Normal Paper ☒

Practical considerations and a realistic framework for a Space Traffic Management system

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Abstract

There is much interest and activity in implementing a Space Traffic Management (STM) system to meet global spacecraft operator needs for actionable Safety-of-Flight (SoF) and Radio Frequency Interference (RFI) mitigation. This paper presents as background information a state of health assessment for current SSA services. STM is defined, accompanied by the key facets of a viable STM system. An STM framework is proposed that attempts to incorporate and/or address each of these key facets. This framework is designed to provide on-going STM basic services free to the end user, while also providing refined pay-for premium STM and RFI mitigation services for advanced spacecraft operators.

Keywords: Space Traffic Management, Safety of Flight, Radio Frequency Interference.

Introduction

Space Traffic Management (STM) is a rapidly growing concern for the global space community today, primarily due to increases in the space population, its interaction with the existing debris population, and the ever-increasing quantity and complexity of space actors and their satellite systems and operations. Where once operators could ignore launch and on-orbit collision risk under a “big sky” assumption, now close approaches, proximity operations, and even collisions are occurring with an alarming and rising frequency.

Definition of terms

While other countries and international organizations have included space weather, Earth orientation parameters and Near-Earth Object [1] asteroids and comets in their SSA and STM definitions, this document assumes the narrower United States Space Policy Directive-3 [2] definitions as follows:

- Space Situational Awareness (SSA) shall mean the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities.
- Space Traffic Management (STM) shall mean the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.

Background and trends

Space Traffic Management (STM) is of intense interest today, primarily due to increases in our space population and the ever-increasing quantity and complexity of space actors. Operators can no longer assume that space is "big"; close approaches, proximity operations, and even collisions are occurring with increasing regularity [3, 4, 5, 6, 7, 8].

While it is unclear whether we have ventured past a space debris tipping point [9], it is apparent that substantive and continual collision risks exist in both LEO [10, 11] and GEO [12, 13, 14]. Should they occur, collisions and other unplanned fragmentation events could adversely affect the operability and commercial viability in space across all orbital regimes and GEO longitude locations [15]. Mitigation of this risk requires satellite operators, commercial and government SSA organizations, and regulatory bodies to be ever vigilant and expend considerable resources to ensure safe and efficient operations in space.

Today, only an estimated 4% of the LEO space population and 4% of the GEO space population sized 1 cm and larger are tracked by the Space Surveillance Network [16, 17]. On this basis alone, we clearly have insufficient SSA today. As if that were not enough, it is estimated that 100 million tiny fragments down to 1 mm are present [18].

Perhaps most importantly, many of today's LEO and GEO operators are already challenged to address all of the possible conjunctions against the 4% of space objects larger than 1 cm that are currently tracked, with little or no "surge capacity" (propellant and staffing resources) to address the other 96%. Were operators to have a truly comprehensive set of conjunctions against all objects larger than 1 cm, they would likely be conducting avoidance maneuvers continuously and risk running out of fuel.

Plans to further increase our already-congested space population with CubeSats, small satellites, and large satellite constellations, coupled with dramatic improvements in spacecraft design and commercial SSA services, provide the US with a unique opportunity to field a new, appropriately designed and globally relevant SSA and STM framework.

Legacy space operator and SSA systems

Today, deficiencies in both satellite operator and legacy debris tracking data are degrading SSA.

Space Operator Data

On the operator side, operators in GEO have typically been shown to have in-track positional biases in their orbit solutions, resulting in unknown collision threats, wasted maneuvers, and potentially even maneuvering toward a collision threat rather than away from it [19]. Inconsistencies in operator ephemerides have also been shown to preclude achieving SSA that can support assessments of collision probabilities higher than 1×10^{-4} (a common collision probability threshold for commercial operations). Further, commercial operators can be constrained by their orbit determination program(s), which often precludes the extraction of covariance data and planned maneuvers to support collision probability assessment.

Legacy government space situational awareness system

Government and agency conjunction assessment (CA) services can be problematic as well, where both Two Line Element (TLE) state vectors and the higher-fidelity Special Perturbations (SP) numerical orbit data may at times be insufficient to yield actionable CA in certain orbits and conditions. In addition, key data are largely unavailable through this enterprise, to include (1) realistic covariance data; (2) debris and satellite object sizes and dimensions; (3) debris and satellite object masses; (4) compatible force model settings (including gravity fields, Dynamically-Calibrated Atmosphere (DCA), trackers used, Radar Cross Section (RCS), Visual Magnitude (Vmag); and (5) spacecraft attitude information.

Moreover, perhaps most problematic is the inability to determine orbits through past maneuvers and/or predict orbits thru future maneuvers. Spacecraft maneuvers are either provided cooperatively by the operator to an SSA system, or they are not provided (non-cooperative). In both of these situations, it is vital to quickly identify process, calibrate and recover from maneuver(s) to avoid large SSA errors in positional knowledge.

The US government's legacy SSA system consists of legacy and modern systems designed for many purposes, to include missile warning, space track, air defense systems. While very capable, it has never specifically been tasked or designed (using a top down requirements approach) to perform the STM mission, nor does it plan, coordinate, manage or synchronize space activities.

While this legacy system works acceptably well at providing SSA capabilities in select orbit regimes and categories of objects and orbit types, the resulting SSA is deficient in other orbits and object categories to feed a broader STM mission. Additional issues arise regarding service level availability, the general unavailability of required elements of information (object size, covariance time history, realistic covariances, and force model settings), slower response to rapidly changing/evolving situations, insufficient algorithms/processes, inability to fuse all necessary data at the observational level and an overall lack of transparency.

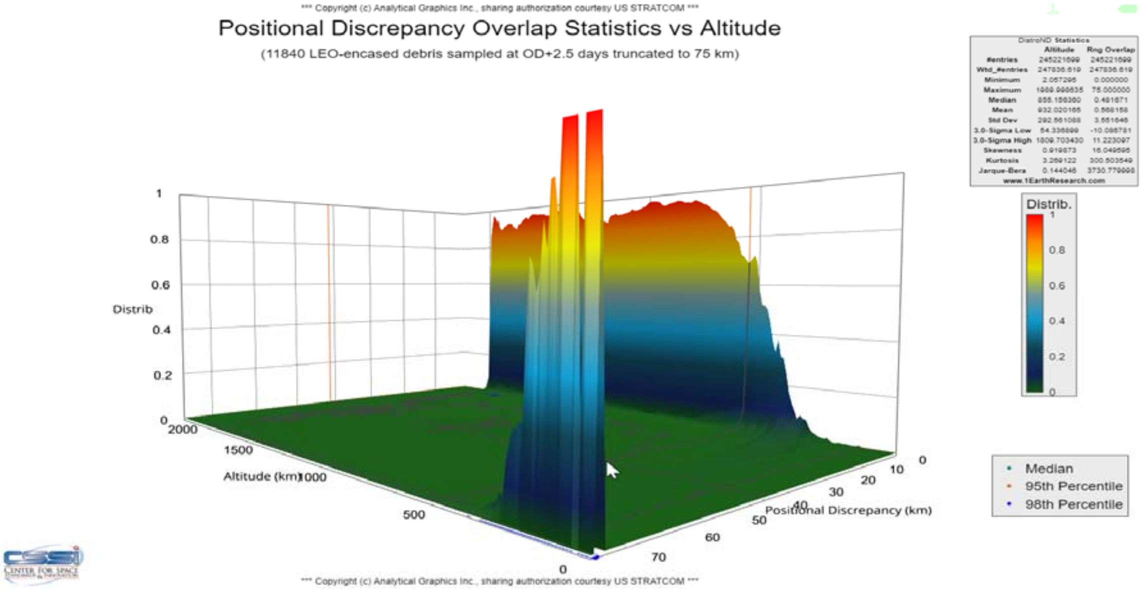
Legacy government SSA performance characterization

At this point, it is worth examining the current performance of the legacy SSA system. Ideally, absolute positional accuracy as a function of time that is of most interest. Unfortunately, there are so few publicly available, positionally well-known "truth" objects in space that it is difficult to draw statistically relevant conclusions on legacy SSA system performance from those.

Instead, since accuracy is a combination of system biases and the inherent repeatability (or "precision") of an SSA system's predictions, system accuracy can be bounded by estimating that system's precision over a large data set. Any observed imprecisions are typically caused by insufficient SSA force models, unknown or unmodelled events (e.g., unknown geomagnetic storms or unknown maneuvers), undersampled observations and/or algorithmic or process-based SSA deficiencies.

One can statistically characterize the repeatability of predicted positions for the entire shared SP catalog of 16,931 RSOs through recurrent positional differencing of each RSO's sequential ephemeris. For collision avoidance, such precision statistics associated with orbit prediction timespans of between one and two days were of greatest interest because that prediction time is most relevant to an operators' typical Observe/Orient/Decide/Act (OODA) loop for conducting collision avoidance maneuvers.

The statistical discrepancies in the precision (repeatability) of one- to two-day positional predictions spanning the entire range of true anomaly (0° - 360°) that have been characterized for LEO (0 – 2000 km altitude) as shown in Figure 1 through Figure 4, and for GEO in Figure 5 and Figure 6 (released by approval of US STRATCOM and the 18th Space Control Squadron).



DistroND Statistics

	Altitude	Rng Overlap
#entries	245221699	245221699
Wtd_#entries	247836.619	247836.619
Minimum	2.067295	0.000000
Maximum	1999.998835	75.000000
Median	855.156360	0.481671
Mean	932.020165	0.568158
Std Dev	292.561088	3.551646
3.0-Sigma Low	54.336899	-10.086781
3.0-Sigma High	1809.703430	11.223097
Skewness	0.919873	16.049595
Kurtosis	3.269122	300.503549
Jarque-Bera	0.144046	3730.779998

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Figure 1 Three-Dimensional Probability Density Function (PDF) of LEO SP precision

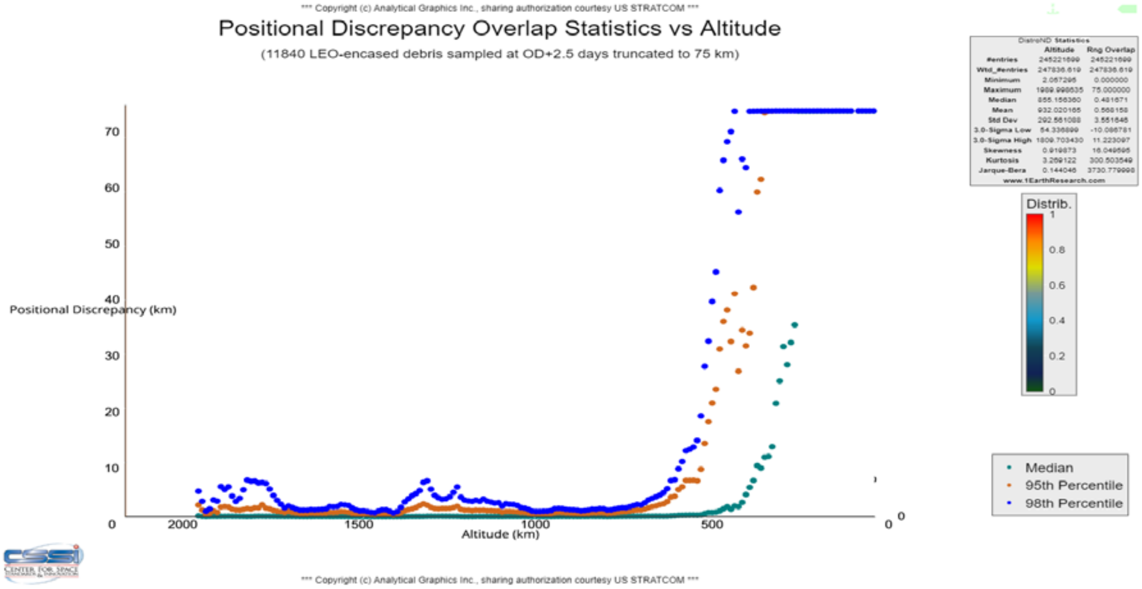

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Figure 2 Percentiles of LEO SP precision Probability Density Function (PDF)

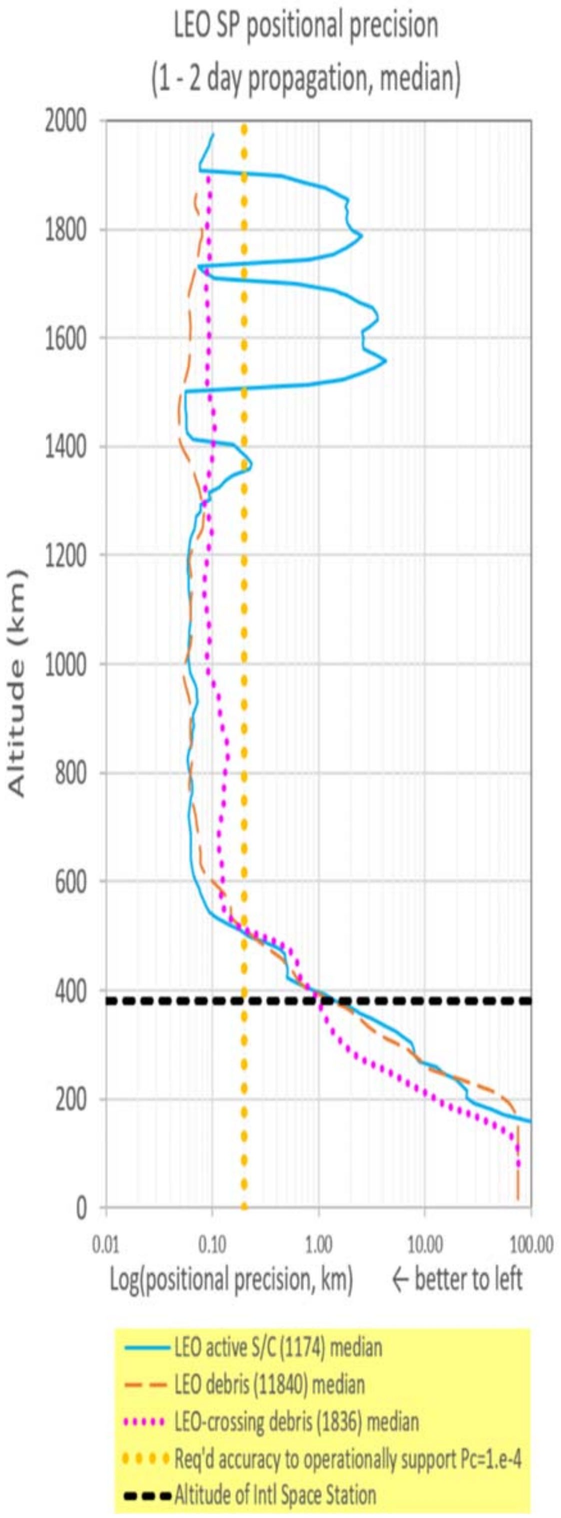

Figure 3 Typical LEO SP positional precision (1-2 day propagation, 50th percentile or median)

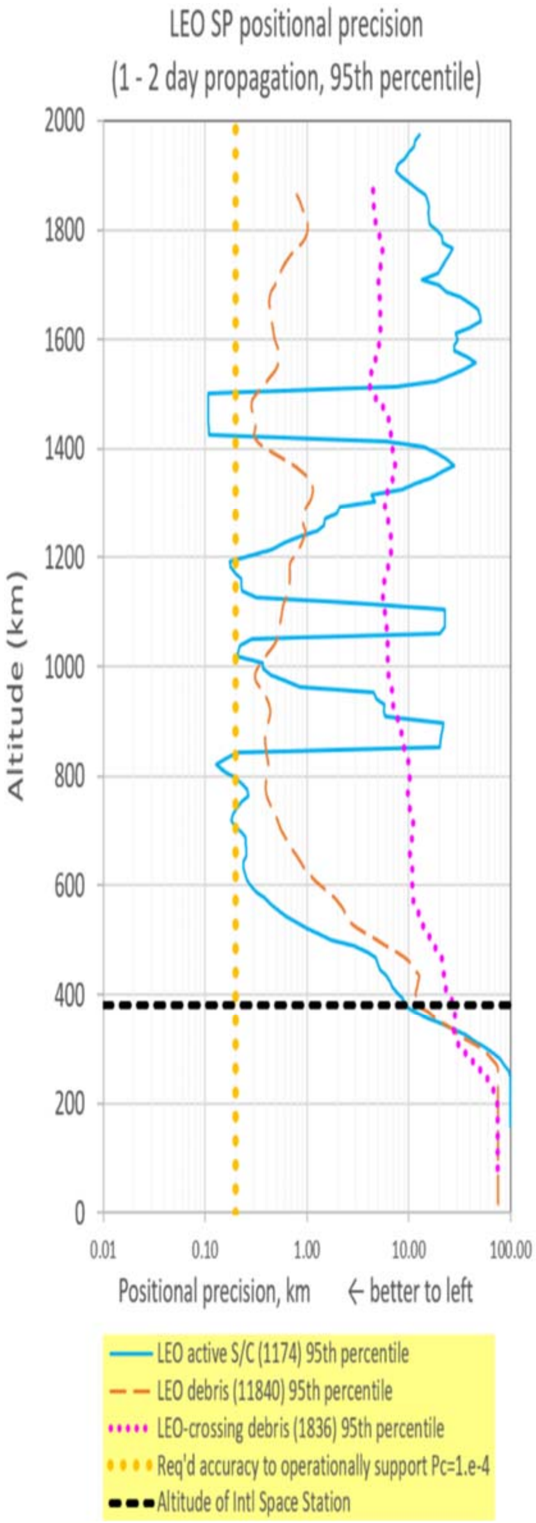

Figure 4 95th percentile LEO SP positional precision (1-2 day propagation)

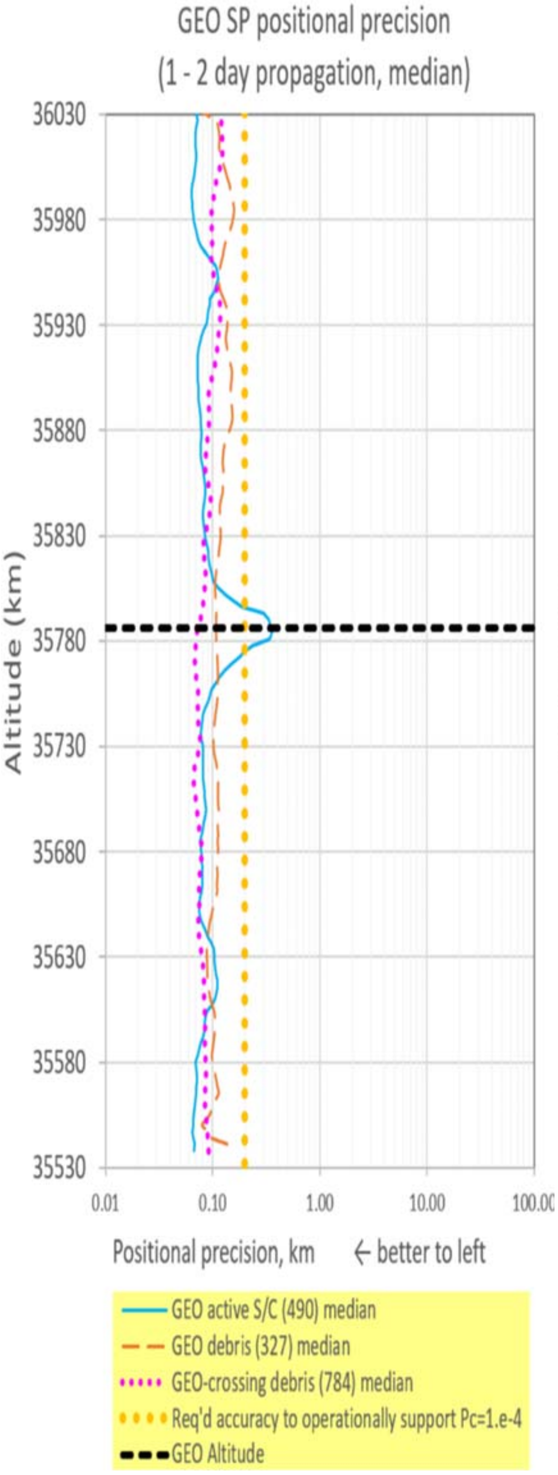

Figure 5 Typical GEO SP positional precision (1-2 day propagation, 50th percentile or median)

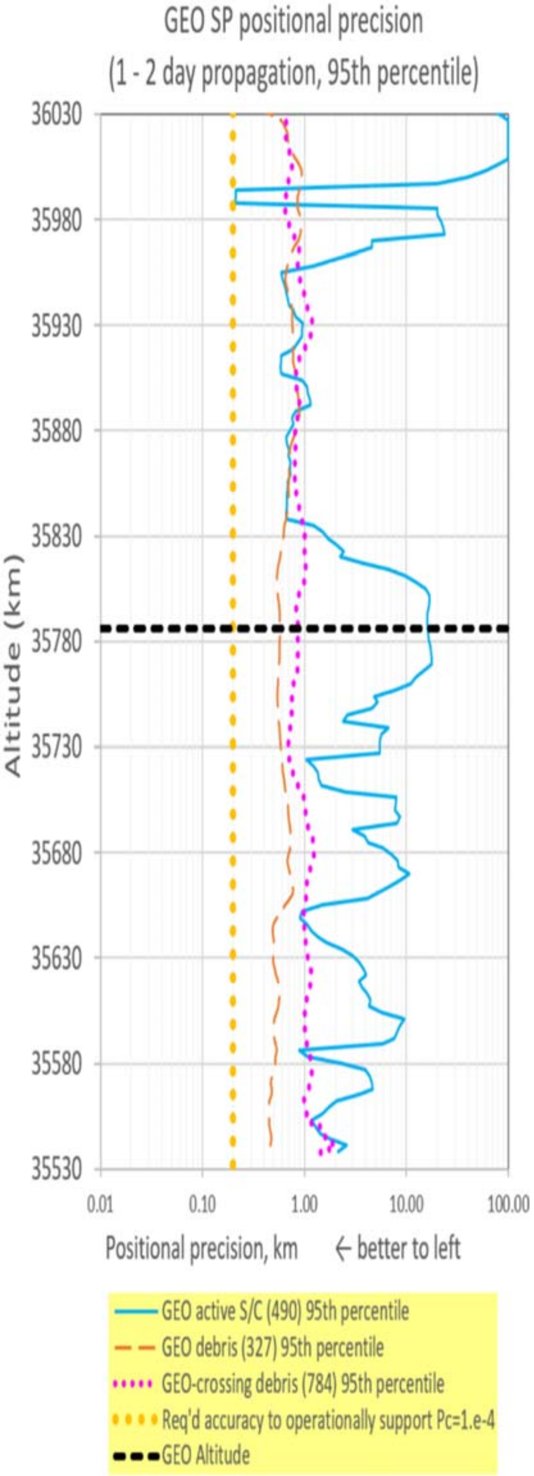

Figure 6 95th percentile GEO SP positional precision (1-2 day propagation)

Discussion: What accuracy is sufficient to meet safety of flight objectives?

Keeping in mind that precision is not the same as accuracy but also noting that accuracy is no better than precision, the reader should select their own precision sufficiency criteria for a particular application, perhaps incorporating sufficient "margin" to reflect the fact that accuracy will be additionally degraded (e.g., by systematic positional biases).

As illustrated in Figure 7 taken from [20], collision probability follows a topology that depends upon aspect ratio, miss distance and covariance. Operators commonly use a one in ten thousand (1×10^{-4}) collision probability (Pc) threshold as the decision metric for deciding when to conduct a collision avoidance maneuver.

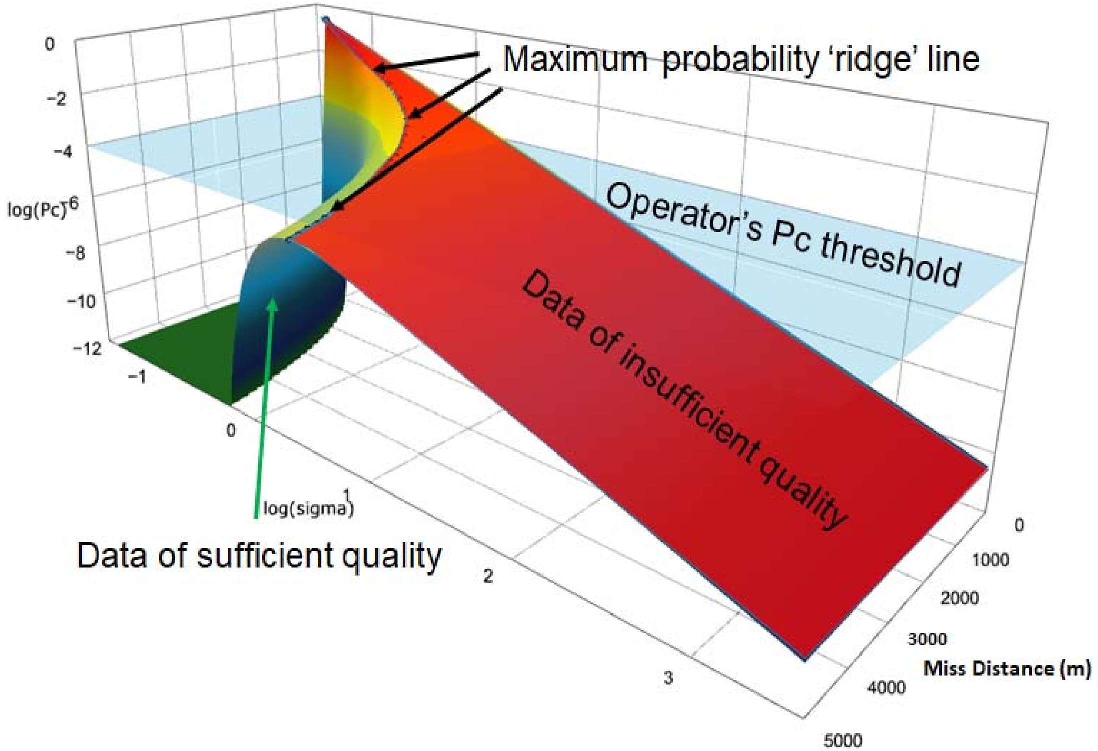

Figure 7 Topography of Pc as a function of miss distance and covariance realism

As indicated in Figure 8 (a higher-fidelity representation of Fig. 10 in [21]) and based upon Fig. 7 and Fig. 8 from [22], a conjunction having an assumed aspect ratio (AR) of 2, a Combined Hard Body Radius (CHBR) of 5 meters, and a Pc threshold of 1×10^{-4} corresponds to an associated miss distance of approximately 450 meters and a combined 1σ major axis eigenvalue (error) of 303 meters for a combined 3σ major axis eigenvalue (error) of 303 x 3 = 909 meters. Assuming equal error allocations to both the primary and secondary conjuncting objects, this 3σ major axis eigenvalue must be divided by √2 to yield each RSO's individual 3σ error allocation as 1836 / √2 = 642 meters apiece.

However, in order to operationally support a collision probability of 1×10^{-4}, the SSA data must be of sufficient quality to not only meet but amply exceed the operator's Pc threshold. For the purposes of this paper, a maximum capability Pc threshold of 1×10^{-3} is assumed to ensure that the typical operator's Pc threshold of 1×10^{-4} can amply be met.

Again drawing from these nomogram figures, under the same underlying assumptions, a Pc threshold of 1×10^{-3} corresponds to an associated miss distance of approximately 135 meters and a combined 1σ major axis eigenvalue (error) of 96 meters for a combined 3σ major axis eigenvalue of 96 x 3 = 288 meters, yielding each RSO's individual 3σ error allocation as 288 / √2 = 204 meters apiece.

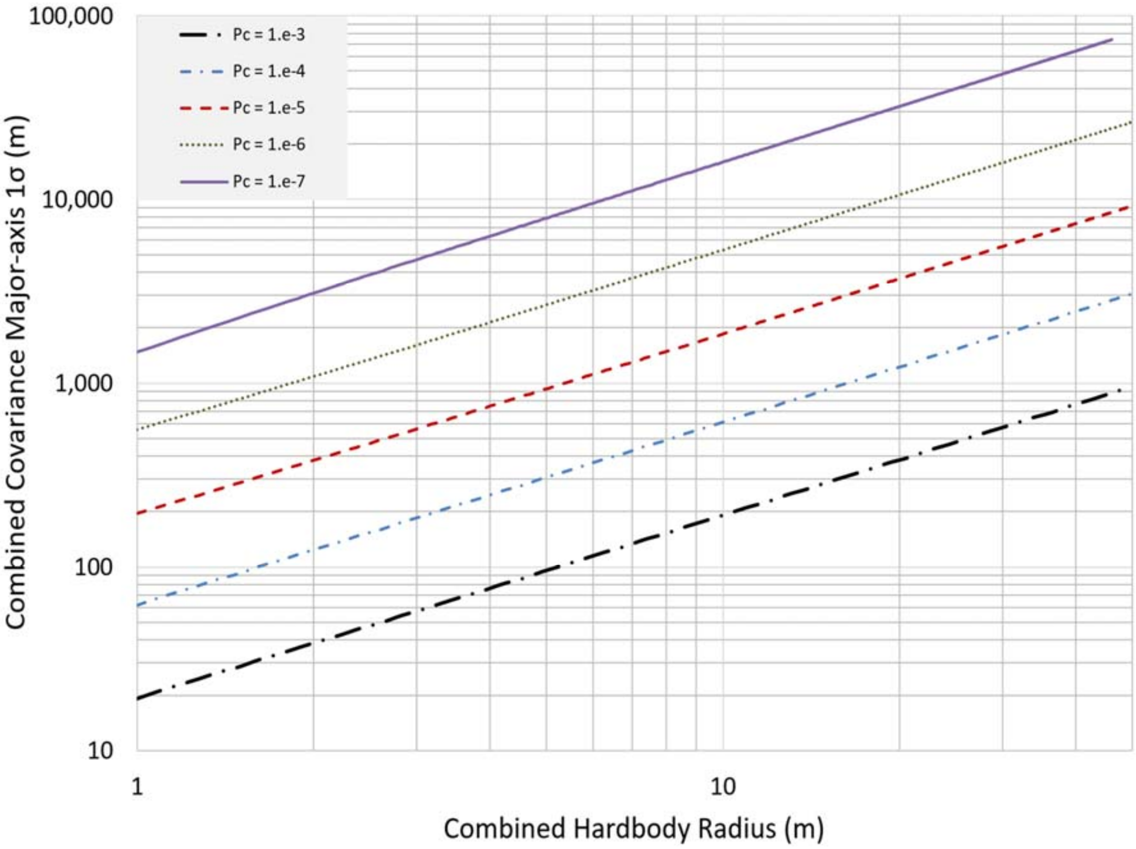

Figure 8 Maximum probability as a function of object size and combined positional error (AR=2)

Finally, note that this worst-case allowable major axis eigenvalue (with an associated 3σ minor axis eigenvalue of half that amount for AR = 2, or 102 meters) may not be fully represented by precision characterized by RSS miss distance, since this miss distance may not be aligned with the maximum eigenvector. Accordingly, a precision threshold of between 150 and 200 meters is suggested as a good 3σ precision threshold that can operationally support collision probability thresholds of 1×10^{-4}.

Discussion: Legacy government SSA performance conclusions

The vertical dotted lines in *Figure 3*, *Figure 4*, *Figure 5* and *Figure 6* depict this 204 m 3σ error bound. Note that while typical precision performance for certain orbit altitudes and object types often meets (i.e., is on the left-hand side of) this limiting accuracy threshold, there are altitude thresholds and object categories for which this SP performance fails to meet the threshold. When one further considers higher levels (e.g., 95th percentile) of performance, this performance threshold may often be further exceeded for certain orbit regimes and object types (e.g., space weather below 700 km, high-eccentricity orbits and maneuvering satellites).

Understanding today's collision risk profile

It is also interesting to roughly characterize the number of potential collisions between currently tracked objects varies as a function of altitude and the type of objects (active satellites vs debris) comprising the conjuncting pair as shown in Figure 9. Note that this characterization is based solely on the current 18SPCS public space catalog, and that the actual collision risk is likely to be substantially higher than portrayed here because we are only tracking 4% of LEO and 4% of GEO space objects larger than 1 cm. In making this estimation, note that these annual collision rates are per 25 km altitude bin, and the Combined Hard Body Radius (CHBR) values constituting a collision were crudely assumed to be 4m for non-GEO satellites-on-satellites, 2.5m for non-GEO satellites-on-debris, 1.5m for non-GEO debris-on-debris, 8m for GEO satellites-on-satellites and 5m for GEO satellites-on-debris.

These figures highlight several key issues: (1) satellite operators are faced with very different collision risk levels depending on altitude; and (2) that the benefits of operators pooling their authoritative data to enable space traffic management vary as a function of altitude. This can be seen in the figure by comparing the estimated collision rate between two active satellites (irrespective of maneuvering capability) with the collision rate between active satellite and collision rate between debris and debris.

In most LEO altitudes, the rate of collision between an active satellite and debris is substantially higher than the collision rate between two active satellites or debris on debris. This can lead a LEO operator to conclude that there is marginal benefit of operators sharing their data with each other since a collision between two active satellites is less likely. Instead, operators depend upon an organization that has a large debris catalog such as 18 SPCS.

The situation is significantly different in GEO, where it is almost equally as likely that a collision would occur between an active satellite and sizable debris as it is between two active satellites. Geo operators feel more empowered by this, in that almost half of their collision risk stems from conjunctions between active satellites. By pooling their authoritative positional, physical and even observational satellite data for analysis, they can actively manage and mitigate a substantial portion of their potential collision risk even a debris catalog did not exist.

Is this approximate collision risk profile consistent with our space flight experience? While that is a difficult question to answer, we do know that (1) at least a dozen collisions have occurred in LEO; and (2) there have been strong indications of a number of collisions in GEO. We should also consider that operators are not likely to publicly announce collisions (or likely collisions) involving their satellite fleet, because it can reflect badly on their company or business case, stocks could be adversely affected, corporate competition could be increased, and the company's customer base could be degraded.

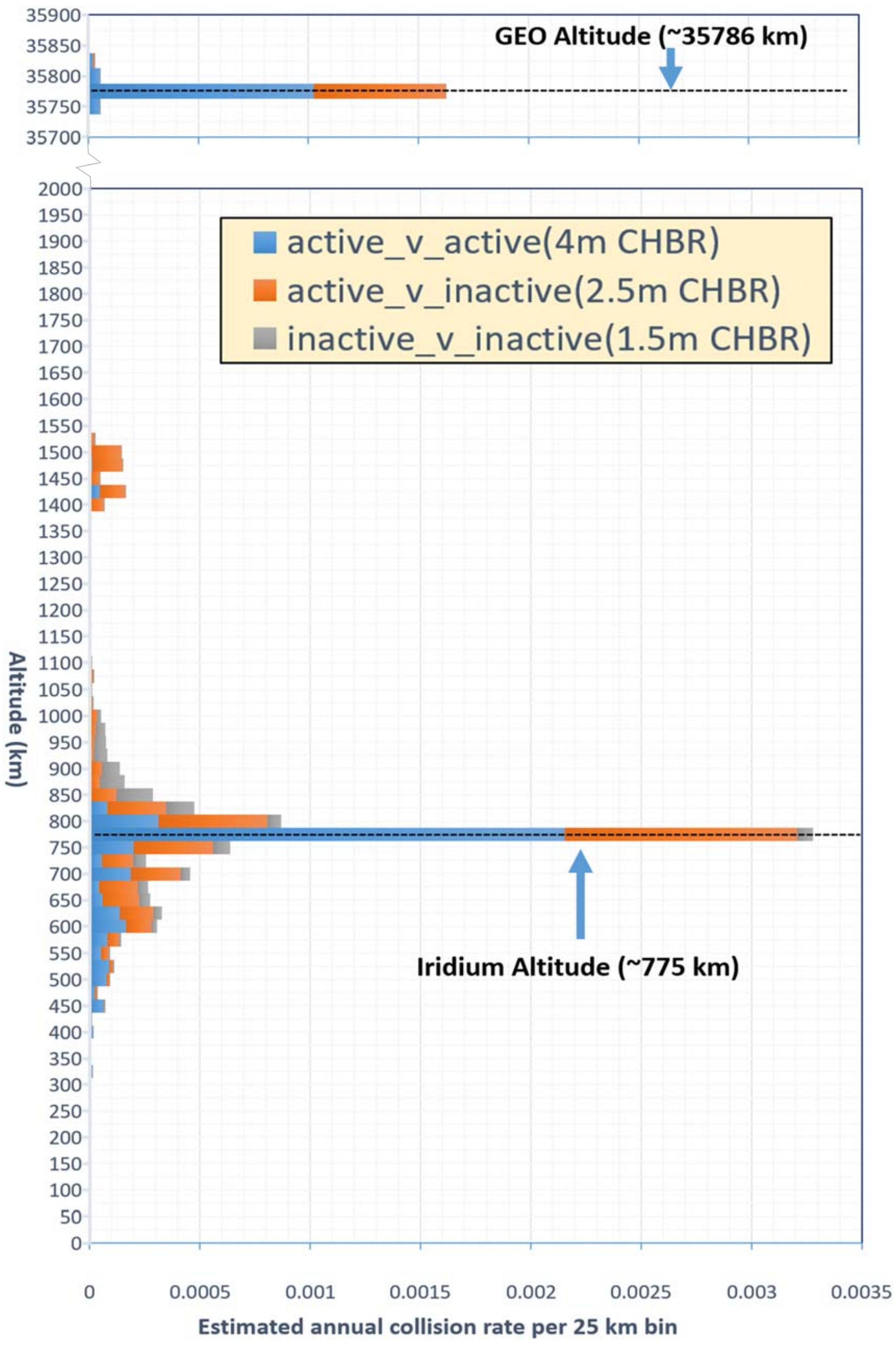

Figure 9 Depiction of annual collision rate as a function of altitude and conjunctor pair types

Tragedy of the Commons, Negative Externalities and opposing market forces

Taken in aggregate across all satellite operator fleets and the debris population, collision and RFI risks can be substantial. However, these risks may be small on an individual satellite operator basis.

Even so, based on the perceived small risk and for financial, anti-regulation, cultural or optics reasons, satellite operators can be motivated to underestimate such space safety and RFI risks and overstate the steps they take to address them. Similar to other tragedy-of-the-commons situations, it would be understandable if an operator's economic business model simply did not account for "worrying about the environment".

In fact, the continual decrease in satellite manufacturing costs due to mass production and smaller satellite sizes may already preclude market forces from protecting our shared satellite operations environment. From a financial perspective, this is a classic example of a "Negative Externality," where a spacecraft operator may willingly lose a satellite to a collision or explosion or hardware failure, especially for large constellations with multiple redundancies and quick re-launch/refurbish capabilities. In this situation, the cost to that operator is substantially less than the potential cost to society for addressing the resulting debris (or subsequent fragmentation event).

These considerations, coupled with a lingering false sense by some that "space is big," can lead to satellite operators accepting their collision risk on behalf of all space operators. They may rely on free legacy systems, either because they feel that these services are sufficient, or simply as a defensive strategy should the unthinkable occur. Yet collisions, once they have occurred, are irreversible and can have long-term, costly effects on the rest of the space operator community.

Safety of flight as a collaborative, coordinated effort

Today, international space sustainability and orbital debris mitigation guidelines and standards lack regulatory mandates, monitoring and enforcement. Against that backdrop, the use of the word "Management" in STM seems potentially misplaced: One can only manage something if one has the authority and capability to do so. What seems to be truly needed is substantially increased Space Traffic Coordination (STC). As a large commercial operator quipped, "I've never seen a case where two operators have not successfully mitigated a known impending serious collision threat."

In recognition of this gap, many space operators and relevant industry stakeholders are proactive in taking steps to quantify and properly address collision risk and promote space safety. Recently, they assembled a set of best practices for sustainability of space operations [23]. These best practices include the promotion, endorsement and striving to implement both existing guidelines and standards (Inter-Agency Space Debris Coordination Committee (IADC) guidelines [24], United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) guidelines [25], International Standards Organization space debris mitigation standards [26] and Consultative Committee for Space Data Systems standards [27]) as well as additional, more stringent space sustainability best practices.

Initially spurred to act by concerns about unpreparedness for the impending increase of new Non-Geosynchronous Orbit (NGSO) large constellations, these best practices now span all phases of spaceflight – from mission design, to launch, checkout, space operations, and disposal – and all orbital regimes, missions and spacecraft form factors.

Primary goals and key facets of a viable STM system

The primary STM goal is to provide decision-quality results to characterize collision risk and to coordinate and synchronize actionable collision avoidance maneuver planning and execution. Yet few appreciate the many moving parts and complexities required to obtain the underlying SSA. Major contributing areas (or links) in the SSA assessment chain include the overall SSA infrastructure, comprehensive space object meta-data repositories, Common Operating Pictures (COPs), SSA sensors, the pooling and fusion of sensor, orbit and RF data, safety-of-flight algorithms and analytics, orbit determination and propagation, and RFI algorithms and analyses. Each of these complex areas consists of many moving sub-assemblies. Providing STM services is an unforgiving task, because STM services do not get "partial credit" if SSA was "mostly right" but a single SSA sub-assembly fails.

Organizations fielding a viable STM system must ensure that, taken in aggregate, it meets many requirements [28]. These can be categorized into the following required key STM traits:

1) **ACTIONABLE**: SSA and derived STM products of sufficient quality to support STM decisions
    a) Ongoing quality control -
    b) Authoritative – Derived from data sources that "know" the situation
    c) Adjustable – SSA performance can be "sized" to meet mission needs and requirements
    d) Generates mandated and/or chosen collision avoidance go/no-go criteria
2) **COMPREHENSIVE**: A complete depiction of the situation
    a) Addresses all relevant orbit regimes and all object sizes, initially down to 2 cm space objects in LEO and 20 cm in GEO, with future goals of even smaller objects.
        i) Low, Mid, and Geosynchronous Earth Orbits (LEO, MEO, GEO)
    b) Good solutions spanning all object categories
        i) Debris
        ii) High Area-to-Mass Ratio (HAMR) objects
        iii) Satellites maneuvering via chemical propulsion, electric propulsion, differential drag
        iv) Rendezvous & Proximity Operations (RPO) and Satellite Servicing Operations (SSO)
    c) "Crowd Sourcing" of satellite & tracking data in an automated "trust but verify" approach
        i) Satellite owner-operators can and should contribute their data, to include planned maneuvers, operator observational data (transponder ranging, GPS measurements, Doppler, optical), predictive ephemerides incorporating their planned maneuvers,

   as-operated RF characteristics and space object meta-data data into a robust, standardized secure and legally-protected framework that protects this operator proprietary data/info
   ii) Automatically monitor and constrain quality of all contributed data – "trust but verify"
   iii) Collect, process and fuse all this authoritative data/information to obtain the best result
   iv) Draw upon the most comprehensive and complete catalogue of space objects available by merging catalogs from multiple organizations
   v) Recognizing that classified operators may be unable to participate directly, the ideal candidate STM system should forward all sharable operator and SSA data to the classified communities, in the hope that that data would be used to exercise due diligence and prevent collision with classified objects.
   vi) One catalog provider may emerge as a trusted gold standard
   vii) Normalized, integrated and quality-controlled inside the STM system to be compatible with both internal data and data collected from other sources
   viii) Identify and remove biases in tracking observations and satellite ops.
   ix) Avoid "extrapolation in a vacuum" whenever possible
3) **TIMELY**: Results must be generated and distributed to relevant space actors in a timeframe sufficient to allow operators to identify, plan, consider, and execute a collision avoidance strategy.
4) **TRANSPARENT**: Data sources, algorithms, processes, operations are well-described and published
5) **HIGH AVAILABILITY**: It is imperative to have assured, secure access to safety of flight products
6) **STANDARDS-BASED**: It is essential that the US lead the development of, promote and adopt internationally standardized space data messages [29, 30, 31] and best practices [32, 33, 34, 35] for all SSA and STM interactions.

Mature commercial SSA and STM services

Mature commercial SSA services in GEO (and maturing in LEO) provide a viable operational SSA and STM option today. Commercial SSA and STM products derive from a diverse set of commercially-gathered data from optical, radar, and passive RF sensors, provide sufficiently accurate and timely information to support operational decisions, and meet STM needs [36, 37]. The Space Data Association (SDA) [38] has used commercial SSA and STM services in an operational capacity for over eight years now, and space industry adoption of commercial SSA services and products continues to increase.

Perhaps some of the greatest commercial innovation has occurred in the development and application of new algorithms. Algorithms really do matter; tremendous algorithmic advances in sensor calibration, recovery from unknown maneuvers, orbit determination, orbit propagation, atmospheric density estimation, and risk assessment all contribute to yield high fidelity SSA. These largely commercial implementations have been routinely applied in the operational environment and properly verified and validated using real-world data.

Noteworthy findings of the National Research Council [39] underscored this importance of SSA algorithms:

- "The key [SSN] system limitations are current sensor coverage, understanding of the quality of the observations [i.e., realistic covariance], and the challenge of [algorithmically] fusing disparate data from different systems and phenomenology."
- "For near-Earth orbiting satellites another limitation is [in] modeling of the atmosphere."

"AFSPC should expand opportunities for astrodynamics and computation specialists to participate in improving the algorithms used in the JSpOC Mission System (JMS, the Air Force's current program (recently cancelled) to modernize the infrastructure used in the JSpOC for maintaining a catalog of objects in space)."

Proposed framework for Space Traffic Coordination (STC)

The overseeing STC entity needs to specify the requirements for an actionable STC system, including the required quantities and qualities of optical, radar and passive RF data. The commercial SSA industry can work with space operators and relevant stakeholders to define the value-added SSA and STC services and analyses needed by operators. With those STC requirements and considerations in hand, it is our view that a public-private partnership should be established between the overseeing STC entity and a known and trusted commercial SSA and STC partner. The private partner can serve as integrator, purchasing agent, quality control monitor and data fusion center for subcontracted observational data providers. A diagram of a proposed framework for this public-private partnership is shown in Figure 10.

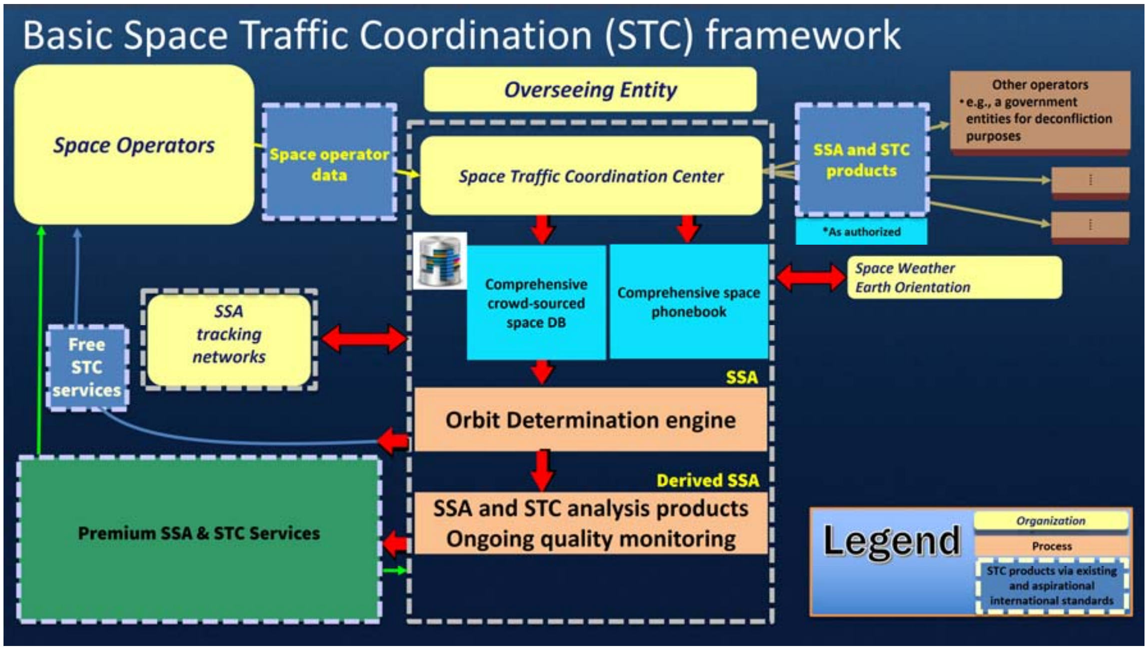

Figure 10 Proposed overseer (public) and commercial (private) framework for comprehensive STC.

In this figure, note that yellow boxes represent organizations, green boxes represent internationally-standardized space data messages, darker blue boxes represent additional shared data, and orange boxes represent processes and analyses.

Space operators have a wealth of authoritative information that they may be willing to share with others in the interest of space safety. The upper left box depicts data from contributing space operators, whether they be operating satellites, launch booster and upper stage vehicles, sub-orbital/exoatmospheric vehicles (e.g. space tourism) and high-altitude balloons or airships. Operator vehicles may include sensors and systems that may be able to provide valuable in-situ measurements of the small debris population to aid the development of refined orbital debris models, or space weather sensors or high-accuracy orbit solutions sufficient to help improve spacecraft charging, space weather and dynamically-calibrated atmosphere models. In this construct, contributing operators are also encouraged to report any satellite and launch vehicle anomalies [40] they may have experienced in the interests of a shared understanding of space risk.

This wealth of operator and refined space weather and debris models can be shared as internationally standardized navigation messages that are fed into the ISSC shown in the bottom center block. By ingesting space catalogue observations and ephemerides and pooling that data with actionable operator-provided data, comprehensive, actionable and timely SSA and STM assessments can be made. SSA and STC results can then be shared back to the space operators, again relying heavily on the current and future internationally standardized messages.

As shown in the upper right-hand corner, this concept further departs from other SSA and STM concepts by explicitly recognizing that because of national security and commercial concerns, there will always be nations and/or organizations who are unwilling to participate in the ISSC but want to do their part to minimize space debris. Such entities are called "Willing Non-Contributor Operators (WNCOs). ISSC data is shared with them, under a fine-grained user access methodology, only when authorized by the original data owners. The intent of officially sharing SSA and STM data with WNCOs is that the WNCO will use this provided information to screen against their non-public (due to intellectual property or classification reasons) space objects to preclude collision or RFI events from occurring.

Note that where one or more WNCOs view the STC operator as a known and trusted organization, further efficiencies to the ISSC framework can be gained by integrating the public-facing ISSC SSA services with the WNCO's SSA and STM services. This would allow authoritative public data to be merged with WNCO data in a self-consistent manner, greatly reduce transmission bandwidth, reduce latencies and eliminate the need to normalize data between systems.

In this framework, accurate, timely and actionable Basic STM services would be provided irrespective of access to government SSA sensor observations by using a "system of systems" aggregation of multiple tracking entities and sensor phenomenologies. Any government sensor observations additionally made available to the proposed STM enterprise by the overseeing entity could also be incorporated into the fused orbit solutions to further enhance orbit accuracy and safety-of-flight notifications for basic safety of flight services.

Central to this framework are (1) extensive crowdsourcing of space data; (2) fusion of available data in a trust-but-verify construct; (3) improved Basic STM standard "free-to-operator" CA and reentry services using best-of-breed commercial processing software and SSA inputs to better meet basic safety of flight needs; (4) value-added "Premium Services" to meet operator needs for enhanced safety of flight and RFI mitigation; (5) reliance on internationally-standardized space data messages for all inter-organizational communications; and (6) augmentation of extant government space data with pre-screened, commercial operator contributed maneuvers, ephemeris, satellite states-of-health, attitude, dimensions, tracking observations and ranging, events and other assorted spacecraft and operator metadata.

In this manner, this public-private partnership can provide a multi-tiered service offering analogous to satellite Earth imagery sold today, with lower tier 30m Landsat data freely available, a commercial provider offering "Premium Services" as a mid-level 0.25 – 5 m imagery where there is a good market for improved imagery services, and an ultra-fine imagery tier provided by special/unique government capabilities for government-internal applications. Also note that in the current imagery service construct, the overseeing entity serves as an underwriter "anchor tenant" by accounting for half of the commercial imagery provider's revenue.

Consistent with Space Policy Directive 3 (SPD-3) sections 5(a)(ii) and 5(b)(ii), such a partnership with a commercial industry partner is well-aligned with SPD-3 requirements. Particular emphases are to (1) improve the coverage, timeliness, accuracy and actionability of the basic "free" level of STM service through SSA data sharing, purchase of SSA data by the overseeing entity, and the provision of new sensors; and (2) enable commercial SSA and STM sectors to continue to lead in developing and providing STM-related technologies, goods, data, and services.

Public-private roles in the partnership

The public partner would be chartered to:

- Arranging funding, either by the overseeing entity (legacy model), or funded in whole or in part by licensing and/or operations fees levied on satellite operators, potentially based on number of satellites, class of operator (as exists in aviation today), orbit regime, estimated lifetime, incurred risk due to operation, etc.
- Authorize for-cost tailored premium services based upon comprehensive space data repository
    - Stimulate high-cadence commercial innovation
    - Do not artificially constrain commercial entities to fit legacy constructs or procurement processes
    - Let multiple commercial SSA entities participate (i.e., do not worry about "picking a winner")
- Provide national regulatory governance
    - Manage complementary and competing interests/equities across government responsibilities and commercial/financial incentives
    - Provide path to monitor compliance with regulatory mandates and conditional license authorizations
- Authorities for international gov't-to-gov't cooperation and collaboration
- After STM services are established, assess roles and responsibilities for free service
    - Establish date for hand off to commercial entity

    - Consider use of data repository for free service, providing an improved basic level of spaceflight safety

The private partner would be chartered to:

- Continue to provide on-going basic free SSA services and actionable CDMs
    - Supports basic users unable to pay for services (e.g., authorized academic institution CubeSat missions)
- Incorporates legacy space object ID mappings and legacy SSA data and derived products as directed by the overseeing entity
    - Augment legacy data products as required to maintain minimum standards of service.
- Form and manage a comprehensive space data repository, "seeded" by commercial SSA-generated tracking observations and OD information and Air Force Space Surveillance Network (SSN) collected observational data, augmented by crowd-sourced data pooling of all available authoritative data.
- Forward all sharable operator and SSA data/information to NSS community for use in SSA analyses and collision avoidance processing for classified objects.
- Provide transparency not possible through legacy national security channels
- Set certification requirements for commercial SSA and STM contributors, based upon quality of service, accuracy, timeliness, etc. (similar to launch and communications industry requirements).
- Encourage spacecraft operators to:
    - Contribute their data and facilitate user accounts and space data exchange;
    - Seek tailored, decision-quality STM services using the space data repository and enhanced (premium) STM services
    - Incorporate enhanced trackability features (RFID tags, re-entry thrusters, or GPS receivers) into satellite designs to enable cost-effective tracking of these satellites to ensure safe operations

Criticality of International Standards for STC

It is critical that international standards serve as the data pooling and/or exchange underpinning to the STM framework, addressing both current and aspirational internationally standardized data message needs.

Currently, CCSDS navigation messages accommodate the exchange of **attitude**, **conjunction**, **event**, **orbit**, **pointing**, **reentry** and **tracking** data in an internationally standardized way. Additionally, internationally standardized messages are needed to address **anomaly**, **fragmentation**, **geolocation**, **launch**, **RFI**, **RF characteristics** and Rendezvous Proximity Operations and Satellite Servicing Operations (**RPO/SSO**) events.

Conclusion

Practical considerations for a Space Traffic Management system have been presented. Based on these considerations, a public-private partnership framework for STM/STC services is proposed that is well-suited for near-term rapid deployment and operations, while also providing defined avenues for ongoing quality assessment and control, agile capability improvements and evolution, science and technology research and robust scalability. This framework is necessary to provide decision quality SSA and STM information and services to space operators for effective collision risk mitigation and RFI mitigation. This framework extensively leverages crowdsourcing of spacecraft operator and operational commercial SSA data.

The foundational facets of such a system, required to produce actionable, decision-quality results, are summarized in Table 1.

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Table 1 Summary of key facets in a viable STM or STC system

Facet	Operational Implementation	Maturity
Trusted crowdsourcing of SSA data from spacecraft operators, SSA centers	Space Data Center	Operational for 8+ years, 99.99% availability
Diverse sensor phenomenologies, types, geographic locations	Commercial SSA market	TRL 9 for 4 years
Comprehensive data fusion of authoritative multi-source SSA data and information (independent of formats, units & coordinate systems) in a normalized, interoperable data repository using a trust-but-verify construct	Commercial SSA market	TRL 9 for 15 years
Use of numerically validated, proven, operationally-ready **advanced SSA algorithms**	Commercial SSA market	TRL 9 for 20 years
Full support to the development and adoption of standardized space data messages (both format and metadata) and space operator best practices	ISO, CCSDS, GVF, CONFERS	>20 years

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