Proposal for an STCM Standard

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When we last discussed a STM standard last Fall:

- I'd stated that more work is needed before STM standards can be developed.
  - Often operators act on false alarms for collision avoidance.
  - LEO & GEO catalogs contain only 4% of the population > 1 cm.
  - According to ESA there have been 246 non-deliberate explosions since 1999. 60% SC and 65%
  - LV in LEO successfully perform a disposal (Including the natural compliant SC).
  - 57,145 new spacecraft have been proposed for the next 10 years. However, they cannot all be launched because of the limitations of launcher availability and capacity.
- An AIAA STM study identified regulations from 11 countries (still missing some). Results were synthesized Into a matrix of governance. The level of governance in different areas was scored according to how detailed and demanding the rules are.
- It was noted that there are some gaps in the information, e.g. SSA, algorithms, data-pooling, standards, and quality assurance. Inputs from countries such as China, India, and Russia would also be useful.

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From AIAA STM Task Force: Observed Gaps in Current STM Governance

- **SSA and STM gaps were observed during evaluation:**

Quality Control	Independent verif/validation
Operator phonebooks, personnel roles	Active Debris Removal (ADR)
Comprehensive, timely, accurate	Just-in-Time Debris Removal (JDR)
Deployment strategies: trackability, association, discrimination	Decision-quality risk assessment procedures and safety metric
"Rules of the road"	Covariance realism tests
Data normalization: Reference frames, units, timing, elements	Standards and regulations that incentivize good behaviors
Rendezvous/Proximity Operations (recently approved NWIP)	Data pooling protecting Intellectual Property, priopríetary dat
On-Orbit Servicing (recently approved NWIP)	SSC suggested inclusions
Earth Orientation Parameters	Standards for Uncorrelated Track association
Space Weather	Ephemeris sharing to support optical transit deconfliction
Atmosphere models	
Tasking	Algorithms, performance assessment and assurance
Anomaly data sharing (and how to share it)	- Orbit determination
Satellites-as-a-sensor	- Orbit propagation (numerical)
Comparative SSA	- Space weather prediction
Standards governing spacecraft visual magnitude, paints, etc.	- Force modeling

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STM detractors…

- Incorrect Earth Orientation
- Insufficient error metrics
- Timing errors and biases
- Uncalibrated sensors
- Unknown space weather
- Unmodeled maneuvers
- Sensor lighting constraints
- Uncalibrated maneuvers
- Inadequate quality control
- Undersampled observations
- Unrealistic covariances
- Low thrust maneuvering
- Sensor staffing time biases
- Non-linear encounters
- Nonstandard data formats
- Error growth
- SRP mismodeling
- Integration errors
- Unmodeled perturbations
- Mission priority conflicts
- Track mis-association
- Cross-tagging
- Atmosphere mismodeling
- Incompatible reference frames
- Poor observability
- Low-fidelity propagator
- Scope creep
- Incomplete space catalog
- Lack of transparency
- Insufficient training
- Overconfidence in tools and methods
- Organizational firewalls
- No comparative SSA
- Poor sensor tracking scheduling
- Poor orbit determination algorithms
- Unknown spacecraft dimensions
- Ephemeris and covariance interpolation errors
- Unknown spacecraft mass properties
- Unknown spacecraft attitude

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Drafted up a pre-NWIP Form 4 and STCM standard for our consideration.

- Introduction
- 1 Scope
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- 4 Technical Requirements
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- A.1 General
- A.2 ISO xxxxx, Space systems - Detailed space debris mitigation requirements for spacecraft
- Annex B (informative) Methods for assessing STCM parameters
- B.1 Positional precision as a proxy for positional accuracy
- B.2 Estimation of historical and predictive positional accuracy
- B.3 Covariance, attitude and vector interpolation via the Euler Axis/Angle method
- B.4 Apparent-to-Absolute Visual Magnitude relationship
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- B.6 Orbit determination
- B.7 STM Quality Control Processes: Ephemeris upload monitoring
- B.8 STM Quality Control Processes: ephemeris precision by operator
- B.9 Diverse avoidance manoeuvre Go/No-Go metrics and threshold
- B.10 Conjunction assessment process

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International Organization for Standardization
Organisation internationale de normalisation
Международная организация по стандартизации

1. Form 4:
2. New Work Item Proposal (NP)

Circulation date 2020-06-01 **Closing date for voting** Click here to enter a date.	**Reference number:** Enter Number (to be given by ISO Central Secretariat) **ISO/TC** 20 **/SC** 14 ☐ Proposal for a new PC **N** Click here to enter text.
Proposer ☒ ISO member body: Click here to enter text. ☐ Committee, liaison or other[1]: Click here to enter text.	
Secretariat Click here to enter text.	

A proposal for a new work item within the scope of an existing committee shall be submitted to the secretariat of that committee.

[1]The proposer of a new work item may be a member body of ISO, the secretariat itself, another technical committee or subcommittee, an organization in liaison, the Technical Management Board or one of the advisory groups, or the Secretary-General. See ISO/IEC Directives Part 1, Clause 2.3.2.

The proposer(s) of the new work item proposal shall:

- make every effort to provide a first working draft for discussion, or at least an outline of a working draft;
- nominate a project leader;
- discuss the proposal with the committee leadership prior to submitting the appropriate form, to decide on an appropriate development track (based on market needs) and draft a project plan including key milestones and the proposed date of the first meeting.

The proposal will be circulated to the P-members of the technical committee or subcommittee for voting, and to the O-members for information.

IMPORTANT NOTE
Proposals without adequate justification risk rejection or referral to originator.

Guidelines for proposing and justifying a new work item are contained in Annex C of the ISO/IEC Directives, Part 1.

☒ The proposer has considered the guidance given in the Annex C during the preparation of the NP.

Resource availability:

☒ There are resources available to allow the development of the project to start immediately after project approval* (i.e. project leader, related WG or committee work programme).

* if not, it is recommended that the project is first registered as a preliminary work item (a Form 4 is not required for this) and when the development can start, Form 4 should be completed to initiate the NP ballot.

Proposal (to be completed by the proposer, following discussion with the committee leadership)

Title of the proposed deliverable

English title
Space Systems – Space Traffic Coordination and Management

French title (if available)
Systèmes spatiaux - Coordination et gestion du trafic spatiale

(In the case of an amendment, revision or a new part of an existing document, include the reference number and current title)

Scope of the proposed deliverable

This recommended standard addressees protocols and operational Space Traffic Coordination and Management requirements critical to ensure flight safety and mitigate collision risk, from pre-launch safety assessment through manoeuvre plans, on-orbit collision avoidance support services, and end of mission disposal. This standard levies requirements of an STCM system to that it will provide high-availability, timely, comprehensive and sufficiently accurate services to support the safe, efficient and sustainable use of space.
This STCM standard addresses:

- Protocols for collection and exchange of data relevant to space safety;
- Protocols for creating, populating and operating an open architecture data repository to facilitating open data exchange;
- Ingestion of data into a data lake as part of an open architecture data repository;
- Data integrity measures and standards to ensure quality from diverse sources;
- Space Situational Awareness (SSA) data derives from multiple and diverse sources.
- Measures to safeguard proprietary or sensitive data;
- Owner-operator notification of flight plans and planned manoeuvres and sharing of orbital location data (ephemerides)
- Timely and actionable warnings; sharing of catalogue data, to predict close approaches;
- Interoperable formats to enable reliable messaging STCM inputs and results, timely and actionable warnings, referencing extant CCSDS standards where applicable;
- Exchange of catalogue data to predict close approaches and assess options for operator collision avoidance manoeuvre plans.
- Formats to enable development of applications to leverage data and perform automated processes for collision avoidance.
- Encryption of satellite TT&C, command and control links and data protection measures for ground site ops
- Coordination for satellites transiting LC radial shells

This standard requires flexibility to accommodate our deeper understanding of the impacts upon the space environment created by increased and emerging space activities and to benefit from technological advances and refined capabilities.

Purpose and justification of the proposal

Space operations are increasingly complex and congested. In the New Space era of large constellations and explosive growth in our space object population, it is time for a Space Traffic Coordination and Management (STCM) standard that specifies methods to coordinate and manage space traffic, which will, in turn, promote safe, efficient and responsible behaviour in space. All spacefaring nations share interest and responsibility to create conditions for a safe, stable, and operationally sustainable space environment.

Consider the following:
Is there a verified market need for the proposal?
What problem does this document solve?
What value will the document bring to end-users?

See Annex C of the ISO/IEC Directives part 1 for more information.

See the following guidance on justification statements in the brochure 'Guidance on New work': https://www.iso.org/publication/PUB100438.html

Please select any UN Sustainable Development Goals (SDGs) that this document will support. For more information on SDGs, please visit our website at www.iso.org/SDGs."

☐ **GOAL 1:** No Poverty
☐ **GOAL 2:** Zero Hunger
☐ **GOAL 3:** Good Health and Well-being
☐ **GOAL 4:** Quality Education
☐ **GOAL 5:** Gender Equality
☐ **GOAL 6:** Clean Water and Sanitation
☐ **GOAL 7:** Affordable and Clean Energy
☐ **GOAL 8:** Decent Work and Economic Growth
☐ **GOAL 9:** Industry, Innovation and Infrastructure
☐ **GOAL 10:** Reduced Inequality
☒ **GOAL 11:** Sustainable Cities and Communities
☒ **GOAL 12:** Responsible Consumption and Production
☐ **GOAL 13:** Climate Action
☐ **GOAL 14:** Life Below Water
☐ **GOAL 15:** Life on Land
☐ **GOAL 16:** Peace and Justice Strong Institutions
N/A **GOAL 17:** Partnerships to achieve the Goal

Preparatory work
(An outline should be included with the proposal)

☒ A draft is attached
☐ An outline is attached
☐ An existing document will serve as the initial basis

The proposer or the proposer's organization is prepared to undertake the preparatory work required: ☒ Yes ☐ No

If a draft is attached to this proposal Please select from one of the following options (note that if no option is selected, the default will be the first option): ☒ Draft document can be registered at Working Draft stage (WD – stage 20.00) ☐ Draft document can be registered at Committee Draft stage (CD – stage 30.00) ☐ Draft document can be registered at Draft International Standard stage (DIS – stage 40.00) ☐ If the attached document is copyrighted or includes copyrighted content, the proposer confirms that copyright permission has been granted for ISO to use this content in compliance with clause 2.13 of the ISO/IEC Directives, Part 1 (see also the Declaration on copyright).
Is this a Management Systems Standard (MSS)? ☐ Yes ☒ No **NOTE:** if Yes, the NP along with the Justification study (see Annex SL of the Consolidated ISO Supplement) must be sent to the MSS Task Force secretariat (tmb@iso.org) for approval before the NP ballot can be launched.
Indication of the preferred type or types of deliverable to be developed ☒ International Standard ☐ Technical Specification ☐ Publicly Available Specification
Proposed Standard Development Track (SDT) To be discussed between proposer and Secretary considering, for example, when does the market (the users) need the document to be available, the maturity of the subject etc. ☐ 18 months* ☒ 24 months ☐ 36 months ☐ 48 months * Projects using SDT 18 are eligible for the 'Direct publication process' offered by ISO /CS which reduces publication processing time by approximately 1 month.

Draft project plan (as discussed with committee leadership) Proposed date for first meeting: 2020-06-15 Proposed dates for key milestones: 1st Working Draft (if any) circulated to experts: 2020-08-15 Committee Draft ballot (if any): 2020-11-15 DIS submission*: 2021-04-15 Publication*: 2021-08-15 * Target Dates on DIS submission and Publication should preferably be set a few weeks ahead of the limit dates (automatically given by the selected SDT). For guidance and support on project management; descriptions of the key milestones; and to help you define your project plan and select the appropriate development track, see: go.iso.org/projectmanagement **NOTE:** The draft project plan is later used to create a detailed project plan, when the project is approved.
Known patented items (see ISO/IEC Directives, Part 1, clause 2.14 for important guidance) ☐ Yes ☒ No If "Yes", provide full information as annex
Co-ordination of work To the best of your knowledge, has this or a similar proposal been submitted to another standards development organization? ☐ Yes ☒ No If "Yes", please specify which one(s): Click here to enter text.
A statement from the proposer as to how the proposed work may relate to or impact on existing work, especially existing ISO and IEC deliverables. The proposer should explain how the work differs from apparently similar work, or explain how duplication and conflict will be minimized As stated above ("Scope"), this standard will levy requirements for Space Traffic Coordination and Management (STCM) systems. This standard will incorporate by reference compliance with relevant existing ISO standards for these disciplines, such as the subset of ISO standards included in the referenced documents below:

A listing of relevant existing documents at the international, regional and national levels		
10784: Space systems — Early operations 14302: Space systems — Electromagnetic compatibility requirements 14620: Space systems — Safety requirements 14622: Space systems — Structural design 14623: Space systems — Pressure vessels and pressurized structures - Design and operation 14950: Space systems — Unmanned spacecraft operability 15864: Space systems — General test methods for spacecraft, subsystems, and units 16126: Space systems — Space systems - Survivability of unmanned S/C against impacts 16127: Space systems — Prevention of break-up of unmanned spacecraft 16158: Space systems — Avoiding collisions with orbiting objects 16164: Space systems — Disposal of satellites operating in or crossing Low Earth Orbit 16679: Space systems — Relative motion analysis elements after LV/SC separation 17666: Space systems — Risk management 18146: Space systems — Space debris mitigation design, operation guidelines for spacecraft 20188: Space systems — Product assurance requirements for commercial satellites 23041: Space systems — Unmanned spacecraft operational procedures — Documentation 23339: Space systems — Unmanned S/C residual propellant mass estimation for disposal DV 24113: Space systems — Space debris mitigation requirements 26872: Space systems — Disposal of satellites operating at geosynchronous altitude 26900: Space systems — Space data and information transfer— Orbit data messages 19389: Space systems — Space Data and Information Transfer— Conjunction Data Message 27852: Space systems — Estimation of orbit lifetime 27875: Space systems — Re-entry risk management for unmanned S/C and LV stages IADC Space Debris Guidelines IADC Statement on Large Constellations U.S. Space Policy Directive 3: U.S. Orbital Debris Mitigation Standard Practices 2019 Space Safety Coalition's Best Practices for the Sustainability of Space Operations (and many other national and international guidelines and regulations)		
Please fill out the relevant parts of the table below to identify relevant affected stakeholder categories and how they will each benefit from or be impacted by the proposed deliverable(s)		
	Benefits/impacts	**Examples of organizations/companies to be contacted**
Industry and commerce – large industry	This standard will provide guidance and normative mandates to designers and operators of STCM systems to promote the responsible and sustainable use of outer space.	Commercial SSA, STC, and STM service providers.
Industry and commerce – SMEs	This standard will provide guidance and normative mandates to SMEs to promote the responsible and sustainable use of outer space.	Commercial SSA, STC, and STM service providers.

Government	This standard will provide guidance and normative mandates for potential interpretation and adoption by government lead agencies responsible for fielding and operating STCM systems.	Space State Actors
Consumers	Click here to enter text.	Click here to enter text.
Labour	Click here to enter text.	Click here to enter text.
Academic and research bodies	This standard can provide research institutions and universities with relevant areas where research in Space Traffic Coordination and Management would best benefit space sustainability and operator efficiency and commercial feasibility.	Universities, research institutions.
Standards application businesses	Click here to enter text.	Click here to enter text.
Non-governmental organizations	This standard can offer guidance and insight into ways that NGOs can promote and adopt best practices for STCM in their aspirational and educational content.	Space Safety Coalition
Other (please specify)	Click here to enter text.	Click here to enter text.

Liaisons A listing of relevant external international organizations or internal parties (other ISO and/or IEC committees) to be engaged as liaisons in the development of the deliverable(s). ISO TC20/SC13 (duality w/CCSDS) NAV WG	**Joint/parallel work** **Possible joint/parallel work with** ☐ IEC (please specify committee ID) Click here to enter text. ☐ CEN (please specify committee ID) Click here to enter text. ☐ Other (please specify) Click here to enter text.

A listing of relevant countries which are not already P-members of the committee

Click here to enter text.

NOTE: The committee manager shall distribute this NP to the ISO members of the countries listed above to ask if they wish to participate in this work

Proposed Project Leader (name and e-mail address) WG3: Dan Oltrogge, oltrogge@agi.com	**Name of the Proposer** (include contact information) Dan Oltrogge, oltrogge@agi.com

This proposal will be developed by

☒ An existing Working Group (please specify which one: TC20/SC14/WG3)
☐ A new Working Group (title: Click here to enter text.)
(Note: establishment of a new WG must be approved by committee resolution)
☐ The TC/SC directly
☐ To be determined

Supplementary information relating to the proposal

☒ This proposal relates to a new ISO document;
☐ This proposal relates to the adoption as an active project of an item currently registered as a Preliminary Work Item;
☐ This proposal relates to the re-establishment of a cancelled project as an active project.

☐ Other:
Click here to enter text.

Maintenance agencies (MA) and registration authorities (RA)

☐ This proposal requires the service of a **maintenance agency**.
If yes, please identify the potential candidate:
Click here to enter text.

☐ This proposal requires the service of a **registration authority**.
If yes, please identify the potential candidate:
Click here to enter text.

NOTE: Selection and appointment of the MA or RA is subject to the procedure outlined in the ISO/IEC Directives, Annex G and Annex H, and the RA policy in the ISO Supplement, Annex SN.

☒ Annex(es) are included with this proposal (give details)

(1) Outline of Space Traffic Coordination and Management standard
(2) Space Traffic Coordination and Management draft standard

Additional information/questions

This item will be developed and reviewed by WG3 with support of WG7.

Annex 1: Outline of "Space Systems – Design, Testing and Operation of a Spacecraft Large Constellation"

DRAFT for NWIP

xxxx

2020-05-22

Space systems —

Space Traffic Coordination and Management

26 May 2020

ISO\TC20\SC14\WG3

PoC D. Oltrogge, oltrogge@agi.com

Contents Page

Introduction

This Space Traffic Coordination and Management standard specifies requirements for the coordination and management of space traffic, which will, in turn, promote safe, efficient and responsible behaviour in space. All spacefaring nations share interest and responsibility to create conditions for a safe, stable, and operationally sustainable space environment.

Space systems — Space Traffic Coordination and Management

1 Scope

This recommended standard codifies the essential facets, protocols and operational Space Traffic Coordination and Management (henceforth referred to as "**STCM**") requirements critical to ensure flight safety and mitigate collision risk and Radio Frequency Interference (RFI), from pre-launch safety assessment through manoeuvre plans, on-orbit collision avoidance and RFI mitigation support services, to mission disposal.

This standard levies requirements on the STCM Lead Agency, STCM Lead Integrator or Operator, STCM Servers and Network, STCM System, STCM Orbit Determination and Prediction, STCM Space Data Interfaces, STCM Data Aggregation and Curation, STCM Operations, STCM Quality Control, and STCM SSA Systems, and STCM Algorithms and Metrics. These requirements are designed to ensure that STCM analyses and services are timely, accurate, comprehensive, transparent, standards-based, progressive, and highly-available to support the operators' risk mitigation decision-making processes:

- **TIMELY** means that Space Situational Awareness (SSA) analyses and risk assessment information and STCM products are produced and delivered on operationally-relevant timescales to allow the operator to develop possible courses of action (e.g. collision avoidance) and implement the selected action.
- **ACCURATE** means that for all required object categories and types (debris, HAMR, manoeuvring, RPO, and OOS), the resulting orbit solutions and predictions are maintained accurately enough to support the decision authority's selected safety criteria and minimally acceptable criteria thresholds.
- **COMPREHENSIVE** means incorporating SSA information on all relevant space objects to the required detectability threshold(s) spanning all required orbit regimes. It also means drawing upon the rich set of "crowd sourced" spacecraft metadata and tracking data from a diverse and comprehensive set of space operators, SSA service providers and tracking sensors via an automated "trust but verify" approach;
- **TRANSPARENT** means that data sources, algorithms, processes, operations and STCM status and anomalies are well-described and published.
- **STANDARDS-BASED** means that the STCM system supports and relies upon international standard space data messages and standardized operational best practices.
- **PROGRESSIVE** means that the STCM system must be flexible to accommodate our deeper understanding of the impacts upon the space environment created by increased and emerging space activities and to benefit from technological advances and refined capabilities.
- **HIGH AVAILABILITY** means assured, secure access to SSA and STCM products and services.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1 Space Situational Awareness (SSA)

As noted in [1 and 2], there are numerous definitions of the over-subscribed phrase Space Situational Awareness (**SSA**). A comparative interpretation of these definitions is shown in Table 1. The principle observation from this table is that some definitions include national security elements and the others do not. For the purpose of space safety for which this standard is intended, Space Situational Awareness shall be defined as "the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities."

2.1 Space Traffic Coordination and Management

Also, as noted in [1 and 2], there have been numerous definitions of the phrase Space Traffic Management. These are comparatively shown in Table 2. Here, we see the valid functions of licensing, regulatory aspects and traffic control to be discriminators for certain definitions, while other definitions are focused on monitoring and coordination.

To properly differentiate between these two legitimate aspects of space safety, the term **Space Traffic Coordination (STC)** shall be defined as "the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment."

The term **Space Traffic Management (STM)** shall be defined as "the licensing, regulation, control and enforcement of activities to enhance the safety, stability, and sustainability of operations in the space environment.

Space Traffic Coordination and Management (STCM) shall be defined as encompassing both STC and STM, i.e., the combination of coordination and enforcement, recognizing that space traffic management and enforcement cannot be effectively and optimally achieved without appropriate attention to coordination.

NOTE: This standard will incorporate both coordination (STC) and enforcement (STM) normative content. The applicability of the enforcement clauses is at the discretion of the applicable State Actor's STCM decision authority.

Table 1 Sample of definitions for Space Situational Awareness (SSA)

Space Situational Awareness Attribute	AFI 14-SPACE	Alfano, CSSI	France/CNES	ESA	EU	Space Foundation	Space Nav	Space Domain Aware.	US Space Policy	US SPD-3
Characterization of Earth-based space capabilities	•	•						•		
Characterization of space/operating environment	•	•		•			•	•		•
Characterization of space-based capabilities	•	•		•			•	•		•
Comprehensive knowledge and status of space objects	•	•	•	•	•		•	•		•
Current and future knowledge	•	•	•	•	•	•	•	•		•
Identification of bad actors in space								•	•	
Monitoring multinational space readiness	•							•		
Near-Earth Objects (i.e., comets and asteroids)					•			•		
Protects space assets to function as designed		•						•		
Radio emissions (ground- and space-based)	•	•						•		•
Safe, sustainable and stable space activities		•						•		•
Space and terrestrial weather	•	•	•		•			•		•
Space Domain Awareness and analysis	•							•		
Threat monitoring and risk assessment	•			•			•	•		•
Timely, relevant, accurate, actionable		•		•				•		•
Understand & predict space object physical locations	•	•	•	•	•	•	•	•		•

Table 2 Sample of definitions for Space Traffic Management (STM)

Space Traffic Management Attribute	Aerospace	Athens Univ.	Blout	DLR	IAA COSMIC	GWU	ITU	NASA/JSC	US Space Policy	US SPD-3
Best practices, standards, tech means	•		•		•					•
Free from physical interference	•		•		•		•			•
Free from RF interference	•		•		•		•			•
Information security								•		
Monitoring and notifications	•			•				•		•
On-orbit collision avoidance	•	•				•		•		•
Plan, coordinate, synchronize activities				•					•	•
Pre-launch risk assessments										•
Safe launch		•		•	•		•		•	•
Safe orbit operations		•		•	•		•		•	•
Safe return from space		•		•	•		•		•	•
SSA		•								
Regulatory/enforcement										
Licensing and allocation				•						
Regulatory		•	•		•					
Rules of the road								•		
Traffic control/enforcement	•	•				•		•		

2.2CCSDS SANA Registry

For the purpose of space data exchange, reference frames, element sets, timing systems, attitude specifications, spacecraft and orbit types, atmosphere and gravity models and spacecraft activity status shall adopt the CCSDS SANA Registry definitions [3].

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NOTE: ISO also maintains a terminological database representing the en masse aggregation of all ISO standards called the Online Browsing Platform (OBP) at: https://www.iso.org/obp/ui/#search. However, OBP content is typically not harmonized across the ISO standards spectrum.

3 Symbols and abbreviated terms

3.1 Symbols

(TBD)

3.2 Abbreviated terms

(TBD)

4 Technical Requirements

The requirements for STCM systems are contained in this section. These requirements are designed to assist State Actors in interpreting existing international treaties and agreements [4, 5, 6, 7]. Additionally, many ISO standards for operations and debris mitigation are relevant [8, 9 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. National space regulations associated with STCM services derive from each State Actor's interpretation of these existing space laws and consensus international guidelines. The set of requirements contained in this standard address coordination, monitoring and regulatory aspects of STCM.

STCM Lead Agency, STCM Lead Integrator or Operator, STCM System, Servers, and Network, STCM Orbit determination and prediction, STCM space data interfaces, STCM Data Aggregation and Curation, STCM Operations, STCM Quality Control, and STCM SSA Systems, and STCM Algorithms and Metrics

4.1 STCM Lead Agency

4.1.1 State Actors and/or international organizations shall appoint a suitable domestic or international STCM Lead Agency for their individual areas of responsibility and shall authorize and fund them to implement, operate, and monitor the STCM system.

4.1.2 The selected STCM Lead Agency shall have a corporate culture, mission priorities and focus that is aligned with and responsive to the flight safety needs of the Decision Authority and STCM customer. NOTE: These should include: Primacy of STCM as a core mission/business objective, the safe and efficient use of space, sustainability of space operations, transparency, timeliness and accuracy.

4.1.3 The STCM Lead Agency shall appoint a Decision Authority to set top-level thresholds, availability targets and operating constraints.

4.1.4 The STCM Lead Agency shall establish an enforceable legal protection agreement with each of its customers to cover legal liability issues and data misuse. Penalties shall be levied on parties commensurate with any violation of this agreement.

4.1.5 The lead authority for the STCM system shall ensure that sufficient legal mechanisms and security controls are in place to discriminate between permitted and prohibited use of contributor data..

4.1.5.1 Legal protections Permitted Data Uses shall include flight safety, EMI/RFI coordination with ITU and resolution of actual harmful interference, support for insurance underwriting, and as legally required by national regulatory authorities.

4.1.5.2 Legal protections Prohibited Data Uses shall include use of data for any commercial purposes (i.e., sales, strategic planning, or marketing), securing orbital-spectrum rights, or release or retransmission of data, STCM results, or derivative products thereof to third parties, except where expressly authorized by the data owner or STCM Lead Agency.

4.1.6 Spacecraft operators participating in the STCM system should contribute spacecraft manoeuvre plans, ephemerides and physical characteristics relevant to flight safety and RFI mitigation, when doing so is permitted by national or contractual requirement.

4.1.7 The STCM Lead Agency shall establish a legal agreement with its service provider(s) as required to enforce the Decision Authority's required Service Level Agreement (SLA) governing responsiveness, SSA data accuracy, and system availability.

4.2 STCM Lead Integrator and/or Operator

4.2.1 The STCM Lead Agency shall select STCM lead integrator and/or operator(s) that have a corporate culture, mission priorities and focus that are aligned with, and responsive to, the flight safety needs of the Decision Authority and spacecraft operator needs. These should include: Primacy of STCM as a core mission/business objective, the safe and efficient use of space, sustainability of space operations, transparency, timeliness and accuracy.

4.2.2 The STCM operator(s) shall ensure that permanent and on-call flight safety Subject Matter Expertise (SME) and STCM system support are provided commensurate with the Decision Authority's requirements for technical support staffing and responsiveness to spacecraft operator questions and needs.

4.2.3 The STCM operator shall properly train and equip its personnel to meet the requirements of the Decision Authority.

4.3 STCM system

A comprehensive, timely and accurate SSA and STCM system enhances the safe and sustainable conduct of space activities. The effective STCM system incorporates international standards, guidelines, multilateral data exchange, registration, notification and coordination of launch, on-orbit, re-entry, safety and environmental events. An example STCM framework is shown in ***Fig. 1***. Inclusion of the “regulators and monitoring agencies” box on the upper right shall depend upon whether the decision authority places requirements on an STCM framework to provide or accommodate such enforcement functions.

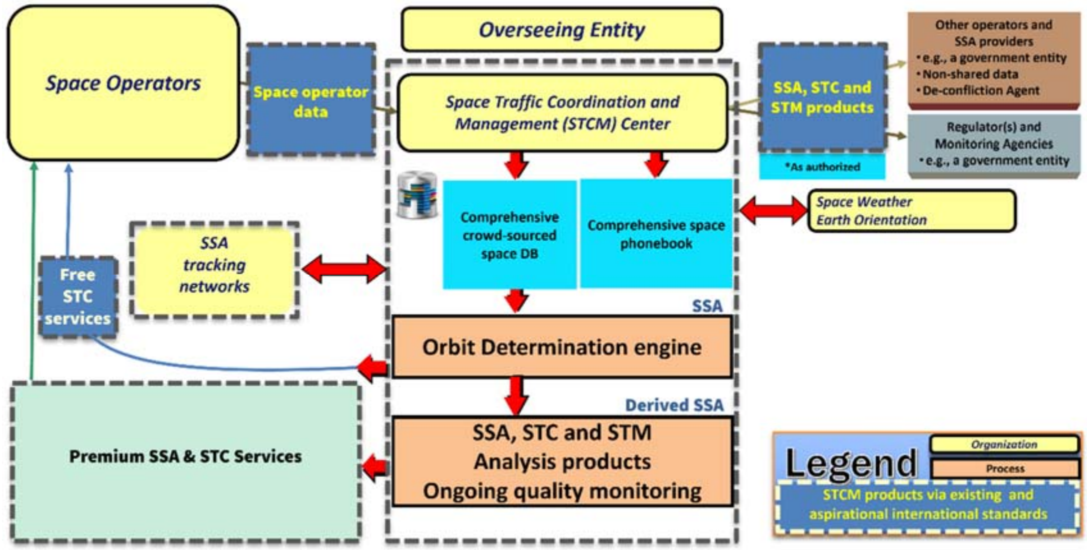

Fig. 1 Example of a Space Traffic Coordination and Management framework

The following requirements pertain to the STCM framework and components:

4.3.1 STCM system requirements document

An STCM system requirements document shall be assembled containing base-level requirements which the system shall meet in order to comprehensively enhance space safety and conduct sustainable space activities, incorporate international standards, facilitate multilateral data exchange, encourage or enable registration, and provide notifications and coordination of launch, on-orbit, re-entry, safety and environmental events.

4.3.2 Aggregate STCM service level availability

The aggregate STCM system and each of its safety-relevant components (including SSA system, computational infrastructure, network access, data fusion centre, SSA and STCM data products generation, and notification systems) shall be highly available, meeting the applicable decision authority's availability requirement.

4.3.3 STCM system geographic diversity

The STCM system's essential components shall operate in at least two geographically-diverse regions, subject to the applicable decision authority's geographic diversity requirement.

4.3.4 The STCM system and its constituent components (to include sensors, sites and algorithms employed by the STCM service provider) shall be at Technical Readiness Level 9 (System Proven and Ready for Full Commercial Deployment) before providing operational flight safety services.

4.3.5 The STCM system shall encourage and empower data owners to use the STCM system as their official space data distribution hub, allowing spacecraft operators and SSA service providers to authorize other entities to access their spacecraft data, SSA data, and/or STCM results. The STCM system shall provide an Open-Architecture Data Repository (OADR) capability to serve this function,

4.3.6 The STCM system shall implement Fine-Grained User Access (FGUA) controls to allow STCM account administrators to control the user accounts for their organization, define personnel roles and responsibilities, and authorize data access for third-party entities.

4.3.7 The STCM system shall promote and facilitate transparency of activities and capabilities on-orbit, through actions such as disclosure, trackability, registration, and status updates.

4.3.8 The STCM system shall provide a comprehensive phone book capability to facilitate inter-operator communications and rapid resolution of threats. The phonebook shall support definition of personnel roles and responsibilities, including roles for management, information security, flight dynamics, operations floor, and RFI mitigation support.

4.3.9 The STCM system shall be capable of notifying users of launch, on-orbit, re-entry, safety and environmental events.

4.3.10 The STCM system shall support standards, guidelines, and regulations that incentivize good behaviour, to include ISO 24113, (TBD).

4.3.11 The STCM system shall have the means to detect, characterize, and respond to incidents while maintaining continuous operational capability.

4.4 STCM infrastructure

4.4.1 The STCM infrastructure shall be highly-available, meeting the Decision Authority's requirements for availability, responsiveness and accuracy.

4.4.2 The STCM infrastructure shall be designed and operated to provide robust, uninterrupted processing in the event that a server or network component fails, with parallel or alternate computer systems and web services able to quickly and robustly replace the failed component.

4.4.3 The STCM infrastructure shall be designed and operated to facilitate rapid reconstitution from total failure in the event of an unforeseen major event or catastrophe, in compliance with the Decision Authority's reconstitution requirement.

4.5 STCM information Security and monitoring measures

4.5.1 The STCM system shall provide a trusted and secure framework (e.g., adhering to formal cybersecurity standards (such as ISO 27001 or NIST SP 800-171) to protect against cyber threats to ensure confidentiality, integrity, and availability.

4.5.2 The STCM system shall maintain and monitor security logs.

4.5.3 The STCM system shall appropriately protect the intellectual property and proprietary data associated with international, governmental, military, civil, and commercial operator space data and systems.

4.5.4 The STCM system shall by design and operations be robust against man-in-middle and Denial of Service attacks.

4.5.5 Transfers of operator predictive ephemerides, spacecraft characteristics, status, tracking observations, planned manoeuvres and RF information to the STCM shall only require outbound (one-way) data transfer from the operational spacecraft systems.

4.5.6 The STCM system shall require that all contributed data provided by SSA service providers and spacecraft operators be encrypted in transit to the STCM centre.

4.5.7 The STCM system shall ensure that space object observations, associations and UCT information are encrypted both while in transit and at rest.

4.5.8 The STCM system shall provide flexible options for ad hoc data export, data interchange, reporting and trending by internal and/or third-party applications to inform the STCM Lead Agency and STCM Operator of system loading, customer usage, and potential data use violations. Users can tailor what notifications they receive, when they receive it, and how they receive it.

4.5.9 Malware vulnerability scans shall regularly be conducted on the STCM system. STCM application source code, binaries and byte codes shall be regularly analysed by Static application security testing (SAST) suites to reveal potential security vulnerabilities.

4.5.10 STCM critical systems shall not be visible to the open internet.

4.5.11 Each approved launch, spacecraft and SSA service provider entity must supply specific network information that uniquely identifies that organization to the STCM system.

4.5.12 Once this information is supplied, anyone within the approved organization's network will be able to connect to the STCM site. This means that as a user of the STCM system, you must be accessing the system from within your company's approved network.

4.5.13 Technical and security controls shall make it impossible for STCM customers to access data other than their own, except where expressly authorized by the owner of that space data.

NOTE: Participating STCM companies generally provide Virtual Private Network (VPN) connections to let their employees have access to their network while not physically located at their job site.

4.6 Data aggregation, exchange, normalization and curation

Space operators have a wealth of authoritative information that they may be willing to share with others in the interest of space safety. Contributing data providers may include operators of spacecraft, launch booster and upper-stage vehicles, sub-orbital/exoatmospheric vehicles (e.g. space tourism), and high-altitude balloons and airships. Operator vehicles may include sensors and systems that can provide valuable in-situ measurements of orbital debris, spacecraft charging, and space weather proxies to aid the development and tuning of refined orbital debris models, space weather predictions and models, and dynamically calibrated atmosphere models.

The following requirements are designed to maximize the aggregation, fusion and integrity of this data.

4.6.1 The STCM system shall be designed and operated in a manner that maintains custody of a comprehensive catalogue of space objects relevant to the orbital regimes that the STCM system user spacecraft inhabit.

4.6.2 The STCM system shall assemble and maintain this comprehensive catalogue by the aggregation of data obtained from multi-lateral data exchanges. Such data exchanges should include active satellite observations, orbits, RF conditions, and spacecraft metadata provided by spacecraft owners and operators, debris observations, orbits, and metadata provided by SSA service providers using non-cooperative tracking methods. NOTE: The STCM system should ideally perform source-agnostic data fusion, combining government, satellite operator and commercial SSA data at the observational level.

4.6.3 The STCM system shall provide an international standards-based Open Access Data Repository (OADR) and user access portal.

4.6.4 The OADR shall adopt and use terminology, definitions, and units for orbital element sets, attitude/orientation, orbit centres, organizations, time systems, reference frames, gravity models, atmosphere models, (TBD) from the SANA registry (https://www.sanaregistry.org/r/navigation_standard_normative_annexes) whenever possible.

4.6.4.1 Space launch operators, spacecraft operators, and SSA service data providers and analysts shall utilize international space data exchange standards from the Consultative Committee for Space Data Systems (CCSDS) Navigation Working Group (NAV WG) family of space data messages [16, 17, 19, 20, 21] to the extent possible.

4.6.4.2 Message exchange partners shall exchange positional ephemeris, manoeuvre and covariance data using the CCSDS Orbit Data Message family of formats. While the Orbit Parameter Message (OPM), Orbit Mean element Message (OMM), and Orbit Ephemeris Message (OEM) may be used to exchange select elements of the space object ontology, use of the Orbit Comprehensive Message (OCM) format is highly recommended for its ability to exchange a comprehensive spectrum of spacecraft data and metadata required by the STCM enterprise**.**

NOTE: International standards are essential enablers in the context of the SSA and STCM landscape. Fig. 2 depicts the role of standards (denoted with dark gray borders) within the context of the STCM framework.

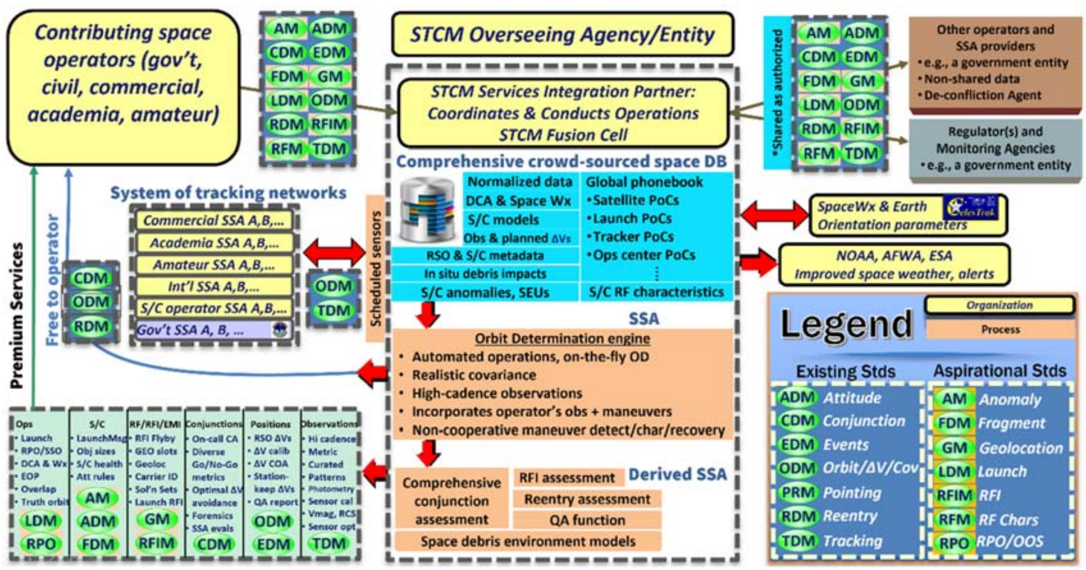

Fig. 2 Role of international space data message standards (green ellipses) in a sample STCM framework

4.6.4.3 (Another wording: There is a rich set of space data that is relevant to coordinating and managing space activities. Where possible, space actors shall adopt internationally-standardized consensus definitions of this content. Space data exchange partners shall use standardized definitions as contained in [22] and [23] whenever possible.)

4.6.5 The STCM system shall monitor the data contributed by spacecraft operators and SSA service providers, automatically notifying them of any expired or out-of-family data exceeding the data provider's specified accuracy bounds, required time spans, latency, or stationkeeping constraints.

4.6.6 The STCM system shall ensure the integrity of received data through secure channel provenance checks, blockchain identification, hashing comparisons and database and XML schema tests.

4.6.7 The STCM system shall ensure the integrity of its databases through consistency and quality checks, and data comparisons with STCM operator-specified constraints.

4.6.8 The STCM system shall have the ability to ingest and fuse operator-provided spacecraft dimensions, attitude time history files, spacecraft current mass and dry mass, drag and reflectivity coefficients and force model settings using the Orbit Comprehensive Message (OCM) format from the Orbit Data Message (ODM) family of CCSDS navigation messages. NOTE: Space object dimensions, attitude and mass are critical to the accurate assessment of collision probability and collision consequence.

4.6.9 For debris or spacecraft that are not participating in the STCM or for which space object size, orientation and mass data have not been provided, the STCM system shall be obtained from a source authorized by the STCM Decision Authority. Use of this data source, and methods and assumptions used to ascertain such size, shape and mass data, should be documented and readily shared with STCM customers.

4.6.10 The STCM service shall provide the ability to ingest and fuse operator-provided planned manoeuvres into SSA and STCM historical and predictive products.

4.6.11 The STCM service shall provide the ability to ingest operator-provided anomaly event data.

NOTE: In this construct, contributing operators are encouraged to report any satellite and launch vehicle anomalies [1] they experience in the interests of a shared understanding of space risk.

4.6.12 The STCM system shall use proper interpolation techniques for space weather, earth orientation parameters, ephemeris, vector time histories and covariance matrices.

4.6.13 The STCM system shall ensure that sufficiently small step sizes and sufficient digits of precision are provided in data exchanges to accurately maintain positional knowledge.

4.6.14 The STCM system shall regularly update its Earth Orientation Parameters as specified by the Decision Authority.

4.6.15 The STCM system shall regularly update its space weather history and predictions as specified by the Decision Authority to maximize performance of atmosphere modelling.

4.6.16 The STCM system shall transparently document and specify any assumptions, approximations and simplifications made in date processing.

4.6.16.1 Digits of Precision

(Add descriptive text).

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[1] McKnight, D., "Examination of spacecraft anomalies provides insight into complex space environment," Acta Astronautica 2017.10.036, https://doi.org/10.1016/j.actaastro.2017.10.036 , 1 November 2017.

4.6.16.2 Interpolation techniques

Covariance matrices may NOT be interpolated on an element-by-element basis. See B.3 for proper algorithms for covariance, reference frame and vector time history interpolation methods.

4.6.17 Upload frequency

(Add descriptive text).

4.6.18 Time span (start, stop) and step size of ephemeris files

(Add descriptive text).

4.6.19 Operational and Manoeuvre Test ephemerides

(Add descriptive text).

4.6.20 Digits of Precision

(Add descriptive text).

4.6.21 Interpolation of space data

There are numerous interpolation techniques available to the STCM analyst. Each interpolation technique typically places constraints upon the data set.

In the case of the Lagrange interpolating polynomial P(x) of degree (n-1) passing through n points, sufficient data points must be provided to

(Add descriptive text).

4.6.22 Precision and accuracy requirements ((historical and predictive)

Space traffic cannot be effectively coordinated or managed without accurate predicted positions for all relevant space objects. Thus, it is imperative that SSA data be timely, comprehensive, and accurate. The STCM system positional accuracy shall be continuously estimated and monitored using techniques as discussed in B.1 and B.2.

The STCM operator shall ensure that the estimated positional accuracy is sufficient for the task of producing SSA products and analytics that the decision authority's collision probability metrics and corresponding thresholds require.

4.6.23 Reference frames

Reference frames utilized for space data shall be selected from [23]

Space data exchange partners shall use standardized definitions as contained in [24] and [23] whenever possible.

Data Lake

4.6.24 Error covariance characteristics, formats and content

(Add descriptive text).

4.6.24.1 Covariance time history step size

(Add descriptive text).

4.7 Tracking and observations

4.7.1 The STCM system's SSA framework shall aggregate (or "fuse") government, satellite operator, and commercial SSA data at the observational level from diverse sensor geometries, sensor phenomenologies (e.g., radar, optical, passive RF, Laser, Doppler, and spacecraft operator active ranging) and SSA tracking service organizations as possible to feed the requisite data fusion process, yielding a higher degree of confidence and overall quality.

NOTE: Reliance upon one or even just a few tracking sensors or tracking organizations can introduce biases and undesirable vulnerabilities to sensor or organizational outages, cessations and limitations. Having more sensors, sensor types, sensor phenomenologies and tracking organizations incorporated into the STCM system increases robustness and meeting formal Service Level Availability (SLA) requirements.

4.7.2 The STCM system shall be designed to readily incorporate new sensor types, measurements and tracking data formats as they become available to quickly enhance STCM performance.

4.7.3 The STCM SSA system shall ensure a proper mix of tracking sensors as necessary to cover the range of tracking capabilities (orbital regimes, tracking rates, frequencies and required object sizes) required to meet SSA accuracy requirements.

4.7.4 The STCM SSA process shall require the regular calibration of each tracking sensor as a prerequisite to accepting observations from that sensor.

4.7.5 The STCM SSA process shall incorporate responsive, dynamic sensor tasking and prioritization commensurate with meeting the Service Level Agreement set by the Decision Authority.

NOTE 1: Where possible, tracking sensor scheduling algorithms should seek to deconflict and avoid known optical or radar sensor transits between two or more space objects.

NOTE 2: Long delays between tracking for RSOs may cause data latencies and inaccuracies that can inadvertently cause or lead to a physical collision or RFI event. Further, the SSA system should strive to maximize the number of sites and tracking observations collected to preclude observational undersampling conditions that can degrade the orbit solution and even challenge track custody and maintenance.

4.7.6 The STCM SSA process shall seek to maximize observational geometries to avoid introduction of biases in the system (e.g., collecting observations at the same time within a work shift, same time of day, or same part of the orbit).

4.8 Data Fusion, Orbit Determination (OD) and Orbit Prediction (OP)

4.8.1 The STCM OD process shall provide access to live data metrics for orbit solution quality monitoring.

4.8.2 The STCM data fusion and OD process shall maintain accurate orbit solutions that meet the Decision Authority's requirements and are commensurate with the selected conjunction safety criteria and thresholds. The spacecraft operator and the STCM operator shall be notified in the event that the data cannot support the user-selected risk criteria.

4.8.3 The STCM OD process shall incorporate comparative SSA (Track association, Cross-tags and track mis-association

4.8.4 The STCM OD process shall solve for time-dependent model parameters.

4.8.5 The STCM OD process shall incorporate the effects of unknown forces.

4.8.6 The STCM system shall be able to model, incorporate, recover from and/or solve for low-thrust manoeuvres performed by spacecraft using electric propulsion. NOTE: Today's more efficient satellites are increasingly incorporating and relying upon low-thrust electric propulsion.

4.8.7 The STCM service shall transparently and clearly ingest and share force model settings to maximize compatibility of orbit prediction.

4.9 Flight safety

4.9.1 The STCM system's conjunction assessment capability shall provide timely, decision-quality conjunction assessment results to spacecraft operators on operational timescales.

4.9.2 The STCM system shall notify potentially affected parties of potential threats to flight safety.

4.9.3 The STCM system's conjunction assessment capability shall provide spacecraft operators and analysts with a diverse, user-selectable set of conjunction & collision avoidance "Go/No-Go" manoeuvre metrics to assess collision risk and develop an appropriate course of action. NOTE: There are over 15 diverse Go/No-Go decision criteria that operators may use [ref].

4.9.4 The STCM system's conjunction assessment capability shall conduct fully-automated flight safety analyses using the latest validated data on a regular basis as specified by the Decision Authority.

4.9.5 The STCM system's conjunction assessment capability shall provide automated alerts of flight safety issues.

4.9.6 The STCM operator shall fully and transparently document and disclose the process, assumptions, and approximations made to generate its STCM products.

4.9.7 The STCM system's conjunction assessment capability shall provide flexible and tailorable user Interfaces, web services and safety analysis reports, to include elimination of in-fleet conjunctions, selection and ordering of reported conjunction assessments and RFI parameters. The STCM system's web services shall allow users to easily and robustly set up machine-to-machine interfaces to flight safety data to support an operational tempo that is too fast for “human in the loop” operation.

4.9.8 The STCM system's conjunction assessment capability shall support ad hoc analyses of alternate manoeuvre plans for the purpose of avoiding a collision threat that is deemed to pose a serious risk.

4.9.9 The STCM system's conjunction assessment capability shall estimate collision probability for a given encounter using multiple collision probability models ranging in fidelity from low to high. NOTE: Arranged from low to high fidelity, collision probability models include spatial density (e.g. background), volumetric encounter, linearized (high relative velocity) with spherical hardbody assumptions, non-linear encounters with spherical hardbody shapes, and non-linear encounters with asymmetric (e.g. rectangular or oblong) body shapes.

4.9.10 The STCM system shall perform and support Launch Collision Avoidance (LCOLA) screening and launch window analysis, maximizing launch opportunity while minimizing interruption of maritime traffic, ATC, UTM, and high-altitude (UpperE) vehicles and related operations.

4.9.11 The STCM system shall support and model proposed en masse deployment strategies (e.g., for more than ten spacecraft on the same launch) to prevent intra- and inter-spacecraft collision and to maximize SSA tracking efficiency, timeliness and accuracy.

4.9.12 The STCM system may provide avoidance manoeuvre calibration and verification products.

4.9.13 The STCM system may support the optimization of avoidance manoeuvres to best adhere to specified collision avoidance criteria thresholds and constraints.

4.10 RFI

4.10.1 Timely & actionable RF analyses: Carrier ID, RFI Fly-by, geolocation): The RF analysis capabilities provided by the STCM system must be timely and accurate as well, including the Carrier ID function, predictive "Fly-by" RFI analyses and support for geolocation systems and pre-geolocation solution set optimizations.

4.10.2 [TBD].

4.11 Quality assurance and control

4.11.1 The STCM system shall conduct regular precision assessment overlap tests for spacecraft operator ephemerides, SSA service provider ephemerides and STCM system fused orbit solutions.

4.11.2 The STCM system shall conduct regular accuracy assessments comparisons based upon positionally well-known reference orbits such as Satellite Laser Ranging (SLR), Wide-Area

Augmentation Service (WAAS), Global Navigation Satellite System (GNSS), and spacecraft with on-board GNSS devices.

4.11.3 The STCM system shall conduct comparative SSA multi-directional analyses, comparing owner/operator, SP, TLE, and reference orbits solutions to characterize agreements and identify discrepancies.

4.11.4 STCM system operators shall be notified of out-of-family orbit determination conditions identified in the live OD data quality monitoring metrics.

4.12 Rendezvous Proximity Operations (RPO) and On-Orbit Servicing (OOS)

4.12.1 The STCM system shall be capable of supporting and coordinating with spacecraft operators conducting on-orbit servicing (OOS) and rendezvous/proximity operations (RPO).

4.12.2 [TBD].

4.13 Algorithms, validation, and development

4.13.1 STCM algorithms and associated documentation shall be rigorously validated against real-world data by one or more trusted entities assigned by the Decision Authority. The Decision Authority shall then accredit the STCM algorithms for STCM use when supported by the numerical validation, at which time documentation of the algorithms used in the STCM shall be made available for review by STCM users and their technical advisors.

4.13.2 The STCM shall include the capability to non-cooperatively detect, characterize, process and rapidly recover from unanticipated spacecraft manoeuvres. The nominal predicted orbit should quickly adjust to the new post-manoeuvre trajectory, and the covariance should reflect the error growth during the recovery phase.

4.13.3 The STCM OD algorithm shall maximize covariance realism, conformity and consistency by incorporating the temporally accurate deterministic propagation of covariance uncertainty, following the best-known dynamical model and accounting for unknown time-dependent force variations.

4.13.4 In parallel with the STCM's operational tools and algorithms, the STCM shall provide an "on-ramp" for testing and incorporation of new (lower TRL) algorithms and models currently in development.

4.13.5 The STCM shall support automated conjunction assessment, drawing on Machine Learning, Artificial Intelligence, Neural Network and other advanced technologies.

4.14 Regulation, compliance and enforcement

4.14.1 [TBS]

4.15 Active Debris Removal (ADR)

4.15.1 [TBD].

For further consideration/discussion:

4.16 STCM for human safety of flight

4.16.1 Screening

It is essential to ensure the safety of human-carrying and human-habitable space objects. The risk of colliding with them shall never be dismissed whenever overlapping orbit altitudes could even remotely place humans at risk. All possible precautions shall be taken to avoid such collisions.

4.16.2 Sources of positional data for human-habitable space objects

(Add descriptive text).

Annex A
(informative)

ISO space debris mitigation standards and technical reports

A.1 General

The following sections describe the set of supporting ISO standards and technical reports that will enable compliance with STCM identified in this International Standard. These lower level documents contain detailed requirements and implementation measures associated with the high-level requirements in this International Standard. While this International Standard can be applied without reference to the lower-level documents, their use is nevertheless recommended to understand the rationale of the requirements specified here.

A.2 ISO xxxxx, *Space systems - Detailed space debris mitigation requirements for spacecraft*

ISO xxxxx is being developed to support compliance with clauses in this International Standard that are relevant to spacecraft.

ISO xxxxx will define detailed space debris mitigation requirements for the design and operation of spacecraft.

Annex B
(informative)

Methods for assessing STCM parameters

B.1 Positional precision as a proxy for positional accuracy

Ideally, one should try to characterize absolute positional accuracy (a primary SSA metric) as a function of time. Unfortunately, there are few publicly available, positionally well-known "truth" objects in space so it is difficult to draw statistically relevant conclusions on SSA system performance from that small set of objects. Since accuracy is a combination of system biases and the inherent repeatability (or precision) of an SSA system's predictions, system accuracy can instead 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 space weather or unknown manoeuvres), undersampled observations and/or algorithmic or process-based SSA deficiencies.

One can characterize the repeatability of predicted positions over a statistically-significant set of objects and sufficiently long timespans as shown in ***Fig. B-1***. 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 operator's typical Observe/Orient/Decide/Act (OODA) loop for conducting collision avoidance manoeuvres.

The median and 95th percentile statistical discrepancies in the precision (repeatability) of one- to two-day positional predictions spanning the entire range of true anomaly (0° - 360°) are characterized for LEO (0 – 2000 km altitude). These statistics must be compared with the accuracy required to operationally support the collision probability threshold of 0.0001 commonly used by spacecraft operators as a collision avoidance manoeuvre Go/No-Go criterion.

Note that while typical, or 50th percentile, SP ephemeris precision often meets (i.e., is on the left-hand side of) this limiting accuracy threshold, there are altitude ranges, orbit types, and manoeuvrability categories for which orbital data performance may fail to meet the threshold. When one further considers higher levels of occurrence, or 95th percentile, this limiting accuracy threshold may often be exceeded for certain orbit regimes (e.g., space weather below 700 km and high-eccentricity orbits) and object types (e.g., active, manoeuvring satellites).

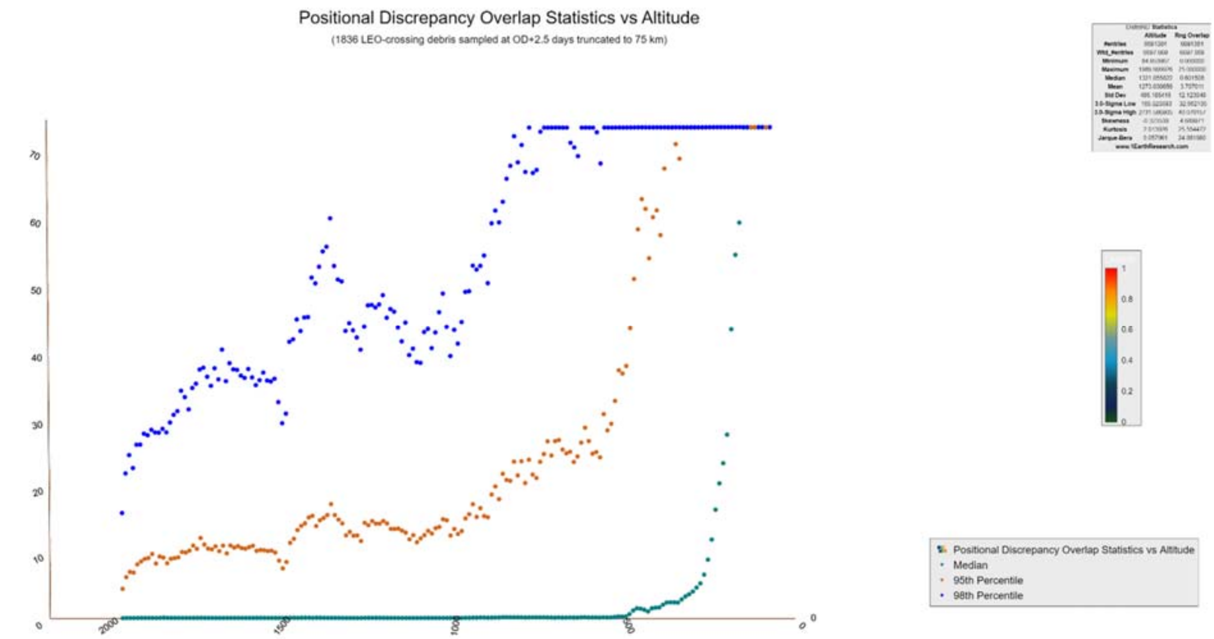

Fig. B-1 Assessment of positional precision, based upon extensive ephemeris "overlap" statistics.

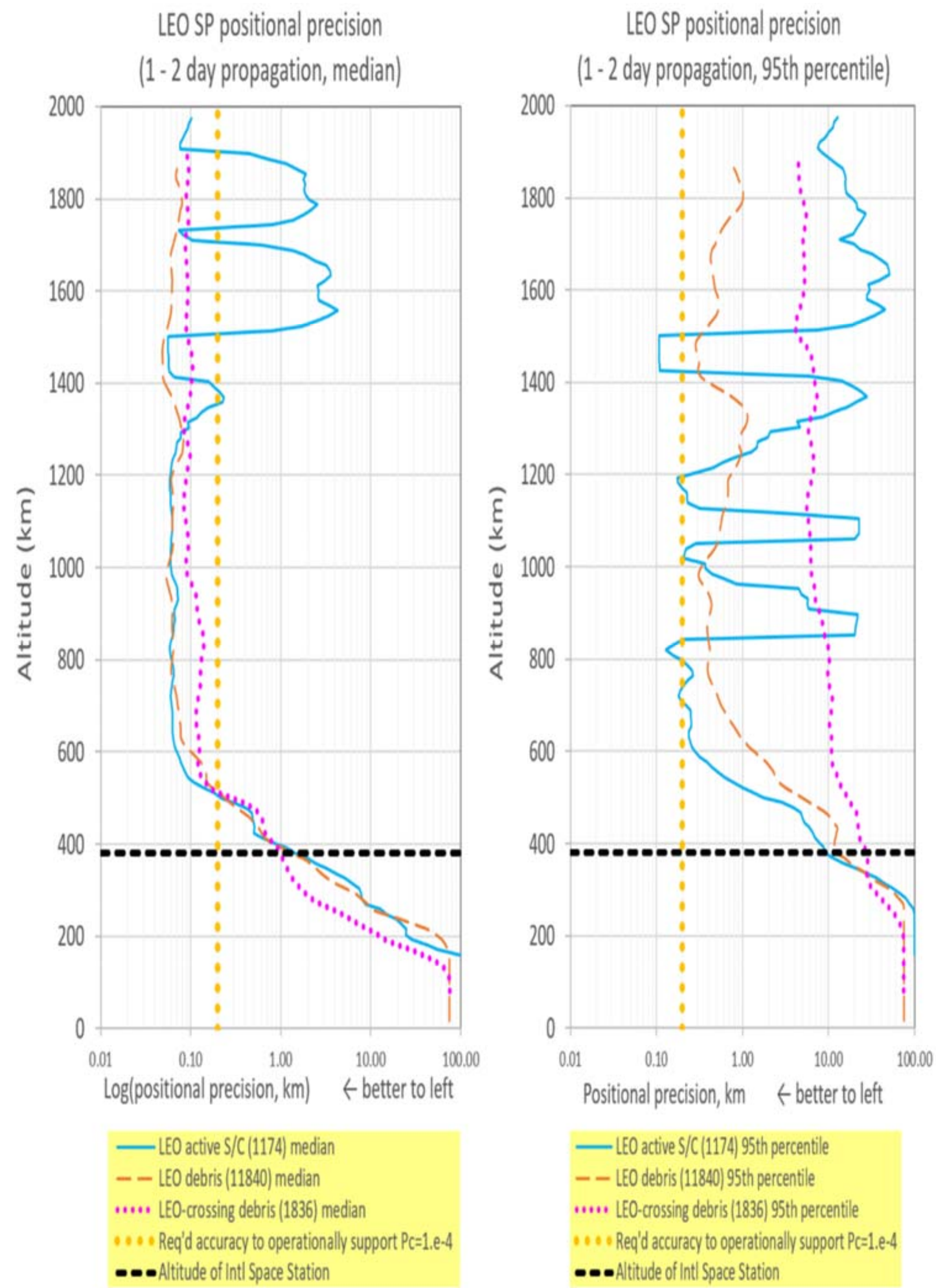

Fig. B-2 Example aggregation of LEO positional precision compared to a minimal conjunction assessment criteria threshold-derived accuracy level.

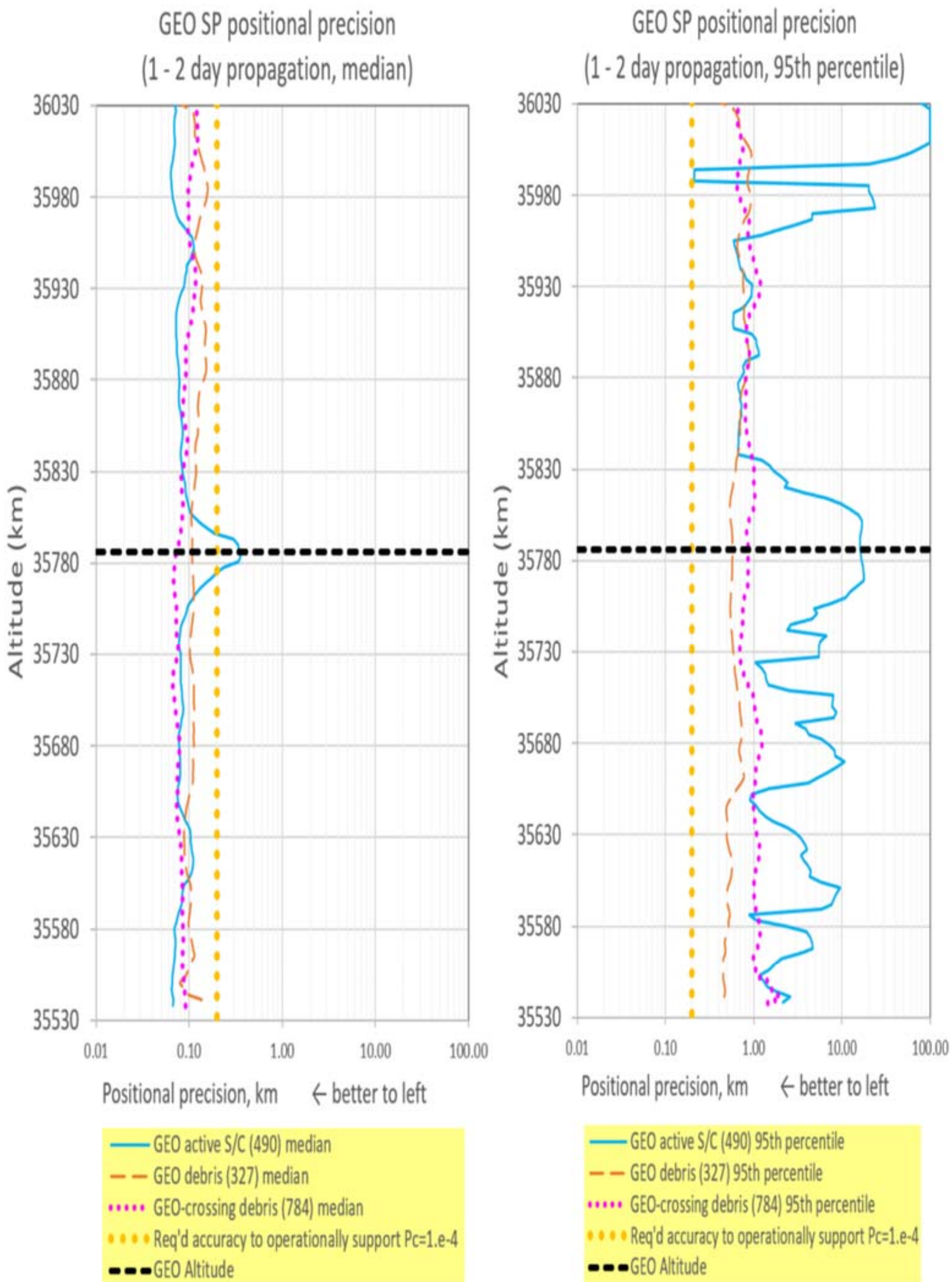

Fig. B-3 Example aggregation of GEO positional precision compared to a minimal conjunction assessment criteria threshold-derived accuracy level.

B.2 Estimation of historical and predictive positional accuracy

Though representing a small fraction of the publicly tracked space catalogue, there are today more than a hundred so-called reference or truth orbits. For these reference orbits, laser tracking and global navigation solutions combine with precision orbit determination to accurately solve for the position of the objects on a positional scale that is smaller than that of the collision metric being determined. As such, these reference orbits are ideal for determining "actual accuracy", at least to the positional scale required for flight safety.

In this case, the reference ephemeris may be differenced from all other positional predictions to determine relative capabilities as shown in ***Fig. B-4***.

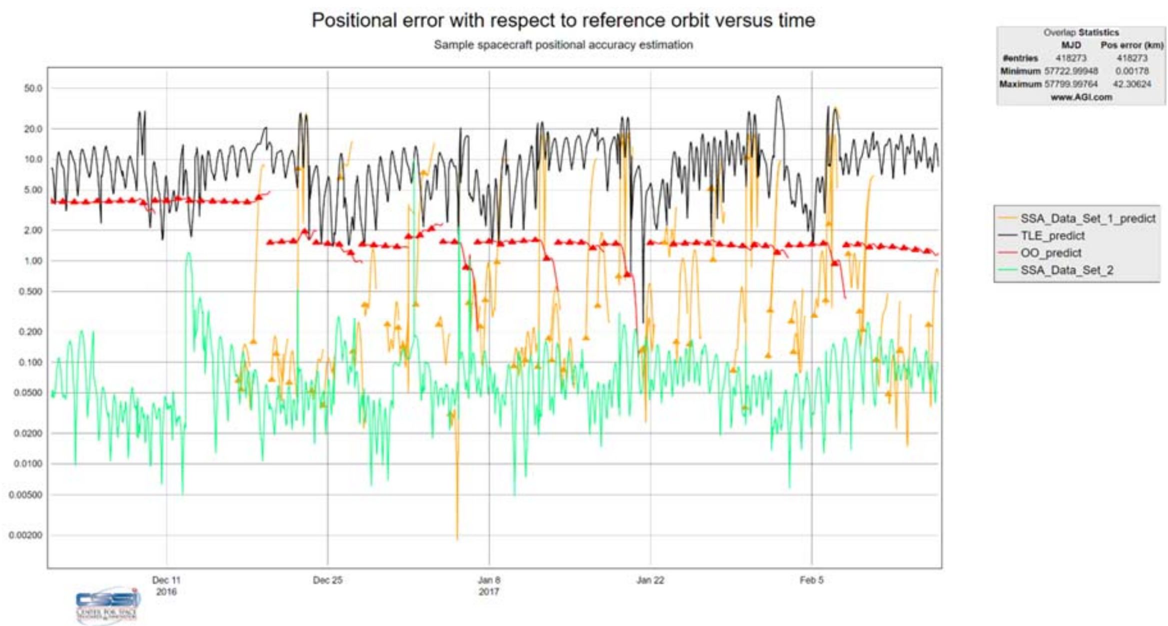

Fig. B-4 Assessment of positional accuracy using precision reference orbits.

B.3 Covariance, attitude and vector interpolation via the Euler Axis/Angle method

The Euler Axis and Angle representation of Euler's Theorem (see [25], pp. 10-14) is an effective way to interpolate a series of manoeuvre thrust or acceleration vector directions. The accompanying vector magnitudes (e.g. eigenvalues or thrust or acceleration magnitudes) may be interpolated using standard Lagrange polynomials or linear expressions.

As presented in [26, 27, and 28] and consistent with the nomenclature of [22], where e_1, e_2, and e_3 represent the three vector components of the axis of rotation $\hat{e}$ and φ represents the angle of rotation, a time-based interpolation of two adjacent unit vectors $\hat{v}_A$ and $\hat{v}_B$ can be undertaken as follows:

(1) The axis of rotation $\hat{e}$ can be obtained as: $\hat{e} = \frac{\hat{v}_B \times \hat{v}_A}{|\hat{v}_B \times \hat{v}_A|}$

(2) Assuming a constant rotational rate during this interval, $\varphi(t) = \frac{(t-t_1)\cos^{-1}(\hat{v}_A \cdot \hat{v}_B)}{(t_2-t_1)}$

(3) The orthonormal rotation matrix $[M(t)]$ is then

$$= \begin{pmatrix} (1-\cos\varphi)\hat{e}_x{}^2 + \cos\varphi & (1-\cos\varphi)\hat{e}_x\hat{e}_y + \hat{e}_z\sin\varphi & (1-\cos\varphi)\hat{e}_x\hat{e}_z - \hat{e}_y\sin\varphi \\ (1-\cos\varphi)\hat{e}_y\hat{e}_x - \hat{e}_z\sin\varphi & (1-\cos\varphi)\hat{e}_y{}^2 + \cos\varphi & (1-\cos\varphi)\hat{e}_y\hat{e}_z + \hat{e}_x\sin\varphi \\ (1-\cos\varphi)\hat{e}_z\hat{e}_x + \hat{e}_y\sin\varphi & (1-\cos\varphi)\hat{e}_z\hat{e}_y - \hat{e}_x\sin\varphi & (1-\cos\varphi)\hat{e}_z{}^2 + \cos\varphi \end{pmatrix}$$

(4) From which the interpolated vector at time t is then $\hat{v}(t) = [M(t)]\hat{v}_A$

The eigenvector matrix $[E(t)]$ contains the row-wise storage of the major, intermediate and minor eigenvectors at time ***t***, taking care to ensure that this ordered "triad" of vectors adheres to the righthand rule. When interpolating between two eigenvector matrices $[E_1]$ *and* $[E_2]$ derived from two adjacent covariance matrices respectively, $[E(t)]$ can be evaluated as follows:

(5) The rotation occurring between $[E_1]$ *and* $[E_2]$ is: $[M_{BA}]=[E_2][E_1]^T$

(6) Compute $\sigma = \left(M_{BA_{11}} + M_{BA_{22}} + M_{BA_{33}}\right)$

(7) The angle of rotation from A to B is: $\varphi_{BA} = \cos^{-1}\left[\frac{1}{2}(\sigma - 1)\right]$

(8) Exercising caution to accommodate nonunique cases (when $\sin\varphi = 0$) as described in [25], the axis of rotation $\hat{e} = \left[\frac{(M_{BA_{23}} - M_{BA_{32}})}{2\sin\varphi} \quad \frac{(M_{BA_{31}} - M_{BA_{13}})}{2\sin\varphi} \quad \frac{(M_{BA_{12}} - M_{BA_{21}})}{2\sin\varphi}\right]$

(9) The angle of rotation at time t is $\varphi(t) = \frac{(t-t_1)\varphi_{BA}}{(t_2-t_1)}$

(10) $[M(t)]$ can be computed using the above expression in step (3)

And finally, the eigenvector matrix $[E(t)] = [M(t)][E_1]$

B.4 Apparent-to-Absolute Visual Magnitude relationship

This section of the informative technical annex presents the relationships to be used to map apparent to absolute visual magnitude for inclusion in an OCM. These equations, based on Reference [29], examine signal magnitude for reflected illumination by a Resident Space Object (RSO) that is exoatmospheric, meaning that its illumination by the Sun is not reduced or impeded by atmospheric transmission losses. The equations do not account for spatial distribution across multiple detectors, which involves characterizing the Point Spread Function of the system.

Definitions:

$\boldsymbol{E_{EntranceAperture}}$	Target's specific entrance aperture radiance [W/m2]
I_{Sun}	Solar Intensity ≈ $3.088374161 \times 10^{25}$ $[W]$
$d_{SunToTarget}$	Distance from the sun to the target (e.g. 1 AU = $1.4959787066 \times 10^{11}$ m)
E_{Sun}	Exoatmospheric solar irradiance, nominally 1380 $[{}^{W}/_{m^2}]$ at 1 AU
φ	Phase or Critical Angle to the Sun (CATS) from sun to the sensor, as shown in ***Fig. B-5*** and measured at the observed target [rad]
$Phase(\varphi)$	Geometric reflectance function [unitless, 0 < $Phase(\varphi)$ ≤1]
F	General shadowing term accounting for the penumbra region's influence [unitless, 0 < F ≤1, 0 = umbra, and 1 = full Sun illumination]

A_{Target}	Effective area of the target $[m^2]$
π	Pi constant
ρ	Reflectance of the target [between 0 (none) and 1 (perfect reflectance)]
I_{Target}	Intensity of reflected energy from target treated as a point source [W]
E_{Target}	Target Irradiance at Sensor without atmospheric loss [W/m^2]
r_{Target}	Effective radius of the target $[m^2]$
$d_{TargetToSensor}$	Distance from target to sensor $[m]$
$\tau_{Atmosphere}$	Atmospheric transmission [unitless, $0 < \tau \leq 1$]
E_0	Ref. Visual Magnitude (Vega) Irradiance $[2.77894\times 10^{-8}\ {}^{W}/_{m^2}]$

Given an optical sensor's measured target entrance aperture radiance:

$VM_{apparent} = -2.5\ \log_{10}\frac{E_{target}}{E_0}$, measured on the visual magnitude scale

$\boldsymbol{E}_{target} = \frac{E_{\boldsymbol{EntranceAperture}}}{\boldsymbol{\tau_{Atmosphere}(\theta)}}$ [W/m^2]

or if $VM_{apparent}$ known: $E_{target} = E_0\ 10^{\left[-\frac{VM_{apparent}}{2.5}\right]}$

$I_{target} = E_{target}\ d^2_{TargetToSensor}$ [W]

$$E_{Sun} = \frac{I_{Sun}}{d^2_{SunToTarget}}\ [\mathrm{W/m^2}]$$

$Phase(\varphi) = \frac{\sin\varphi + (\pi-\varphi)\cos\varphi}{\pi}$

$\boldsymbol{\rho\ A_{Target}} = \frac{\boldsymbol{\pi\ I_{Target}}}{\boldsymbol{E_{Sun}\ F\ \ Phase(\varphi)}}$ [m^2; F>0 for area and reflectance, else area/reflectance is undefined.]

$r_{Target} \approx \sqrt{\frac{A_{Target}}{\pi}}$ [one can assume a standard reference reflectance of fifteen percent, dividing the above $\boldsymbol{\rho\ A_{Target}}$ quantity by 0.15].

From the above equations, $VM_{absolute}$ "normalized" to a 1 AU Sun-to-target distance, a phase angle of 0° and a reference 40,000 km target-to-sensor distance (equivalent to a GEO satellite tracked at 15.6° elevation above the optical site's local horizon), is obtained as:

$$VM_{absolute} = -2.5\ \log_{10}\left\{\frac{\left[\boldsymbol{E_{Sun\,1\,AU}=1380}\ {}^{W}/_{m^2}\right]\left[\boldsymbol{Phase(0\ rad)}=1.0\ \right]\left[\boldsymbol{\rho\ A_{Target}}\ from\ above,\ \ in\ m^2\right]}{\boldsymbol{\pi}\ \left[E_0 = 2.77894\times10^{-8}\ {}^{W}/_{m^2}\right]\left[(1.6\times10^{15})\ m^2\right]}\right\}$$

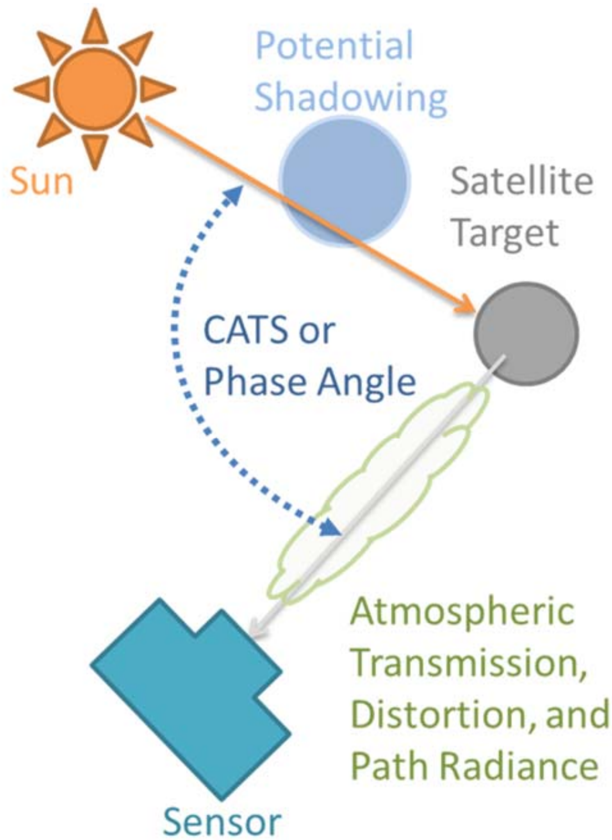

Fig. B-5 Depiction of optical viewing Critical Angle to the Sun (CATS) phase angle geometry

B.5 Benefit of sensor data fusion in STCM system

(Add descriptive text).

Table 1.3: General performance comparison of sensors that can track both space debris and spacecraft.

Sensor type	GEO coverage	LEO coverage	Not lighting-dependent	All weather	Range	Range rate	Angles
Monostatic Radar	◒	●	●	●	●	◒	◒
Bistatic Radar	◒	●	●	●	●†	◒	◒
Optical Telescopes	●	◒	○	○	○	○	●
Passive RF (TDOA/FDOA)	●	●	●	●	●†	●	○
LIDAR	●	●	◒	○	●	○	◒

† Derived quantity ● full ◒ partial ○ little or no capability

Table 1.4: General performance comparison of sensors that can "only" track actively-transmitting spacecraft.

Sensor type	Doesn't require operator cooperation	GEO coverage	LEO coverage	Not lighting-dependent	All weather	Range	Range rate	Angles
Spacecraft transponder ranging and range rate	○	●	○	●	●	●	●	◒
1-way Doppler	●	●	●	●	●	○	●	○
Radio Telescopes	●	●	●	●	●	○	○	●
Passive RF (TDOA/FDOA)	●	●	●	●	●	●†	●	○
Onboard GNSS	○	●	●	●	●	●†	●†	●†

† derived quantity ● full ◒ partial ○ little or no capability

Fig. B-6 General performance comparison of sensors capable of tracking both space debris and spacecraft.

Fig. B-7 General performance comparison of sensors only capable of tracking actively-transmitting spacecraft.

There are a wide variety of space object tracking sensors. One may draw a distinction between those that are capable of tracking both space debris and spacecraft (), versus those that require some sort of active transmission (spacecraft).

B.6 Orbit determination

(Add descriptive text).

B.7 STCM Quality Control Processes: Ephemeris upload monitoring

(Add descriptive text)

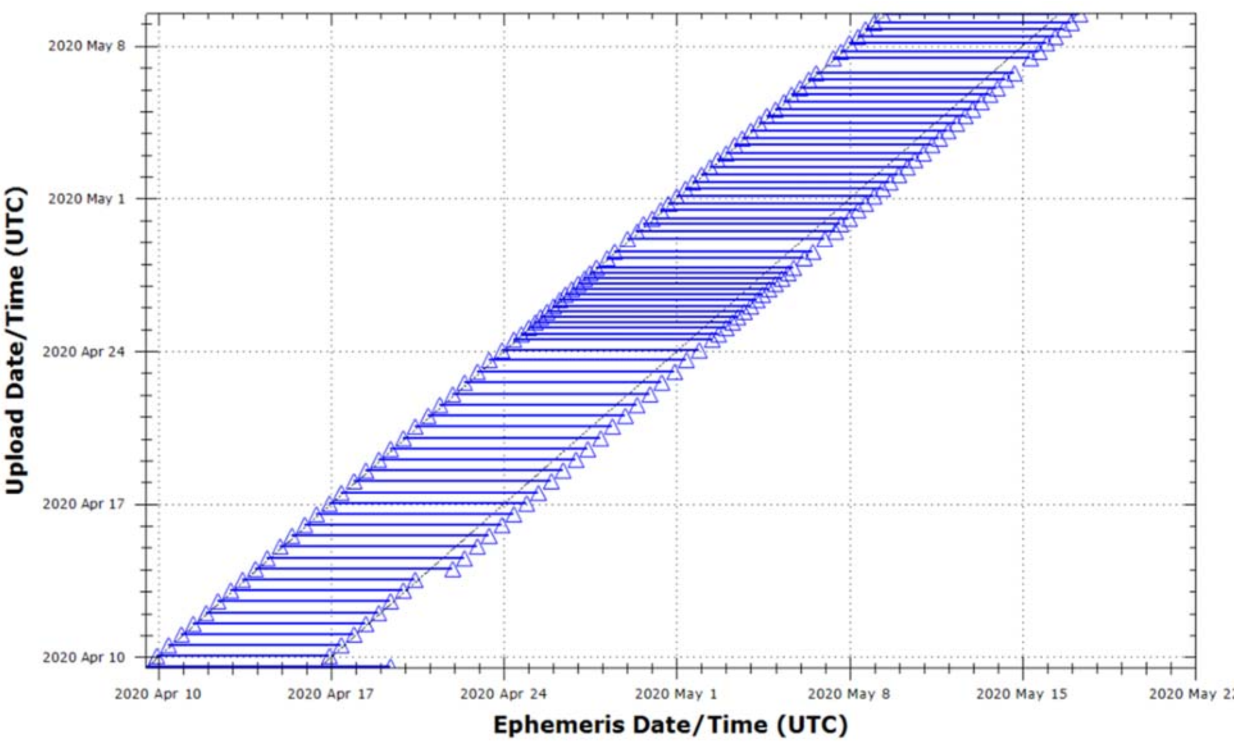

Fig. B-8 Conjunction assessment analysis process within the STCM framework

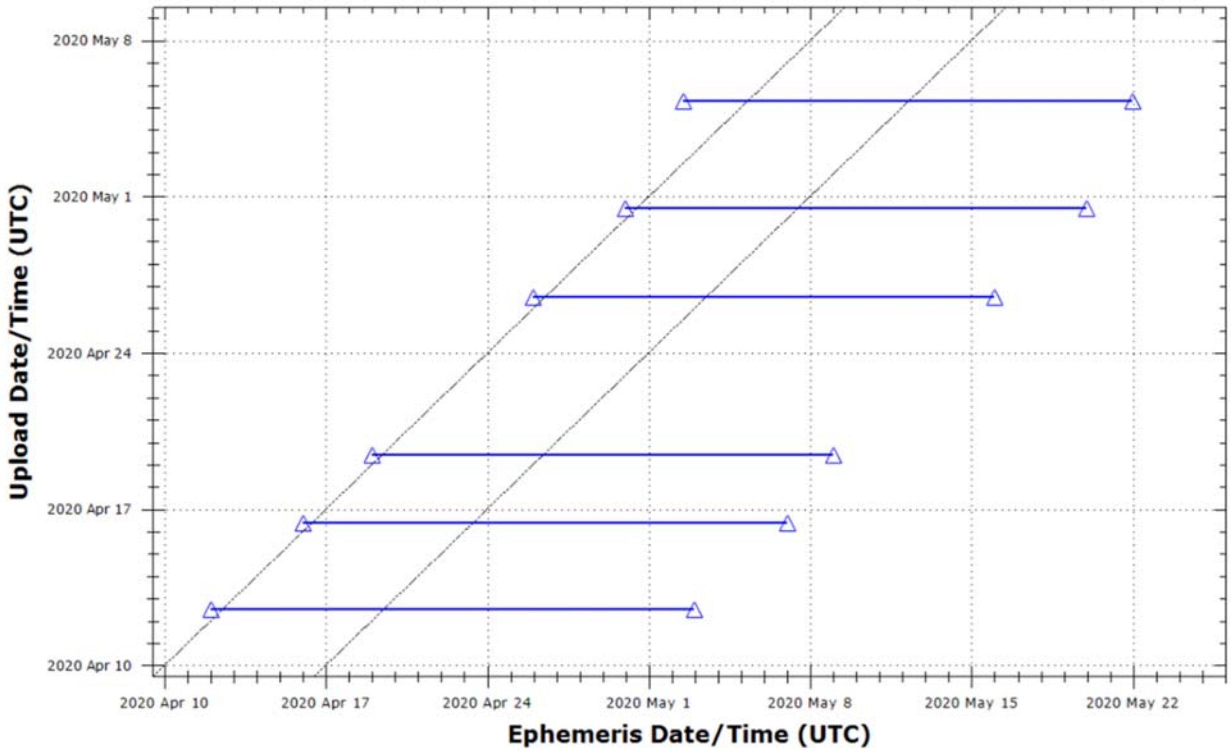

Fig. B-9 Conjunction assessment analysis process within the STCM framework

B.8 STCM Quality Control Processes: ephemeris precision by operator

(Add descriptive text).

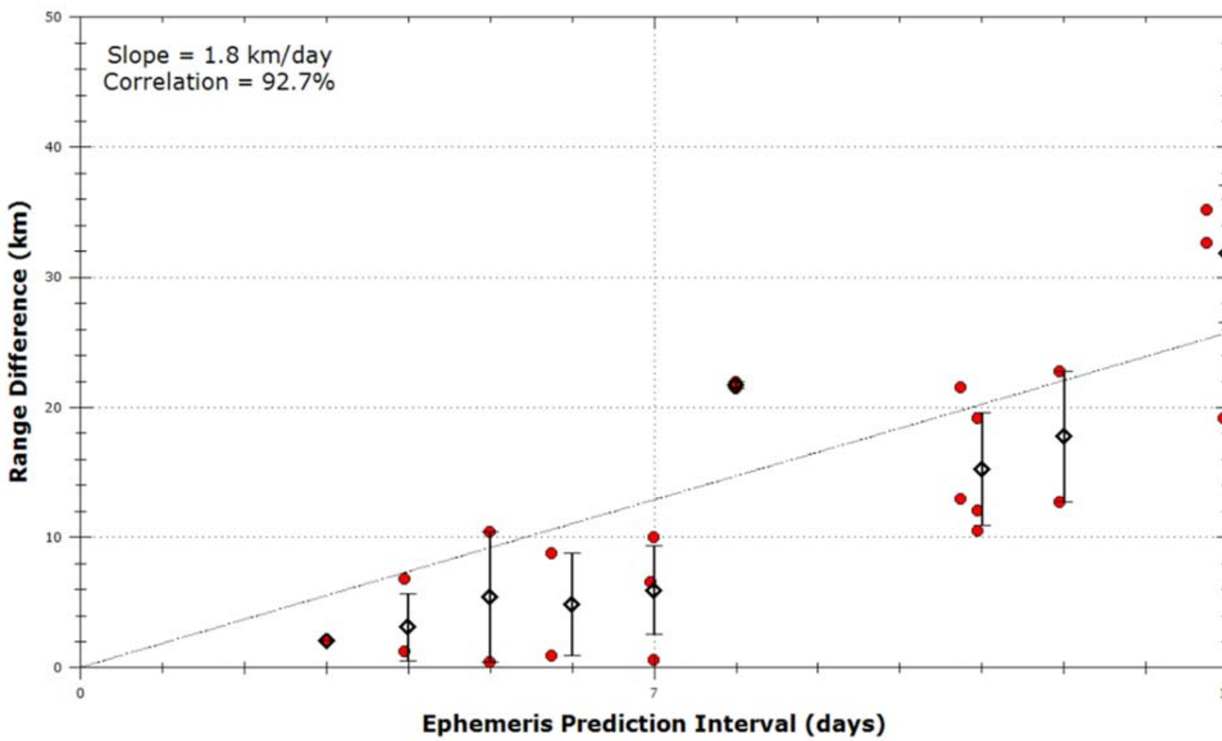

Fig. B-10 Conjunction assessment analysis process within the STCM framework

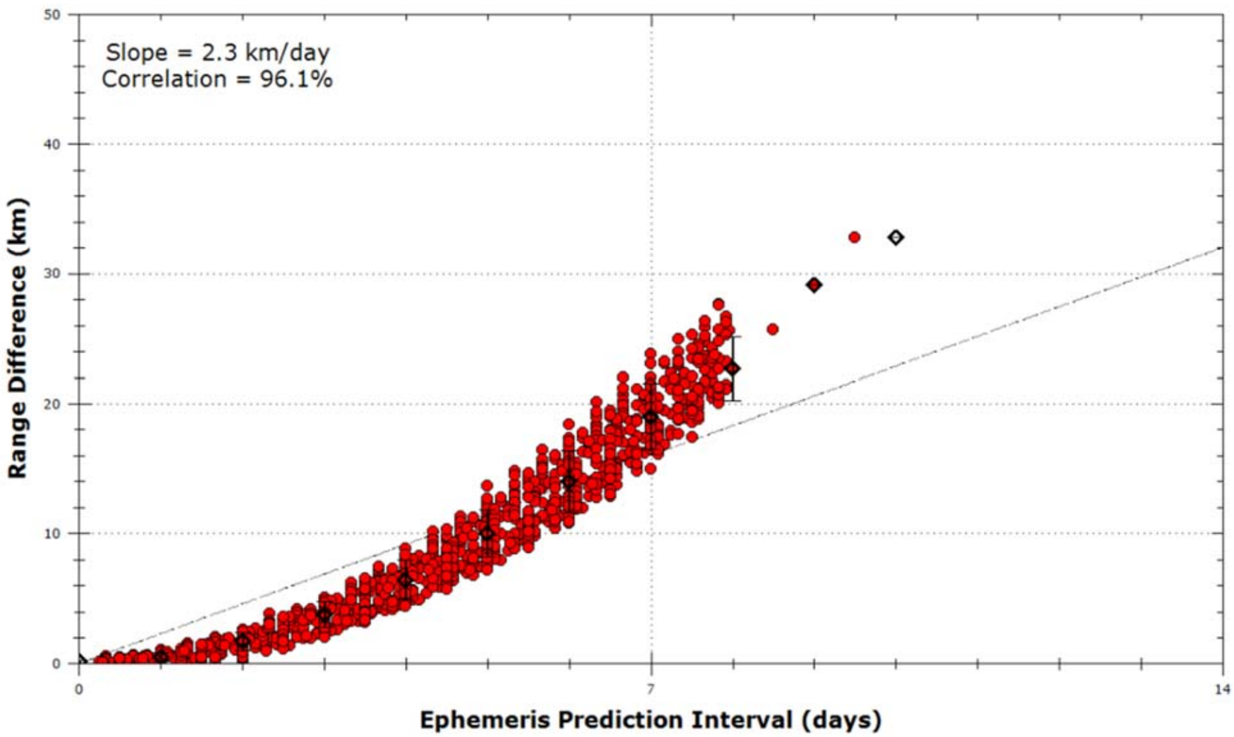

Fig. B-11 Conjunction assessment analysis process within the STCM framework

B.9 Diverse avoidance manoeuvre Go/No-Go metrics and threshold

There are many different types of warning thresholds, ranging from straightforward (predicted miss distance) to somewhat complex collision probability incorporating the uncertainty in the predicted orbits, and information about the shape and orientation of the objects involved. An operator's choice of threshold type may be driven by crew resources, available data, and the orbit regime their spacecraft occupies.

Compounding this complexity, SSA and STCM are not one-size-fits-all because the threat profile and the timeliness, completeness, accuracy, and transparency of available SSA data is highly dependent upon the orbit regime. Spacecraft operators in less-dense orbital regimes may have the luxury of being overly careful and manoeuvring whenever another object comes remotely close because they have sufficient fuel margin to ensure safety. Conversely, operators in high-density orbital regimes will not have the luxury to avoid everything that comes remotely close because the millions of potential close approaches would rapidly deplete their staffing resources and fuel budgets.

The safety thresholds that an operator selects and employs tend to be driven by spacecraft cost, mission priority, perceived value to their customer, potential value of derived data, and how long it takes to replace the mission capability by another means. In stark contrast, a spacefaring country (a "State Actor") likely decides to regulate the safety thresholds, algorithms, and metrics employed to be consistent with internationally-adopted treaties, principles, and guidelines designed to ensure the long-term sustainability of the space environment.

B.10 Conjunction assessment process

(Add descriptive text).

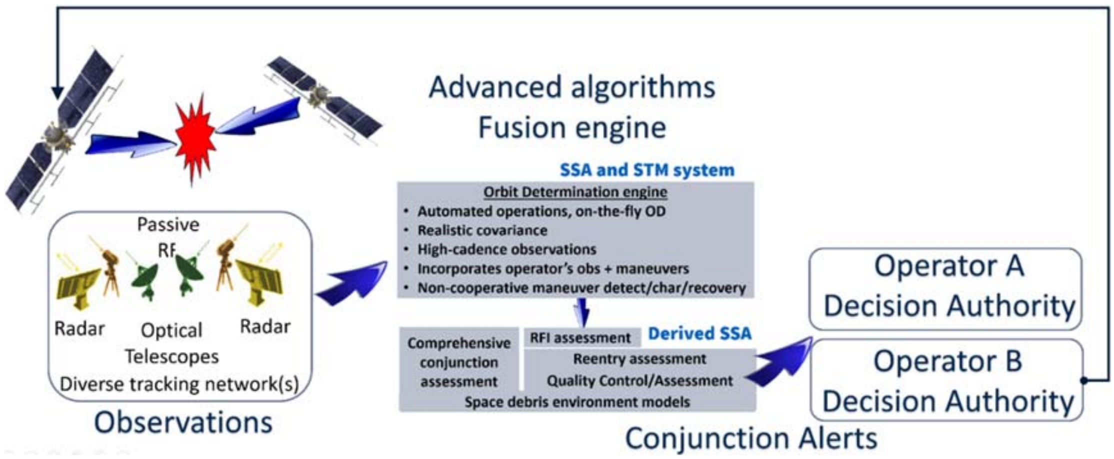

Fig. B-12 Conjunction assessment analysis process within the STCM framework

B.11 General

(Add descriptive text).

Annex C (informative)

Methods for ...

C.1 General

(Add descriptive text).

Biography

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