Challenges in Space Traffic Management

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ABSTRACT

This paper will explore technical and policy issues regarding Space Traffic Management (STM) related to the characterization and dissemination of space weather information and the data services challenges related to making available integrated multi-source space situational awareness (SSA) tracking information available to all users. Specifically, how those warnings are provided, how SSA services can be made more broadly accessible for the common good and establishing operational standards and thresholds. This paper will assert the necessity of a civil space domain organization similar to the mission of the International Civil Aviation Organization (ICAO) that was founded in 1944 in the early days of civil aviation to:

> *"…promote the safe and orderly development of civil aviation around the world. The organization sets standards and regulations necessary for aviation safety, security, efficiency, and regularity, as well as for aviation environmental protection. ICAO also serves as a clearinghouse for cooperation and discussion on civil aviation issues*… [1]"

The National Aeronautics and Space Administration (NASA) and other governmental agencies have been remarkably successful in developing the commercial environment for Earth orbital industries. We are seeing that success in the rapid, almost exponential, growth in the number of active satellites today compared to that estimated through 2030. The associated trackable debris (>10 cm) volume is also growing but has remained at an approximate 4x multiple of active satellites. Assuming these conditions remain, then approximately 5,500 satellites and 22,000 trackable objects in 2022 will grow to over 58,000 satellites and over 230,000 trackable objects by 2030 [2]. This presents challenges in tracking, characterization, threat assessment, safety of flight, STM, and data integration.

The National Orbit Debris Research and Development Plan [3] and the follow-on National Orbital Debris Implementation Plan [4] identified the following focus areas for improvement of Space Domain Awareness (SDA), Space Environmental Effects, and Safety of Flight Management:

- Characterize orbital debris and interactions with the space environment
- Improve observations and models for estimated atmospheric drag for better orbital predictions and forecasting
- Develop technologies to improve orbital debris tracking and characterization
- Reduce uncertainties of debris data in orbit propagation and prediction
- Improve data processing, sharing, and filtering of debris catalogs
- Transition research on debris tracking and characterization into operational capabilities

The 3 February 2022 Starlink incident where the loss of 38 of 49 satellites occurred as the result of increased drag during a G3 class solar event spectacularly illustrates the need for better precision in environmental monitoring, characterization, modeling, and forecasting of atmospheric conditions in the Low Earth Orbiting (LEO) regime [5]. The National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center (SWPC) provides high-quality information that can now be widely augmented with additional open access and commercial sources. SSA systems are already operating in the commercial market. ExoAnalytics is the first commercial data provider operating a global network of optical tracking systems. LeoLabs has entered the field operating 12 radars at six sites providing high-precision tracking of LEO objects. Additional support is provided by an ever-increasing marketplace extending from LEO to lunar orbit. The rapid proliferation of LEO/Very Low Earth Orbiting (VLEO) systems and the entry of commercial entities into the SDA realm is providing a data-rich resource to build the

deterministic environmental models leading to better fidelity and longer-range forecasts needed to deliver a responsive and accurate space traffic management system.

To meet the goals of a civil STM capability, the data architecture will need to interact with the existing space domain functions of the U.S. Space Force (USSF) and U.S. Space Command but also integrate with the nascent civil SDA/STM building out of NOAA's Office of Space Commerce. To be effective, the civil SDA/STM will need to seamlessly operate with the USSF Uniform Data Library (UDL), incorporate detailed space weather/environment information from both NOAA and industry sources, deliver an integrated situational awareness of all detectable space objects, determine current and future locations of active satellites within this environment, perform conjunction analyses, warn of potential collisions, and provide these data and notices within a low-latency, easily accessible communications framework. Additionally, a common means of sharing course of action capabilities for maneuverable assets that does not disclose critical vulnerabilities, will be important to formulate potential recommended responses to collision warning messages. To meet these demands, a foundational data/services framework will be required. Operating within Cloud-Cloud environments, and with an "any source" integrated calibration/validation data repository, the integrated SDA/STM environment will provide current and future motions of tracked objects, identify, and assess any changes of state (fragmentation or maneuvers), and ideally forecast changes to the operational environment in response to solar effects. Alerts and warnings will need to be delivered as close to near real-time as possible and will depend on a yet defined "rules of the road" for conflict resolution for recommended actions.

1. INTRODUCTION

This paper will provide context for the STM system with a brief background defining important terminology, STM history and a description of the current and future STM problem. The paper will then identify key challenges and discuss each in detail to provide a deeper understanding of the impacts and risks to a successful STM system. Following a discussion of the challenges, this paper will conclude with a proposed path forward and technical recommendations for the STM system.

This paper will explore technical and policy issues regarding Space Traffic Management (STM) related to the characterization and dissemination of space weather information and the data services challenges in fusing integrated multi-source SSA information with the goal of achieving 100% reduction in uncorrelated tracks. Specifically, how those warnings are provided, how SSA data and services can be effectively integrated and establishing operational standards and thresholds. The timeliness of this research is punctuated by the crucial role that space-based activities play in the American way of life, essential global activities, and the U.S. economy. As of 2019, the activities of on-orbit spacecraft account for nearly $250 billion in equity. In 2019 alone, the U.S. commercial space industry accounted for nearly 350,000 private sector jobs and over $120 billion to the U.S. gross domestic product. Since then, the number of spacecraft on orbit has nearly tripled resulting in an increasing risk of congestion and collisions [6]. The associated trackable debris (>10 cm) volume is also growing but has remained at an approximate 4x multiple of active satellites. Assuming these conditions remain, then approximately 5,500 satellites and 22,000 trackable objects in 2022 will grow to over 58,000 satellites and over 230,000 trackable objects by 2030 presenting corresponding challenges in STM [2].

To meet the goal of a round-the-clock, 100% reduction in uncorrelated tracks (UCTs), the STM data architecture will need to interact with the existing space domain functions of the U.S. Space Force (USSF) and U.S. Space Command but also integrate with the nascent civil SDA/STM building out of NOAA's Office of Space Commerce (OSC). To be effective, the civil SDA/STM will need to seamlessly operate with the USSF Uniform Data Library (UDL), incorporate detailed space weather/environment information from both NOAA and industry sources, deliver an integrated situational awareness of all detectable space objects, determine current and future locations of active satellites within this environment, perform conjunction analyses, warn of potential collisions, and provide these data and notices within a low-latency, easily accessible communications framework. Additionally, a common means of sharing course of action capabilities for maneuverable assets that does not disclose critical vulnerabilities, will be important to formulate potential recommended responses to collision warning messages. To meet these demands, a foundational data/services framework will be required. Operating within Cloud-Cloud environments, and with an "any source" integrated calibration/validation data repository, the integrated SDA/STM environment will provide current and future motions of tracked objects, identify, and assess any changes of state (fragmentation or maneuvers), and ideally forecast changes to the operational environment in response to solar effects. Alerts and warnings will need to be delivered in operationally relevant timelines and will depend on a yet defined "rules of the road" for conflict resolution for recommended courses of action.

2. BACKGROUND

Definition of Terms

The first widely recognized definition of STM was developed by the International Academy of Astronautics in the 2006 "Cosmic Study on Space Traffic Management" which defined STM as "the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space, and return from outer space to Earth free from physical or radio-frequency interference"[7]. Similarly, the Trump Administration, in 2018, defined STM in Space Policy Directive-3 (SPD-3) as "[The] planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment"[8].

Frequently within the space community, the term "Space Situational Awareness" is used interchangeably with STM. While the distinction between SSA versus STM is not always well understood, SSA is defined as the data about what is in orbit, where an object is at a given time, and who (if anyone) controls the object. Space Policy Directive-3, issued in 2018, accordingly defined SSA as, "the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities." Joint Publication 3-14 also notes that Space Situational Awareness, "is dependent on integrating space surveillance, collection, and processing." Additionally, it is "fundamental to conducting space operations" because, without a sound understanding of what the space environment looks like or what activities are taking place, operations can be hazardous and difficult [9]. Space Situational Awareness provides the foundational knowledge of the location for all objects in near-Earth space. SSA enables STM and SDA functions.

Space Domain Awareness is defined by the Space Capstone Publication released by the Chief of Space Operations as, "the effective identification, characterization, and understanding of any factor associated with the space domain that could affect space operations and thereby [impact] the security, safety, economy, or environment of our Nation" [10]. Space Domain Awareness data is aggregated from intelligence, surveillance, reconnaissance, environmental monitoring, and other data sharing agreements to "provide operators and decision-makers with a timely depiction of all factors and actors—including friendly, adversary, and third party—impacting domain operations." It is predictive, ideally intended to assess the probable future activities of objects in space [10]. Space Domain Awareness is the next step beyond Space Situational Awareness because it not only includes which objects are in the space domain—Space Situational Awareness—but what those objects are, where they are going, and what they are likely to do. As noted in the Space Capstone Publication, "complete Space Domain Awareness also includes mission-related details such as missions, intentions, system capabilities, patterns-of-life, and the status of consumables and expendables."

History of STM in the U.S.

Historically, the DoD led the SSA and STM activities for the United States. Nightingale et. al. conducted research on behalf of the Federal Aviation Administration (FAA) Office of Commercial Space Transportation (CST) to identify and evaluate potential approaches for providing SSA for civil and commercial operations in space [11]. Their research proposed a reconsideration of the DoD being the arbiter of SSA for three primary reasons:

1. The DoD was signaling a desire to reduce its role in SSA starting in 2014.
2. A civil agency would allow for increased government oversight of private sector space activities.
3. A civil agency would not be encumbered by the DoD's arduous procurement process allowing for the U.S. to take advantage of the significant increase in SSA/STM technology being developed by the private sector [11].

Similarly, researchers identified that the biggest obstacle to STM is trust, and his research recognized the U.S.'s decision to move STM functions under a civil agency rather than the DoD as "opening the door for U.S. leadership in STM, especially if the U.S. ensures that the system is based on clear, open data and modeling" [12][13]. Brian

Weeden, a recognized subject matter expert on STM, also testified before the U.S. House Committee on SSA that one of his main recommendations is for the SSA mission to be transferred away from the DOD and to a federal civil agency [12]. The U.S. government must increase trust and transparency for SSA, and additionally noted that the DOD had consistently failed to update their existing SSA computer systems [13].

The Obama Administration began investigating options for transitioning STM to a civil agency in 2011, and the Trump Administration also conducted their own internal review of possibilities in 2016 [12]. Overall, there has been a consensus among U.S. federal leadership and researchers that the U.S. stands to benefit significantly both technologically and politically by transferring STM responsibilities out of the DOD and under a civil agency. However, there is significant debate about which agency is most appropriate and what actions should be taken to ensure that the transfer is successful.

Defining the Problem: Uncorrelated Tracks and Increased Congestion On-orbit

As of February 2023, the activities of on-orbit spacecraft account for nearly $250 billion in equity. In 2019 alone, the U.S. commercial space industry accounted for nearly 350,000 private sector jobs and over $120 billion to the U.S. gross domestic product. Since 2019, the number of spacecraft on orbit has nearly tripled resulting in an increasing risk of congestion and collisions [6]. The associated trackable debris (>10 cm) volume is also growing but has remained at an approximate 4x multiple of active satellites. Assuming these conditions remain, then approximately 5,500 satellites and 22,000 trackable objects in 2022 will grow to over 58,000 satellites and over 230,000 trackable objects by 2030 [2]. This presents challenges in tracking, characterization, threat assessment, safety of flight, STM, and data integration.

3. STM CHALLENGES

Similar to how ICAO has established standards and norms for aviation, the U.S. and international space community must establish a civil International Space Traffic Management Organization (ISTMO) for the same reason. The civil ISTMO, like its ICAO analog, would establish STM norms of behavior (STM Rules of the Road), regulations and standards for STM data collection and exchange. To meet the needs of any future ISTMO, and to ensure we meet the goal of eliminating UCTs, this paper identifies seven key technical challenges that the STM system must be address:

1. Data fusion challenges including calibration and validation of data
2. Atmospheric drag forecasting
3. Space weather impacts on atmospheric drag
4. SSA sensor coordination
5. Conjunction Assessments, Warnings and Traffic Control Protocols
6. Pattern of Life Monitoring
7. Airspace-to-Space Transitions

3.1 Data Fusion

Effective data fusion is key to delivering an integrated situational awareness picture of all detectable space objects that provides round-the-clock, 100% reduction in UCTs. No single sensor network or data source can provide high frequency revisit times on all trackable objects. As such, a numerous data sources and types will need to be ingested and fused. These data types include owner/operator POD data and ephemeris, SSA observations and the various sources and formats of this data. Several key concepts and capabilities will need to be established for successful STM data fusion including:

- Data standards: Much like ICAO has established common standards and protocols for air traffic management communications and data exchange, common data standards are needed for STM as well. Currently SSA obs, owner/operator telemetry formats and other data sources require customized interfaces due to minor variations in format. Agreement upon and enforcement of data exchange standards such as those formats defined by the Consultative Committee for Space Data Systems (CCSDS) recommended by the NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook as a condition of participating in the STM system are necessary.

- Calibration and Validation: The data fusion capability must be able to calibrate and validate the data and data sources to ensure conjunction analysis and screening is normalized around a common operating picture. The Office of Space Commerce Director, Richard Dalbello, at the November 2022 Global Network on Sustainability in Space, highlighted this issue when discussing data standards, "You can understand each other in the same language, but if your sensors are out of alignment, you may not be able to communicate effectively" [14]. The NASA Spacecraft Conjunction Handbook Appendix L, notes several challenges when incorporating commercial SSA data that will need to be addressed:

    1. NASA and the 18^{th} SDS, when incorporating commercial SSN data, currently only use raw satellite tracking data in their conjunction assessment process due to challenges in comparing high-level SSA products such as state vectors.
    2. While NASA has found that O/O ephemeris may generally be more accurate than SSA obs due to innate knowledge of the O/O spacecraft, variations in orbit determination software introduce errors that exceed those potential benefits.
    3. Data assimilation techniques have been found to remove obs "outliers" that may in fact be the most accurate timely obs data reflecting a recent maneuver.

- Authoritative sources and provenance: An important concept in data fusion is establishing authoritative data sources and data provenance. When fusing data from multiple data collection sources, a rubric must be created to assess the most authoritative data source. Additionally, the rubric needs to address data timeliness to handle the situation where data from a secondary or tertiary source is timelier than the authoritative source. As noted previously, it may be that a tertiary source reflects observation data after a maneuver that has not been observed by other sensors. Thus, the STM system needs an ability to assess the appropriateness of issuing an alert from the timeliest data source if there is reason to believe it is the most accurate and the situation is deemed sufficiently urgent.

3.2 Atmospheric Drag Forecasting

A high-fidelity atmospheric drag model capability is critical to create a reliable space traffic model that maintains gap-less custody of space objects. While improvements have been made to propagation models, such as the Simplified General Perturbations 4 (SGP4) model and the newer SGP4-XP (eXtended Perturbations) model, that incorporate improved gravitational and solar radiation effects, the models still rely on generalized assumptions about neutral density values [15].

As such, without accurate neutral density values, orbital propagation models and tools are failing to account for one of the most critical and variable factors impacting LEO and especially VLEO satellites. To be useful in propagation, the atmospheric drag model must provide improved neutral density environment characterization for current conditions, but also for future forecast conditions in response to space weather events. Additionally, the neutral density value outputs should be accompanied by relative uncertainty values for incorporation into actionable conjunction assessments.

Creation of an accurate picture of the current neutral density environment is a big-data problem and requires inputs from many sources including Precision Orbit Determination (POD) data from owner/operators, obs from SSA sensors and space weather data inputs. Coordinating these data inputs will be an important function that will require cooperation from owner/operators and timely and coordinated tasking of SSA sensors to fill any atmospheric sampling gaps and maintain obs on calibration targets. Properly normalized and validated SSA and POD data inputs along with current space weather data, can be used to create an accurate now-cast picture of neutral density values.

3.3 Space Weather Impacts on Atmospheric Drag

Space weather impacts on atmospheric drag create a number of issues for owner/operator orbital planning and for SSA sensor custody maintenance. A few well publicized events involving SpaceX and Capella Space illustrate the need to better predict and understand the effects of space weather on satellite orbital planning operations. A key is to communicate not only space weather events, but to clearly communicate plain language impacts to the STM community.

SpaceX experienced the cost of space weather impacts when 38 of 49 Starlink satellites deorbited prematurely shortly after launching into a mild geomagnetic storm on 3 February 2022. In the SpaceX case, the storm had been forecast by the Space Weather Prediction Center (SWPC). However, the impacts were not broadly understood by the owner/operator community in general and the specific SpaceX modeling did not sufficiently anticipate the increased drag caused by the Coronal Mass Ejection (CME). A key recommendation of the joint post-event analysis paper issued by SWPC and SpaceX found that:

> *"Currently, no alerts and warnings issued by SWPC are focused on satellite users concerned with atmospheric drag and related applications. Thus, during geomagnetic storms, it is crucial to establish suitable alerts and warnings based on neutral density predictions to provide users guidance for preventing satellite losses due to drag and to aid in collision avoidance calculations"* [5].

In July 2022, Capella space announced a number of their satellites deorbited, or were planning to deorbit, earlier than anticipated due to a combination of issues with propulsion and space weather, "Capella CEO Payam Banazadeh confirmed that some of the satellites have been deorbiting faster than expected 'due to the combination of *increased drag due to much higher solar activity than predicted by NOAA* [emphasis added] and less than expected performance from our 3rd party propulsion system" [16]. Even if NOAA had more accurately predicted the higher rate of solar activity, there would still be a need for accurately modeling the impact of that weather on the Capella Space satellites.

Space weather impacts on atmospheric drag also create custody maintenance issues for SSA sensors. When objects are adversely impacted by unanticipated space weather event induced drag, additional time and sensor resources are required to reestablish custody and drive down UCTs. This can result in a time period whereby conjunction analysis is compromised. As discussed previously, higher fidelity neutral density values are key to extending the accuracy and validity timeframe of propagation results. However, these alone cannot help maintain custody during a space weather event unless we also have long-term forecasts that accurately forecast space weather effects on the atmosphere. Reference [17] states, "Predictions of CME arrival time at Earth and the impact on…the thermosphere and ionosphere still require significant advances by the research community." As the VLEO/LEO environments become more congested, forecasting and understanding space weather effects on atmospheric drag to enable long term precision propagation will be a critical area of research to reduce the number and duration of UCTs.

3.4 SSA Sensor Coordination

With the expected exponential growth of satellites and debris on-orbit in the coming years, persistent observations will be important to obtaining the goal of 100% round-the-clock custody. No single sensor network, sensor phenomenology or nation can independently maintain persistent coverage. A network of SSA sensors can also compensate for any inevitable downtime or system failures of any one particular system such as the issues suffered by the 18th Space Defense Squadron in July 2023. An international coalition of government and commercial SSA sensor networks will need to work in concert to provide the necessary collection.

A significant challenge in coordinating sensor collection will be in calibrating and normalizing the data. NASA's Spacecraft Conjunction Assessment Handbook discusses limited success incorporating disparate SSA sensors by frequent tasking of calibration targets, but more work remains before disparate sensors can been seamlessly integrated into a combined conjunction screening assessment system. Speaking at the Global Network on Sustainability in Space (GNOSIS) on November 30, 2022, Richard DalBello, director of the U.S. Office of Space Commerce, expressed concern about how these disparate commercial and international networks will cooperate and exchange data. Specifically, between the European Union and United States he stated:

> *"We will have some common data, but they will also be operating on unique sensors. Sensors are not always in alignment and the math doesn't aways agree on SSA calculations," he said. That creates a scenario where, for example, one operator gets a warning of a collision with another satellite based on data from one system, while the operator of the other satellite, using another SSA system, concludes there is no risk of a collision* [14].

An additional challenge is optimizing collection across the various SSA sensors and networks. Currently, government and commercial SSA sensors operate in independent stovepipes prioritizing collections based on internal collection scheduling criteria. Ideally, these SSA networks would work in a collective fashion that coordinates SSA observations in a manner that prioritizes observations to maximize the reduction of covariance similar to methods described and prototyped by Herz et al in the 2022 AMOS paper, "Utilizing Novel Non-Traditional Sensor Tasking Approaches to Enhance the Space Situational Awareness Picture Maintained by the Space Surveillance Network" [18]. To move this capability to an operational international scale would require a very intricate level of cooperation involving common communication and data standards not currently in place today.

3.5 Conjunction Assessments, Warnings and Traffic Control Protocols

With increased activity, the requirement for reliable, rapid, and resilient conjunction assessments of on-orbit space objects is becoming ever more critical to safety of operations in space--especially for objects in the VLEO/LEO altitudes. The collision of the KOSMOS 2251 (derelict) and the Iridium 33 (active) in 2009 created over 2000 catalogued debris items. Though the Iridium control team was notified of the conjunction potential, they elected to not conduct a collision avoidance (COLA) maneuver as a commercial company assessed the risk as low based on their distance to closest approach [19]. A more recent example of this growing challenge occurred in 2020 with the near collision of two decommissioned satellites--the U.S. Gravity Gradient Stabilization Experiment (GGSE-4) and the Infrared Astronomical Satellite (IRAS). Fortunately, the satellites crossed paths without incident, but analytics estimated they missed by a mere 18 meters. Had collision occurred it would have created a debris field of an estimated 12,000 detectable fragments and tens of thousands of smaller objects. Threats to adjacent satellites would have been almost immediate due to anticipated rapid dispersion of the debris field. As an example of the scope and growth of the problem, SpaceX recently reported to the U.S. Federal Communications Commission (FCC) that they performed 25,000 avoidance maneuvers in the first 6-months of 2023 which is the same number in the previous year and a half [17]. Given the launch projections over the next 10 years, the issue is certain to grow worse if conjunction assessment improvements are not made.

The current SSA and STM services provided by DoD are, to some extent, becoming saturated by the rapid expansion of the commercial space industry. With NOAA/OSC taking over the charge to support commercial (non-DoD/USG) SDA/STM, a means to interleave the commercial and government data used to provide domain awareness supporting STM will be necessary. With the increased interactions between space objects, conjunction assessments need to be continuously made in near-real time with communication issued within operationally relevant timelines. USSF and NOAA/OSC will need to define scopes of authority, spans of control, interactions between data sources and the catalog, and a robust calibration/validation/verification function so that operational information is available in near-real time across the SDA/STM combined architecture. Once data is ingested, fused and normalized, incorporating artificial intelligence (AI)/ machine learning (ML), can enable the assessments to be conducted and communicated as expediently as possible. AI can be used to automate conjunction notices and produce conjunction warning messages in operationally relevant timelines. Eventually, onboard spacecraft to spacecraft awareness of conjunctions and automated maneuvering may be possible as is planned to be demonstrated by the joint NASA/SpaceX Starling 1.5 mission [17].

Rapid dissemination of critical conjunction warnings with recommended Courses of Action (COAs) should be automated and include quality or reliability scoring on probability of occurrence. Affected owner/operators (O/O) should be expected to respond to these advisories to reduce or eliminate risks to themselves and others. Today, the 18th Space Defense Squadron communicates conjunction warnings via email and voice communications. Currently, there is insufficient and inconsistent information on satellite ownership that causes delays in communication. A future STM system will need near real-time machine-to-machine alerts issued to O/O's with clearly specified courses of action recommendations similar to the Airborne Collision Avoidance System directives issued to pilots to avoid impending collisions [19].

In Mr. Kepler's space there are no generally accepted "rules of the road" and the ability for any satellite to avoid a conjunction is entirely dependent on burning propellant to maneuver or, given sufficient time, adjustments in drag profile to either raise or lower the orbit. Outside maintaining orbital position to assigned slots in the GEO belt, there are no established protocols in the stateless orbital space to define, for one example, which satellite is "burdened."

These rules might be similar to marine or aviation rights-of-way rules but take into account the unique nature of space operations. Some of those unique challenges may include instances where two active satellites are in conjunction and a decision regarding who has to maneuver needs to be made. In this case, the cost to maneuver one may exceed the cost to the other even though it may not have the right of way. In this case, and especially when the decisions and actions may be time critical, a clear understanding of who is "burdened" needs to be established within an international regulatory framework. The Director of the Office of Space Commerce, Dr. DalBello, noted this issue in his comments to the National Space Council's User Agreement Group in 2023, stating that there have been insufficient efforts from the U.S. government to address the responsibilities of spacecraft operators. He called on the council to implement new safety rules for on-orbit objects and space debris mitigation and emphasized that all space vehicles must be required to effectively communicate with an operator [6].

An international operational framework for STM would establish "rules of the road" protocols for establishing and maintaining:

- Safety and autonomy of flight
- Space domain awareness
- Separation assurance
- Collision avoidance
- Optimization of orbital flows
- Orbit Flight Rules ("rules of the road")
- Standards and certification for operations

3.6 Pattern of Life Monitoring

In airspace traffic management, there are approximately 10,000 aircraft in the air at any given time. The vast majority of aircraft follow regular patterns of behavior following established airways or flying directly to a point or destination. Converging aircraft are given directions or expected to follow established protocols (Rules of the Road), to maintain safe separation. Aircraft that unexpectedly diverge from their planned trajectory are flagged and queried. In the case of a non-cooperative or unresponsive aircraft, as in the recent cases where pilots were disabled, alerts and warnings are issued and airspace along the forecast route of flight are cleared to avoid potential collisions. The STM community needs similar capabilities to identify the departure from the norm and respond accordingly with updated conjunction analysis and warnings (akin to clearing the airspace) and a means to communicate with the O/O over an emergency communications link (akin to the 121.5MHz guard frequency). Ideally, O/O's would provide advance maneuver notifications to a future ISTMO, but due to anomalous situations or lack of participation in the ISTMO, the STM system will need to be able to identify these occurrences independently.

Just as in aviation the weather environment has a significant impact on operations. Space weather effects, however, differ in form and impacts to operations in that they are dominated by solar events and conditions with resultant changes to the orbital environment. These effects range from solar pressure, drag from the solar wind, charged particle interactions with magnetosphere and upper atmospheric/ionospheric modifications, and particle interactions with the spacecraft itself resulting in surface charging and discharging and single event phenomena/upsets. Drag effects for objects operating in or transiting the LEO/VLEO regime may be significant and result in large dispersions in orbital ephemeris from one orbit to the next and a resultant loss of custody for the affected space object. Better forecasting of likely changes in response to solar events will reduce the uncertainty in orbital position during and after the event and maintain positive custody of all objects, active or inactive. To achieve the goal of reducing the number and duration of UCTs, active data collection of drag effects before, during, and after an event and the results applied to an AI/ML simulation and modeling system will lead to less uncertainty (better maintenance of custody) for all space objects. This will require much higher precision in observing, tracking, locating, and forecasting of space object motion to remove the uncertainty during and post-event. A critical capability in reducing and eliminating UCTs is the ability to establish a pattern of life (PoL) to support the identification of objects departing from their anticipated trajectory. This is especially important for O/O's that are not active participants in the STM system and have not registered with the USSPACECOM or any future civil ISTMO with the information recommended by the NASA Conjunction Assessment Handbook. To the extent the O/O has not provided a maneuver notification message and the variation is outside the anticipated effects of atmospheric drag or other uncertainty factors, it can result in a loss of custody of the object. When this happens, as with all UCTs, it is imperative to identify the situation as soon as possible to prevent any unwarned conjunctions and potential collisions or to identify a potential threat.

3.7 Airspace-to-Space Transitions

The handoff between Earth's airspace and orbital space, including the coordination of pre-launch, launch, and reentry activities; presents a significant STM challenge as the pace of launches increases dramatically. "[SpaceX is] now launching its reusable rockets about once every four days. Last year, it launched 61 times, so far [August 26, 2023] this year the number is approaching 60…" [20]. In addition to the number of launches, the number of satellites per launch is increasing as well. According to NASA Best Practices and Lessons learned presented at AMOS in 2022:

> *A regularly encountered problem with spacecraft deployment timing are the launches by a US commercial O/O who deploys 50 spacecraft simultaneously. It takes two full-time operators over a week to establish spacecraft identity and add these spacecraft fully to the catalog, meaning that orbital safety activities during that period must resort to non-standard processes that are not fully sufficient for CA* [Collision Avoidance] [21].

With the advent of commercial SDA companies entering the market, there will be an expanding data volume available to support early launch characterization and catalog entry. An opportunity exists to automate this catalog capture activity to remove latency as well as expensive human overhead.

Uncontrolled reentry of space debris is also increasingly becoming an issue. In July 2022, "…a Chinese rocket broke apart in the atmosphere above Southeast Asia…Some of this debris fell within 100 meters of a nearby village" [22]. Earlier that same month, debris from a 2020 SpaceX Dragon vehicle was, "…found…in the southeastern part of Australia. Three pieces of debris were eventually recovered and linked to the "trunk" of the Crew-1 spacecraft…One of the pieces was about three meters long…" [22]. Another example of uncontrolled reentry was the failure to insert 38 of 49 Starlink satellites into orbit after a successful launch on 3 February 2023. Expansion of the upper atmosphere in response to heating by a geomagnetic storm resulted in higher than anticipated drag and the failure of the Starlink satellites to transition from safe mode.

Currently, the FAA maintains authority for the launch and reentry licensing into controlled airspace (≥FL600) and governs launch/reentry licensing for commercial space launches under 14CFR450 ("Part 450") traffic management of the airspace from Earth's surface until the upper reaches of the Earth's atmosphere. The FAA has processes for managing launches, but those are being stressed as the pace of launches increases. Furthermore, there is no expectation on O/O's to track and forecast reentry of launch-related debris or passivated satellites and therefore no coordination or planning for the deorbit of these objects occurs.

4. RECOMMENDATIONS

The growth of private sector space activities is quickly driving a need to update existing and create new U.S. and international STM regulations and capabilities. The Aerospace Corporation's report on The Future of Space Traffic Management urged taking action as quickly as possible, "…we cannot let "perfect" be the enemy of "good enough" in space traffic management, especially if "good enough" allows us to make immediate, practical progress that can set the foundation for more robust solutions in the future" [23]. In that spirit, OSC director, Richard Dalbello, noted that, "we need to start reimagining what regulation looks like and what that boundary between the government and the commercial sector is going to be in the future" [6]. Given the ICAO was established in 1947, 44-years after the Wright brothers' first powered flight and that it has now been 66-years since the launch of the first orbital satellite, the time is clearly now for the establishment of an international STM governing body. This paper recognizes the success of ICAO in the early days of aviation and recommends that the STM community create a parallel system of regulations and capabilities to foster STM cooperation among the broader space operator community.

An effective ISTMO needs to implement a number of policies, rules, compliance, enforcement and conflict adjudication mechanisms that will likely take a number of years to agree upon and implement. Based on the goals and challenges highlighted in this paper, we recommend the following achievable, concrete foundational technical capabilities and initial policy decisions that can be implemented by the United States to deliver a robust, reliable, rapid, resilient civil STM system. We believe these objectives can be achieved in the near-term and help position the U.S. as a leader in creating the foundation for a future ISTMO.

- **Data Standards** – Until common data standards are established, the STM system will need to be able to operate in a data-agnostic manner that can evolve as common data standards are established for the exchange of SSA data, collision warnings and other STM related data.
- **Data Automation** – An effective STM system will need to ingest, process and analyze vast volumes of data that far outstrips the current manually intensive processes. Utilizing artificial intelligence/machine learning (AI/ML) techniques to manage large data volumes, assess potential conjunctions and orchestrate courses of action and tasking across multiple international commercial and government SSA networks will be required.
- **Cyber Security** – Zero Trust layered cyber security solutions will be required to ensure a secure system that can securely ingest data from DoD, commercial and international organizations and guarantee data provenance and validity.
- **Calibration and Validation** – custody maintenance and conjunction analysis must be accurate, precise and trusted. This can only be achieved if the data is calibrated and validated to a common standard. The STM system must implement a means of validating and normalizing data from all SSA sensor data sources.
- **Resilient and Scalable STM Architecture** – A centralized national STM infrastructure must be created and architected in a way that ensures resiliency in any number of contingencies. The STM infrastructure needs to be scalable by design to seamlessly add new data streams and applications and scalable for performance to withstand high user demand loads during crisis situations.
- **Space Vehicle Status Information Sharing** – A common means of securely sharing vehicle state and capabilities for maneuverable assets (that does not disclose critical vulnerabilities) is required to appropriately formulate potential recommended courses of action in response to collision warning messages.
- **Pattern of Life monitoring** – In addition to monitoring for changes due to space weather or planned maneuvers, the STM system must identify departures from normal patterns of life that may be caused by a vehicle anomaly, some other unexpected activity or simply by vehicles not participating in the ISTMO notification protocols.
- **High Fidelity Drag Model** – A high fidelity drag model is essential to help maintain custody, task SSA sensors more efficiently as they must track an increasing number of objects and create more precise conjunction assessments resulting in fewer unnecessary conjunction warnings.
- **Space Weather Notifications** – The SWPC freely provides raw space weather data to all users; however, the data requires interpretative modeling skills to understand the impacts to any given space vehicle. Time-sensitive space weather alerts need to be pushed to impacted operators and communicated with plain language impacts.
- **Space Weather Impacts** – Research needs to be devoted to predicting CME events and understanding their impact on the atmosphere to enable long-term space weather forecasting and any impact on atmospheric drag and orbital propagation.
- **Rules of the Road** – The U.S. can establish best-practices, rules and norms of behavior for U.S. owner/operators related to participation in data-sharing and collision warning notifications and responses. As an international leader in space, establishing these norms of behavior will set precedent and lay the groundwork for defining international norms.
- **Conjunction Assessments and Warning delivery** – As the number of potential conjunctions increases in lockstep with the projected number of orbiting objects, the STM system must move away from the current manually intensive notification process and implement an automated means to communicate conjunction warnings and recommended courses of action.
- **SSA Sensor Coordination** – As the number of trackable objects increases, no single SSA network will be able to effectively retain custody of all the objects. A means of communicating obs requirements to the SSA networks is required. This should be done in a manner that does not dictate obs collections, but in a manner that incentivizes prioritization of collection on objects with high covariance such that SSA sensors know where to focus scarce resources.
- **Airspace-to-Space Transitions** – As the launch cadence increases the system for managing what was previously a relatively small handful of annual launches must be modernized and streamlined. Additionally, de-orbit planning and notifications is becoming imperative as the amount of launch-related and defunct

satellite debris becomes more numerous as evidenced by the increasing number of objects that are impacting the earth's atmosphere and surface today.

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