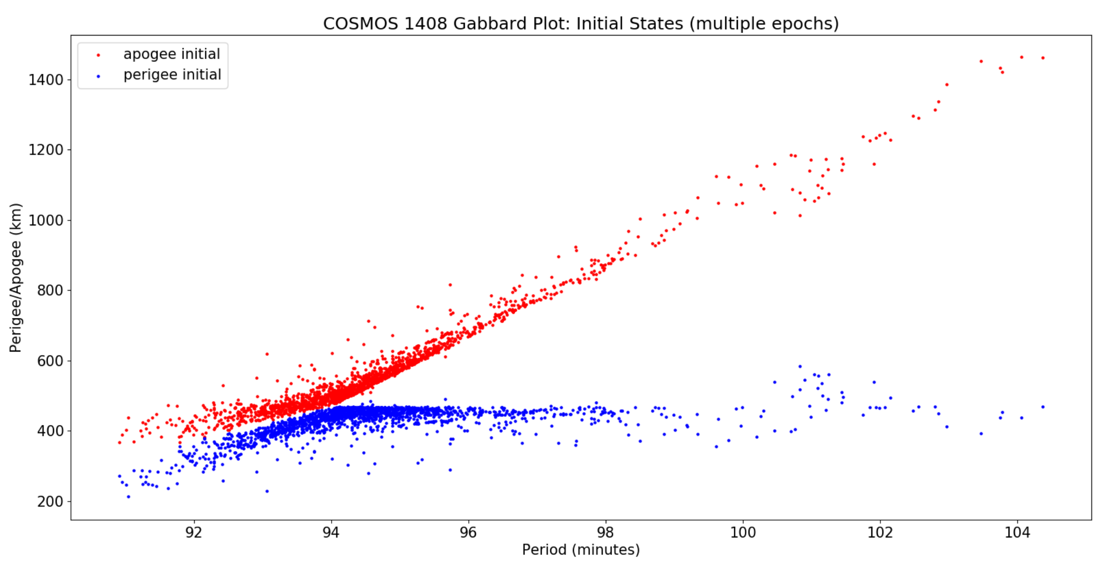

Fig. 5. Cosmos 1408 Gabbard Plot-Initial States

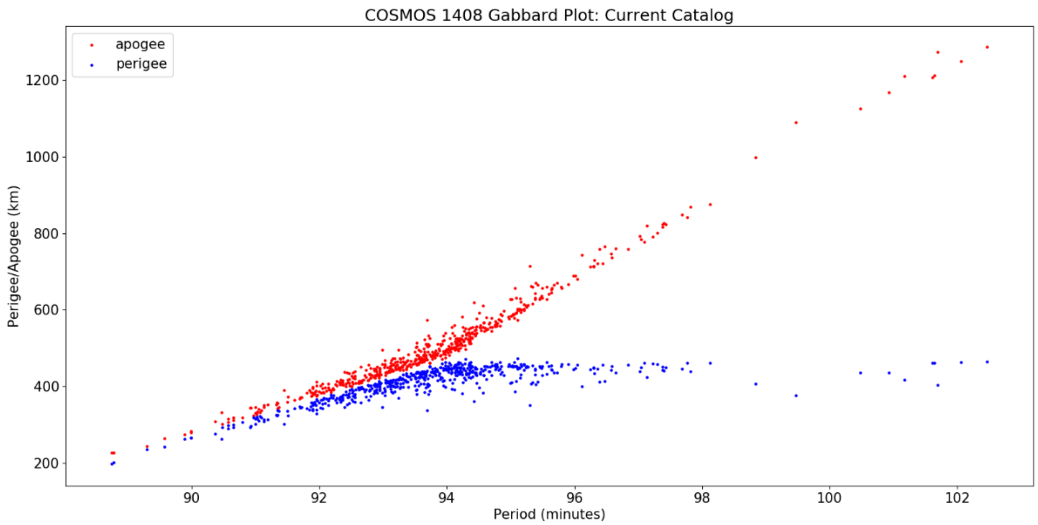

Fig 6. Cosmos 1408 Gabbard Plot-Current Status

Perigee and apogee height for the various debris pieces is a strong determining factor in how quickly they will decay. The orbit of COSMOS 1408 before the DA-ASAT was approximately 465km x 490km at 82.5 degrees inclination, and much of the debris retains a 400-500km perigee. In Fig. 5, the Gabbard plot of the initial states of all cataloged pieces for COSMOS 1408 shows a large number of low-perigee, near-circular orbits. These pieces have the shortest-lived orbits of the pieces from this event. Fig. 6 shows the current state of cataloged COSMOS 1408 pieces still in orbit. Pieces still at lower altitude will continue to decay but will do so over years rather than within the first half year after the event so far. The 18 SDS's Astrodynamic Support Workstation (ASW) software predicts that some of the higher altitude COSMOS 1408 may not reenter until early 2033 depending on the effects of the next solar max. COSMOS 1408 debris from this event will continue to be of concern in conjunction with the ISS and astronauts arriving or departing the station for several years to come.

Fig. 7. ASAT Events Cataloged Over Time

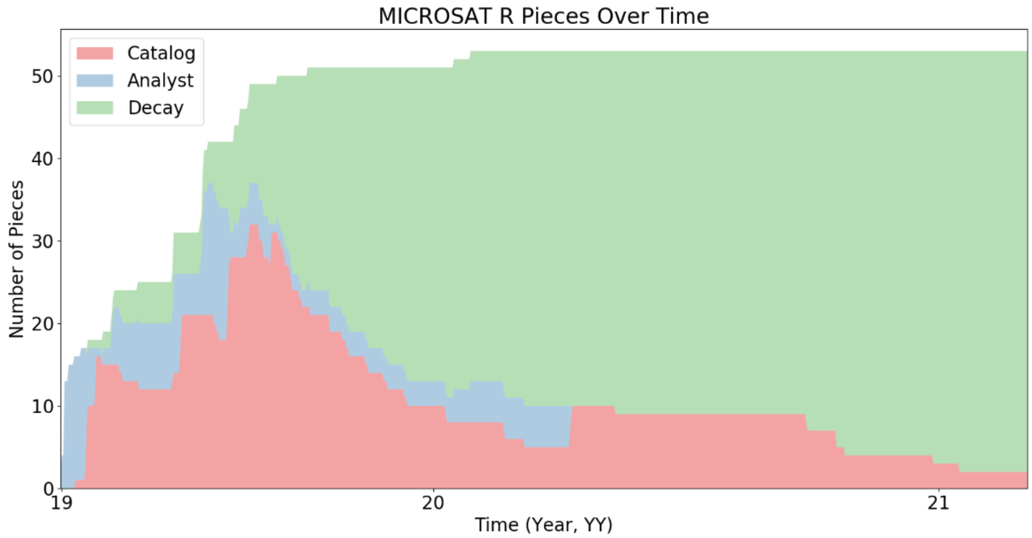

Fig. 8. MICROSAT-R Event Cataloged Over Time (First 400 days)

When comparing ASAT events, FENGYUN 1C and COSMOS 1408 created significantly more debris in more populated orbits and in orbits that would not decay quickly. Fig. 7 shows a comparison of the two large ASAT events and one smaller ASAT event with less overall impact on the SDA community and space safety. The smaller ASAT event, MICROSAT-R, is an order of magnitude smaller in scale and has associated debris pieces that decayed very quickly. Fig. 8 and 9 show a closer look for the event and the speed of total event decay is evident. MICROSAT-R had ten or fewer pieces still to decay after one year. The final piece of the cataloged MICROSAT-R debris decayed in June 2022.

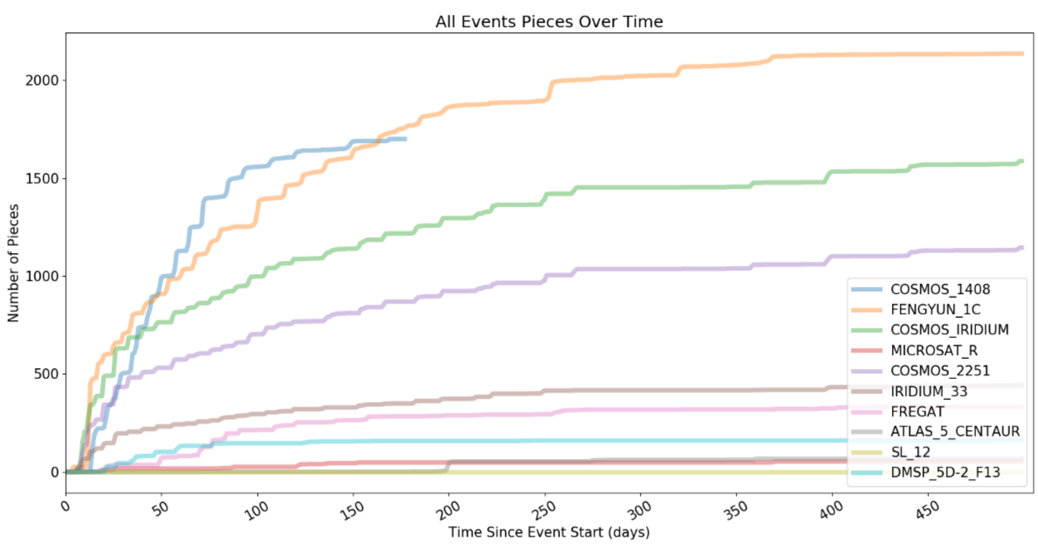

Fig. 10. Common and Large Debris Events-First 500 Days

When compared to events outside of Fengyun 1C and Cosmos-Iridium, the difference in scale for these massive debris-causing events becomes clear. A selection of more typical debris-causing events is shown in Fig. 10., along with the three large debris events previously discussed. The figure shows cataloged pieces over time, similar to Fig. 3. The events for this comparison include those caused by fuel tank ruptures, rocket body/upper stage explosions, and battery explosions. These more common debris-causing events result in significant amounts of work for 18 SDS and SDA sensor site analysts and operators. Table 1 lists the total debris pieces for these specific events in order of event size. Though more common, the number of total debris created in the past two decades by these smaller events only just exceeds the number of debris created by the three largest debris-causing events. When looking at the three largest events since 2007 the amount of debris created by these events alone accounts for over half of all cataloged debris by 18 SDS.

Table 1: Debris Event Catalog Totals

Name	Debris Piece Total	Cause
Fengyun 1C	3531	ASAT
Cosmos-Iridium	2369 (1600+ Cosmos, 700+ Iridium)	Hypervelocity Collision
COSMOS 1408	1777	ASAT
Fregat	334	Fuel Tank Rupture
DMSP 5D-2 F13	237	Battery Explosion
Atlas 5 Centaur	180	Propellant related
MICROSAT-R	53	ASAT
SL-12 R/B	31	Battery Failure

3. EVENT PROCESSING WITH NEW CAPABILITIES TO MEET CHALLENGES

The candidate nomination process for the COSMOS 1408 DA-ASAT event consisted of extracting Uncorrelated Target (UCT) observations from data files and creating candidate Resident Space Object (RSO) Two-Line Element Sets (TLEs). The 18 SDS Advanced Analyst Section used several applications and tools within the Correlation, Analysis, And Verification of Ephemerides Network (CAVENet) to accomplish this to include Slingshot Aerospace's Odyssey Tactical Event Assessment Suite (OTEAS), Astrodynamic Support Workstation (ASW), and an 18 SDS Analyst-created tool called Zach's Association Processor (ZAP). For previous large debris events such as the Fengyun 1C and the Iridium-Cosmos collision, SPADOC and the 19 SDS mission system Mission Processing System (MPS) were primarily used. Over 10 years has passed since those events have occurred and during this timeframe CAVENet has received several upgrades and automated enhancements. Due to these improvements, 18 SDS Breakup Officers decided to make CAVENet the primary processing system for the COSMOS 1408 DA-ASAT.

OTEAS is the primary tool used for UCT processing by the 18 SDS and it contains the Aerospace Corporation Legacy UCT processor and the Slingshot Aerospace Multiple Frame Assignment Space Tracker (MFAST) UCT processor.

The Legacy UCT processor is based on the orbit geometry of the individual tracks. It groups tracks based on both the orbit geometry and the dynamic consistency of the tracks. It does well in both dense and sparse data environments. It also has enhanced processing for lower orbits experiencing more significant atmospheric drag.

MFAST is a Multiple Hypothesis Tracking (MHT) solution that includes customized algorithms for non-linear filtering, orbit determination, orbit and uncertainty propagation, and advanced physics-based gating techniques. [1]

OTEAS processes radar and (ground- and space-based) optical data from the Space Surveillance Network. OTEAS takes a file of uncorrelated observations as input and attempts to find collections of observations that are dynamically consistent. The output of OTEAS is a data file consisting of two-line element sets (TLEs) that represent each candidate orbit followed by all observations that were grouped for each candidate. Each candidate must pass strict quality checks of greater than four tracks, greater than a day fit span, and a root mean square (RMS) value of less than 10 km.

OTEAS was the primary processor used as it demonstrated the capability to generate candidate TLEs at a continuously efficient rate. To put this in perspective, the amount of candidate TLEs produced before COSMOS 1408 were estimated at 250 to 300 per day. Post COSMOS 1408, OTEAS began averaging 700 to 900 candidates daily until early January when a majority of this debris event was in 18 SDS custody and catalogued. Processing this large quantity of candidate objects presented a significant challenge for 18 SDS and extra resources were allocated in order to accomplish this effort.

New methods were applied in order to separate the OTEAS candidates that specially correlated to the COSMOS 1408 ASAT event. The OTEAS TLE output file was organized based upon the quality checks previously mentioned. Candidate TLEs passing these quality checks were placed at the top of the file. Furthermore, the candidates were then sorted based upon inclination, right ascension, perigee, and apogee making them much more distinguishable for extraction. With this process implemented, 18 SDS Orbital Analysts were able to quickly accomplish the nomination process and move on to candidate promotion.

OTEAS candidates passing the initial quality checks were then entered into the second stage of refinement. The 18 SDS Advanced Analysis section used ZAP, a tool used for UCT processing that allows Orbital Analysts to associate observations, perform element set comparisons against existing objects, and transmit TLEs. Once the objects are processed in ZAP, they are then promoted to an analyst satellite number in the 80000-range and tasked to the SSN for further observation collection.

Collaboration between sections within 18 SDS was vital and new workflows were established to increase efficiency. For example, the introduction of the Mega-Constellation Analysis Tool (MECATRON), an application developed by Omitron SMEs, which was designed to give users the ability to organize multiple-piece events (e.g Starlink, One-Web, breakups) into separate categories and view orbital characteristics and elements from a consolidated graphical user interface. The 18 SDS Mega-Constellation Analysis Team were the first adopters of the MECATRON application and their skills in processing multiple piece events translated very well to the COSMOS 1408 DA-ASAT event. Their expertise was swiftly shared with others within the unit which gave 18 SDS leadership the ability to leverage more manpower. With this increased attention, users were able to identify areas of improvement with MECATRON and the feedback was passed to Omitron SMEs to provide responsive code development on site. Their team continued to provide upgrades to many applications in addition to MECATRON, all while also providing real world operations support.

MECATRON allowed 18 SDS to monitor when objects received new observations, an object's element set age, and the last differential correction status (pass or fail). Objects that had new data or were in failure status were prioritized and ASW was used to update or correct any of the debris pieces. Once ASW processing was complete, the element sets were then transmitted through the proper communication paths and received by the SSN to be further tracked. Constant maintenance was conducted until the analyst objects were ready for cataloging.

Referring back to Fig. 4., cataloging for the COSMOS 1408 DA-ASAT began on November 30th, 2021, and occurred more expeditiously than the cataloging of the Fengyun 1C DA-ASAT and Iridium-Cosmos collision. The reason for this rapid increase in efficiency was that the evaluation process for cataloging was conducted on CAVENet. This process involved performing element set comparisons to identify orbit uniqueness, point of origin, and element set history. The CAVENet applications previously described delivered these capabilities to 18 SDS Orbital Analysts. Upon completion of this analysis, the 18 SDS Advanced Analysis Team will catalog the objects and make them readily available for viewing on Space-Track.org. The Cosmos 1408 ASAT objects are labeled as "COSMOS 1408 DEB."

4. CONJUNCTION ASSESSMENT & ISS IMPACT

The on-orbit conjunction assessment (CA) process which operationally still resides with 18 SDS[1] is currently producing over 300,000 Conjunction Data Messages (CDMs) per day which is an increase from 2019's starting average of 219,000 per day. Of these daily conjunction messages, an average of 53,651 messages are in relation to COSMOS 1408 debris a day. Satellite operators commonly send 18 SDS predictive ephemeris files for maneuver clearing against the existing High Accuracy Catalog (HAC) and other predictive owner/operator ephemeris. On average, the 18 SDS receives 3600 customer ephemeris files to screen every day, and of those 1139 files are in relation to COSMOS 1408.

The increase of debris at this altitude also has substantial effects on the data input/output and system requirements of the 18 SDS. The aforementioned increase in satellite owner/operator ephemeris from the ASAT event, coupled with the increase in metric observations from the Space Surveillance Network, has imposed major data implications on the systems that store and utilize this ephemeris information which must constantly scale with demand. In 2021, 18 SDS generated ~70 million CDMs; assuming a linear growth, the SDA enterprise is estimated to eclipse well over a 100 million CDMs generated in 2022. All this data also flows to and through 18 SDS' public-facing website, Space-Track.org.

The 18 SDS has a team dedicated to human spaceflight support, referred to as HSF Orbital Safety Analysts (OSAs). The OSA team is tasked with providing specialized conjunction assessment products and analysis to Johnson Space Center and their crew counterparts in Mission Control known as the Trajectory Operations Officers (TOPOs). When the destructive COSMOS 1408 event occurred on November 15, 2021, the OSAs immediately notified the TOPO team of the impending threat. The ISS crew was awoken by the ground and instructed to enter an augmented shelter that included closing segment radial hatches for 48 hours per analysis performed by NASA's Orbital Debris Program Office. The US crew was sheltered in place within the Dragon capsule during the initial nodal crossings that occurred at 0706z and 0838z the same day. US radial hatches were eventually opened when the environment converged and the reduction in risk was outweighed by loss of mission objectives.

In 2021, the 18 SDS OSAs reported a total of 445 conjunctions to the TOPO team. As of June 27, 2022 the OSAs have now reported 785 conjunctions to the TOPOs and Mission Control. Of those 785 conjunctions reported, 560 of them are against COSMOS 1408. Table 1 shows the breakdown of how many of those 560 conjunctions were of concern.

Table 1. ISS COSMOS 1408 Conjunctions

COSMOS 1408 Conjunctions for ISS*	
Total conjunctions notifications	560
High/Medium Concerns	34
Debris Avoidance Planning	15
Debris Avoidance Maneuvers	1**

*Through June 27th, 2022

**Note: ISS has the ability to make the final decision to maneuver for the conjunction just several hours prior to TCA. This flexibility allows debris avoidance burn decisions to be made using the best available data as close to TCA as possible.

[1] The on-orbit and launch conjunction assessment missions will be transitioning to the 19th Space Defense Squadron (19 SDS) at Dahlgren, VA, effective June 2022.

The number of conjunction notifications that TOPO has received from COSMOS 1408 debris in the last six months exceeds the total amount of conjunctions that NASA has ever seen in a single year. Table 2 shows the total number of conjunctions for the ISS from 2017 through June 27th, 2022, and how that compares to previous years.

Table 2. ISS Conjunction History

5 year History ISS total Conjunctions	
Year	Total # Conjunctions
2017	141
2018	137
2019	226
2020	436
2021	445
2022	785

*Through June 27th, 2022

On June 13, 2022 the HSF OSAs reported a high concern conjunction between the International Space Station and a piece of COSMOS 1408 Debris (SCC# 52590). With an initial Probability of Collision (Pc) of 2.53E-04, TOPOs in NASA Mission Control Center immediately began Pre-Debris Avoidance Maneuver (PDAM) planning. Due to the consistency in conjunction data message updates from the OSAs at a high-concern level, and the final Pc leading up to the Time of Closest Approach (TCA) being a 1.19E-03, the TOPOs ultimately made the final recommendation to Flight Directors that an avoidance maneuver was necessary. This was the first conjunction in 2022 that has caused the ISS to maneuver. The definitive post-analysis solution using 18 SDS's truth data for drag modeling determined that the Pc leading up to the event was consistent to what predicted conjunction messages were reporting to Mission Control. Table 3 shows the progression of Pc values throughout the conjunction event.

Table 3. Miss Distance and Pc Updates

Update	Time to TCA (hrs)	U (km)	V (km)	W (km)	R (km)	Official Pc
1	79.3	-0.091	-1.021	-0.723	1.254	2.53E-04
2	71.9	-0.099	-3.893	-2.772	4.780	9.97E-05
3	63.7	-0.183	3.477	2.473	4.271	1.62E-05
4	55.7	-0.194	4.088	2.909	5.021	2.33E-05
5	47.8	-0.260	4.972	3.539	6.109	2.62E-05
6	39.6	-0.194	-1.580	-1.121	1.947	2.50E-05
7	30.9	-0.177	1.295	0.921	1.599	1.60E-04
8	23.7	-0.193	3.380	2.405	4.153	6.21E-04
9	20.2	-0.200	2.880	2.048	3.540	2.71E-04
10	16.1	-0.141	0.688	0.490	0.856	1.18E-03
11	7.3	-0.147	0.740	0.529	0.922	1.19E-03

5. CONCLUSION AND WAY AHEAD

Despite the accelerated congestion of debris in Low Earth Orbit and the exponential increase in high volume satellite deployments, the 18 SDS made significant strides in overcoming the challenges of maintaining SDA in the face of a destructive DA-ASAT debris-causing event. In the past, the cataloging and orbit determination of major debris causing events of this magnitude would have taken years to accomplish in what the squadron was able to achieve in just a few months. The 18 SDS continues to pursue enhancements in breakup processing tools, increased automation, and replacing legacy C2 software applications. Future analysis and developing innovative tactics and toolsets will require additional resources, time, and Senior Orbital Analysts to execute. This will also need to happen concurrently while database management of COSMOS 1408 debris, ensuring Human Space Flight Safety, and mega-constellation processing continue to be performed. There are numerous means to alleviate the burden of this work including increasing automation, growing the personnel workforce, fostering more collaboration, and continuing to push the agile product development line of future C2 software applications. All of these courses of action will likely need to be accomplished to ensure the continued advancement of the 18 SDS mission.

References

[1] J. M. Aristoff, D. J. C. Beach, P. A. Ferris, J. T. Horwood, A. D. Mont, N. Singh, and A. B. Poore, "Multiple Frame Assignment Space Tracker (MFAST): results on UCT processing," in Proceedings of the 2015 AIAA/AAS Astrodynamics Specialist Conference, Vail, CO, August 2015 (Paper AAS-15-675)

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