Space Traffic Management with a NASA UAS Traffic Management (UTM) Inspired Architecture

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Space is becoming increasingly congested as the number of on-orbit satellites and debris objects continues to grow. Space traffic management (STM) is critical for ensuring that the expanding orbital population operates safely and efficiently, avoiding collisions and radio-frequency interference while still facilitating widespread space operations. Recent events such as the FCC approval of SpaceX's ~12,000 satellite constellation, the signing of Space Policy Directive 3 (which moves Space Situational Awareness responsibilities away from the Department of Defense and to a civil agency), and the growth in rideshare and small launch vehicles illustrate the rapidly changing nature of this domain. This paper will describe the concept of operations (ConOps) for a civilian STM research initiative, which has been developed from previous NASA work to enable safe operation of small unmanned aircraft systems. The STM ConOps proposes an architecture to enable efficient data sharing and coordination between participants to facilitate safe spaceflight operations. It is designed to utilize and promote the emerging field of commercial STM services, as a complement to existing government-provided STM services. The concept envisions a phased evolution that would gradually integrate additional capabilities, proposing a first phase architecture and tentative plans for a broader system. Work towards developing an STM research and prototyping platform is also discussed.

I. Introduction

Space is undergoing a dramatic expansion in the quantity and diversity of spacecraft and operators, and the orbital debris problem continues to grow. STM is becoming more complex and difficult at the same time that it is growing in importance. Previously, the high barriers to entry in space ensured there were only a few, highly expert operators. Today, a large number of universities and startups around the world (with widely varying levels of sophistication) join governments and large commercial ventures in utilizing this globally shared resource. It is in the common interest that all participants be able to fly safely and to coordinate with others. A successful STM system will need to accommodate users ranging from small academic cubesats to proposed megaconstellations with thousands of satellites, while addressing communication gaps, interoperability challenges, regulatory gaps, and reluctance to share spaceflight information. In this concept of operations, we propose a comprehensive and scalable STM system that leverages existing government and emerging commercial capabilities to provide state-of-the-art STM services accessible to all participants.

The ConOps introduces an open architecture approach to STM heavily influenced by the Unmanned Aircraft System Traffic Management (UTM) system developed at NASA Ames Research Center [1], [2]. As with UTM, the architecture relies heavily upon standardized data models and Application Programming Interfaces (APIs) to provide an efficient, scalable, and decentralized data-sharing infrastructure, enabling a community-driven and operated approach to traffic management. Under this system, participants retain responsibility for the coordination, execution, and management of operations, subject to only broad rules of the road established by the appropriate regulatory authorities. The envisioned system defines means of technical interchange to avoid fragmentation between private

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STM efforts, reduce barriers to entry to using STM best practices for less sophisticated operators, and enhance the development and commercial viability of new private-sector STM-related capabilities. For the purposes of this paper, the architecture is imagined as a U.S. run system with any potential foreign participation determined and approved by regulators and the operational agency. Nevertheless, the concept could be implemented in another national context, or at a multinational level. The national frameworks established by first-movers countries with significant space activities will likely be key to establishing the outlines of any future internationally harmonized system.

II. Background and Requirement Definition for a New STM System

A. Threats to Space Operations Addressable with Space Traffic Management

We consider four main external hazards that threaten safe spacecraft operations and can be mitigated by an STM system: physical collision, radio-frequency (RF) interference (both accidental and intentional), space weather, and energy from lasers or directed energy devices. With access to just the information internal to an operator, only limited awareness of the environment is achievable. For an operator to recognize and mitigate external threats, pooling of information from other satellites, from ground and space-based radars, telescopes, and other sensors is necessary. As utilization of space increases, a more integrated STM system will be critical to the safe and effective use of limited orbital volume and spectrum.

Although the space around Earth is vast, this orbital volume is nonetheless finite and spacecraft tend to concentrate in a few particularly useful orbits. Earth orbits are divided into different regions, which vary in their physical characteristics, typical uses, and levels of congestion. The three major categories are Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO). Most debris is within LEO altitudes (below 2,000 km). The sun-synchronous orbits are particularly crowded due to their ability to provide continuous illumination for solar power and constant Sun angle for Earth observation. Many Earth observation satellites, a growing number of communications satellites, and the International Space Station (ISS) orbit in LEO. Medium Earth orbit (MEO) extends from 2,000 km up to geostationary orbit at 35,786 km and is notably used for navigation systems such as the U.S. Global Positioning System (GPS). MEO is much less densely populated and is less impacted by orbital debris than LEO or GEO. GEO is a unique, very commercially important belt at 35,786 km that is heavily populated by large, exquisite systems including communications and weather satellites. GEO satellites orbit at the same speed that the Earth rotates, and they appear to stay stationary in the sky (useful for communications with fixed ground antennas) or can continuously observe the same region of the earth (useful for weather satellites). Although orbital velocities are much lower at GEO and debris is spread over a much larger circumference, GEO is still quite crowded. The International Telecommunications Union (ITU) manages orbital slots to prevent RF interference.

1. *Threat from Physical Collision*

A very low likelihood, but very high consequence risk to spacecraft in Earth orbit is physical collision with other objects. These objects range from natural micrometeoroids and fragments from previous collisions, to active satellites and entire intact rocket upper stages.[5] Such collisions can involve large amounts of energy due to the high velocities of the objects involved. In general, the kinetic energy per mass involved in an on-orbit collision exceeds the energy density of high explosive. Although the actual damage caused by an impact will depend on many parameters such as impact location and debris composition, kinetic energy can be considered as a rough proxy for hazard. Figure 1 shows the scaling of energy with varying impactor sizes. From 2 to 10 centimeter diameter, the energy equivalent scales from a hand grenade to a missile warhead. 10 km/s is an average LEO conjunction approach speed, although values in excess of 14 km/s are also common.

[5] Depending on altitude and inclination, the current flux of man-made orbital debris can be much larger than the natural meteoroid flux. For example, a ram-facing, one millimeter thick aluminum plate in a 1000 km altitude polar orbit can expect to be penetrated 20 times per year, per square meter of area [56]. The orbital debris flux at this inclination and altitude is 500 times larger than the natural meteoroid flux.

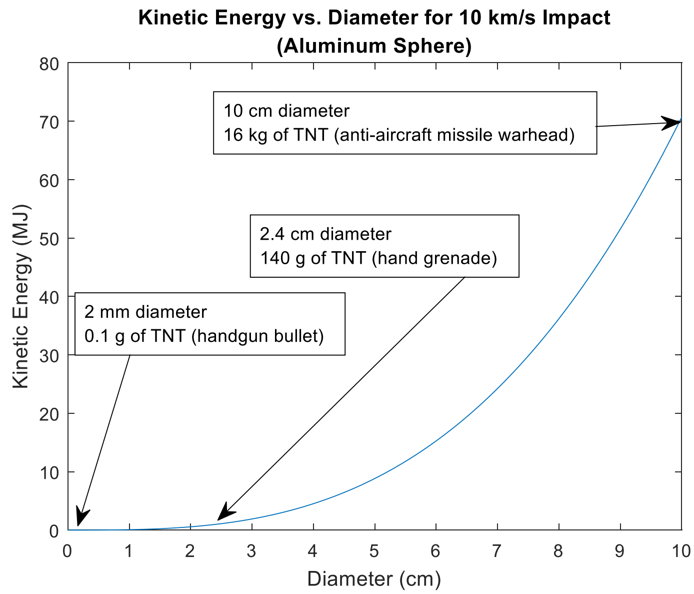

Figure 1: TNT Equivalent Energy for Impacts

Debris objects can be divided into three categories based on trackability and appropriate mitigation strategy.

The smallest objects with diameters less than 1 cm cannot be tracked and primarily pose threats to spacecraft subsystems (e.g. penetration of unshielded fuel lines, erosion of optical sensors). These are threats that must be assessed probabilistically and mitigated in spacecraft design. Shielding, such as the Whipple shields used on the ISS, can be effective against this category. Fortunately, sub-cm objects are generally too small to pose a significant likelihood of disabling or fragmenting an operational spacecraft. The population of 1 mm to 1 cm size debris objects is estimated to be larger than 100 million [3] and the sub-millimeter population is far more numerous.

Intermediate size objects between 1 and 10 cm cannot be reliably tracked with current technology, but can destroy (although generally not catastrophically fragment) an operational spacecraft.[6] This is sometimes referred to as the "lethal non-trackable" population. It is not practical to shield spacecraft against this population, and most sub-10cm objects are not tracked and characterized well-enough for collision avoidance maneuvers.

Objects larger than 10 cm in diameter can generally be tracked in LEO. At these sizes, shielding is ineffective and the only mitigation is to maneuver to avoid the collision. Collision with such an object generally results in 'catastrophic' fragmentation.[7] The 2009 Iridium-Cosmos collision between two intact spacecraft produced almost 2,000 pieces of trackable debris measuring at least 10 cm [4]. Figure 2 shows high-speed video frames from the 2014 DebriSat test, where a 50 kg small satellite model was impacted by a 600 gram projectile at 7 km/s and the resulting fragments captured in foam barriers lining the test section. The test was performed to improve satellite breakup models. As of 2017, more than 130,000 fragments larger than 2 mm have been collected, and approximately 250,000 fragments are expected to be collected in total [5].

[6] The U.S. Air Force's next generation Space Situational Awareness (SSA) system, the Space Fence, and future on-orbit SSA surveillance platforms may be able to provide better tracking of these smaller objects. Earth-based sensors are able to resolve smaller objects in LEO than GEO. The second generation Space Fence currently under construction is expected to detect and track objects larger than the size of a softball.[57]

[7] Specifically, a catastrophic collision occurs when the relative kinetic energy of the smaller object divided by the mass of the larger object is equal to or greater than 40 J/g [7]. In this case both objects are totally fragmented. In non-catastrophic collisions, the smaller object is fragmented and the larger object is cratered.

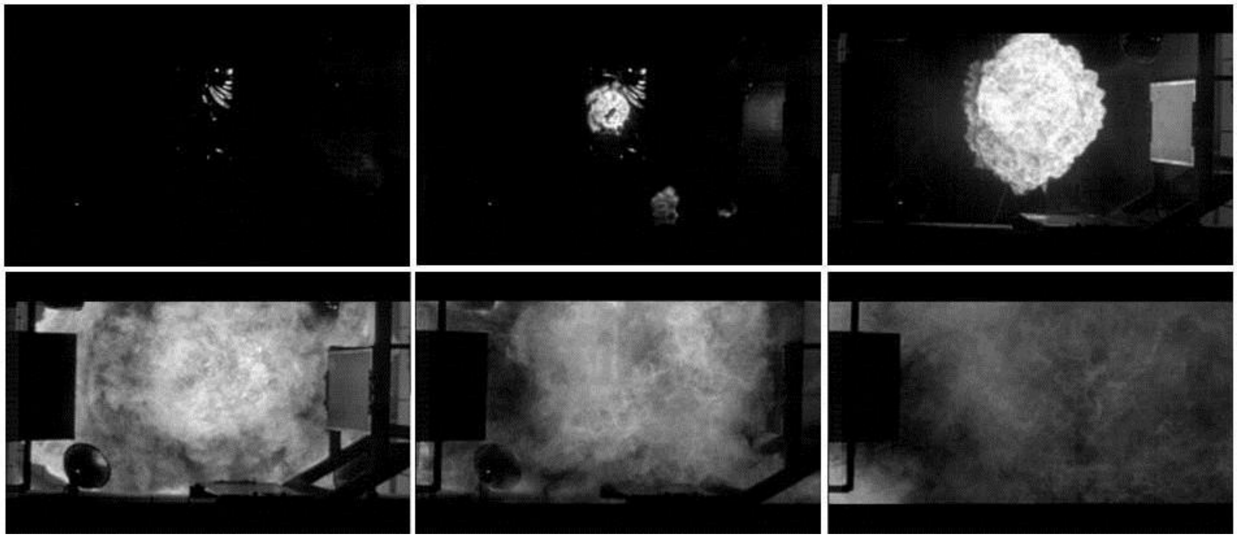

Figure 2: DebriSat impact sequence showing impact and subsequent expansion cloud [6]

Catastrophic fragmentation events are especially harmful because they produce a large number of smaller objects, each of which poses an independent collision risk. The NASA standard breakup model [7] predicts that in a catastrophic collision, the number of fragments scales with characteristic length to the -1.71 power. This implies that 50 times more untrackable yet still potentially lethal 1 cm objects will be produced than trackable 10 cm objects, and 2,630 times more damaging 1 mm objects.

Above a critical concentration, debris on debris collisions will result in a self-sustaining exponential increase in the number of debris objects – a phenomenon known as "Kessler syndrome". Already, in certain regions, debris on debris collisions will result in growth in the debris population at a rate that exceeds orbital decay [8]. Atmospheric drag causes orbital decay, and the orbital lifetime of a debris object depends primarily on altitude and also on solar activity (which expands or contracts the atmosphere). Objects remain in orbit (and remain hazardous) for months or years at ISS altitudes (~400km), to decades or centuries at sun synchronous orbit altitudes, to essentially forever at above 1000km altitudes.

When two active satellites execute a collision avoidance maneuver, coordination is necessary to ensure that they maneuver to reduce, rather than increase, collision risk. In September 2013, a close approach was predicted between the NASA EOS Aura and the Chinese Shijian-11-02 satellite [9]. Lacking a means of two-way coordination between NASA and its Chinese counterpart, both satellites maneuvered within hours of each other in an uncoordinated fashion, potentially making collision more likely instead of less. Fortunately, in this case the two maneuvers successfully mitigated the collision risk. Even when avoiding debris (which cannot maneuver), coordination is necessary to avoid additional conjunctions with other satellites on the satellite's post-maneuver trajectory. Because uncooperative tracking of satellites (e.g. by telescope or radar) does not give information about future maneuvers, sharing maneuver information is important for conjunction assessments. However, this may require sharing competition-sensitive data, which can be of particular concern to commercial satellite operators.

In addition to on-orbit collision, launches pose potential hazards to air traffic that necessitate disruptive airspace restrictions. Uncontrolled space objects that survive atmospheric re-entry may also pose a risk to people and property on the ground if they reenter over a populated area. Spacecraft intended for post-mission disposal are generally designed to either undergo controlled reentry over a remote area (typically in the south

Pacific Ocean), or to burn up on re-entry.[8] While this initial concept of operations is limited to on-orbit activities, it is intended that subsequent versions will integrate management of launch and reentry hazards.

2. Threat from Radio-Frequency Interference

RF Interference (RFI) can be a major problem for communications satellites, especially in the crowded but commercially important GEO belt. According to the Space Data Association, a non-profit organization of satellite operators that facilitates RFI resolution and collision avoidance, 85-90% of commercial communications satellite customer issues are due to RFI[10, p. 92] . RFI from Earth based sources is also a problem for Earth science instruments, like ESA's Soil Moisture and Ocean Salinity (SMOS) mission's radiometer. Although it uses an ITU protected region of the L-band to map soil moisture, interference from ground sources is common and affects data quality [11]. RFI includes both deliberate interference intended to degrade or block use of a range of spectrum ("jamming"), and unintentional interference. RFI can prevent communication between a satellite and ground station, or reduce the speed of a data link. Satellites, terminals, and ground stations experience interference from both other satellites and terrestrial sources. Particularly in the case of unintentional interference, sophisticated coordination between operators can greatly accelerate the process of attributing, geolocating, and resolving interference events.

3. Threat from Space Weather

Space weather can impact satellites, space vehicles, and Earth-based systems. Satellites are vulnerable to solar activity that produces significant electromagnetic radiation. Coronal mass ejections release large amounts of magnetically charged solar plasma, and may cause geomagnetic storms on Earth. Solar flares can send solar energetic particles toward Earth at relativistic velocities along with electromagnetic radiation at wavelengths in the X-ray, extreme ultraviolet, and radio bands. Space weather can produce a variety of undesirable effects on spacecraft including surface or internal charging, single effect upsets, increases in upper atmospheric density (significantly changing the orbital decay rate), total dose effects (where cumulative radiation exposure degrades components), and impacts to star trackers and other attitude determination and control systems[12, p. 35]. The National Oceanic and Atmospheric Administration's Space Weather Prediction Center releases various space weather forecast products [13]. The Deep Space Climate Observatory can often provide warning of an Earth-directed CME approximately 15-60 minutes prior to its arrival[14]. Warnings or forecasts of severe solar weather may prompt operators to place satellites into safe mode temporarily or reorient sensitive components. Ultimately, the ability to generate and disseminate such warnings should be integrated into the STM architecture.

4. Threat from Lasers and Directed Energy

Externally directed lasers are used on-board satellites for functions include optical communication and remote sensing. There are also various Earth-based laser use-cases that involve lasers directed towards space including optical communications, laser ranging, adaptive optics, and directed energy weapons testing. Future speculated uses for directed energy include propulsion and planetary defense (diverting the course of a potentially hazardous asteroid or comet)[15], [16]. Even relatively low-powered lasers have the potential to overload and temporarily or permanently damage or disable sensitive satellite-based optics. Higher energy military lasers might have more significant impacts depending on the nature of an exposure.

[8] Hazardous reentries do occur occasionally. Some widely publicized historical examples include the 1978 uncontrolled reentry of Cosmos 954, which spread radioactive debris over northern Canada, and the 1979 reentry of Skylab. The unique case of the breakup of the space shuttle Columbia over Texas and Louisiana resulted in a rain of debris in active airspace, although no one on the ground was injured. The CAIB analysis [58] estimated a 10-30% chance of one or more casualties on the ground. It should also be noted that had the reentry occurred one orbit later, the debris field would have included Houston and raised that probability to 89-98%.

USSTRATCOM operates the Laser Clearinghouse to prevent accidental illumination of satellites by Department of Defense activities [17]. The Laser Clearinghouse also provides voluntary deconfliction to non-DoD laser operators as resources allow. Analytical Graphics' Systems Tool Kit software includes a tool called LaserCAT that helps model and avoid lasing-induced satellite damage[18].

Necessary Capabilities for an STM System

The preceding sections have explained the threats to satellites that can be mitigated through greater coordination, information sharing, and deconfliction. The nature of these threats informs the capabilities needed for an STM system to mitigate these threats. Specifically, a comprehensive space traffic management system must be able to:

- **Deconflict resident space objects** (including launch vehicles, active spacecraft, and debris)
    - **physically**, in order to prevent collisions
    - in the **RF** environment, to prevent interference
    - in the **optical** environment to prevent damage or mission disruption from unintentional lasing
- **Work with all operators** – military, civil, or commercial, and from any nation
- **Quickly dissiminate information** of critical importance to enable rapid responses
- **Deconflict during all regimes of a space mission**: launch, on orbit, and disposal (either re-entry or to a graveyard orbit)
- **Include all classes of stakeholders and participants** necessary to enable key functions, including SSA supplier, traffic management/conjunction assessment suppliers, supplemental data sources (such as space weather), government regulators, and of course spacecraft operators.
- **Accommodate interfaces with other external stakeholders**, in particular air traffic management and national security
- **Leveraged and integrate existing technology and best practices**, drawing on the state of the art for current Space Situational Awareness (SSA) and STM.

B. Current State-of-the-Art

Numerous existing entities and systems contribute to current SSA and STM capabilities. This section begins by surveying existing institutions, technology, practices, policies, and other dimensions that inform the context in which the STM system is being developed. The architecture of a proposed STM system should be informed by and responsive to these elements. It then briefly describes current expectations about relevant near-future trends and events. Section C subsequently synthesizes these current and near future factors to derive a set of implications that inform the proposed STM system design.

1. Existing and Near Future STM and SSA Suppliers

Following the February 2009 Iridium-Cosmos collision, the U.S. Congress passed legislation empowering the U.S. Air Force's Joint Space Operations Center (JSpOC) to provide SSA information and services more broadly[19]. Today, JSpOC serves as the de facto space traffic management system. It gathers SSA data through the extensive radar, optical, and space based sensors of the US Space Surveillance Network, as well as submissions from satellite owner/operators. JSpOC provides a variety of services to the public and satellite operators including dissemination of Two-Line Element (TLE) ephemerides through space-track.org, as well as basic emergency on-orbit conjunction assessment, collision avoidance, and anomaly resolution services[20]. Parties can also sign an SSA Sharing Agreement with USSRATCOM to gain access to advanced services including launch conjunction assessment, expanded conjunction assessment and collision avoidance, Disposal/End-of-Life Support, and Deorbit and Reentry Support[20].

NASA's Conjunction Assessment Risk Analysis (CARA) team, located at the Goddard Space Flight Center, serves as a valuable intermediary between JSpOC and NASA missions, particularly the members of the International Earth Observing Constellations[21]. CARA obtains ephemerides from mission owner/operators, converts it to the appropriate format, and provides that information to JSpOC. It also uses predictive ephemeris information from missions to perform conjunction assessment and flag high risk conjunctions for mission owner/operators. The CARA team provides customized capabilities to NASA missions beyond the level of support JSpOC is able to provide, while also reducing the amount of space traffic management expertise required on an individual mission owner/operator team. A team at Johnson Space Center performs a similar role for the International Space Station and crewed NASA missions. Since 2012, the French Space Agency CNES's CAESAR has performed a similar middle-man role for CNES missions, and for other satellite operators that sign a contract with CNES[22]–[24].

The Space Data Association (SDA), a non-profit organization founded in 2009 by major GEO communication satellite operators, acts as a trusted third party and provides technical infrastructure for sharing of position, contact, RF, and other sensitive proprietary information for the purposes of conjunction analysis/collision avoidance and RF interference attribution and mitigation. SDA contracts with AGI, a commercial provider, to operate the Space Data Center, the technical infrastructure to facilitate such data exchange.

Numerous commercial providers are beginning to provide commercial SSA data collection and analytics, offering services that complements and expands upon freely available JSpOC data and services:

- Analytical Graphics Inc. operates the Commercial Space Operations Center, offering space situational awareness products and services using data from a network of commercial sensors[25].
- ExoAnalytic has compiled a network of 25+ observatories and 200+ telescopes that it uses to provide SSA capabilities and analysis on a commercial basis[26].
- High Earth Orbit Robotics is developing a constellation of 6U GEO observing cubesats to provide more accurate commercial SSA in addition to asteroid prospecting[27].
- LeoLabs uses a network of ground-based phased-array radars to provide commercial characterization and tracking of objects in LEO[28].

Additionally, telescopes normally used for astronomy are sometimes retasked for space surveillance, especially as the astronomically useless twilight hours are the best time to detect reflected light from objects in orbit. The International Scientific Optical Network (ISON) is a space surveillance project which partners with academic and scientific institutions, and is managed by the Russian Academy of Sciences. The International Laser Ranging Service is part of the international association of geodesy, and provides laser ranging to provide high precision ephemerides[29]. In addition, ESA's Space Situational Awareness program includes a space surveillance segment, as well as space weather and near earth object tracking. Amateur observers can also prove surprisingly capable, and often find classified spacecraft whose orbital elements are not disclosed by governments[30]. Recently, an amateur radio astronomer searching for a classified satellite found the thought-to-be-dead NASA IMAGE satellite, transmitting and apparently having come back to life[31]. Currently, all of these disparate sources of information operate independently, with a limited number of bi-lateral connections for data sharing (i.e. SDA/JSpOC), but without an overall coordinating framework. In a future STM system, the intention would be transition these communications to efficient and standardized machine-to-machine methods, with highly autonomous coordination and decision-making that minimizes the need for human decision-making or review.

2. *Message Standards*

The Consultative Committee for Space Data Systems (CCSDS) is a standards development organization created by the world's major space agencies. CCSDS has created standards for a variety of spacecraft navigational data messages (NDMs) (CCSDS 500.2-G-1) including the Attitude Data Messages (ADM) (CCSDS 504.0-B-1), Orbit Data Message (ODM) (CCSDS 502.0-B-2), Tracking Data Message (TDM) (CCSDS 503.0-B-1), and Conjunction Data Message (CDM) (CCSDS 508.0-B-1), and the under-development Spacecraft Maneuver Message (SMM) (CCSDS 511.0-W-4, *proposed*). These formats provide a standardized way to exchange information relevant to spacecraft states and intentions, including most of the information critical for STM.

JSpOC supports receipt of Satellite Owner/Operator ephemeris in five formats, and receipt of maneuver notifications using a modified version of the ODM Orbital Parameter Message.

3. Launch and Re-Entry

The Federal Aviation Administration licenses US commercial spacecraft launch and reentry activities. To ensure the safety of aircraft and the flying public, it imposes airspace restrictions using a combination of Notices to Airmen and Air Traffic Control System Command Center Advisories[32]. Spaceflight is inherently risky, and such constraints are designed to protect the public during launch. The current process requires significant manual coordination between the FAA and launch provides, and results in airspace closures that are static and highly conservative[32], [33]. This results in a sizable impact on the air traffic system by restricting access to large airspaces, requiring traffic to be diverted. With launch cadences expected to significantly increase over the coming years, a more flexible and automated system is needed to scale to safely accommodate growing space launch traffic while minimizing impact on air traffic. In the future, the use of space transition corridors or dynamic 4D keep-out envelopes that change spatially and temporally can greatly reduce this impact [32]. In August 2014, the FAA released a Space Vehicle Operations Concept of Operations that identified deficiencies in how FAA handled space vehicle operations, a potential approach to address the identified issues, and areas where further research would be needed[34]. As part of NEXTGEN, the FAA is developing Hazard Risk Assessment and Management (HRAM) as a solution to enable dynamic airspace management for both launch and reentry phases of operations[35], [36, p. 15]. The FAA's Space Data Integrator tool is being developed to bring real-time launch vehicle information to air traffic controllers' screens, providing improved situational awareness. Sharing data between space traffic and the air traffic management system is a critical part of enabling these innovations.

4. FAA/NASA Unmanned Aerial Systems Traffic Management System Concept of Operations

FAA and NASA are collaborating through the NASA UTM Research Transition Team (RTT) to "collaboratively explore concepts, develop prototypes, and demonstrate a possible future UTM system to enable large-scale low altitude UAS operations" [2, p. 3]. In May 2018, the FAA released version 1.0 of the Concept of Operations for UAS Traffic Management, focusing on UTM operations below 400 feet above ground level. The proposed solution relies on a set of Application Programming Interfaces (APIs) to enable highly autonomous and scalable coordination between a dynamically shifting set of operators and service suppliers continuously entering and leaving the system. The project continues to advance through a set of four Technical Capability Levels (TCLs), sequential program phases that correspond to incrementally evolved capabilities and scope. As of summer 2018, TCL 1 and 2 are complete, TCL 3 has finished field testing, and TCL 4 is planned. The FAA continues to operationalize concepts developed for the Concept of Operations, including UAS service supplier provision of Low Altitude Authorization and Notification Capability system (LAANC) service to allow for near-real time approval of operation of UAS in controlled airspace[37]

5. Emerging Trends

This section briefly lists emerging trends related to space that provide relevant background considerations for the design and urgency of an STM system.

a) ***The role of emerging space nations, non-state actors in space, and particularly smaller actors, has grown and will continue to expand.*** Space is undergoing a dramatic expansion in the quantity and diversity of launch vehicles, as well as spacecraft and their operators. In February 2017, a single Indian PSLV launch deployed a record 104 satellites into sun-synchronous orbit. Planet Labs, a private US earth imaging company, currently operates a constellation of over 150 satellites, the majority of which are 3U cubesats launched as secondary payloads. A new class of small launchers, exemplified by the successful flight of Rocket Labs' Electron (launched from a new privately owned complex in New Zealand), will enable new high-frequency, dedicated small payload launches. Lower launch costs, quicker timelines to launch, and expanded satellite capabilities are reducing barriers to using space and expanding the number of space actors to a wider group of users in start-ups, education, non-profits across the globe.

b) ***Planned mega-constellations of hundreds or thousands of satellites will require new levels of autonomy within space traffic management, and new consensus on how to manage aggregate risk and impact across large constellations of satellites.*** Those constellations, including those proposed by OneWeb (648 spacecraft) and SpaceX (~12,000 satellites), would increase the number of active orbiting satellites to unprecedented multiples of the number of satellites active today. Safely and sustainably accommodating such an increase will require new levels of autonomy in both space operations and STM. Regulatory considerations, including satellite on-orbit failure rates, collisional risk, and risks associated with re-entry will need to be conceived and measured in a more holistic rather than per-satellite basis.

c) ***Industry analysts anticipate significant expansion in space industry revenues over the coming decades.*** Bank of America Merrill Lynch expects space industry revenues to grow to $2.7 trillion within 30 years, from the 2016 value of around $350 billion[38]. Morgan Stanley estimates growth to $1.1 trillion by 2040, with higher values possible if LEO satellite broadband providers manage to successfully execute their business plans[39].

d) ***On-orbit satellite servicing capabilities are under development and will eventually impose additional requirements on an STM system.*** Companies including Northrop Grumman, Space Systems Loral, and others are also developing technologies to enable construction of satellites to conduct on-orbit satellite inspection, servicing, and mission extension for client satellites. Such technology holds significant promise to assist with anomaly resolution and reduce costs of space-delivered services. However, these use cases will also require safe operations in close proximity to target satellites, which will require integration and timely real-time feedback from the STM system.

e) ***Despite recent progress, the orbital debris problem continues to grow.*** Developments such as the standard passivation of upper stages and decommissioned spacecraft and the 25 year rule have had positive effects. Nevertheless, certain orbits have already reached the Kessler limit tipping point where debris objects will continue to collide and generate new debris objects at a rate faster than atmospheric drag deorbits them. In the long term, stabilizing the debris population in these orbits will require the use of Active Debris Removal technology (ADR) to remove large debris objects with high likelihood of future collisions. Such technology still requires significant technological development, clearer funding models, and resolution of policy issues relating to dual-use, ownership of debris objects, and liability. New technologies such as electrodynamic tethers and drag brakes can help hasten re-entry but impose costs and also complicate orbit propagation. Small GPS beacon technologies can improve on the accuracy of non-cooperative tracking techniques, but will require widespread adoption and norms regarding access to the generated positional information [40]. Even with widespread agreements for information sharing, infrastructure is needed to convey information accordingly and ensure it is actionable for system participants. This challenge will only become more significant when the U.S.'s next generation Space Fence comes online, increasing the size of the tracked catalog, and potentially false positives, by an order of magnitude [41].

6. Legal/Regulatory Context

International Space Law: The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, known as the Outer Space Treaty, lays out the obligations for nations in their space activities, including commercial entities that launch under the authority and supervision of a nation. The Outer Space Treaty declares space to be "free for exploration and use by all States without discrimination of any kind,…on a basis of equality and in accordance with international law"[42]. There is no one international body with regulatory authority over space. States retain jurisdiction and responsibility over space objects they launch and national space laws establish regulatory authority over both governmental and nongovernmental entities. While an international set of rules exists relating to geostationary orbital slots, nations are otherwise free to launch satellites to whatever orbits they wish with no external limitations on numbers or congestion.

This state-authorized nature of space activity authorization under international law complicates any U.S. attempt to independently implement an STM system, as the system needs to deal with non-participants and many of the benefits of an STM system scale based on the amount of participation. While a U.S. STM system might accept registration and participation by non-U.S. entities, it could not compel participation by any non-U.S. entity. Further, under current U.S. law it is not clear if any U.S. regulatory authority exists to compel participation even by U.S. entities. Jakhu, Sgobba, and Dempsey argue for the extension of International Civil Aviation Organization (ICAO) jurisdiction to cover space traffic management, and such a system is one potential end state[43]. However, as Brian Weeden argues, standardization at the international level will be challenging before national frameworks have developed; indeed, standardization among such frameworks was the mission ICAO was first created to address[44].

U.S. Space Licensing Entities: Within the U.S., regulatory authority to supervise and license commercial space activities is split across several agencies. The National Oceanic and Atmospheric Agency licenses private space-based remote sensing, under authority derived from the National and Commercial Space Programs Act[45]. The FAA Office of Commercial Space Transportation (AST) regulates space vehicles, launch and reentry activities, and launch/reentry facilities under U.S. jurisdiction[46]. The Federal Communications Commission licenses satellite communications using authority from the Communications Act of 1934 (as amended)[47]. As part of its evaluation of whether launch activities are in the public interest, the FCC imposes certain obligations regarding orbital debris mitigation as a condition for licensing[48]. Other agencies including the Department of State and Department of Defense, participate in interagency discussions conducted as part of the licensing process for various space activities. Space Policy Directive 2 tasks various government agencies including the Department of Commerce, Department of Transportation, the Federal Communications Commission with exploring ways under their respective jurisdictions to streamline regulation of commercial space flight activities[49].

Interagency Space Debris Coordination Committee: The Interagency Space Debris Coordination Committee (IADC) is an international forum comprised of national space agencies to exchange information regarding orbital debris research. The IADC also produces space debris mitigation guidelines (but is not a regulatory organization). One of IADC's key recommendations is that objects in LEO should be deorbited promptly following the end of operational life, with 25 years as a recommended maximum lifetime limit[50]. There is evidence that compliance with this 25 year rule may be quite low - a 2014 study [51] found only between 40% to 60% compliance in recent years in LEO.

Satellites in orbits where such deorbiting is impractical move to 'graveyard' orbits (disposal orbits). The cost of reserving propellant for these end of life maneuver is significant, however. For example, for a chemically propelled GEO communication satellite, the propellant used to boost to a graveyard orbit can comes at the cost of 6 months of additional operations, which may be worth $50 million in revenue [52]. Since 2002, as part of getting a GEO license, the FCC requires all GEO satellites to commit to moving to a graveyard orbit at the end of their lifetimes.

Space Policy Directive 3: The recently signed Space Policy Directive 3 supports the transition of civil STM responsibilities to a civilian entity, the Department of Commerce, and provides additional guidance relevant to the development of an STM architecture. Specifically, it affirms the importance of an STM ecosystem that offer free government-provided "basic SSA and basic STM services" in a manner consistent with "supporting new opportunities for U.S. commercial and non-profit SSA data and STM services." It also reiterates that the U.S. should "seek to lead the world in the development of improved SSA data standards and information sharing" and directs the Secretary of Commerce, in conjunction with State, DoD, NASA, and the Director of National Intelligence to "develop standards and protocols for creation of an open architecture data repository to improve SSA data interoperability and enable greater SSA data sharing."

C. Conclusions and Implications for STM System Design:

Based on the description of STM-addressable threats in Section A and the factors contributing to the current and near future context for SSA and STM in Section B, the authors draw the following conclusions as guidance for the outlines of a potential STM system architecture.

1. Automation is needed to make the system sustainable.

Increases in the number of spacecraft on orbit, particular small spacecraft in orbit, will require a highly automated system for STM to keep staffing and associated STM system costs reasonable. This is especially true as a linear increase in spacecraft and debris leads to a larger non-linear increase in potential conjunctions. In a separate paper, the authors explore the role of autonomy within an STM system in more depth, but we summarize some of the content here [53].

Additional research is needed to develop methods to apply autonomy to STM. Several factors complicate the application of autonomy to STM including: 1) the necessity of dealing with non-participants, who may be uncontactable and whose intentions are unknown; 2) the existence of tracking observations and positional knowledge that is held privately by some parties within the system and not shared, as well as the limited accuracy of tracking observations overall; and 3) the fact that the STM system will need to rely on imperfect owner/operators to consent and correctly execute maneuvers, adding additional decisional complexity and failure modes as compared to a top-down system where the autonomous agent has the ability to execute the maneuvers it develops.

We identify three key applications of autonomy in STM: 1) categorizing conjunctions as non-threatening, requiring further observation (and if so, by what sensor and when), or as requiring collision avoidance maneuvers (and if so, when); 2) negotiating to determine who moves to avoid a threatening conjunction between two operational satellites (and the broader question of autonomous negotiation and resource allocation when using suppliers that charge fees); and 3) ingesting multiple and potentially conflicting tracking observations from different sources and determining RSO positions and trajectories. Across these and other applications of autonomy, an important challenge is understanding when to escalate decision-making for human review or decision-making and when autonomous systems can proceed without needing to request human review or intervention.

2. A hierarchical system analogous to Air Traffic Control is not realistic in the short-term.

While the responsible regulatory agency will ultimately make decisions regarding who, if anyone, is required to participate in the STM system, such a system will likely start as a voluntary best practice and will never achieve 100% participation. Existing regulatory authority probably does not allow the U.S. government to compel private American-supervised spacecraft to move, and technical limits to SSA mean that even JSpOC does not have exquisite knowledge of the position of all resident space objects. A hierarchical system would also need to contend with the fact that space is not segregated into physically distinct jurisdictions by national authority. The U.S. lacks legal authority to compel participation by non-U.S. entities and has shown little interest in pursuing an internalized STM system, preferring to develop a U.S. controlled system first. Absent widespread participation, regulatory authority, and well-characterized positional information, it is difficult to imagine a hierarchical command-and-control system functioning well for STM. Instead, a proposed STM system must be able to accommodate a mix of participatory and non-participatory entities, and cannot rely on a single organization at the top of a hierarchy with command authority to compel maneuvers, or even just unified and comprehensive situational awareness. Numerous private entities, both commercial and non-profit are developing and providing value-added STM services that a hierarchical system could undermine or prevent from developing further if not very carefully designed.

3. *The system must be designed to address the presence of non-participating entities and malicious actors.*

Most major space powers will be unwilling to share positional or maneuver information for unacknowledged national security spacecraft with a civilian STM system, especially an international system or one controlled by another country. Some commercial providers may consider their operational information so sensitive that they will refuse to provide it unless required by law to do so, and may choose to seek a less-restrictive flag of convenience for spacecraft rather than comply with disclosure. Policy-makers will need to offer clear guidance for how to interact with non-participants, mindful of both free-rider concerns and the improvements to spaceflight safety associated with ensuring that even non-participants have access to SSA and deconfliction information.

As access to space becomes cheaper and more widespread, malicious actors may deliberately refuse to comply with and participate in the system, and may attempt to exploit the system to gain access to privileged information or cause harm to rivals. The system must be designed to be robust against different potential threats, even when participating entities act in bad faith. It must have the capability to monitor these malicious actions, feed this monitoring back into the STM system, and enable responses in a rapid and highly autonomous manner. Appropriate cybersecurity and system rules will represent a major component necessary for operational use that may be absent or under examined in a testing and development setting.

4. *Standardized, open interfaces are critical to ensuring system functionality and enabling wider commercial STM activities.*

With an increasing number of entities providing, consuming, or contributing to STM-related services, the task of interfacing between those entities in an effective and flexible manner will become more and more important. As the number and nature of data sources and sinks grows, the problems of data sharing become more pronounced. Established, sophisticated operators today may be able to deal with a proliferation of point-to-point, unique interfaces, but smaller operators or STM consumers will not. Even for sophisticated large operators, standardized interfaces to an STM ecosystem promises greater efficiency and offers the potential to exploit smaller data sources and sinks that might add value at the margin, but would be too small to justify intensive development to facilitate custom interconnection and data validation.

With such a framework in place, a supplier of conjunction assessments could easily and autonomously request tasking of a high-interest RSO, and decide between different SSA suppliers based on phenomenology, cost, time of next observation, etc. rather than either having to conduct manual research to determine potential suppliers or simply accept the next observation from a single or limited number of contracted firms. In the future, it may become commonplace that spacecraft operators who have never even heard of each other to have to suddenly coordinate collision avoidance maneuvers on a tight timeline. A wider, highly scalable framework to facilitate these kinds of complex interactions in the emerging STM ecosystem would need to be developed.

5. *The system should begin with voluntary participation to achieve benefits for small operators/suppliers and interoperability.*

Small satellite operators can gain significant benefits from outsourcing STM compliance and operational responsibilities to a specialized third party and may be less concerned about secrecy regarding their positional information. A voluntary system is more acceptable to potential participants, and requires the platform to demonstrate value to drive adoption. Development of STM should address these operators early on.

6. *The system should be flexible enough to accommodate future regulatory requirements, including potential for mandated maneuvers under certain conditions.*

Over the coming years, there will likely be significant changes in the nature of the U.S. STM and SSA regulatory environment. An STM system should be designed to be expansible so that potential requirements can be addressed and either verified or enforced by the system without requiring substantial fundamental changes to the underlying platform.

7. *The system should be able to integrate data from multiple sources, providing information to those who need to know while being responsive to source-imposed restrictions on sharing. It will be challenging to achieve this objective without either technical solutions to enable desensitized sharing or a trusted third-party environment for performing SSA and conjunction assessment.*

   When trying to screen for potential satellite on satellite collisions, different SSA suppliers may have different estimates of satellite positions or future propagated states. If measurements at the sensor level can be shared, they can be combined help identify RSO positions with greater precision and accuracy. If all that is available is a final calculated state, it is much more difficult to fuse that information with other state estimates, and deconfliction is more complicated.

   Developing a unified understanding of object position will need to occur at the SSA supplier level, or by Conjunction Assessment Suppliers (CASs) and Space Traffic Management Service Suppliers (S3s) during Conjunction Assessment (CA) and collision avoidance maneuver development (these roles are discussed more extensively in Section III.D). If owner/operators (O/Os) are unwilling to widely share high-precision maneuver ephemeris information, it risks the creation of a single or limited set of SSA and CAS suppliers with the ability to produce higher precision more accurate CA and collision avoidance maneuvers, which will lead to a privileged position in the architecture/market.

   Addressing these concerns will be a major challenge for the ecosystem and something that will need to be resolved in partnership with stakeholders during architecture development and testing. This problem is explored in more depth in other work by the authors [53].

8. *The system architecture should be open-access and encourage the involvement of commercial and other non-governmental entities.*

   Space Policy Directive 3 provides clear guidance on this point. To be successful and useful to potential operational agencies, the architecture should be responsive to existing policy guidance.

III. Concept of Operations

The ConOps described in this section is informed by the context, trends, and conclusions articulated in the previous sections. Its primary motivations are 1) ensuring safety of flight in an increasingly congested space environment and 2) meeting objectives associated with the transition of civilian STM from the Department of Defense to a civilian entity. An important, but secondary motivation is facilitating the development and expansion of an American commercial STM economy. It provides a robust framework for the necessary interfaces between key STM stakeholders. The functions of this system are described, and the overall approach is explained, including the architecture and key roles and responsibilities. The architecture draws heavily from the development and experiences of the NASA UTM project.

A. Scope

This STM ConOps proposal focuses on the data sharing and decision-making infrastructure necessary to enable a comprehensive space traffic management system. It proposes both an overall architecture concept, as well as the development of a research platform to explore supplier roles, interface APIs, and other details in partnership with industry. This section explores the conceptual design. The research platform design is described in section IV.A.

The scope of both the concept and research platform will expand incrementally through progressive development of several technical capability levels (TCLs). The plan deliberately begins with a more limited scope, on-orbit collision avoidance for voluntarily participating small satellites, but includes a development path that would gradually increase scope and capabilities. It envisions an end-state ecosystem that provides comprehensive STM services to satellite owner/operators, integrating both government services and robust private commercial offerings to increase mission assurance and preserve sustainable access and use of space.

The ConOps is intended to be largely agnostic to broader legal, regulatory, and policy structures. It addresses these dimensions only to the extent necessary to reasonably define and enable this architecture, or to reflect existing decisions and constraints. While we nominally assume that some component of the government will be given a regulatory mission related to STM and will need to interface with the system, we do not rely on any assumptions about who that group will be, or what policies it might seek to implement. The actual provision of civil STM services can be conceptualized as a free (and non-exclusive) public supplier of SSA and CAS (conjunction assessment) services. As such, the ConOps is applicable to a Department of Commerce system as articulated in Space Policy Directive 3, an FAA system, or even the continuation of civil STM provision by JSpOC. The ConOps also does not articulate how the proposed STM system should be funded - a variety of funding mechanisms or combination of funding mechanisms, including subscription, per use fees, public financing, etc. could be implemented.

B. High Level Principles

This section describes the high-level principles guiding the STM ConOps in three areas: underlying mantras, principles for the data exchange architecture, and operating principles for satellites. The mantras guide the design of the overall architecture. The principles for data exchange inform the technical architecture that will be implemented through the specified roles and APIs. The satellite operating principles describes the tasks expected of any satellite participating in the STM scheme.

Two basic mantras drive the definition of the STM system, derived from work for UTM[1, p. 7]:

- **Flexibility where possible, structure where necessary.** The system should preserve flexibility in decision-making, methods, participating entities, etc. to the largest degree that does not impair the function of an overall STM system. In areas of high demand, more coordination and operating restrictions may be necessary to accommodate larger amount of traffic. The international coordination around GEO slots is one example of this principle already in place. The STM system does not aim to make these regulatory choices, but would provide the means of technical implementation for decisions by regulators.
- **Risk/Consequence-based approach where STM should work to address the most serious problems first, generating consensus among actors and demonstrating utility.** A build-a-little test-a-little philosophy will help keep the project responsive to stakeholder needs and provides an opportunity to build support and buy-in among a community that already is building and using various unconnected tools to accomplish aspects of STM. Large owner/operators are used to nearly complete freedom of action in space, and are highly technically capable and autonomous. To be palatable to these users, and ultimately generate adoption of what will likely begin as a voluntary system, the project must demonstrate that it is an improve on the status quo that generates value for users and suppliers.

1. Data Exchange Architecture

Effective data exchange among numerous and diverse participants is a driving consideration. In the development of this system, templates with basic functionality will be built to establish standards, but with the expectation that most functional implementations will be developed by third parties that will write their own that better address specific needs. The data exchange infrastructure is heavily influenced by the principles developed for System Wide Information Management (SWIM) [54], the system developed for modern air traffic management. The relevant principles are listed below:

- **Loose coupling:** The components of the system should not need knowledge of the definitions of other components. This allows for clean interfaces between components, and the ability to replace or introduce a new component with minimal impact on the rest of the system.
- **Separation of information provision and consumption**: The production of information and the consumption of it should be independent of each other. Rather than creating a point-to-point pipeline from a particular data source to a particular data sink in order to accomplish a function, standardized interfaces should be used to allow the source to provide data to any number of sinks, and vice versa. This will make it easier for the system grow and evolve over time.

- **Open standards:** The standards in the STM system and the processes by which they were developed should be publicly accessible.
- **Service oriented architecture:** The services of the system should easily discoverable, self-contained, modular, and easily usable, so that users can combine and reuse them in the production of applications.

These principles are important for the usability of the system, and are essential for managing the ever-increasing complexity, diversity, and quantities of participants. Special precautions will be necessary to ensure data integrity and security. In addition to standard web service security measures such as OAuth2 and TLS authentication and encryption, the STM system may require additional measures such as cryptographic protocols and digital watermarking to secure data provenance, allowing the origin and integrity of information to be verified even after passing through multiple 3rd parties. Encryption may also be needed to allow multi-party calculations that avoid revealing sensitive proprietary satellite information.

2. Spacecraft Operators

These basic principles describe the minimum requirements and responsibilities for satellites and their owner/operators to participate in the STM system. External measures will be required to ensure that these conditions are met, but detailed discussion of such measures are outside the scope of the current discussion. These principles are adapted from those described by Kopardekar et al. for UTM [1, p. 7].

- **All satellites and owner/operators are authenticated** before participating in the STM system, and shall obtain approval to operate from their launching state.
- **All owner/operators are responsible for control of their satellites** and avoiding harm to other spacecraft through their actions (either to standards set based on their own judgment or by a regulator)[9]
- **All participating owner/operators are required to contract with an S3 or undertake activities to perform the S3 role** for their spacecraft including deconfliction, constraint compliance, etc.
- **All owner/operators are responsible for providing notification** of activities and spacecraft properties relevant to STM to their S3/S3 (which may be disseminated to the system, depending on their nature, and S3 and O/O preferences).
- **Owner/operators are responsible for complying with any regulator-imposed requirements,** but may rely on S3s to assist them in achieving compliance.

C. Notional Architecture

This section presents a notional architecture consistent with the above principles. As in the UTM architecture, relevant regulatory agencies maintain their regulatory and operational authority. However, operations are managed by a decentralized network of highly automated systems that interface via a standardized set of application programming interfaces. The network involves several key classes of participants, whose roles are described in more detail in the next section and in Figure 3:

- Owner/Operators (O/Os)
- Data and Service Suppliers (i.e. Conjunction Assessment Services, Space Situational Awareness Suppliers, etc.)
- STM Service Suppliers (S3s)
- Regulators, who interface with the system via the Spaceflight Information Management System (SIMS).

This architecture assumes the presence of multiple data sources and sinks for the various services, and provides a way to tie them together into a single framework. Decentralization also implies that new nodes can be added easily,

[9] We do not explicitly address liability in these principles. Instead, we intend for liability to be determined between S3s and O/Os, and potentially with the inclusion of third-party insurance suppliers. There is a spectrum of potential arrangements between an O/O and an S3, with the O/O ceding various levels of control. It may be an S3 is willing to take liability for maneuver recommendations if it is granted full determination over when to maneuver, but might refuse to do so if an O/O sets a risk threshold for maneuvers higher than the S3 views as responsible.

and common standards allow software developed for one supplier to be reused to interact with another. This architecture forms the framework for an STM ecosystem, and the entry of 3rd parties (particularly commercial ones) who can identify and fill niches by providing new, useful services is encouraged. Previously, the high barriers to operating in space ensured that the community was small with highly concentrated silos of expertise – in the future, expertise must be more broadly available. By making some of these functions easily available as services, the architectures reduces the amount of expertise that must be available internally within a particular organization, thereby reducing the barriers to operating in space and providing participants with the information necessary to behave responsibly.

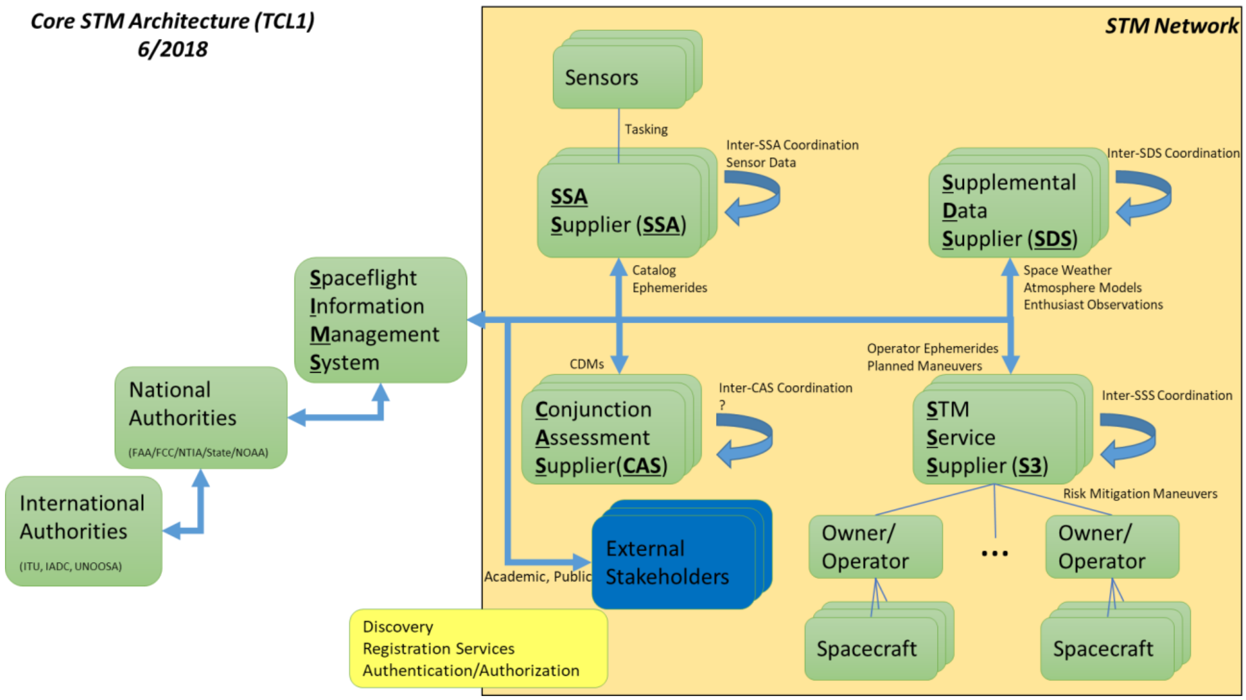

Figure 3: Diagram of Notional STM Architecture

Under the proposed architecture operational support for collision avoidance, separation, etc. is managed through a decentralized architecture, rather than via a single centralized government-administered system. However, the key differentiator is the development of a standardized API to allow easier interconnection and conceptual definition of roles to more easily allow suppliers with different capabilities to add value to the ecosystem.

The architecture will need to handle certain basic functions including registration, discovery, authentication of participants, and auditable tracking of data provenance and integrity. As an open-access architecture, any interested entity needs to be able to join the system and be discoverable as a new participant in the system. This could be accomplished by either a centralized registry of participating entities or various decentralized discovery techniques. Authentication is important to ensure that entities are able to securely demonstrate their own identity, as well as validate the identity of other system participants. Authentication is particularly important given the sensitivity of the information exchanged across the system and the high level of trust in an S3 necessary for an O/O. Establishing auditable records of data provenance is necessary for accountability, particularly as data is transformed from raw observations into SSA products or used as a basis for maneuver decisions. Data accuracy might be at issue in potential liability suits, and upstream suppliers may wish to negotiate payment strategies that monetize all downstream uses of their data. Data integrity verification is necessary to protect against malicious actors or simple errors during transmission, both of which could have profound and expensive consequences if a reliance on erroneous data leads to a breakdown in the STM system that results in a collision.

D. Roles and Responsibilities

Each supplier role, i.e. space situational awareness supplier, is designed to accommodate multiple entities offering that service. The system also accommodates a single business or legal entity that wishes to fulfil more than one function. For instance, sophisticated owner/operators may serve as their own S3s, and firms operating as SSA suppliers may also provide collision assessment services. Standard interfaces and a common API structure (with required and optional fields) allow easy communication between entities, each entity making its own decisions about which suppliers to use. It is also expected that an entity may choose to augment the standard set of interfaces with new features specific to its own use cases.

This ConOps assumes the U.S. government would continue to provide a free public SSA catalog and CAS services, in addition to whatever private actors participate (whether on a non-profit or commercial basis), and would adhere to the same interface requirements as other actors fulfilling any of these roles. A spaceflight information system would serve as a standardized interface into the system for U.S. government regulatory entities. At some point in the future, service suppliers might be subject to certain regulatory performance or licensing requirements. If so, the architecture could be adapted to support this feature.

The roles and responsibilities listed in this section correspond to TCL1 and relate to physical deconfliction rather than radio-frequency interference, space weather, or other capabilities that might be added to the service in subsequent phases of the STM ecosystem.

1. Owner/Operator (O/O)

Owner/Operators maintain responsibility for and control of their satellites, including maintaining safe separation from other trackable RSOs to avoid potential collisions. The operator executes all maneuvers and has decision-making authorities and overall responsibility for the actions of its spacecraft. Owner/operators vary in sophistication from satcom fleet operations with well-staffed, 24/7/365 operation to small university labs staffed part time with grad students only periodically.

2. STM Service Supplier (S3)

The S3 serves as a link between the O/O and the wider STM system (including other S3s). The relationship between S3 and spacecraft O/O is analogous to that between an air traffic controller and a pilot. The pilot has direct control and ultimate responsibility for the aircraft, but exchanges information with and cooperates with the controller. The controller has the big picture understanding through access to a wider network of data sources and tools, and uses them to generate directives that perform deconfliction. In this architecture, the S3 is not a human controller issuing voice commands, but a software system that communicates through a standardized API interfaces and generates instructions algorithmically or with human help. The complexity of performing and uncertainties associated with conjunction assessment will likely demand the use of human judgement for the immediate future.

The S3 maintains ability to contact the O/O, and passes information as needed to achieve regulatory or operational requirements. The S3 collects metadata regarding each spacecraft under its supervision, disseminates information regarding satellite operational status to the broader STM network, clears potential maneuvers, acquires information about potential conjunctions, and clears and deconflicts collision avoidance maneuvers. It also archives data regarding satellite actions for subsequent analytics, regulatory, or O/O requirements. S3s may additionally provide other services, if demand from O/Os justifies their creation.

Several organizations are already performing the S3 role for O/O who do not wish to perform these duties themselves. Examples include NASA’s CARA, CNES’s CAESAR, and the SDA, all playing the role of “middle men” as value-added in-betweens between SSA organizations such as the JSpOC system and O/Os[55]. Importantly, these middle-men serve to tie together groups of operators with similar objectives and constraints which may not be shared with the wider space community. The SDA, for example, represents operators that compete commercially with each other, and have developed ways of sharing commercially sensitive information in the interest of common spacecraft safety, while NASA spacecraft do not operate under the same constraints and can interact differently with external actors.

3. *Space Situational Awareness Supplier (SSA)*

Space Situational Awareness suppliers (SSA) acquire and pool observations from sensors and/or owner/operators to generate and collect catalogs of information relating to the space environment, primarily position and trajectory information for resident space objects (both active satellites and debris). The sensors that feed SSA suppliers are a mixture of those operated by SSA suppliers themselves and others run by third parties who share information the SSA suppliers on a commercial, free, or reciprocal basis. These third parties may include other commercial or government entities, academic institutions (e.g. astronomical telescopes), or potentially crowdsourced (and appropriately curated) space enthusiast observations.

Because conjunction assessment suppliers may rely on data from different SSA suppliers, coordination is important to ensure that conjunctions accurately model the state of resident space objects in orbit. Coordination among SSAs, particularly those that rely on different sensor measurements using different sensor phenomenologies would also provide a potential mechanism to improve covariances and achieve better data accuracy and precision.

High accuracy tracking of active satellites can be greatly enhanced by provision of owner/operator ephemerides which can exceed the possible accuracy of non-cooperative tracking information (e.g. GPS derived). These owner/operator ephemerides are protected by many operators as sensitive and proprietary. Owner/operators may be unwilling to publicly share this information, but have demonstrated a willingness to share information through a trusted third party (e.g. the Space Data Association), which can minimize information sharing to only that necessary to avoid an identified conjunction, and prevent misuse of information through contractual requirements. If this preference continues, there may be a consolidation of SSA and conjunction assessment services to a single main organization, that can acquire information to perform high accuracy assessments using sensitive information while maintaining trust of operators, a case for which this STM architecture allows.

4. *Conjunction Assessment Supplier (CAS)*

Conjunction assessment suppliers use information from SSAs and S3s to identify potential conjunctions, which are instances where two or more RSOs approach within a hazardous distance of each other. After initial conjunction identification, a CAS may be involved in subsequent steps depending on the S3 and preferences of both suppliers. If an S3 requests CAS involvement in conjunction assessment,, they would work jointly to identify which conjunctions might require collision avoidance maneuvers and which could be cleared with further analysis. In cases where there is insufficient information to rule out a potential conjunction, a CAS or S3 may request additional observations from an SSA to reduce uncertainty in the trajectory of a tracked object. The decision to maneuver to avoid a collision is not taken lightly, since it may significantly disrupt operations and may reduce the operational lifetime of the spacecraft. Once a collision avoidance maneuver is determined to be necessary, either the S3 or the CAS would generate a proposed maneuver and screen it against known SSA information. Even for spacecraft without propulsion, potential action can be taken with sufficient warning to enter a high drag configuration to alter orbital phasing or to change attitude to minimize collision cross-section.

5. *Supplemental Data Supplier*

The proposed architecture concept specifically describes roles for S3, SSA, and CAS given their importance to the system. Numerous others services and suppliers will likely emerge as part of the STM ecosystem and the supplemental data supplier role is designed to allow these entities to connect to the system and flexibly provide data. For example, space weather is an anticipated supplemental data supplier category. In addition to affecting LEO orbits (via its effects on atmosphere) space weather has the potential to temporarily degrade communications between satellites or between satellites and the ground. There are also temporary or permanent mechanisms by which space weather can damage spacecraft electrical components. Eventually, a space weather supplier role might help prevent damage to spacecraft by predicting space weather events where feasible and allowing operations to take preparatory actions such as reorienting spacecraft or entering safe mode. Another valuable source of information might be information about micrometeoroid flux, which could help inform shielding requirements in various orbital regions or warn suppliers of unexpected increases in micrometeoroid populations.

6. *External Interfaces*

a) Public. Various non-participant actors may wish to connect to the STM system, ranging from commercial ventures seeking to deliver new value-added services to investigative journalists seeking to understand how orbits are being used. An external interface would allow other non-participants to request voluntary access to information from participants.

b) ***Spaceflight Information Management System (SIMS).*** For regulatory, analysis, or public safety purposes, US government regulators may need mandatory access to information from the STM system. Similarly, they may need to disseminate emergency warnings or restrictions quickly to participating spacecraft (the U.S. regulators would lack authority to issue binding use restrictions on non-US participants, even with additional domestic legislation). The SIMS interface would allow communications in both these directions. Unlike the supplier roles, actual implementation of SIMS would need to be developed by the government, with substantial input from industry.

E. Example Use Case

To clarify the concept of operations, this section presents an example use case - the resolution of a potential satellite on satellite collision in LEO. For the sake of this example, we assume both satellites are active, possess maneuvering capabilities, and participate in the STM architecture. None of these assumptions are strictly necessary, but they allow a fuller explanation of system capabilities. The description will be primarily from the viewpoint of the first satellite and its owner/operator.

1. *Step 1: S3 Selection and Registration*

As shown in Figure 4, each satellite controlled by an owner/operator participating in the system must be registered with an S3. In the case of an established owner/operator with sufficient infrastructure, the S3 role may be handled internally by the organization. In other instances, the owner/operator would enter into an agreement with a second-party S3 (which might be a non-profit or commercial entity). The owner/operator would arrange to consistently share its contact information, commit to provide timely replies to the S3, provide positional data it gathers for its satellites (periodically or in near real-time), meta-data (satellite geometry, attitude, etc.), and generalized preferences for collision avoidance (i.e. provide information on operations so avoidance maneuvers can be combined with operational station-keeping burns) and operational risk tolerance (within the relevant regulatory or S3-determined limits). The S3 then updates the STM system roster to indicate that it provides service to this particular satellite. In this case, both satellite operators have done this prior to the start of the scenario and have registered with different S3s (neither owner/operator is sufficiently large to provide their own S3 services).

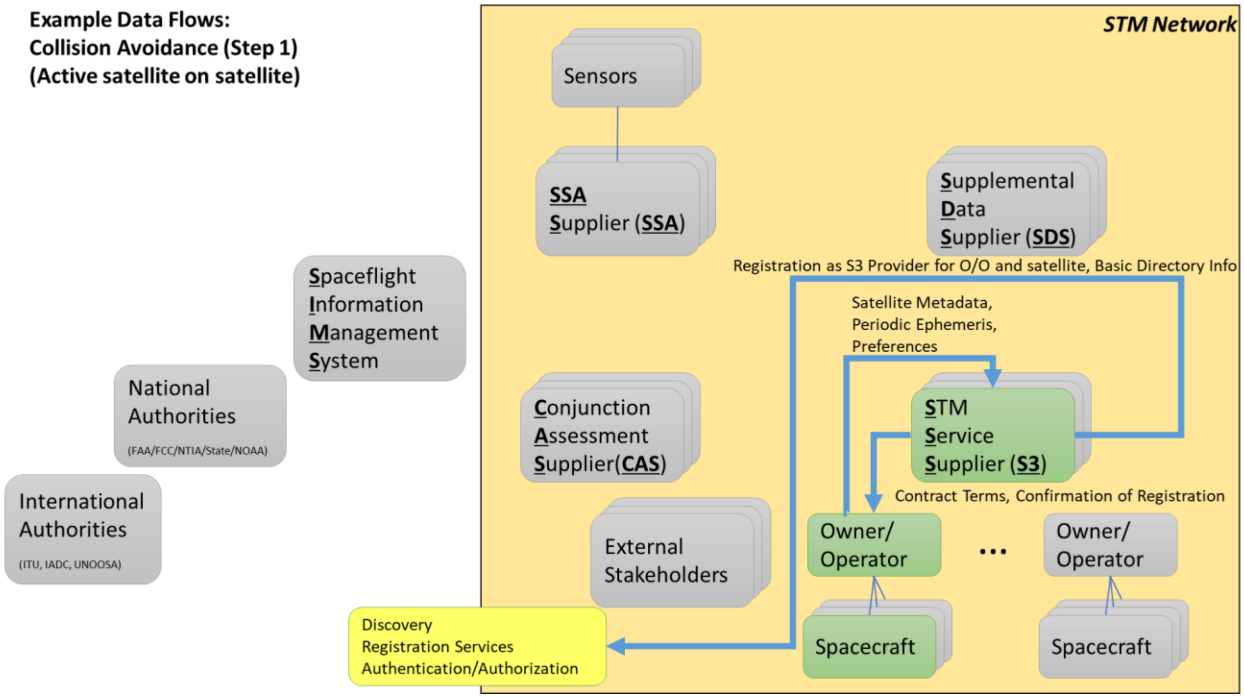

Figure 4: Initial Registration of Satellite and O/O with S3. O/O retains an S3 and transmits ephemeris and metadata for its satellite(s).

2. *Step 2: Regular Conjunction Screening*

As shown in Figure 5, one of the roles of an S3 is to regularly screen satellites under its care for potential conjunctions with other active satellites or debris objects. For this service, S3s would partner with a CAS, passing satellite information along with any necessary meta-data or self-reported ephemerides to the CAS. The CAS propagates the orbits of the satellite and other resident space objects, drawing on data from one or more SSA suppliers. As necessary, the CAS may request specific tasking of sensors by the SSA supplier. The CAS may also draw upon other sources of supplemental data, such as atmospheric modeling measurements. The CAS would then return conjunction data messages (CDMs) to the S3 warning of potential conjunctions.

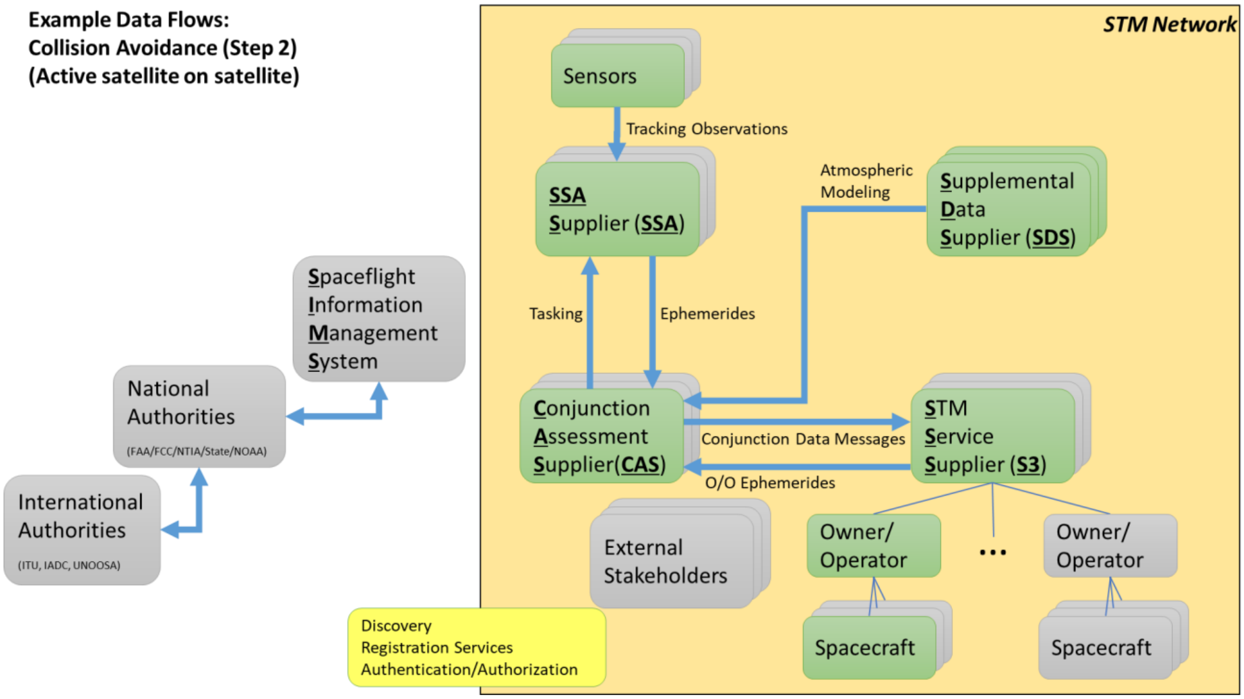

Figure 5: Collision Screening Request and Data Flow. S3 requests screening for one of the satellites and receives a set of conjunction data messages listing potential conjunctions.

3. *Step 3: Collision Avoidance Maneuver Generation, Sharing, and Coordination*

As shown in Figure 6, the S3 next assesses the reported conjunctions and selects high risk events to monitor. Additional sensor observations to refine ephemerides can be tasked, and at a certain time prior to closest approach it will determine whether a conjunction merits a collision avoidance maneuver. The standards for each action would be agreed by the S3 an O/O in advance, and might be subject to regulatory minimums or best practices. For conjunctions that are determined to present a sufficient threat, the S3 notifies the O/O and proposes a collision avoidance maneuver. In this case of a high-risk conjunction with another active satellite, the S3 would also notify the other satellite's S3.

Before requesting that the O/O implement a maneuver, the S3 must clear the proposed collision avoidance maneuver with the S3 of the other satellite and a CAS. Coordination is needed to safeguard against uncoordinated maneuvers by the two satellites that may increase collision risk. The CAS acts a check to confirm the original S3's analysis that the new maneuver does not result in third-party conjunctions (where the satellite now has a conjunction with another satellite or debris object). The S3 may also need to broadcast the maneuver to the system, or to S3s of close-approaching satellites to ensure that the maneuver will not result in a conjunction with RSOs about which it does not have accurate awareness. The owner/operator also needs to consent and verify both ability and willingness to perform the maneuver. The owner/operator might alternatively counter-propose a different maneuver that it prefers from a propellant usage or mission operations perspective, but that also meets the S3 or regulatory requirements. [10]

[10] The precise order of these validations and agreements may vary depending on the situation. For instance, for a less sophisticated owner/operator that must manually verify and validate maneuvers, it may be preferable to obtain S3 and CAS clearance first, as those steps could be algorithmically achieved with significantly less time delay than waiting for a manual approval.

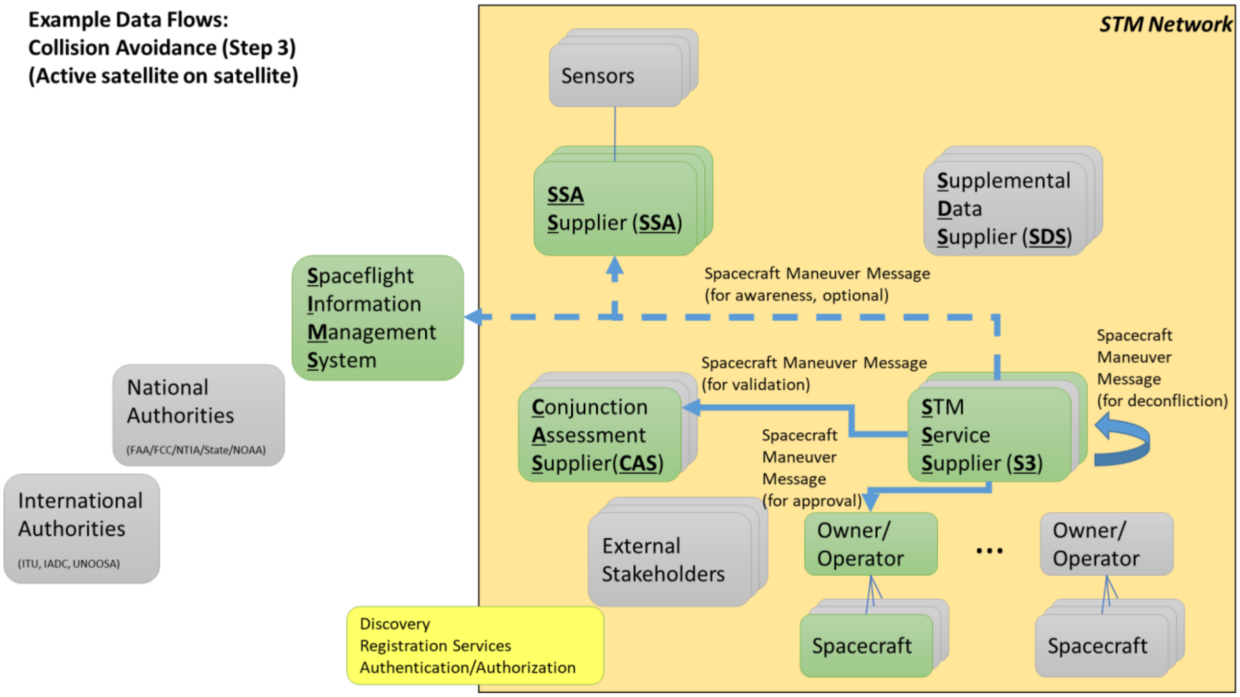

Figure 6: Collision Avoidance Maneuver Generation, Sharing, and Coordination. The S3 evaluates each CDM and contacts S3s for each high risk conjunction. It then generates a proposed collision avoidance maneuver and clears it with other S3s, validates with its CAS, and obtains approval from the O/O.

4. *Step 4: Maneuver Execution and Verification*

Once the maneuver is cleared by the participants (CAS, S3s, owner/operators), the owner/operator of any satellites that the maneuver plan involves performs the maneuver(s) at the specified time(s). The O/O and SSA would verify each maneuver was performed nominally, and update the maneuvering object's ephemeris information accordingly.

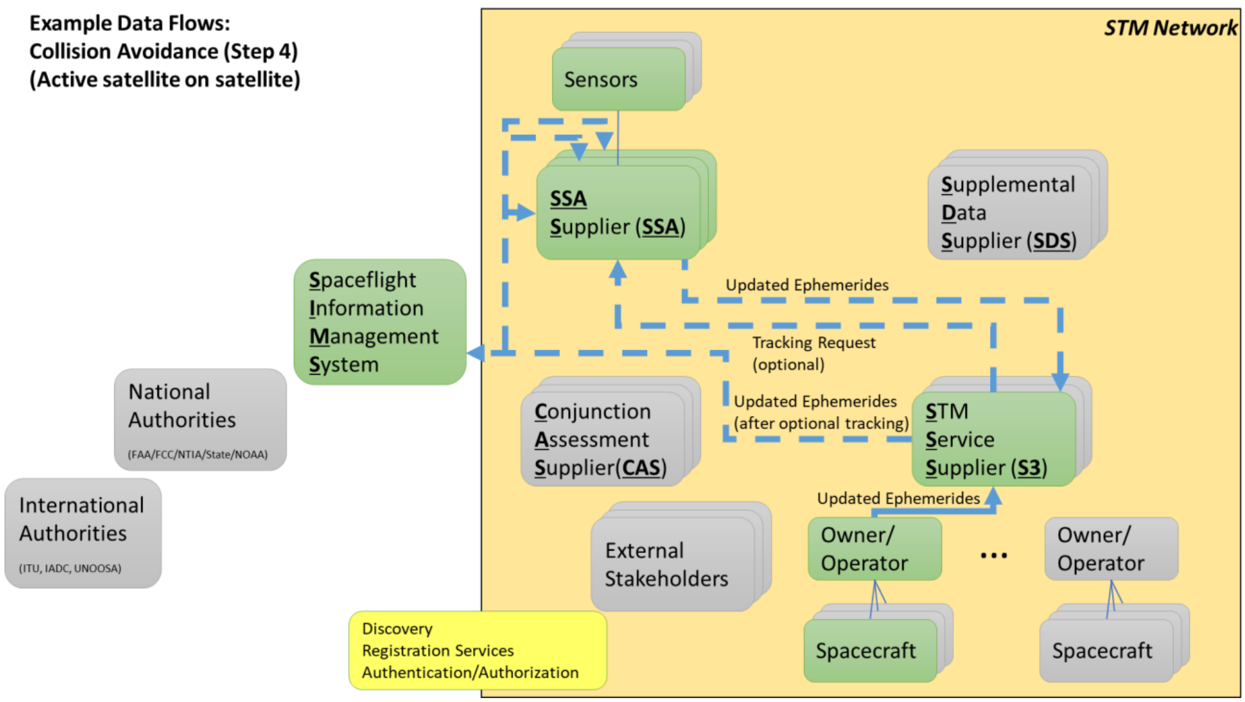

Figure 7: Maneuver Execution and Verification. The O/O executes the agreed upon maneuver, conveys new ephemerides to its S3, who may optionally task other observations to confirm the maneuver and/or share the new ephemerides.

IV. Research Considerations

A. STM Research Platform Description

Following initial refinement of the architectural concept, the project team envisions the development of a research platform implementation of this concept as a next step. The research platform will be designed to visualize, assess, and validate system design and eventually performance under increasingly complex test cases. Development can be done in partnership with other government agencies as well as academic and commercial users for tests using the platform to generate insights to inform regulatory decision-making and actual platform implementation by a civilian regulatory entity.

The initial emphasis for the platform will be on data exchange, rather than the specific services offered by each entity. Implementation of actor roles will feature reduced complexity, detailed enough to allow for useful testing, but without the intention for the role to be production ready, or replicate the state of the art in industry. In some cases, it may make sense for the research platform model to simply feature a wrapper around existing data sources or services. In a production environment, we anticipate that entities will code their own implementations of their unique approaches, using the common interface defined by the system APIs.

At a technical level, the proposed research platform is based on common web API interfaces. Data formats will be based on CCSDS and other industry standards where applicable. The API standards are intended to be written in a manner to make it very easy for software written to interface with one data source (e.g. a particular SSA supplier) to be modified to interface with any another. Where applicable, the project will leverage code from the UTM project.

To facilitate software development and collaboration with stakeholders, an STM simulation lab equipped with workstations, software tools, and large video displays has been developed. Operators will simulate various roles during tests, as well as interact in real-time with external participating stakeholders.

B. Development and Testing Methodology

The STM research platform will be developed incrementally, gradually expanding to provide capabilities to address additional functions, roles, and use cases. The system will begin by focusing on a core set of service suppliers relevant to conjunction assessment and collision avoidance. The first technical capability level will focus on conjunction assessment and collision avoidance for small satellites O/Os, who operate simpler spacecraft, may be more willing to share positional information, and have a significant potential gain by being able to outsource portions of their STM responsibilities to an S3. Other operators will benefit also by being able to engage with a clear and sophisticated point of contact rather than individual small satellite operators. While the existing STM requirements of short-lifetime cubesats without propulsion are largely met by current systems, more and more future cubesats will include propulsion, particularly those with missions that require them to reach higher orbits, or pursue missions involving proximity operations.

For each role relevant to a technical capability level (TCL), the project team will develop an architectural concept, and then develop internal templates and prototypes of each role and associated services. This internal testing will help define and refine both the prototype and APIs. After the team is satisfied with the model and APIs, the API definitions and example code will be released to external stakeholders for feedback, and for collaborative testing using their own implementations and use cases. Once development is complete, the intention is to open source the platform code to enable use and further development by all stakeholders interested in participating in an STM ecosystem, as well as eventual transition to operational agency.

A very early list of potential TCLs is below in Figure 8:

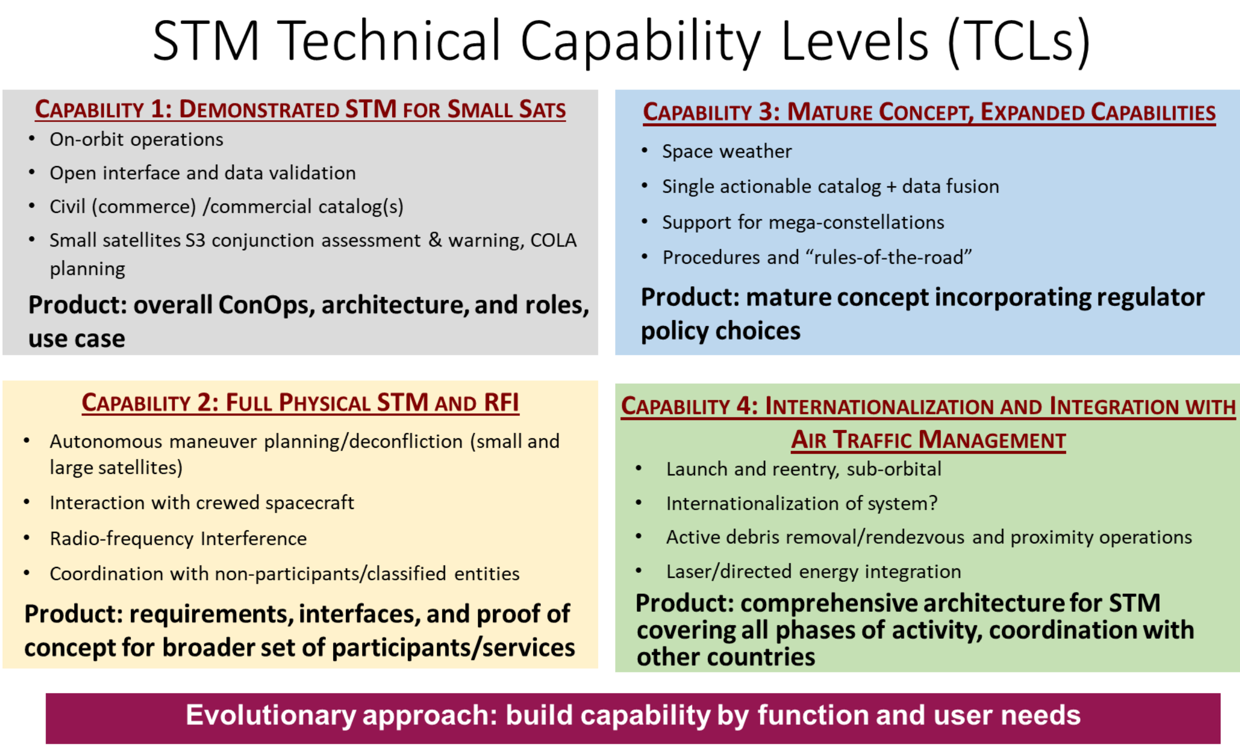

Figure 8: Notional Chart of STM Technical Capability Levels

V. Conclusion

From cubesats built by high schools, to commercial on-orbit space surveillance, to frequent on-demand small satellite launches and mega constellations, space is changing in fundamental ways. The debris environment consequences of not performing space traffic management effectively in this new, crowded environment are long-lived and potentially dire. A new space traffic management system must be developed that can handle the unprecedented quantities and diversities of spacecraft, operators, and data sources anticipated in the coming years.

The STM framework described in this paper is a decentralized method of deconflicting spacecraft operations. Instead of concentrating these functions in a single STM organization, the functions are distributed among the civil and commercial members of an STM ecosystem that is in some ways already organically emerging. Such decentralization facilitates flexibility to meet different needs for different operators and will encourage the emergence of new and world-leading commercial STM services. Participants are connected through a common API that allows for interoperability and flexibility to meet a variety of needs and use-cases. At the same time, the framework provides a vision to guide the establishment of the open-access architecture required by Space Policy Directive 3.

This ConOps describes a pathway of four TCLs, each of which would add additional capabilities and scope to the STM system. This architecture will be developed in partnership with satellite builders, owner/operators, existing SSA and CAS suppliers, organizations providing S3-like capabilities, and other stakeholders, using the proposed API and software research platform.

VI. Acknowledgments

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