Lessons Learned on Mega-Constellation Deployments and Impact to Space Domain Awareness

Christian Ramos
Omitron, Inc.
Diana McKissock
Space Delta 2
Capt Nicholas Herzer, Capt Katelyn Eppich
19th Space Defense Squadron
Bailey Bourque
Omitron, Inc.
Joshua Parris
NASA Johnson Space Center

ABSTRACT

The breakneck expansion of multi-payload launches in low Earth orbit (LEO) has seen significant escalation over the last three years in the Space Domain Awareness (SDA) enterprise. The uptick in satellite deployment frequency, gradation of mega-constellation deployments utilizing electric propulsion, and surge in metric observation density from the Space Surveillance Network (SSN) have driven major system enhancements to ensure spaceflight safety. Beginning with the launch phase, new tactics, software, and procedures have been developed over the last few years to optimize the tasking of the SSN and ensure custody of all recently launched satellites that are added to the space catalog. Ensuring appropriate tasking levels was pivotal during the satellite separation phase, which necessitated updates to the mission systems for improved delineation between clustered satellites in a short window of time. The improved incorporation of satellite owner/operator-provided ephemeris coupled with critical code improvements have revolutionized how we maintain custody of Earth-orbiting objects. The exponential growth of satellites in low Earth orbit has also increased the quantity of conjunction data messages sent out to partners such as the Trajectory Operations Group (TOPO) at Johnson Space Center. We will discuss the need for continued collaboration between the National Aeronautics and Space Administration (NASA) and other mega-constellation satellite operators to safeguard human spaceflight operations. Lastly, we will discuss how mega-constellations are driving best practices for safe operations across the space community.

1. Introduction

The growth of payload launches in low Earth orbit (LEO) over the past five years has drastically changed the landscape of Space Domain Awareness (SDA) operations. The proliferation of LEO objects was further accelerated in 2019 by multiple commercial entities beginning launch operations of their mega-constellations. Unlike previous launches of large numbers of satellites, mega-constellations are characterized by the large number of payloads combined with their movements following orbital insertion.

The lowest part of LEO, specifically below 600 km, is experiencing an increase in the number of spacecrafts with nearly 10,000 satellites projected over the forthcoming years. Although malfunctioning satellites within these planned low LEO mega-constellations will naturally decay from orbit within a few years, it's prudent for the United States Government (USG) to closely monitor the number of failures in achieving orbit given the nascent and dynamic nature of mass spacecraft deployments. The evolving landscape of activities in the space above the 600 km threshold, including numerous large-scale satellite constellations planned at even higher altitudes, will also exert significant influence on the LEO realm, which could lead to the long-term build-up of space debris and the generation of new collision-prone fragments in the upper LEO. A mitigation strategy is thus being devised for the retirement of constellation satellites into orbits that ensure relatively swift reentry into the Earth's atmosphere with minimal or no impact to human spaceflight operations. While this approach is highly recommended for the sustained mitigation of orbital debris across the entirety of the safeguarded LEO domain, it introduces transient challenges for the lower LEO region. This is because, during the active phase of mega-constellations situated in the upper LEO, a substantial number of discarded satellites will inevitably traverse the lower LEO zone as well. This dynamic equilibrium between new end-of-life disposals and atmospheric reentries characterizes this situation.

It's also pertinent to note that constellation satellites are initially dispatched and tested at altitudes lower than 320 km, even though their intended operational altitudes are higher, around 550 km, for instance. Through gradual orbital elevation driven by minimal thrust and nearly continuous propulsion, these satellites traverse the lower LEO region, adding an additional challenge for external parties to track and avoid.

The implications of these advancements for human spaceflight endeavors could hold substantial significance. Following the final Apollo mission to the Moon in 1972, all subsequent human spaceflights have taken place within the lower LEO. Aside from the International Space Station (ISS), the expanding Tiangong Space Station launched by China in 2022, and scheduled crewed missions by both India and private entities will also operate within this segment of space. This preference is rooted in the operational advantages of circular orbits beneath 550 km, which serve as an energetically efficient gateway to more distant destinations that benefit from the protective effects of the magnetosphere against radiation, and can effectively counteract atmospheric drag through propulsion adjustments. Naturally, the favorable logistical and safety elements are not overlooked in this context.

The primary organizations charged with executing United States Space Command’s (USSPACECOM) SDA mission are the United States Space Force (USSF) Space Delta 2’s 18th Space Defense Squadron (18 SDS) and 19th Space Defense Squadron (19 SDS), who provide combat-ready forces who operationalize Space Domain Awareness to identify, characterize, and exploit opportunities and mitigate vulnerabilities in the national security space domain. Specifically, 18 SDS is charged with the management and publication of USSPACECOM’s catalog of resident space objects (RSO) and associated orbital data. In 2020, an intriguing complication was introduced to 18 SDS’s conventional strategies with the inaugural period of substantial mega-constellation activity, the continuous influx of launches coupled with a record-breaking method of mass orbit-raising satellites. The traditional structure of SDA was designed to align with the anticipation of minimal satellites per launch, considerable gaps between satellites, and swift orbital adjustments through traditional thrusters. These conventional paradigms have been upended by the advent of mass multi-payload launches, profoundly impacting every facet of space operations. In a proven blend of ingenuity and innovation over the last five years, the 18 SDS, 19 SDS, and the US Space Surveillance Network (SSN) have effectively addressed and surmounted the most pressing obstacles, thereby positioning USSPACECOM to successfully handle the forthcoming challenges that persist within the US space sector and the wider community of space operations.

2. PRE-LAUNCH CONJUNCTION ASSESSMENT

In accordance with the Department of the Air Force (DAF) and USSPACECOM instructions, every launch provider (LP) launching from a United States Space Force (USSF) installation will receive pre-launch conjunction assessment (LCA) screening from the 19 SDS, a mission set which was executed by 18 SDS previous to July 2022. This process requires the LP to provide trajectory data for each piece separating from a launch vehicle including rocket boosters, fairings, satellite deployment vehicles, and satellites. Along with the trajectory data, the LP must also provide the 19 SDS with a screening request and other supplemental information. The process relies solely on LP data for the launch vehicle which the 19 SDS screens against the most current version of the RSO database, and as of 2023, external satellite owner/operator (O/O) provided ephemeris. The results of these screenings are closure reports defining which time-based launch opportunities yield potential conjunctions.

Mega-constellation launches continue to pose a challenge to LCA operations, which the 19 SDS is positioned to meet. For context, the time between SpaceX Starlink launches alone can be as little as 4 days. Thus, in between servicing other launch providers--as well as other mega-constellation providers—the 19 SDS averages 1-2 LCA screenings per day in addition to providing on-orbit conjunction assessment (CA) services for over 725 satellite organizations.

To reduce processing strains on multi-payload launches, the 18 SDS worked with the Federal Aviation Authority (FAA) in 2019 to reconfigure Starlink LCA screenings by having a single trajectory with an over-estimated hard body radius represent a subset of the satellites on board the rocket. Through this method, groups of satellites are screened as a single trajectory with the hard body radius representing the maximum distance between all satellites in the cluster. This reduced the number of trajectory files and the overall screening time, allowing accelerated delivery of results to the LP that represented an effective keep-out zone. It is important to note that this configuration was only applicable and approved for SpaceX Starlink launches. Thus, for other mega-constellations that are launched and require LCA servicing, the 19 SDS is required to execute the standard procedures of screening each trajectory individually at every time step in the launch window requested by the LP. This results in longer operational timelines to deliver applicable results to LPs, but ensures adherence with DAF instructions and regulations.

Many LPs have moved to LCA based solely on the probability of collision rather than the historical methodology of miss distance based on stand-off separation. This move was largely due to decreased launch opportunities based on a highly increased population density in LEO. Both methodologies are permitted by current instructions, but the lack of covariance standardization and validation of trajectories precludes full reliance on this approach. Furthermore, as launch cadences have increased, the 18 SDS continues to make strides to catalog mega-constellations in a timely manner; however, the process of identifying and cataloging these closely spaced objects depends largely on the number of observations received. Therefore, there is a period of time between the moment an object is launched and the moment there is enough data for it to be officially catalogued in the high-accuracy catalog (HAC). This ever-growing gap between the launch and on-orbit phases of spaceflight safety has been challenging and needed to be addressed. To meet this need, the 19 SDS began including O/O-provided ephemerides in the LCA process in 2023 to increase the comprehensiveness of these reports and ensure that objects not yet catalogued are being provided to LPs at the next opportunity to launch. To account for the inconsistency of O/Os providing realistic covariance (or covariance being omitted entirely) in their ephemerides, the 19 SDS generates and provides a report for both miss distance and probability of collision violations to ensure all relevant data is being captured appropriately. Considering this data is not officially validated by DoD standards, these reports are treated as supplemental information to regular LCA reports; however, in some cases it may be the only information available.

Overall, the 19 SDS continues to meet LCA challenges through continuous innovation. They continue to work with LPs, mission system experts, and higher headquarters to identify the best way to represent a proposed trajectory's path through the RSO catalog. The data, software, resource, and policy limitations have created a need for continuous updating of the entire pre-LCA segment to continue providing meaningful and actionable results to launch agencies.

3. Initial Object Separation

The first phase following the launch focuses on achieving custody of newly launched RSOs, which is a primary role and core responsibility of SDA operations. Historically, this process began with the creation of an initial element set for tracking that ultimately enabled the reacquisition of objects during subsequent orbits for precise observation association and state updates. The rise of mega-constellations, however, characterized by numerous satellites in close proximity with rapid separation velocities, posed distinctive challenges in this phase. Two distinct strategies emerged among mega-constellation operators. SpaceX employed angular momentum to effectively separate vertically stacked satellites during multi-payload deployment. This method was typically utilized for payloads ranging from 20 to 60 satellites depending on Starlink satellite generation, and they were initially secured by four tension rods until orbital insertion was achieved. Subsequently, the tension rods detached and were rendered passive. The vertically arranged satellites then gradually dispersed from the launch vehicle – driven by angular momentum – and proceeded to execute orbit-raising maneuvers. DoD SDA Operators commonly refer to this deployment style as the passive deployment model. Conversely, the OneWeb satellite constellation utilized an active deployer with timed separations, known as the active deployment model.[i] The passive approach delayed satellite acquisition until sufficient separation occurred, while the active model achieved quicker custody due to reduced tracking requirements resulting from timed deployments and more predictable separations.

Acquisition of satellites through metric observations via the passive deployment approach was postponed until a satisfactory achievement of separation distance, allowing for unique objects to be seen via the SSN. During the period between initial deployment and complete custody, consistent observations of all distinct objects were required. If an SSN sensor detected a quantity of objects less than the quantity launched in a pass, it increased the necessary time for processing and analysis for the 18 SDS analysts to identify the missed objects and associate observations accurately for early-orbit state updates. Thus, it was decided that Analysts would refrain from attempting object separation for the initial 48 hours. Doing so would ensure sufficient inter-satellite spacing. However, OA availability and orbit-raising initiation were observed to be influential factors of shorter or longer durations. Significant increases of separation between payloads due to the controlled orbit-raising phase resolved satellites spacing issues. Analysts then began manual observation assignment to satellites and generation of initial states in the HAC subsequent to the 48-hour period. This manual process facilitated the identification of objects that had achieved optimal separation from neighboring satellites, which enabled automated maintenance of their orbits.. Two to four Analysts would assume responsibility of individual objects over several days, progressing from deployment sections of lower ambiguity to higher ambiguity until custody of all payloads was established. Transition of the objects to the maintenance phase would not occur until observation association errors, known as cross-tagging, were minimized to an appropriate level in the initial separation phase. This transition did not imply automatic maintenance but rather a less likely need for manual intervention to sustain orbital updates. Once objects experienced minimal to no cross-tagging in a 24-hour period, the Analysts considered the launch acceptable for transitioning out of the initial object separation phase. This transition typically aligned with the inclusion of payloads into the public satellite catalog, usually around one week after launch. In 2020, the 18 SDS Analysts were observed to have contributed approximately 160 hours of labor as the overall effort for the initial separation phase in the passive model. Notable mission system updates discussed in the Catalog and Database Management section of this paper has reduced the number of manual updates to an average of closer to 60-80 hours of labor during the initial object separation phase.

In contrast, the active deployment model involved deploying satellites in groups of four to six with short intervals between groups. From an observational standpoint, this reduced the demand for comprehensive tracking per pass and considerably decreased the time between initial deployment and full custody of all launched objects. If a sensor failed to collect data on every unique payload, then only the group of four to six satellites where observations were missed was affected rather than the entire multi-payload launch. The reliability of object deployments also contributed greatly to automatic observation association, as each group was known to include four to six payloads. The 18 SDS Analysts could quickly identify the untracked satellite among the four to six within the partially tracked group due in large part to greater separation between payloads and neighboring deployment groups. This nullified the partial tracking's impact on the timeline required to achieve and maintain custody of all objects. Additionally, the payload deployer imparted velocity between intra-constellation payloads, expediting the timeline for initial custody. Due to these pivotal features of the active deployment model, initial custody could be established within a few hours after orbital insertion, contingent on SSN availability and analyst readiness. However, final cataloging and processing often occurred 24 hours post-launch to accommodate higher data density. The increased satellite separation achieved through the active deployment model aligned better with conventional SDA processes with respect to system response and analyst expectations, which solidified the systemic success of the 18 SDS. Although there were more payloads per launch than a traditional multi-payload launch, the active deployment model's strategy and timing were conducive to clear observation association and automatic orbital state updates by extension. Total labor costs for the initial separation of an active deployment on the DoD amounted to no more than an hour or two, and the satellites could be cataloged and smoothly transitioned to the routine catalog maintenance phase with minimal manual intervention afterwards. The gains in initial custody and payload separation are expected to be conducive to scalability while maintaining full custody with minimal manual involvement from the 18 SDS analysts. Recent launches from SpaceX's Starlink constellation in 2023 have been more consistent with an active deployment model, which has greatly assisted initial object separation and association. Starlink deployments in 2023 also commonly no longer deploy rods with each of their satellite launches, which has reduced the burden and metric SSN observations that 18 SDS Analysts have to comb through.

The 18 SDS took significant measures to address the unique challenges posed by the passive deployment model by allocating six senior analyst and enlisting an additional five military support analysts to cater to the sudden demand for this novel skill set. Training for some of these analysts had commenced in 2019, and the unit effectively filled these roles in 2020, which led to the establishment of a new division named the Mega-Constellation Analysis (MECA) Cell. The MECA Cell in 2023 is now comprised of six contracted senior analysts, one government lead, and an additional eight military personnel. These analysts underwent training in the distinct techniques essential for initial separation, catalog maintenance, and administrative tasks linked with SDA maintenance. Mechanisms were also integrated to incorporate ephemeris data from satellite operators during the early phases of passive initial separation. This swift modernization was achieved without dedicated training systems or programs. Given the timeframe, the most effective approach to training involved acquainting team members with catalog maintenance functions first, which allowed them to grasp the tools and principles behind management of multi-payload launches and orbits maintained via electronic ion propulsion. The junior analysts could then collaborate with senior analysts during live launch separations to gain hands-on experience and insights in real-time once they were familiar with these functions. However, this approach stretched the responsiveness of initial separation because senior analysts had to simultaneously teach and supervise junior analysts during most launches. The accomplishment of the 18 SDS in overseeing the mega-constellation launches over the last five years is directly linked to the on-the-fly innovation, mentorship, and the optimization of manning and personnel by 18 SDS.

The separation of payloads during the first several hours after insertion proved insufficient for clear distinction by the SSN or 18 SDS analysts. However, satellite operators were able to communicate with their payloads and obtain onboard telemetry within the first hours of deployment. Data sharing arrangements, executed under the auspices of the USSPACECOM SSA Sharing Program were forged between the 18 SDS and both SpaceX and OneWeb to periodically provide ephemerides generated from the downloaded telemetry data. Satellite operators supplied projected ephemerides, initially based on predicted insertion data and later augmented by onboard telemetry, to the 18 SDS either as 36-hour predictions updated every 8 hours, or 7-day predictions refreshed every 24 hours. These ephemerides were subsequently utilized by the 18 SDS to generate two-line element sets (TLEs) for tracking and observation association, mitigating many of the challenges outlined in the launch processing section above. During the initial separation phase, these TLEs aligned observations with object identification as designated by payload owners, removing the need for 18 SDS analysts to allocate resources for identifying object names. In the active deployment model, these TLEs enabled SSN sensors to directly correlate observations with the correct object within the first day of launch. Though the passive model yielded relatively fewer autonomous outcomes in observation association, the impacts were still significant enough to ease the burden on tracking sites and swiftly identify tracked objects potentially representing non-responsive payloads. Upon receiving ephemerides at the 18 SDS, automated procedures were devised to carry out a general perturbation's differential correction on a 4-hour data fit centered around the current time to generate TLEs. This process occurred hourly, ensuring constant updates to element sets that accounted for the electric propulsion's variability, a factor included in ephemeris predictions but not covered by the HAC or Simplified General Perturbations #4 (SGP4) prediction models available to the 18 SDS and SSN sensors. As infrastructure has drastically and rapidly improved for SpaceX in recent years, the accuracy of ephemerides and the quality of covariance has increased and enabled accurate SSN tasking.

The integration of satellite O/O ephemerides into the 18 SDS Astrodynamics Support Workstation (ASW) software was a significant development, capitalizing on shared data from all satellite operators. This integration was mainly implemented in the ASW Multiple Piece Separation (MPS) software, which was upgraded to allow analysts to visualize operator-provided ephemerides alongside SSN observation residual data. Additionally, when accompanied by covariance data, the ephemerides can now be used to supplement SSN observations in updating orbital states, although this functionality remains untapped pending more numerical validation from senior analysts. Through viewing ephemeris data alongside SSN residuals, 18 SDS analysts gained improved capabilities to overcome SSN partial tracks in the early stages of separation and identify unobserved payloads. This integration also enabled analysts to determine which satellites may have commenced orbit raising earlier than traditional orbit determination methods would have led us to believe. In totality, the incorporation of O/O data substantially reduced the workload for analysts to achieve initial object separation by 75% with further potential for improvement. Beyond aiding tracking and correlation processes, this integration allowed the 18 SDS to alert O/Os when their predicted satellite positions deviated from SSN observations, indicating a likely missed maneuver. It also facilitated the provision of TLEs for observations not aligned with ephemerides for antenna pointing, allowing quick separation of those observations that did not correspond to any user-provided ephemerides. The operational integration of O/O data marked a significant advancement in 18 SDS operational capabilities, benefitting both the SDA mission and satellite operators. While this data was primarily used for conjunction assessment processes in the past, it is now seamlessly integrated into the SDA framework. With these enhancements and acquired skillsets, the potential for integrating O/O data into the catalog and database management functions of the 18 SDS is just beginning to be realized. However, it is important to note that this data remains supplementary, as it represents unverified solutions pertaining to predicted future positions of active payloads.

4. Catalog Maintenance

After the initial separation phase, ongoing updates are essential to maintain the current status of mega-constellation satellites within the HAC. This continuous process is known as catalog maintenance. While several techniques from the initial separation phase are carried over into catalog maintenance, the primary focus shifts away from isolated launch-related challenges like cross-tagging, instead addressing the broader management of mega-constellation satellites. Upon entering the catalog maintenance phase, satellites generally exhibit considerable separation, and instances of cross-tagging are usually minimal. However, these general patterns aren't absolute rules, as certain 2020 launches experienced persistent close proximity and cross-tagging throughout this maintenance phase.

The criteria for transitioning into this phase of orbital upkeep are established based on the workload of analysts. During the initial separation, analysts concentrate solely on individual launch events, whereas the maintenance phase involves a small group of analysts managing changes to states rather than their initial definition. A satellite's lifecycle within the maintenance phase encompasses an initial orbit, orbit raising, final orbit, and orbit lowering. These phases involve various maneuvers that leverage a non-constant electronic propulsion thruster. The existing software framework was originally designed around maneuvers modeled as either instantaneous or continuous thrust. However, the extended burn durations characteristic of continuous electric propulsion in LEO deviated from both models, prompting the 18 SDS to devise a fresh approach.

Within the ASW software, the parameter representing continuous thrust is determined and corrected in each update using an iterative process. The software permits the division of the resolved thrust value over time, accommodating variable values during different segments of the observation period instead of adhering to a uniform value across the entire orbit determination interval. Initially, this feature was intended to handle deviations in performance or inaccuracies in the drag model, which could lead to perceived fluctuations in thrust values. While this segmentation is conventionally applied to the B term to address drag variations over time in traditional LEO payloads, extending this segmentation approach to multiple variables has generated challenges in terms of performance and accuracy. Consequently, orbit determination procedures were tested for segmenting both the drag parameter and the thrust parameter prior to their implementation in this configuration.

The ASW Mission System was updated to apply a feature known as the Adaptive Thrust Uncertainty (ATU). ATU evaluates alterations in thrust status to make a determination regarding whether all thrust should be applied or none at all within a specific segment. This creates a binary configuration instead of a measured approach. The influence on the accuracy of TLE propagation is striking and has led to a reduction in errors at the 36-hour forecast point by more than tenfold. The research that paved the way for ATU primarily focused on the stable orbits of a satellite within a mega-constellation, encompassing both the initial and final orbits. While there was a degree of enhancement in prediction accuracy during the phases of raising and lowering orbits, it was not as pronounced. This discrepancy is likely attributed to the choice of not extending anticipated maneuvers in the space catalog, in addition to the frequency and duration of maneuvers during these transitional orbital phases.

Apart from the segmentation approach, various other upkeep parameters were evaluated and fine-tuned to improve the success rate of the automatic differential correction updates for objects within mega-constellations. These adjustments were implemented to minimize the need for manual orbital updates, while still upholding a satisfactory level of accuracy for all SDA operations to include conjunction assessment. The primary alterations to these configurations involved considerations for the Weighted Root Mean Square (WRMS) value calculated for a particular satellite update such as raising the acceptable maximum allowable value traditionally found in other payloads. This metric represents the ratio between observational residuals and the standard deviation, reflecting the sensor's data collection capability and indicating the overall fit quality for a state update. The expanded allowance for WRMS and the application of ATU result in a broader and less representative covariance field for the mega-constellation satellites. Nevertheless, they still present a considerable enhancement over past modeling endeavors by reducing the frequency of manual intervention, identifying thruster on/off times, and reducing uncertainty at epoch.

5. CONJUNCTION ASSESSMENT

In addition to LCA, 19 SDS is also responsible for on-orbit CA for all RSOs, and provides conjunction data to U.S. and international commercial, civil, military, and academic O/Os. As of Aug 1, 2023, this encompasses approximately 30,000 RSOs, 8,700 of which are active payloads. As part of the current on-orbit CA process, 19 SDS generates approximately 600,000 Conjunction Data Messages (CDMs) per day as compared to 2020's average of 200,000 per day. Of these daily messages, 51.7% are based on Starlink satellites either as a primary or secondary with another 14% being dedicated to other large constellations (OneWeb, Iridium, and Planet).

The majority of CDMs for active constellations are provided in support of intra-constellation management as a result of the satellite operator proactively sending predictive ephemerides with planned maneuvers to 19 SDS for CA screening. 19 SDS screens these predictive ephemerides against the existing HAC states, which do not include predicted maneuvers. A high rate of movement within any constellation creates a litany of close approach reports. Seeing as the satellite operator often has exquisite knowledge of their constellation, most of the messages that are sent provide little meaningful data or further insight, but the reports are provided in case maneuvers are not executed. The satellite operators also benefit from a second-party identification of the state for their satellite which can be used for operational tuning of their telemetry and planning systems.

Prior to 2021, 18 SDS performed both inter-constellation and intra-constellation CA management; however, this became rapidly overwhelming. In 2021, 18 SDS worked with the Starlink team to implement a burden-sharing strategy since the large majority of close approaches identified were between any two Starlink satellites. The current metrics are indicative of said agreement in which Starlink handles intra-constellation CA for its active satellites augmented with 18 SDS ephemerides and 19 SDS special perturbation screenings (those based on SSN data). If this posture was not implemented, 19 SDS would generate an additional 660K CDMs per day for Starlink alone. Therefore, this burden-sharing strategy could serve as a potential example for future enterprise CA management.

Both 18 SDS and 19 SDS continue to manage data throughput challenges and computer network requirements brought on by the vast amounts of data received from and sent to O/Os.. The number of O/O ephemerides submitted to USSPACECOM's public website, Space-Track.org, per day increased from 6,000 (reported in the 2020 iteration of this report) to over 18,000 (77.8% SpaceX, 16.7% Oneweb, and 5.5% all others). Beyond the quantity of files transmitted, there are data implications on the systems that store and utilize these ephemerides which must constantly scale with demand. In 2020, 18 SDS generated 31.5 million CDMs; as of August 1, 2023, 19 SDS produced 123.5M CDMs. All this data must also flow to and through Space-Track.org. This growth in data presents a constant challenge to all information technology systems, to include those of the O/O, which drives continuous upgrades and optimization of existing platforms at an exponential pace.

Collectively, mega-constellations are responsible for over 67.6% of the total conjunction data that is output by 19 SDS, with 53.3% being dedicated to O/O-provided ephemeris processing. To ensure 19 SDS continues to meet this demand, they are continuing to build on the groundwork of the Reduction of Conjunction Assessment Processing (ReCAP) efforts, annotated in the 2020 report, in order to ensure sustainability and scalability of operations. Current efforts are focused on adapting processes to integrate even more processing power as well as a study in partnership with NASA's Conjunction Assessment and Risk Analysis (CARA) Program on understanding uninterrupted CA custody of HEO objects as they pose a mounting threat to the growing population in LEO.

As mega-constellations have become more prominent, there has been continuous dialogue between 18 SDS, 19 SDS, NASA and constellation representatives in order to build a common understanding of operational practices. This dialogue as annotated has created load-sharing opportunities between organizations and optimization of spaceflight safety. The initial data and mission-sharing lessons learned from cooperative mega-constellation management and CA mission sharing may offer a foundation of best practices such as data transparency and communication. Future companies are also likely impacted by these decisions and reactions and should continue to learn best practices from these. With the multitude of mega-constellations, further reductions to data generation, transmission, and storage are needed to continue to balance the need for safety of spaceflight with operational responsiveness and resource management. USSPACECOM will address these challenges with the Department of Commerce (DoC) as they stand up their Space Traffic Coordination (STC) capability for commercial and civil entities to ensure comprehensive support across the space community.

6. NASA Human Space Flight Operations

The International Space Station is a world-class orbiting laboratory that has been continuously inhabited since 2000. Researchers from around the world can take advantage of access to a sustained microgravity environment, exposure to the extreme conditions of space, and a unique LEO vantage point to push the boundaries of science and technology for the betterment of humanity. To date, over 3000 different scientific investigations have been performed on the ISS by researchers from over 100 countries and areas, resulting in over 3,500 total publications representing breakthroughs across the spectrum of scientific disciplines. [1,2]

Keeping this orbital outpost, along with its cargo and crew resupply vehicles, safe from the threat of orbital debris requires close collaboration between the Trajectory Operations Officer (TOPO) based at NASA's Johnson Space Center (JSC) and the 18 SDS at Vandenberg Space Force Base. The recent addition of the expansive SpaceX Starlink satellite constellation has presented an opportunity to implement a successful collaboration with the private sector that can be considered a model for future large-scale commercial spaceflight endeavors.

To ensure the safety of both the ISS and the more dynamic visiting vehicle cargo resupply and crew rotation flights to and from the ISS, the Human Spaceflight Orbital Safety Analyst at 18 SDS screens the ISS trajectory against a high-accuracy catalog and provides CDMs to the TOPO for all threats that are predicted to enter a ± 2 x 25 x 25 km box centered on the ISS. The table below summarizes the number of notifications received over the last 5 years as well as the number of debris avoidance maneuvers ISS has performed to avoid potential collision with another space object.

5 Year ISS Conjunction & Avoidance Maneuver History		
Year	**Total # Conjunctions**	**Avoidance Maneuvers**
2018	137	0
2019	227	0
2020	436	3
2021	445	2
2022	1458	3
2023 CAO July 5	585	2

The ISS Flight Control Team can make the final decision to maneuver for a conjunction as late as 3.5 hours prior to the time of close approach. This flexibility allows for avoidance burn decisions to be made using the best available data from 18 SDS as late as possible, which ultimately minimizes the number of debris avoidance maneuvers that must be executed.

The large spike of conjunctions in 2022 is directly correlated to the destruction of COSMOS-1408 in the Anti-Satellite Test performed by Russia in late 2021. More than half of the conjunctions identified in 2022 were from COSMOS-1408 debris and that debris has resulted in 3 ISS debris avoidance maneuvers to date.
The ISS currently flies at an average altitude of 416 km. This altitude lies in the transit zone of the Starlink satellites, which are inserted below ISS and then raise their orbits to operational altitudes above ISS. While thousands of Starlink satellites have transited above ISS, conjunctions with Starlink satellites represent only a small fraction of the ISS conjunction notification totals, and the ISS has never had to perform an avoidance maneuver due

to Starlink. This is no accident, but rather the direct result of a Nonreimbursable Space Act Agreement between NASA and SpaceX for Flight Safety Coordination with NASA Assets that was coordinated and signed by both parties.

As a part of this agreement, the ISS ephemerides are shared with SpaceX which then allows the Starlink team to design the orbit-raising and orbit-lowering maneuvers to avoid the ISS reportable conjunction screening volume. Any Starlink satellites that do enter that volume are usually non-maneuverable and discussed between the NASA and SpaceX trajectories teams days in advance to ensure the ISS is safe. Although SpaceX and NASA have dedicated lines for data exchange, work is currently ongoing to make the ISS ephemerides publicly available on Space-Track.org. This would ensure all space operators with a Space-Track account could have access to the latest ISS trajectory data for safety of flight purposes.

In addition to the high accuracy catalog discussed previously, 18 SDS also screens against O/O- supplied ephemerides. The importance of these O/O-supplied ephemerides to ensuring spacecraft safety is particularly apparent during highly dynamic visiting vehicle missions where launch slips and other unforeseen factors could change predicted trajectories on a short time frame. For example, during a 2021 ISS cargo vehicle rendezvous with the ISS, a Starlink satellite undergoing an orbit-lowering maneuver was found, using the O/O-supplied ephemerides, to be conjuncting with the ISS cargo vehicle. Once the threat was identified, NASA and SpaceX were able to utilize established lines of communication to quickly address and successfully mitigate the threat without changing the visiting vehicle rendezvous trajectory.

Another area where NASA and SpaceX have created processes to ensure spacecraft safety is in launch collision avoidance. Insertion altitudes of Starlink are below ISS mitigating any risk to ISS during the launch and early ops phase but an ISS visiting vehicle during rendezvous or return could be impacted. An additional process was set up to analyze these potential conflicts between an ISS visiting vehicle and a soon-to-be-launched Starlink spacecraft. If a risk is identified, launch time options can be discussed to minimize the risk to the NASA assets.

For future operators of large (or small) constellations that will be operating in the ISS altitude regime, this cooperation with SpaceX provides an effective model of successful collaboration that can contribute to the goal of ensuring mission success without sacrificing safety. Another good reference for safety of flight is the NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook (https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_50.pdf).

7. Best Practices

Over the past five years, the space environment has become increasingly complex and dynamic due to not just mega-constellations but also to increased access to space, new technologies, and more space surveillance data and awareness than ever before. As space activity grows and space actors become more diverse, the need for standards of responsible behavior in space is critical to reduce the risk of miscalculations and misunderstandings.

Since the advent of mega-constellations in 2019, several industry experts and government organizations have published documents that provide best practices and guidelines for spaceflight safety, some written for all space actors, and others targeted to specific orbital regimes or phases of operation. These include, but are not limited to, AIAA's "Satellite Orbital Safety Best Practices," the Space Safety Council's "Best Practices for the Sustainability of Space Operations," and NASA's "Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook." USSPACECOM contributed to NASA's Best Practices Handbook, which includes the following recommendations that are a direct result of the lessons learned from supporting and processing mega-constellation operations:

Communicate early and often. Initiate communication with USSPACECOM, NASA, and applicable data providers well before launch to share launch delivery and deployment strategies, on-orbit concept of operations, satellite characteristics, and orbital maintenance strategies. Share contact information with data providers and other satellite operators and establish relationships with satellite O/Os in nearby orbits to ensure timely coordination of maneuver actions.

Mega-constellation operators, both current and future, have proven the value of early and open communication with USSPACECOM and NASA. Many of them initiated information sharing years before launch to ensure that they were designing their spacecraft and operations to ensure trackability and sustainability and minimize overall spaceflight safety risk. These exchanges also allowed USSPACECOM to anticipate how the constellations could drive changes to existing tracking techniques and operational procedures, which, as this paper shows, have dramatically evolved over the past four years. Mega-constellation operators have also set the standard in communicating with other satellite operators, which has reduced the burden on USSPACECOM to act as a middleman when maneuver negotiations are required.

Understand risk before it's encountered. Understand the population of the planned operational orbit to determine close approach frequency and overall risk. Identify orbital neighbors and assess their willingness to establish methods of communication and data sharing. Determine proximity to current and potential manned spacecraft to set up specific protocols for human spaceflight safety.

Both current and future mega-constellation operators fully utilize USSPACECOM's service to screen hypothetical orbital trajectories months prior to launch, recognizing its benefit when assessing and planning for conjunction risk in anticipated orbits and during various phases of potential operations, specifically the early orbit phase. The resultant data also aids in identifying frequent conjunctors, whether they are other active spacecraft or debris. All cooperative mega-constellation operators have actively engaged with NASA JSC to establish lanes in the road, and those constellations currently on-orbit have also set up methods to minimize risk to other human spaceflight missions.

Share data as widely and consistently as possible. Share predictive ephemerides with USSPACECOM, data providers, and other satellite operators on a cadence appropriate to the spacecraft regime to support both conjunction assessment and orbital maintenance; consider sharing publicly for maximum transparency. Employ standard formats, specifically in the Consultative Committee for Space Data Systems (CCSDS) format, to ensure interoperability with the O/O community. Share spacecraft status and maneuver capability to support risk mitigation actions with other O/Os.

Mega-constellations have upheld these best practices and pushed them to levels not seen before. Today, Space-Track.org receives an average of 51 GB of data per day, the majority being ephemeris files for mega-constellations that are shared not only with USSPACECOM but also with other O/Os. SpaceX led the initiative to set up public file-sharing on Space-Track.org that allows entities to share with all Space-Track.org users, not just O/Os. They have also implemented near-real time updates to spacecraft status information. In addition, SpaceX, OneWeb, and Kuiper have pushed for expanded functionality to share maneuver capabilities and strategies, which will be released on Space-Track.org in the coming year.

8. Conclusion

The topics throughout this paper illustrate that mega-constellations have created new challenges through all facets of space operations but are also driving innovation and improvements that will enable the space community to scale as current constellations expand and future constellations begin to launch. Thus far, the focus has been on launch and on-orbit operations; as existing mega-constellations reach their end-of-life reentries will occur at a record-breaking rate, requiring the same innovative approach to be applied to deorbit techniques and reentry assessments. Mega-constellation operators, as the owners of the preponderance of active satellites in orbit, will continue to drive best practices but face the most scrutiny if they don't adhere to them. The lessons learned over the past four years have resulted in improved procedures, more efficient systems, and increased communication and collaboration between government, industry, and the space enterprise at large. All of this progress, however, can be largely attributed to the willingness and transparency of cooperative partnerships. The upcoming challenge lies in applying these insights to uncooperative mega-constellation operators, who may opt not to adopt best practices recommended by the majority of space entities, leading to heightened operational intricacies and an increased cumulative risk for all those operating within their orbital regimes. Conversely, this raised operational complexity could incentivize previously uncooperative operators to initiate communication channels and establish novel data-sharing relationships. Irrespective of the situation, USSPACECOM, via DEL 2's 18 SDS and 19 SDS, alongside international partners and interagency teammates such as NASA, will continue to work with the global space community to create and pursue opportunities to enhance the safety and long-term viability of orbital space for everyone.

References

[1] "2022 Annual Highlights of Results from the Internationals Space Station". https://www.nasa.gov/sites/default/files/atoms/files/annual_highlights_results_iss_2022_np.pdf

[2] "International Space Station Utilization Statistics". https://www.nasa.gov/sites/default/files/atoms/files/expeditions_0-62_statistics_brochure_-_final.pdf

Acknowledgments

The authors would like to extend thanks to several people who aided and advised this research, including Steve Casali of Omitron Inc., the Guardians of the 18th and 19th Space Defense Squadron, Aaron Mitchell of 18th SDS, and Ryan Hiles of Omitron Inc. for being the senior Orbital Analyst in pioneering many of the processes for characterizing Mega-Constellations that we still use today.

[i] Active and passive style deploys signify where additional devices are used to deploy payloads in a specific sequence beyond separation from the booster and do not imply deficiencies in methodologies in regards to achieving positive spacecraft control