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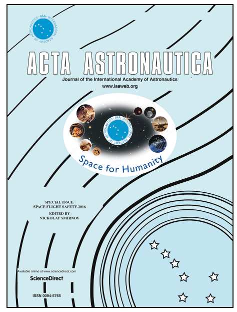

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Technical Aspects of an International Space Traffic Management Framework

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Abstract

As part of the International Space University (ISU) Space Studies Program (SSP) 2023 Team Project on Space Situational Awareness (SSA), a group of students, researchers, and professionals with a very diverse background, focused on proposing a global framework for Space Traffic Management (STM) [1, 2]. Present statistics indicate that more than 7,000 operational satellites coexist within the same orbital regime, together with more than 36,500 medium-sized trackable fragments of space debris. Following the last few years big constellations' deployment, and considering the ones that are scheduled for launch soon, the way satellites operations were carried out is rapidly becoming obsolete. This situation substantially increases the threat of potential collisions, emphasizing the necessity for an open and internationally coordinated STM framework. This paper introduces an international framework derived from the research conducted by Murakami et al. in 2019 [3]. It offers a comprehensive approach to addressing the STM challenges, with a particular emphasis on fostering precise data exchange, establishing channels for clear and direct communication, and encouraging international collaboration.

In the current work, after some considerations on the policy and legal aspects of our proposed international framework, we present the technical features and provide a broader perspective on the reasons that led to its definition. In our analysis, we considered the vibrant scenario involving new commercial actors offering Space Surveillance and Tracking (SST) services, collision risk prediction, recommendations for Collision Avoidance (CA) manoeuvres, and autonomous CA systems. The authors of this work believe that the variety and complexity of this ecosystem can only be beneficial, and by no means is the proposed framework intended to substitute those players. Instead, its goal is to fill the gaps where the current system would be incomplete. As multiple entities offer insights into space traffic and predict potential collisions among space objects, determining the most dependable source becomes a challenge when significant inconsistencies arise. Still being aware of these challenges, we want to foster collaboration within the evolving New Space landscape. Our proposed framework is designed to integrate existing suppliers rather than replace them, allowing for the seamless inclusion of their data within our system. These suppliers can continue to run their independent analysis and operations while also be contributing to, and benefiting from, the enhanced functionality within our unified system.

Keywords: Space Traffic Management, Collision Avoidance, International Framework, Space Situational Awareness

1. Introduction

In the current era, where satellite technology is fundamental to global connectivity, navigation, climate monitoring, and many other crucial functions, the safety and sustainability of space activities are of paramount importance. The orbital environment is undergoing a rapid transformation, not merely due to the launch of thousands of new satellites, including ambitious large constellation projects such as Starlink, OneWeb, and Kuiper, but also because of the growing population of man-made inactive objects in space. The escalating risk of collision between satellites and space debris is nowadays a reality each satellite operator must deal with closely. Current data suggests that over 7,000 active satellites share orbital space with at least 36,500 medium-sized debris pieces, significantly elevating the risk of potential collisions [4]. As stated by Oltrogge and Alfano in 2019, already more than 10 years ago, "If operators were to have a truly comprehensive set of conjunctions against all objects larger than 1 cm, they would likely be continuously conducting avoidance manoeuvres at the risk of running out of fuel" [5]. A recent publication by Yoon et al. gives an insider perspective on the challenges faced by large constellations operators and the amount of times manoeuvring was considered necessary to mitigate collisions risk. This analysis also shows the impact of events such as the break-up of COSMOS 1408 (November 2021) on the corresponding altitude [6].

Society's reliance on space infrastructure has reached a critical point. In this scenario, the long-term sustainability of space-based infrastructure - both in orbit and beyond - is becoming a key space policy issue of this century. An analysis of the considerable socio-economic reliance of modern societies on space assets and the potential threats posed by space debris was presented in the OECD project on the economics of space sustainability [7].

Recognizing these challenges, our team proposes an international framework for STM, drawing upon the recommendations and insights from current research practices and policies. This framework is designed to be inclusive, adaptable, and scalable, catering to the needs of a growing number of space operators, from those with single satellites to large constellations. Enhanced communication between operators, facilitated by new technologies, will enable the sharing of relevant and sensitive data, ensuring that every party has access to the best information for decision-making.

Our proposed STM system represents a global solution that fills the gap in international space governance. It aims to ensure safe access to space for operators worldwide, underpinned by international consensus, cooperation, and accords. This framework will not only address the current challenges of space debris through an integrated approach combining SSA and STM but also pave the way for future policy adaptations by nations to enhance global space governance. As such, it serves as a crucial reference point in ongoing and future debates surrounding the conceptualization and implementation of an International STM system.

To ensure clarity, this paper adheres to the following definitions:

- Space Situational Awareness (SSA): The collection, processing, and sharing of information on space objects and their environment. SSA Suppliers provide data and tools to monitor and predict the behavior of these objects.
- Space Traffic Management (STM): The coordinated actions and policies aimed at preventing collisions and ensuring safe and sustainable space operations. STM Service Suppliers integrate SSA data with operational procedures to facilitate collision avoidance and other traffic-related activities.

The proposed framework integrates these domains by leveraging SSA data to enhance STM processes, ensuring consistency and precision in addressing collision risks.

This paper is organized in the following way: Section 2 introduces the global entities involved in STM and their needs; Section 3 discusses about implemented policies and the legal aspects of the current scenario; in Section 4 we present the proposed international framework, the technicalities of which are illustrated in Section 5; finally, some remarks and considerations are given in Section 6.

2. Global Actors in STM and their needs

Various (state and non-state) entities are actively developing SSA capabilities for tracking objects in space and STM capabilities for coordinating satellite operations based on SSA data. Besides from the United States 19th Space Defense Squadron (SDS), managed by the US Space Command, featuring a network of numerous sensors, including international partners, also Russia, China and the European Union have prioritized SSA capabilities in the last few years. Many other global actors are recently joining the SSA collaboration, as demonstrated by the U.S. Strategic Command's over 100 SSA agreements, which include over 20 countries, such as Brazil [8]. In Europe, following a Commission's Decision, the European Union Agency for the Space Program (EUSPA) operates the Space Surveillance and Tracking (SST) Front Desk as of July 2022 [9].

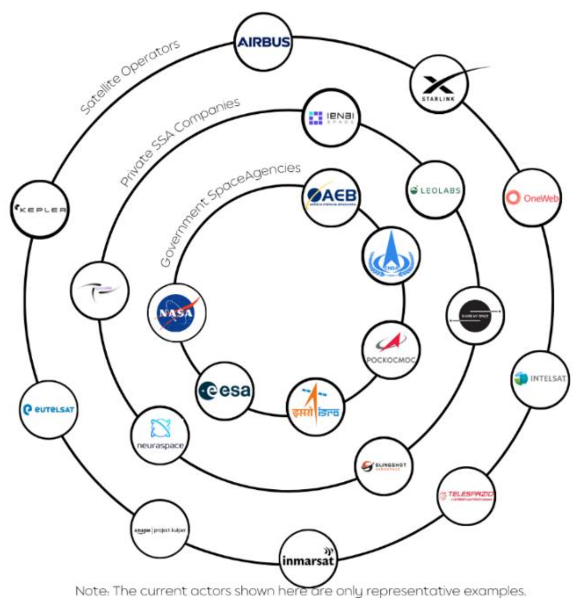

Figure 1: Example of global actors involved in SSA activities.

Additionally, to help companies assessing the impact of a space mission on the space debris environment, and to encourage the whole space community to pursue sustainable practices, the European Space Agency has founded the development of a tool for "Tracking the Health of the Environment and Missions in Space" [10]. The *THEMIS* project was led by Politecnico di Milano in collaboration with DEIMOS UK and was presented in 2024 at the "ESA Zero Debris Week".

Beyond major players, innovative companies and startups are making strides within the SSA landscape. An example of one of these that is already fully operational and providing support to constellations in the crowded LEO regime is LeoLabs; with its extensive network of S-band and UHF radars, LeoLabs generates a significant volume of radar measurements and Conjunction Data Messages (CDMs) daily [11]. Given the proven capabilities of companies like LeoLabs, in the USA the Office of Space Commerce awarded the first contracts to shape the long-awaited Traffic Coordination System for Space (TraCSS), a multi-year effort to move the federal space situational awareness mission from the Department of Defense (DoD) into civilian hands [12].

Intergovernmental organizations such as the Inter-Agency Space Debris Coordination Committee (IADC) and the Committee on the Peaceful Uses of Outer Space (COPUOS) provided guidelines that are widely accepted in the current handling of mitigation of risk for collision in space.

Fig. 1 gives a representation of global actors involved in the process: from satellite operators, those interested in keeping their satellites safe, to private SSA companies, who sell this as "service", to governments and space agencies, that are either regulating and supervising, or providing this support themselves to keep LEO orbits usable for everyone.

Thanks to SSA Service Providers, satellite operators receive warnings about potential collisions through sensor data and updated space object catalogues, to anticipate close encounters. This information, shared in the file format of a CDM, helps the satellite control centres to assess if a potential manoeuvre needs to be planned. The workflow for CA using CDM goes as follows:

- **Conjunction Assessment**: Continuous space surveillance identifies potential close approaches and initial screenings occur from days to weeks before potential conjunctions, based on orbit types and tracking capabilities.
- **CDM Creation & Distribution**: A detailed analysis follows potential conjunction detection, compiling data into a CDM. Then, operators receive the CDM promptly for maximum response time, often several days to hours before the predicted close approach.
- **CDM Analysis by Operators**: Operators verify the CDM using their tools and data. CA needs are evaluated based on CDM data, mission goals, available fuel and other parameters. Coordination may happen between operators, if the conjunction is between two active satellites. The analysis typically spans from days to hours before the expected close encounter.
- **CA Maneuver** (if needed): The operator plans a maneuver. The CA maneuver characteristics (timing, direction, magnitude) are shared with SSA providers, that would screen the plan against their catalogue and confirm if the maneuver is safe. Execution occurs well ahead of the close approach to allow adjustments, usually hours to a day before the expected close approach.
- **Post-Maneuver Assessment**: Operators verify the maneuver success and reassess risks. After the execution, maneuvers and outcomes are reported to authorities and surveillance networks.

From the workflow above, it is then clear how crucial CDMs are for STM, offering standardized conjunction data. A timely CDM process helps in risk mitigation. The procedure is time-critical, thus effective coordination, communication, and adherence to standards are the only way to ensure the process's success.

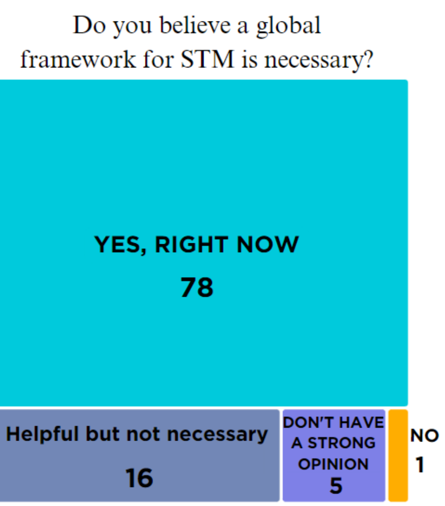

Figure 2: Survey results on the need of an International STM framework.

The aim of this work was to tackle the key issues in STM, and to achieve this goal, our team opted to collect insights directly from individuals engaged in the field. The feedback provided by the survey participants played a crucial role in defining impactful solutions that resonated with everyone involved and having to face those challenges daily. To gather this input, we came up with a specialized online survey tailored for aerospace professionals, encompassing engineers, policymakers, and satellite operators.

The survey featured a mix of multiple-choice questions, scale ratings, and open-ended responses. Within less than 48 hours, a total of 90 experts actively participated.

The diversity of the respondents' background was remarkable: from space agencies to the military sector, from academics to satellite operators and private companies offering SSA services. Results gathered were pivotal in identifying those issues that the team then tried to address with the proposed framework. As expected, 90% of respondents indicated that addressing current and future STM related issues was a critical concern, and more than 75% reported that a global STM framework would be needed "right now", as shown in Fig. 2.

Fig. 3 shows that more than 85% of respondents would be in favour of a third-party in charge of the mentioned framework.

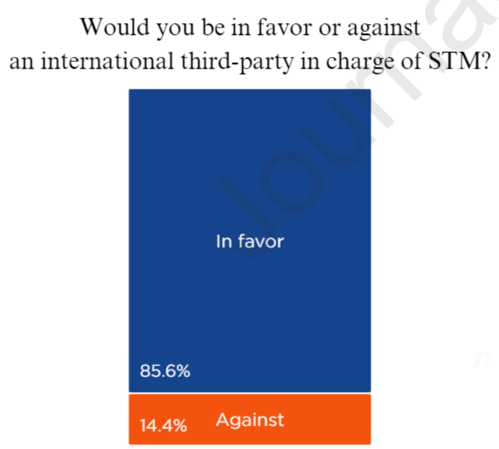

Figure 3: Preference for an international third-party in charge of STM.

However, only less than 10% of the audience would trust a commercial entity to fill that role, as shown in Fig. 4.

By combining the responses from multiple-choice questions with the more elaborated perspectives shared by stakeholders in the open-ended questions, the team gained a comprehensive view of STM's challenges and shared needs. Although a complete analysis of the survey results is available in [1], it is worth reporting here the following couple responses to open questions, that summarize the main challenges in the current situation when it comes to STM:

"*We lack an integrated platform where operators can seamlessly coordinate.*"

[We need] "*a cohesive approach to be followed by everyone. There is too much division and single frameworks proposed by this or that entity. A unified framework with some serious international backing is needed.*"

One of the most important understandings is that a new framework with a central information provider is needed, but it is hard for all stakeholders to trust a third-party to distribute their sensitive information. Therefore, a solution based on a supernational entity or intergovernmental Agency would hardly be accepted or would cover only a limited number of countries. This understanding helped the team conceptualize the framework based on a decentralized and shared open software where all stakeholders can have safe channels to share their data.

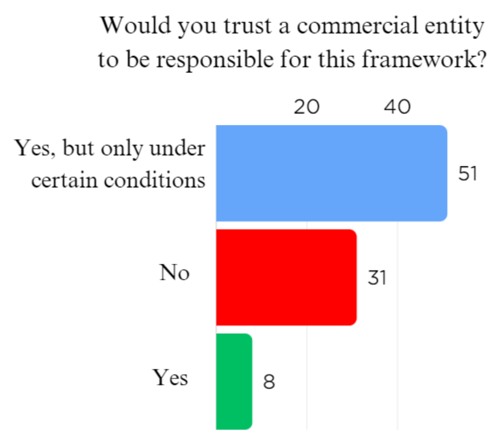

Figure 4: Respondents' trust in a commercial entity being responsible for an international framework. Out of 90 participants, only 8 replied "Yes", whereas the majority would need additional guarantees to address their concerns.

3. International Policy and Legal Aspects in STM

In this section we examine the existing legal and policy ecosystem concerning STM, highlighting gaps in the set of rules and guidelines that should be addressed. We focus on the binding and non-binding agreements and treaties, whereas specific national laws are out of the scope of the present work.

3.1 Binding instruments

The legal framework for international space activities is set within five binding treaties of the UN. Among these, the Outer Space Treaty, the Registration Convention, and the Liability Convention contain the most relevant provisions to SSA.

The Outer Space Treaty is the key legal treaty that outlines the fundamental principles of space law. Given the treaty was drafted in the 1960s and space debris had not reached significant levels of concern, it is understandable that it does not explicitly address the matter. However, Article IX of the Treaty obliges States to conduct all their activities in outer space with due regard to the corresponding interests of all other States Parties to the Treaty. Space debris puts in risk the exercise of the most fundamental right in international space law: the freedom to use and to explore outer space [13]. Another core provision in Outer Space Treaty, Article VI, is that States Parties to the Treaty shall bear international responsibility for national activities in outer space, whether such activities are carried on by governmental agencies or by non-governmental entities. When proposing our framework and establishing the relationship between States and economic operations, we take this “state oversight” aspect into account. Finally, the term “international cooperation” has been used in the majority of the Articles in this Treaty (namely, Preamble and Articles I, III, IX, X, XI). When making recommendations to the international community, we would like to emphasize that international cooperation is key for the activities in outer space.

Expanding on the principles outlined in Article VII of the Outer Space Treaty, the Liability Convention, in its Article II, states that a State responsible for launching space objects holds absolute liability to provide compensation for any harm caused by its objects on Earth's surface or to aircraft. However, according to Article III, a launching State is only liable for damages if they result from its own fault or the fault of those it is responsible for. This applies specifically to damages that occur outside of Earth's surface, such as when a space object from one launching State causes harm to another space object or to persons or property aboard it.

Regarding space debris and fault-based liability, a United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) report of the Legal Subcommittee, on its fifty-fourth session, concludes that the “the launching State is liable under Article III (of the Liability Convention) if the operational control of the space object is deemed to have negligently disregarded the relevant code of conduct in outer space adopted by competent space agencies and international bodies”. The Liability Convention also covers “component parts” in the definition of “space object” in its Article 1(d), concluding that a State is liable also for the damages caused by component parts even if they are removed from its body following a collision or accident.

Article VII of the Outer Space Treaty states that “A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object (…).” The Registration Convention further details the obligations regarding the registration of space objects. According to the Convention, States and international intergovernmental organizations that agree to abide by the Registration Convention are required to establish their own national registries and provide information on their space objects to the Secretary-General for inclusion in the UN Register. One significant issue associated with the Registration Convention pertains to the inconsistent reliability of data due to the absence of an obligation for States to maintain updates following any alterations [14]. In contemplating a comparable registration framework for the national authorities designated to be the point of contact regarding SSA, we highlight that the continuous upkeep of data by states will hold importance.

In summary, the binding instruments of international space law provide general principles applicable to SSA and STM, yet they lack explicit framework. As a result, the establishment of practices aimed at addressing these gaps and establishing responsible conduct through customary norms becomes important to build a sustainable STM framework. Since no treaties about space activities in space have been agreed upon since 1979, focusing only on making new treaties should not be the only option and we should also consider alternative solutions. We believe that a treaty making process requires extensive time and effort and poses challenges achieving consensus on a binding document. We therefore propose, in Section 4, a framework that relies on states to take actions on their domestic laws to establish easier communications, which has the potential to create a widely accepted code of conduct for responsible behaviour in STM.

3.2 Non-Binding instruments

In 1986, a pivotal development unfolded as NASA and ESA embarked on a collaborative initiative to establish a Working Group on Space Debris [15]. In 1993, the cooperation evolved into a 12 State and one International Space Agency (ESA) cooperation, that is, the Inter-Agency Space Debris Coordination (IADC) Committee which was officially adopted in Moscow. This committee was formed by the national space agencies of Italy, France, China, Germany, India, Japan, the US, Russia, Ukraine, and ESA. Thanks to the consensus reached in 2003 within IADC, the guidelines were sent to UNCOPUOS who then established a dedicated working group. This working group was tasked with evaluating input from member States regarding the earlier proposals presented by IADC on the critical subject of debris mitigation. The collaborative efforts of these initiatives culminated in the eventual publication of the Space Debris Mitigation Guidelines by the UNCOPUOS in 2010. Concurrently, the IADC also played an active role by continually updating its own Guidelines, with the most recent version dating back to 2020. It is important to point out that both the IADC and United Nations Office for Outer Space Affairs (UNOOSA) Guidelines are on space debris mitigation and do not make any recommendations on the STM. These guidelines offer advice on aspects such as design, operation, and end-of-life disposal of space objects to minimize the creation of space debris. While not legally binding, it is an important achievement that the UN General Assembly endorsed the guidelines and invited Member States to implement them through relevant national mechanisms.

While the guidelines are considered a remedial scheme, there are a few weaknesses. Firstly, they are not legally binding under international law. Secondly, most of the recommendations are broad in nature, therefore, they may be implemented differently subject to interpretation. Lastly, and most importantly, these guidelines only contain actions on reducing the amount of space debris. In that regard, while the guidelines have resulted in a positive effect, we need more international cooperation in the areas that are not limited to space debris mitigation but also covering STM.

An additional noteworthy initiative is the Space Sustainability Rating (SSR), developed to incentivize responsible space behaviors by assessing and certifying satellite operators' adherence to sustainability practices [16]. By promoting transparency and accountability, the SSR complements efforts like our proposed STM framework, aligning with its goals of fostering international cooperation and enhancing data-driven decision-making.

The already mentioned OECD’s 2022 report "Earth’s Orbits at Risk" highlights the economic implications of unsustainable orbital practices [7]. In particular, a contribution from the Polytechnic University of Bari examined the costs associated with the irreversible deterioration of orbital regimes, proposing an "orbital toll" system [17]. Such a mechanism would require operators to pay fees proportional to the risks their activities introduce, aligning financial incentives with sustainability goals. These economic considerations underline the importance of integrating technical, policy, and market-based approaches to ensure the long-term viability of orbital activities.

We believe that any future guidelines specifically for the STM should be established with a bottom-up approach to capture the general practice and be more effective. In that regard, focusing on international cooperation, communication and transparency should have the utmost priority. A recent initiative that seems to be very aligned with this approach is the “STM Stakeholder Mechanism” proposed by the EU: in this project, space operators (among other entities) have been directly involved and are asked to assist DG DEFIS and EEAS in the preparation of legislative proposals and policy initiatives in the field of STM [18].

4. An International Space Traffic Management Framework

After discussing the actors and the international cooperation legal and policy aspects, we here present the proposed International STM framework in Fig. 5.

In accordance with this framework, the Operator is anticipated to transmit the encrypted spacecraft state vector, derived from on-board sensor information, to a decentralized Conjunction Assessment Software (CAS) database. Upon sharing this information, the operator attains the status of a "Compliant Owner/Operator." The CAS leverages data from sensors provided by SSA Suppliers and Supplemental Data Suppliers as described in the next section. Notably, our framework does not delve into the practical aspects of data gathering. By amalgamating on-board data from Compliant Operators with third-party data, the system facilitates a comprehensive understanding of space traffic. Using this augmented data, collision risks can be calculated by both STM Service Suppliers/Compliant Operators and Non-Compliant Operators.

The Designated National Authority maintains an up-to-date list of communication data for the STM Service Supplier and enforce compliance with national laws and regulations, therefore establishing a federated approach This approach is in line with Article VI of the Outer Space Treaty stipulating that States Parties to the Treaty are internationally responsible for national activities in outer space, irrespective of whether these activities are conducted by governmental agencies or non-governmental entities. The role of UNOOSA (the United Nations Office for Outer Space Affairs) would be limited to maintaining a web-based public repository to facilitate and centralize the management of the contact information of designated national authorities for each registered spacecraft.

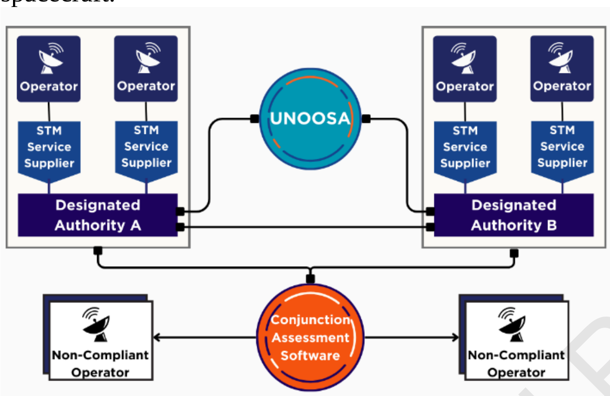

Figure 5: Proposed International Space Traffic Management Framework. The direct communication between operators is facilitated by the National Designated Authority of each country. UNOOSA is acting as a public repository of contact information.

Direct communication between Operators is initiated once the National Designated Authority is informed. During this stage, operators must reach consensus on manoeuvres. Post-planning, operators, with support from STM Service Suppliers and Non-Compliant Operators, upload their proposed manoeuvres to the Conjunction Assessment Supplier Software. The Software subsequently conducts another calculation to anticipate the effects of the planned manoeuvres. This feedback loop, facilitated by the software, determines whether the proposed orbit changes might result in a new conjunction, or worsen existing ones. With more precise data from the Software, Operators can then make well-informed decisions about manoeuvring. Upon completion of the manoeuvre, Compliant Operators add this information to the Conjunction Assessment Supplier Software database.

The International STM system's proposed framework emphasizes key players crucial to its successful implementation. These players, each with distinct roles and responsibilities within the STM ecosystem, constitute the backbone of the system. Detailed descriptions of technical aspects are provided in the subsequent section.

4.1 Alternative approaches for SSA and challenges to the implementation of an International STM Framework

The development of an effective STM framework requires consideration of multiple governance models, each with distinct advantages and limitations. It is worth mentioning that when talking about STM, we refer to actions (thus decision-making and responses changes in the space environment), oversight and coordination activities. These highly depend on (and are only meaningful in the presence of) valid systems for data collection, data processing, and data sharing – these systems are commonly referred to as SSA. Previous studies, such as the 2017 AMOS Dialogue [19] organized by the Secure World Foundation (SWF) and the Science and Technology Policy Institute (STPI), explored four archetypal scenarios for future SSA, and how it might support future STM regimes: (1) an extension of the current U.S. government-led system, (2) a private-sector-led SSA system dominated by U.S. entities, (3) a globally governed SSA system, and (4) many national SSA systems. Each scenario reflects varying degrees of government involvement and internationalization. Similarly, the U.S. Department of Commerce’s 2024 white paper envisions a decentralized network of national or regional hubs for SSA services, supported by international partnerships and robust commercial sector contributions [20].

While these alternative approaches offer viable pathways, each has significant limitations compared to the globally governed scenario we propose. Scenario 1 relies heavily on unilateral governance, risking a lack of inclusivity and transparency. Scenario 2 places disproportionate emphasis on market-driven solutions, potentially sidelining global security and equitable access concerns. Scenario 4's fragmented system of national frameworks could exacerbate operational inefficiencies and create conflicts over data sharing, standards, and compliance mechanisms. In contrast, a globally governed SSA system would facilitate the implementation of an international STM framework, establishing standardized protocols, fostering transparency and collaboration, addressing the inherently international nature of space operations.

Achieving a globally governed STM framework, however, poses considerable political, operational, and financial challenges. The primary obstacle is securing broad international cooperation, which requires reconciling competing national interests, sovereignty concerns, and variations in technical capabilities. Establishing the necessary trust for data sharing and compliance will also be complex, especially for nations with differing levels of space activity and strategic priorities. Additionally, coordinating a centralized system across diverse stakeholders could introduce delays in decision-making and implementation.

Despite these challenges, the global approach remains the most effective means of addressing the growing risks of space congestion and collisions. It provides a unified framework for ensuring long-term sustainability and equitable treatment of all spacefaring nations, in line with the principles of shared responsibility outlined in international treaties. However, achieving this vision requires a concerted effort to foster transparency, build capacity, and deliver mutual benefits to secure global support and effective implementation. In this context, the recent advancements in regional STM systems, such as the U.S. Department of Commerce's TraCSS initiative and the EUSPA SST program, represent inevitable intermediate steps. These systems serve as vital contributors to the evolution of a global, federated approach as envisioned in this paper, playing a significant role within a broader, collaborative framework.

5. Technical implementation

Our proposed Framework is designed to integrate existing suppliers rather than replace them, allowing for the seamless inclusion of their data within our system. These suppliers can continue to run their independent analysis and operations while also contributing to, and benefiting from, the enhanced functionality and collaboration within our system. For instance, a private company already providing conjunction assessment services can continue to function using its existing business model, where the generation of CDM is exclusively based on its own SSA database and conjunction analysis models. Along with this approach, they can also take advantage of our suggested framework by accessing our enhanced database and utilizing their proprietary models on our newly proposed system. This process is carried out in a wholly confidential manner: the SSA/STM service provider conveys its exclusive conjunction analysis algorithms model as encrypted Intellectual Property, eliminating the need to access any sensitive SSA data within our system. Consequently, our system can execute their algorithms without infringing on any of their trade secrets, and without requiring them to access any data from foreign operators unwilling to share information with anyone other than the trusted international authority. The technical architecture of our proposed International STM framework is outlined in Fig. 6.

5.1 Concerns and challenges

As we venture further into the era of space exploration and utilization, the development of an effective International STM system has become imperative. This system aims to address the increasingly complex dynamics of space traffic, ensuring safety and sustainability in outer space activities. However, the realization of such a system is fraught with numerous concerns and technical challenges, each requiring careful consideration and innovative solutions.

International reluctance to share accurate SSA data, which is foundational for effective STM, arises from a myriad of factors. These include national security concerns, the dual-use nature of space assets, lack of trust, competitive and commercial interests, and legal or policy constraints. Technical limitations, existing bilateral or multilateral agreements, geopolitical considerations, and unwillingness to expose vulnerabilities in surveillance capabilities further compound these issues.

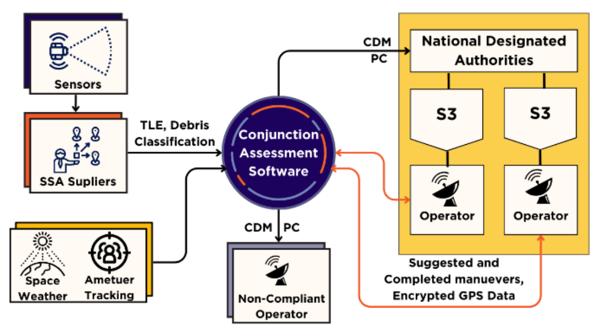

Figure 6: Technical architecture of the proposed International STM Framework.

To enhance SSA data sharing, a trustworthy technological solution is essential. Such a technology must ensure data integrity and immutability through a decentralized approach, making it challenging to alter or tamper with recorded data. This approach bolsters data integrity, ensuring the reliability and trustworthiness of shared information. Additionally, the inherent redundancy in a distributed system guarantees data availability, even if some nodes are compromised.

A transparent, traceable process in this system is vital for verifying data origin and history, enhancing transparency and accountability. Implementing a consensus mechanism for data verification ensures the authenticity of shared data. Significant progress on this crucial aspect has been made by the team responsible of Space DAO (Decentralized Autonomous Organization), that "sets the base infrastructure to agree on consensus mechanisms to reduce confusion and augment trust in key decision-making information" [21].

The proposed framework, requiring extensive national and international collaboration, faces several technical challenges including:

- **Real-time Data Processing and Analysis:** Handling and analysing vast amounts of data in real-time for precise positioning and trajectory prediction.
- **Communication Latency and Integrity:** Establishing a secure, real-time communication network with minimal latency and integrity issues.
- **Interoperability of Systems:** Harmonizing diverse technological standards and systems across various entities.
- **Security Concerns:** Protecting the system from cyber threats.
- **Error Handling and Redundancy:** Developing algorithms for error management and implementing redundant systems for continuous operations.
- **Scalability Issues:** Ensuring the system scales efficiently with the increasing number of satellites.
- **Integration with Existing Systems:** Seamlessly integrating the framework with existing STM systems.
- **Technology Development:** Advancements in Artificial Intelligence and communication technologies are needed to automate the STM system, requiring research and development through collaborative efforts in academia and industry.

These challenges underscore the need for an innovative and collaborative approach to develop a robust and scalable system.

5.2 Technical Aspects of an International STM Framework

The advancement of space technologies and the increasing congestion in outer space necessitate a robust technical framework for STM. It must be grounded in modern technology and global cooperation, ensuring the safe and sustainable use of outer space. In this context, the role of international organizations and state-of-the-art technological solutions becomes paramount in developing and implementing an effective system.

International organizations like UNOOSA, ISO, IADC, and the Space Data Association have the potential to shape International STM standards, as discussed in Section 3. UNOOSA and ISO address space debris mitigation and could extend guidelines to CA standards, while the IADC and Space Data Association, with their existing focus on debris mitigation and traffic coordination, can contribute significantly to the development of universally accepted STM standards through collaborative efforts.

The recommended approach aims to leverage state-of-the-art technologies to redefine STM. The technical framework that supports our vision is based on the following key points:

- **Data Integration and Real-Time Analytics:** A robust cloud-based infrastructure to integrating datasets from various sources, including Operators/Owners (O/Os), Satellite Service Stations (S3s), and SSA Suppliers. This integration is achieved through an advanced data processing pipeline, which ensures accurate and timely situational awareness.
- **Unified Communication Protocols:** To address communication challenges among S3s, the system employs standardized communication protocols. These protocols facilitate secure and efficient data exchange, leveraging modern encryption and distributed ledger technologies for enhanced security and reduced data latency. Additionally, efficient cross-border data exchange mechanisms are employed to ensure minimal overhead and a harmonized approach to space management.
- **Advanced Conjunction Assessment:** High-precision conjunction assessments are enabled by integrating advanced deterministic algorithms, which provide both depth and transparency in analysis. This method, bolstered by robust statistical models and data assimilation techniques, significantly enhances accuracy and reduces the likelihood of false alarms. So far, systems based on Artificial Intelligence have found application limited to characterization of and classification of space of space object (i.e. SSA), but not direct application to STM.
- **Unified Monitoring & Control System:** The framework includes a unified monitoring and control system, offering real-time insights and integrating various data feeds for

comprehensive oversight. This system is supported by distributed databases, ensuring prompt identification and resolution of technical issues.

- **Agile System Architecture:** A microservices-based architecture ensures that the system remains adaptable and responsive to changing requirements. Dynamic policy updates, informed by real-time technical data, ensure that regulatory frameworks stay at the cutting-edge of technology.

In the considered system, Satellite Service Stations (S3s) act as critical intermediaries, aggregating data from SSA providers and ensuring seamless data compatibility for STM actions. Their role encompasses maintaining interoperability standards, supporting real-time processing of conjunction data, and providing operators with actionable insights for collision avoidance. The proposed framework also allows for flexibility in the relationships between operators, service providers, and national authorities. Service providers and operators may belong to different nations than the National Designated Authority, provided they adhere to internationally accepted data-sharing and operational standards. This design reflects the global nature of space operations, promoting inclusivity while respecting national oversight responsibilities. For instance, an operator based in one nation could rely on an SSA provider from another, with both entities coordinated through their respective national authorities and the broader framework.

In summary, the proposed STM framework is a tapestry of innovative tools and distributed systems, supported by strategic collaborations. It envisions a future where space operations are not just streamlined and efficient but are also resilient and secure, effectively managing the evolving dynamics of space traffic.

6. Conclusions

This paper has underscored the urgency and necessity for an innovative International STM framework in the wake of escalating space traffic and the resultant increased risk of collisions. The rapid proliferation of satellites, especially with the advent of large constellations, alongside a growing population of space debris, has made the development of a cohesive and globally recognized STM system an imperative.

In a decentralized federated framework like the proposed one, standardization is crucial. Standardization facilitates communication, collaboration, quality control, and economic efficiency within the global space community, serving as a foundational element for safe and efficient operations. Software enhancements for improved orbital determination are expected to mitigate collision risks. Effective CA systems, particularly crucial for large satellite constellations and autonomously manoeuvring satellites, will become increasingly vital.

With the surge in data, deterministic algorithms and advanced statistical methods will become increasingly important in predicting potential conjunctions, optimizing satellite trajectories, and analysing space environment trends. This development indicates a shift towards more refined computational approaches for orbital determination and collision avoidance. As these techniques advance, commercial opportunities may arise, potentially benefiting the growing private space industry with innovative services and solutions. For example, also Amazon has entered the STM scenario with Project ARGUS, a new platform designed as an open architecture to integrate with first and third-party data, models, and visualizations to deliver targeted insights for critical mission use cases [22].

The framework advocates for the seamless inclusion of data from various stakeholders, emphasizing the importance of international collaboration and transparent data sharing. By fostering an environment of mutual trust and cooperation, the framework aims to bridge the gaps between different space actors, be they commercial entities, governmental organizations, or international bodies. The challenges in implementing such a comprehensive system are acknowledged, particularly in terms of data security, technological integration, and adherence to international standards. However, these challenges also present opportunities for innovation and cooperation at a global scale, encouraging advancements in space technology and governance. In envisioning the future of STM, it is imperative that we adopt a proactive and collaborative approach. The proposed STM framework is not the final solution but rather a significant step towards a safer and more sustainable space environment. It is a call to action for all space-faring nations and entities to unite under a common goal – to preserve the space environment around Earth as a shared resource for the benefit of all humankind.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to speed-up the content organization process and improve the clarity of writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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TECHNICAL ASPECTS OF AN INTERNATIONAL SPACE TRAFFIC MANAGEMENT FRAMEWORK

Elena Ancona, Diego Guerra, Steven Armstrong, Henrique Oliveira da Mata, Claudia Medeiros, Jaime Silva, Eric Dahlstrom

- Over 7,000 satellites and 36,500 debris fragments share the same orbital space.
- Satellite operations are outdated due to increasing launches and space traffic.
- A new global Space Traffic Management framework is essential to prevent collisions.
- The framework promotes data sharing and international cooperation among space actors.
- The goal is to ensure safe space access and guide future global space policies.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *[Journal name]* and was not involved in the editorial review or the decision to publish this article.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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