The International Academy of Astronautics (IAA), the International Astronautical Federation (IAF) and the International Institute of Space Law (IISL),
agreed to join in a

Cooperative initiative to develop comprehensive approaches and proposals for Space Traffic Management (STM)

and *formalized the initiative* with a Memorandum of Understanding during the IAC in Bremen, on 1 October 2018.

The collaborative work resulting from this initiative was to assist the decision-makers on national and international level, to promote the safe use of outer space. Since then, all three organizations founded Working Groups dedicated to Space Traffic Management (STM), which worked in parallel and in liaison with one another, with the goal of creating a joint comprehensive document addressing key concepts of Space Traffic Management (STM). In 2006, IAA provided the first comprehensive definition for STM: the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference. This joint effort has built upon this initial definition and accounted for the evolution of the STM domain through experience and global dialogue. The following Executive Summary provides a concise description of the full report that can be found at https://iafastro.directory/iac/folder/tc/spacetraffic/.

The next logical step will be to have discussions as to the appropriate organizations to implement follow-on activities to this joint document.

IAA, IAF and IISL note with great satisfaction that action set forward in 2018 has been successfully achieved and hope that this joint document, which will continue to evolve, will have a positive impact and benefit for the safe, sustainable, and secure use of outer space.

Done at IAC in Paris on 17 September 2022

International Astronautical Federation	International Institute of Space Law	International Academy of Astronautics
Pascale Ehrenfreund President	Kai-Uwe Schrogl President	John Schumacher President

COORDINATORS:
IAF: Christophe Bonnal and Darren McKnight
IISL: Maruška Strah and Tanja Masson-Zwaan
IAA: Moriba Jah and Corinne Jorgenson

EXECUTIVE SUMMARY

The goal is to synthesize concepts and facts; identify key attributes of STM; and recommend actions to be taken by the global space community. As such, the focus will be in creating compelling insights and recommended behaviors over a comprehensive review of all dimensions and nuances of the STM challenge. The research activities of this composite group cover essentially all technical topics related to the general STM ecosystem, including:

- Space Domain Awareness (SDA), which includes military and national security aspects of space operations.
- STM, Operational Coordination Services, Collision Avoidance (in orbit, at launch and at reentry), including the link and coordination with airspace users during launch and re-entry operations and frequency management & coordination.
- SEP (Space Environment Preservation) which includes activities such as Debris Mitigation, Debris Remediation (Active Debris Removal, ADR), JCA (Just in time Collision Avoidance), LDTM (Long-term Debris Traffic Management), etc.
- SSA (Space Situational Awareness) which includes SST (Space Surveillance & Tracking) and space weather.
- SOA (Space Operations Assurance) which covers SDA, STM, SEP, and SSA.

The interdependencies between topics covered in this report can be categorized as: effective Space Traffic Management (STM) will be difficult to execute without immediate changes in our SEP objectives and behavior. These topics were studied extensively by several working groups across the three organizations between October 2020 and September 2022.

The topical area coverage and current status of each are summarized in the table below.

Topical Area	Started	Completed
1. STM Terminology	Oct 2020	Dec 2021
2. New Technical Means of Space Debris Monitoring	Oct 2020	Dec 2021
3. Improvement of Orbital Data Precision and Accuracy	Oct 2020	Dec 2021
4. Reentry Risks	Oct 2020	Dec 2021
5. Collision Avoidance Processes	Oct 2020	Dec 2021
6. Future Operations: In-Orbit Servicing, In-Orbit Manufacturing, and Space Tugs	Oct 2020	Dec 2021
7. Impact of Constellations on Astronomical Observations	Oct 2020	Dec 2021
8. Effective Compliance with Technical Regulations	Oct 2020	Dec 2021
9. Technical Regulations - New Activities	Oct 2020	Dec 2021
10. Improving Trackability and Identification of Small Objects	Oct 2021	Sep 2022
11. Data Fusion and Shared Catalog	Oct 2021	Sep 2022
12. Large Constellations	Oct 2021	Sep 2022
13. Space Capacity Management	Oct 2021	Sep 2022
14. Outreach	Oct 2021	Sep 2022

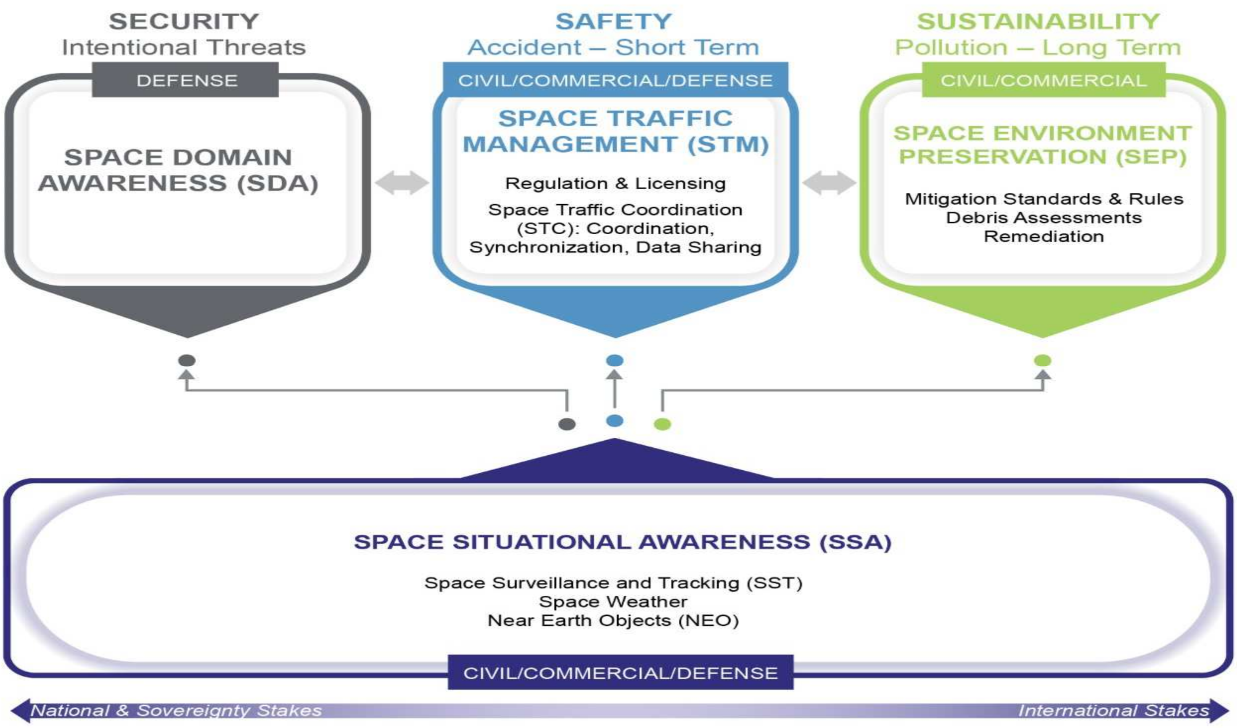
Each of the topical areas are summarized below with an emphasis on status, terms, and actionable recommendations.

STM Terminology

The purpose of these terms and definitions is to foster cooperation and encourage their use of these terms and definitions in international guidelines, standards, and agreements. The terms defined are foundational and specific but not exhaustive. SSA provides foundational positional, electro-magnetic, and situational information on objects as a function of time. It also summarizes the overall state of the space environment, including debris and space weather conditions, upon which STM, STC, SDA, and SEP actions are based.

The figure below shows the relationships between these disciplines, which taken together constitute SOA which addresses the three critical space operations issues of security, safety, and sustainability. These issues are dependent upon an underlying foundation of SSA capabilities, data, and information. Furthermore, safety, sustainability, and security overlap in each of the SDA, STM/C, and SEP domains.

- Security issues previously have fallen primarily under SDA. However, with the ever-blurring lines between commercial space systems and support to national security, this dynamic is becoming increasingly complicated. Space security issues can exist between any number of active spacecraft and ground systems, where external entities may intentionally pose a threat to the operational health, stability, and capabilities of other spacecraft. The results of space security events are starting to affect orbital safety (STM) and space operations; over time it may also start to affect space sustainability (SEP).



- Safety issues primarily fall under STM and exist between the many operational spacecraft as well as in their interaction with the current space debris and space security environments. Safety issues exist even if space debris and intentional security threats are not present. Safety concerns are exacerbated by the increase in commercial space traffic associated with large constellations. Collision risk – the product of the likelihood and consequence of space object collisions – can best be mitigated through a combination of licensing, aspirational best practices, international guidelines and standards, national regulations, responsive onboard collision avoidance capability, and operational synchronization via data and information sharing. Safety issues also fall under STC because no operator acts in isolation. STC provides the critical collective communications, information exchange, and coordinated actions taken by space actors to ensure the safe movement of spacecraft in orbit. To ensure compliance and accountability with the overarching goals of safety and sustainability, operators must also satisfy the regulatory and licensing conditions established by their governing authority.
- Sustainability issues primarily fall under SEP. While safety and sustainability are interrelated, even in the absence of new space launches or space security threats, the debris population will continue to increase due to orbital explosions; fragmentation events; and collisions between debris fragments, derelict spacecraft, and/or upper stages. This pollution issue, stemming from past space traffic and previous end-of-life disposal practices, jeopardizes current and future space activities. Sustainability can be addressed through (1) remediation (removal of space debris) and (2) mitigation (prevention of future debris growth). Key mitigation actions include (1) improvements to spacecraft and launch system design, materials, and reliability, and (2) increased capacity-building and operational adoption of launch, on-orbit, and disposal guidelines, standards, and commercial best practices. SEP draws on SSA to characterize the space environment and its evolution; based on this understanding, new mitigation standards and STM regulations can be developed to stabilize and minimize collision risk.

These three functional areas are distinct, spanning national/sovereign interests, international interests, defense community needs, and civil community concerns yet are still interdependent in many ways. STM garners high international interest because it exists at the confluence of national and international stakes and defense and civil community concerns.

From this discussion of key STM concepts, the following simple definition of STM is provided:

- Space Traffic Management (STM) is the assurance value chain that contributes to a safe, secure, and sustainable space operations environment, composed of Space Traffic Coordination (STC) and Regulation & Licensing, and dependent upon a foundation of continuous Space Situational Awareness (SSA).

New Technical Means of Space Debris Monitoring

Space objects monitoring data represents the foundation of any STM system. In the first place, monitoring activities are required for the build-up and maintenance of the catalogues containing orbital information of objects in space. This can be used for operational activities in space, such as collision avoidance, and to assess the status of the debris environment, not only in terms of the number of objects in orbit, but also to monitor behaviors such as the application of mitigation guidelines. In addition, space debris monitoring also plays an essential role in deriving statistical information about the size and spatial distribution of smaller particles of space debris and deriving the associated mission-terminating collision risk.

The Long-Term Sustainability (LTS) Guidelines of the UN Committee on Peaceful Use of Outer Space (COPUOS) explicitly mention the relevance of the collection and accuracy of orbital data (B.2) and the development of related technologies (B.4), together with the importance of promoting and supporting research and novel approaches to ensure sustainable operations in space (D.1, D.2).

The primary means of space object monitoring include radar observations; passive RF observations; passive and active optical observations; and in-situ monitoring. Key on-going developments include optical surveys in LEO; laser ranging of non-cooperative targets to maintain a catalogue of LEO objects with high accuracy orbits; a European Union consolidated SST system (EU-SST); a new commercial global radar network; development of techniques (such as light curve analysis) for attitude determination; and the adoption of active LED systems to support identification of small satellites and attitude characterization for any platform.

While this report focuses on Earth orbit, the challenges related to cis-lunar applications are identified as daunting due to various new international activities and the vast distance to cis-lunar objects.

It is recommended that technology developments in the field of space debris monitoring are needed, with the objective of increasing not only the data volume, but also the dimensions of data quality (i.e., accuracy, timeliness, uniqueness, validity, consistency, and completeness) of observations. An example in this direction is the adoption of ground-based laser tracking as a complementary technology, with the potential to reach sub-meter ranging accuracy, and thereby reducing by one order of magnitude the number of conjunction alerts. Passive optical LEO surveillance systems may complement the visibility zones of radars for very low altitudes, e.g., during re-entry. On the other hand, radar monitoring can complement the existing infrastructure by improving data timeliness and enable later decisions in the collision avoidance process. Finally, additional data is required for small size objects (e.g., mm- and cm-range), for which discrepancies in environment models are observed and validation means are still lacking. For such an application, space-based measurements may contribute to improve the knowledge of the environment. New terrestrial S-band radars being deployed globally are aiding to catalogue the 1-10 cm debris population in Low Earth Orbit (LEO).

Besides the development of new sensors, improvements can be made also in the tasking, collection, processing, exploitation, and dissemination of data (TCPED). For example, the emergence of active debris removal missions and on-orbit servicing concepts would benefit from the definition of standards to describe (long-term) attitude motion as derived from observations.

Improvement of Orbital Data Precision and Accuracy

STM is highly reliant on our capability to detect, characterize, and model the short- and long-term evolution of the manmade orbital population, as well as on our ability to predict and evaluate the consequences of the physical (e.g., collisions) and nonphysical (e.g., electromagnetic, EM) interferences among the on-orbit population.

Acting upon a given analysis to act in the event of a potential physical or nonphysical interferences among space objects, access is needed to information that allows a given operator or a service provider to act. Such information, which is usually identified as actionable information, need to be precise and accurate. As an example, currently only a small percentage of the collision data messages processed by operators or service providers leads to a mitigation action (e.g., collision avoidance maneuver). This situation can be improved through more frequent high-quality observations and/or more responsive onboard collision avoidance capabilities.

Improving orbital data precision and accuracy is, therefore, of paramount importance in the framework of an STM system, where interactions among orbiting objects need to be anticipated and close approaches mitigated efficiently.

Several building blocks contribute to the final precision and accuracy of an orbital solution computed for a given orbital object, which will be used to evaluate to what extent such object suffers from or generates collision risk or EM interference to other objects. The ability to improve the orbital data precision and accuracy of a given object which in turn enables predicting, characterizing, and mitigating risks between objects will vary depending on the following:

- The geometry, maneuverability, and attitude stability of an object;
- The orbital regime at which the object performs its mission (e.g., LEO, Geostationary Orbit, Medium Earth Orbit, etc.);
- The solar activity;
- The time horizon considered (e.g., hours, days, weeks);
- The number of objects in a constellation; and
- The quantity, quality and diversity of available observational data.

It is important to focus not only on the improvement of the orbital data precision and accuracy, but also on the development of practical approaches to integrate the inherent uncertainty of the orbital states of orbiting objects within any STM system and to couple this with responsive ground and onboard command & control of spacecraft.

Reentry Risks

Based on what has been observed between 2010 and 2020, it was found that:

- On average, approximately 100 metric tons of artificial space objects reenter without control in the Earth’s atmosphere every year. About 80% of this mass consists of orbital stages, while the remaining 20% comprise spacecraft;

- Objects with a mass exceeding 500 kg reenter uncontrolled almost every eight days;
- Objects with a mass greater than five metric tons reenter once or twice, per year.

Considering that, in most cases, a returning dry mass between 500 kg and 700 kg might correspond to a casualty expectancy of the order of 10^{-4}, uncontrolled reentries potentially at risk could be very frequent, likely representing more than 70% of the total number of reentering intact objects.

Since approximately the 1990s, there has been a growing consensus at the international level in considering a casualty expectancy of 10^{-4} as the risk threshold for an uncontrolled reentry. However, the risk evaluation is left to the object's owner/operator, and only in a very few cases is there an open disclosure of the expected casualty expectancy before the uncontrolled reentry of a spacecraft or upper stage. Moreover, if this were the case, a quite frequent violation of the risk threshold should probably be expected, maybe once a week, or at least once a month. This situation is clearly unsatisfactory.

It should be noted that the risk to aircraft in flight is a large concern as they are more vulnerable to small debris and global flight corridors are dynamic and steadily growing.

On one side, intact objects frequently reenter without an open disclosure of the expected casualty risk. Conversely, the accepted threshold might be violated so often as to produce a situation of near permanent reentry alert, if openly disclosed.

The reentry risk assessment process consists of an evaluation of the survivability of the reentry object and an evaluation of the risk that the surviving object poses to persons or property on the ground or to aircraft in flight. It should also take into account the risk of collision during deorbit (between the initial orbit and the terminal entry phase), either in a nominal scenario, or in case of a deorbit malfunction.
A status of permanent reentry alert, with the consequent and heavy involvement of human and facility resources, would not be justified given the very low risk currently associated with uncontrolled reentries. On the other hand, the reentry risk cannot be neglected since it will likely increase with the intensification of space activities and the growth of the world population density.

A possible reasonable compromise is:

- To maintain, for security reasons, the 10^{-4} hazard threshold as a design and mitigation guideline for space systems;
- To make the 10^{-4} alert threshold requirement much stricter for systems comprising hundreds or thousands of satellites; and
- To increase the current 10^{-4} alert threshold by at least one order of magnitude, i.e., to 10^{-3} or more, for triggering a reentry prediction campaign for civil protection purposes.

Future activities include, but are not limited to, the following: 1) studying examples of debris that has survived & lessons learned; 2) careful consideration of hazards associated with disposal of satellites from large constellations; 3) verifying accuracy of spacecraft-oriented reentry risk assessment models; 4) increasing focus on design for demise; and 5) increasing focus on limiting hazards to persons and property on the ground and aircraft in flight.

Collision Avoidance Processes

Collision Avoidance (COLA) is the process of planning and possibly executing a maneuver to mitigate the risk of collision between two space objects. The three parts of the collision avoidance process are Conjunction Assessment (CA) screening; Conjunction Analysis and Risk Assessment (CARA); and collision mitigation planning.

Effective COLA processes require sufficiently accurate and timely information on the orbits of the two objects involved in a conjunction to determine that a collision risk is high enough to warrant the expenditure of resources required to take a mitigation action like maneuvering the satellite. The COLA process needs to be performed over the entire active lifetime of a satellite and so is a part of regular spacecraft operations. A COLA process can protect a satellite from mission failure due to collisions with trackable objects but can also mitigate the generation of orbital debris if collisions are prevented. The need to perform COLA as a sustained part of operations makes it different from many other debris mitigation measures.

COLA processes can be improved through several efforts:

- Improved coordination is necessary to improve space safety. This includes both bilateral sharing of orbital data and international coordination of STM principles.
- Sharing of data and information with respect to position of spacecraft and their movement between several stakeholders is important and necessary to understand what is happening in the orbital environment and is a key step to effective STM.
- One potential solution to the ever-increasing numbers of conjunction warnings and potential CAMs is through the use of automation, to improve data analysis and support in-orbit operations.
- Space traffic rules to minimize the degree of interaction between operational satellites have been suggested. One best practice endorsed by the Space Safety Coalition (SSC)[1] is to design constellations that do not intersect, for example, by implementing altitude separation for near-circular orbits.
- Increased capabilities to include process improvement, data fusion, and better (more, more accurate, and better size resolution) measurements.

[1] The Space Safety Coalition (SSC, SpaceSafety.org) is an *ad hoc* coalition of companies, organizations, and other government and industry stakeholders that actively promotes responsible space safety through the adoption of relevant international standards, guidelines and practices, and the development of more effective space safety guidelines and best practices.

Future Operations: IOS, IOM, and Space Tugs

The term In-Orbit Servicing (IOS) refers to a large variety of in-orbit operations involving physical contact or very close proximity operations between two or more space vehicles. Based on this definition, they include not only the supply of services (e.g., re-fueling and repairing) to already existing space assets, but also the assembly of modular parts into functional aggregate structures (In Orbit Assembly, IOA) and the fabrication of components (In Orbit Manufacturing, IOM) in space. Activities which foresee the use of space tugs as transportation means to perform orbit correction of mal-deployed satellites, orbit relocation (e.g., LEO to GEO transfers), or even removal of dead satellites from their orbit are also considered IOS. Hence, the execution of IOS missions has the potential to provide several benefits to customers ranging from increased volumes and reduced launch costs; preservation or improvement of satellite performance; and helping to ensure a sustainable use of outer space. For these reasons, several recent market studies have highlighted that IOS is projected to become a multi-billion-dollar market driven by the continuous growth of LEO and GEO commercial activity.

Throughout the space age, plenty of missions have been carried out showing capabilities to perform robotic operations in orbit including rendezvous and docking maneuvers, Northrup Grumman's MEV-1 and MEV-2 vehicles successfully serviced the IS-901 and IS-10-02 satellites, respectively in early 2020 and 2021, completing the first commercial IOS missions. In addition, many technology demonstration missions are under development and ready for launch by the late 2020's. This is motivated by the fact that many technical challenges must still be overcome to improve the reliability, efficiency, and autonomy of IOS activities so that they can become routine operations. Key technological aspects to be addressed include spacecraft modularity; autonomous guidance, navigation, & control (GNC); and propulsion systems. Modular architectures require the definition of standard payloads and interconnectors. A careful design must be foreseen to ensure that they do not introduce additional structural mass which can negatively impact the total life-cycle cost of a spacecraft and its scientific return. Navigation solutions, typically relying on electro-optical sensors, must become more robust in terms of illumination conditions and fast relative rotational dynamics (e.g., in case the target is tumbling). GNC functions must ensure capability to design and accurately control safe trajectory (for both approaching and collision avoidance maneuvers) of complex multi-body systems typically composed of a servicer vehicle, a robotic manipulator (which may be characterized by redundant degrees of freedom) and, potentially, the captured object. Other challenges of the use of space tugs are related to the need to carefully select the most convenient propulsion system since not all types of propulsion will satisfy mission requirements.

Aside from technical aspects, additional efforts must be aimed to address regulatory issues, since IOS operations must be correctly framed in the larger STM context.

Impact of Constellations on Astronomical Observations

The launch of large constellations of satellites in Low Earth Orbit (LEO) poses significant challenges for observational astronomy at all wavelengths ranging from the radio to the ultraviolet, and to instruments ranging from the unaided human eye to 8-meter class and larger telescopes. These new satellites can be very bright at all wavelengths, much brighter than most of the objects currently tracked in LEO. For optical ground-based observations in the 300 nm to 2.5 μm range, the satellite is visible when the observer has a dark sky, and the satellite is still in sunlight. Once the satellite enters the shadow of the Earth, it is no longer visible. The length of time during which the satellite is visible depends on the latitude of the observer, the time of year, and the particular orbit. Objects in higher orbits (e.g., above 1,200 km) can be visible all night long in summer. However, an object in lower orbit (e.g., below 600 km) might be brighter but would be in Earth shadow and thus would not leave detectable artifacts in optical astronomical data for several hours in the middle of the night during the summer. The number of such visible satellites above the horizon can range up to 10 percent of the total constellation, with up to several thousand in sunlight at any one time.

There is no Earth shadow for observations in the thermal infrared (10 microns for example, where the satellite emits thermal radiation or 'glows in the dark') nor at radio wavelengths where the satellite is an active radio transmitter.

Space-based telescopes in LEO (such as the Hubble Space Telescope) are not immune from the streaks caused by satellites crossing their field of view.

The exact amount of data lost or compromised from satellites depends on the aperture of the telescope, and its field of view. Large telescopes with large fields of view are most affected. Several studies have quantified the impact of satellites' trails on current and incoming astronomical observatories' data.

Recommendations on how to partially mitigate this bright satellite problem have been discussed in several conferences, including steps in space debris mitigation which benefit astronomy, in developing tools to predict passage of satellites and optimize planning of astronomy observations. To keep the night sky pristine for human observers it is recommended to make satellites fainter than a Visual magnitude of 7 at all times. Further recommendations are discussed in the main text of this report and the cited references.

There is no law or regulation at international or national level that prescribes a limit on the brightness of satellites. There are principles of international space law that oblige States to exercise due diligence and to refrain from harmfully interfering with the activities of other States. Discussions are ongoing at UN COPUOS about possible legal solutions to mitigate the effect of large constellations on astronomical observations.

A Special Session on this topic was held at the 2021 IAC in [Impact of Satellite Constellations on Astronomy and Society: a Multi-disciplinary Approach (iafastro.org)]

Effective Compliance with Technical Regulations

Since the 1990s, space debris mitigation guidelines and associated rules have been studied in various international technical committees, such as the Interagency Space Debris Coordination Committee (IADC). Despite this fundamental work, the initiatives from groups of private companies and the technical work within the International Organization for Standardization (ISO), there is no unique and undisputed, technically precise reference applicable to all space missions of all countries. Empowered by the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (i.e., Outer Space Treaty, OST), each State is free to select its own national debris mitigation standards, policies, and regulations. Thus, differences may exist in the technical references that need to be complied with when entities apply for licenses to launch to and operate in space.

Compliance with technical regulation is of paramount importance for the long-term sustainability of space activities, primarily to reduce and control the generation of debris in space, especially in the context of privatization and commercialization of space activities. The most important technical factor is the success rate of post-mission disposal, which is far from the perfect goal of 100% (i.e., near 40%[2]). The capacity to avoid collisions is also a strong driver, and with the increase in the number of large constellations and derelict hardware, some regions of space are approaching a precarious level of collision hazard. This situation should ideally be managed by governments or international bodies rather than by organizations that develop standards or private consortia.

It is possible that commercial satellite operators will pursue regulation shopping to achieve the cheapest and easiest means to secure their necessary licenses to launch and operate, though no documented cases have been reported yet. The UN Office of Outer Space Affairs maintains an international register of objects launched into outer space, but this is not suitable for operational aspects of space safety. Indeed, there is a lack of active monitoring of both the licensing parameters and the register updates of most licensing countries.

The post-mission disposal (PMD) success rate is not reaching the requested levels. PMD has a cost for the satellite operator/owner and brings no benefit, while there is no penalty for noncompliance. The licensing authority often does not request anything beyond best effort, liability insurance is not always requested, and there are no major consequences if a deviation from the original license occurs. Space radio frequency (RF) interference is governed by national and ITU processes, but there is no sanction in case of interference across countries. The bottom line is that there is no international consensus on systemic risk in space, no international monitoring organization (similar to, e.g., the International Atomic Energy Agency, IAEA), and no international consensus on approaches to space security.

Harmonization of basic measures across multiple jurisdictions to discourage regulatory shopping should be encouraged. To do this, national policies should align with the COPUOS Long-Term Sustainability (LTS) Guidelines. The second step is to have technical requirements consistent across the community (developed by organizations such as ISO). Third, a common and unique licensing process with a living register and systemic impact analysis needs to be developed. A basic "no compliance, no launch" rule should be accepted by all stakeholders together with transparency and data sharing as much as possible. The collision avoidance process can be improved by increasing the

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[2] Ruch, V., "Analysis of EOL Lifetime in LEO and GEO, 2000-2018", 37th IADC, Rome, Italy, 6-10 May 2019.

accuracy of tracking, reducing the timeline for the issuance of conjunction data messages, and using a just-in-time systems. While it is unlikely that the post mission disposal success rate will ever reach 100%, the general aim must be to reach this goal. Active Debris Removal will be needed, especially for massive spacecraft, and an ‘ADR-ready’ standard interface could be developed and proposed for implementation. An “ecotax” (Pigouvian tax) to promote environmentally responsible behavior should also be explored along with encouraging the ongoing develop of the Space Sustainability Rating (SSR).

Technical Regulations - New Activities

All these goals may be easier to achieve with the more harmonization of national licensing frameworks to ensure homogeneous licensing practices around the world. This report examines emerging New Technologies and Activities in terms of existing technical regulations. Specific New Technology and Activities were grouped into four natural, distinct, categories:

- In-Orbit Servicing, In-Orbit Manufacturing and Space tugs
- Sub-orbital Activities and Spaceports
- Active Debris Removal, Just-in-time Collision Avoidance, and Large Debris Traffic Management
- Lunar and Mars Extension

These categories may broadly be considered as either (1) cross-cutting technologies that are logical extensions of current or near-term technical capabilities or (2) are “vertically oriented” with respect to our shared home planet, and seek to provide a logical, integrated and seamless extension of current regulatory paradigms from the surface and atmosphere to cis-lunar and planetary spaces.

Technical Regulations were examined in terms of statutory regulatory authority at the national, supranational, and international levels, so-called Hard Law enacted via statue or treaty and characterized by formal regulation, compliance, and licensing, to Soft Law regulation via guidelines, best practices, etc. Specialized regulations for select activities as well as international domain governance were also examined for applicability to the space domain. The task team looked at existing general regulations and their coverage of New Technologies and Activities, observed gaps in regulatory coverage and category-unique risks, and made recommendations.

Key developments recommended in the near-term (1-5 years from present) include, but are not limited to:

- Promoting existing space debris mitigation guidelines and best practices, relevant to all aspects of Space Operations Assurance (SOA), including encouraging compliance with these guidelines, particularly in the area of post-mission disposal;
- Encouraging technology developers/deployers to integrate their use cases with existing and proposed guidelines and regulations in a transparent fashion and thereby move from minimal metadata (UN registration, national launch licensing) to enhanced metadata (unique identifiers, transponders) and practices (common space data formats and transmission/sharing/notification) while recognizing legitimate national security interests.

- Facilitating further industry standards via, e.g., the ISO, including the in-development ISO Standard 24330 “Space systems — Rendezvous and Proximity Operations (RPO) and On Orbit Servicing (OOS) — Programmatic principles and practices” and logical follow-ons.
- Fostering the formal development of ADR guidelines and supporting documents. Relevant to Space Environment Management (SEM) and cross-cutting technologies and activities.
- Fostering and enhancing dialog between existing IGO, NGO, commercial, and other organizations and stakeholders, *e.g.* the IISL and other legal bodies, relevant to SOA and with particular focus on SEM and STM; relevant primarily to the vertically-oriented technologies and activities.
- Foster the continuation of best practice development but allocate resources to the establishment, within existing commercial associations equivalent to the International Air Transportation Authority (IATA), of global commercial standards and professional support to industry stakeholders;
- Founding an UN-level mandated organization equivalent to the IMO and ICAO. This “International Spacefaring Organization” is fundamental to SOA, STM, and the vertically-oriented technologies and activities.

These goals and recommendations are realistic and actionable. The IAF, IAA, and IISL provide a unique ensemble of guiding bodies, and have a direct responsibility in providing guidance to realize these goals and their manifest benefits to humanity.

Improving Trackability and Identification of Small Objects

Small orbital debris objects pose challenges to ground-based surveillance efforts, in terms of small signal-to-noise ratios and shorter detection ranges despite their ability to create mission-terminating effects on operational spacecraft. The results are ambiguous correlations and large orbit covariances generating operational burdens and, ultimately a safety issue to spacecraft operations. Onboard means to improve the trackability of space objects, hence, to improve the quality of the resulting orbit information are stipulated by international guidelines.

In addition, small satellites are often released simultaneously in a single launch with almost identical initial orbital states. This prevents surveillance systems from discriminating orbital parameters in reasonable timespans, often leading to mission failures where the absence of orbit information prevents timely commanding.

This chapter identifies design measures that can be taken for space systems before launch to improve the quality of orbit information generated on them through independent surveillance and tracking systems using radar or optical techniques. This chapter furthermore addresses onboard techniques that allow to identify a space system and associate it to a launch and an owner.

The following design measures are discussed:

Improving Trackability	
Optical tracking	Corner-cube reflectors (CCR), are special mirrors designed to reflect laser light back in the direction from which it arrived (to be detected by a fast camera). Varying configuration of several CCRs on board can help to differentiate between space systems. Cost effective variants to this are reflector arrays (such as Mt Fuji) and the light-weight retro-reflective foils (RRF).
Radar Tracking	Efforts concentrate on design means to increase the Radar Cross-Section of a space objects, by adding panels or optimizing configuration features. Van Atta array, a passive device which re-radiates RF energy back towards the source of that energy.
Identification	
Passive Systems	RFID (radio frequency identification) tags, can be energized (or queried) via ground-based RF beams, in addition to the usual range-range-rate measurement, they also return a unique ID to allow identification of the object. Light-curve signatures can also be used for identification and characterization purposes.
Active Systems (RF)	independent PNT receiver and independent radio capable of transmitting ID and positional data to an independent communications provider (e.g. space-based. The position data would come from combine a low-power GPS receiver.
Active Systems (Optical)	An independent and powered source of coded optical laser pulses (e.g., ELRIO), allowing to also transmit data messages. Alternatively, single or multi-colored LED signals also provide identification through their blinking (Morse) codes.

Data Fusion and Shared Catalog

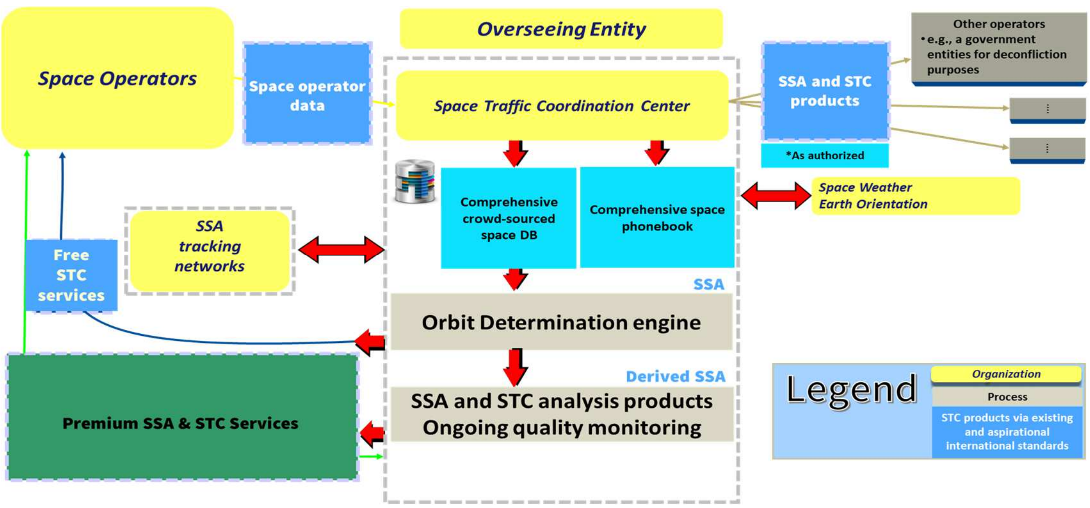
The COPUOS Guidelines for the Long-Term Sustainability of Outer Space Activities contain effective guidance on how to achieve safe and sustainable operations in space. Broadly speaking these guidelines state that the sharing and dissemination of space data should be promoted, and accuracy of data should be improved to support space safety.

Data fusion has been shown to be an important way of improving the accuracy and timeliness of orbital data when astrometric observations of space objects are not plentiful or are not of exquisite quality. And sharing of a space object catalog has been a critical element of current and future flight safety approaches, providing transparency, capacity-building, and a shared understanding of the space environment and operational risks. However, for catalog sharing to be effective, it will be important to develop and utilize open-access space data exchange standards, methodologies, best practices, and potentially even open-source tools at the international level.

The chapter discusses the concept of one or more "shared catalogs" of space data and information. The concept of "data levels" is introduced, with many STM-relevant data types characterized by data level. This chapter also examines the technique of fusing space data from multiple sensors, sensor types, SSA organizations, and space operators to obtain more accurate positional knowledge using technically-mature and operationally-mature data fusion methodologies, tools, and analytics.

Data fusion is the process of integrating multiple data sources to produce more consistent, accurate, and useful information than that provided by any individual data source. It is insufficient to merely aggregate data sets (called Data Integration). Data fusion is the process that not only merges the data but additionally applies a reduction technique (i.e., orbit determination) to the combined data set of diverse observations to yield a unified (fused) solution having improved confidence (i.e., reduced positional errors). Publicly shared catalogs are available through some organizations, but much detail (e.g., as to how the contained data was generated) may be omitted for national security or proprietary reasons, leaving recipients unable to leverage (e.g., incorporate and fuse) the data to its full extent.

To provide the most utility, and enable data fusion, SSA data should be archived in an accessible data repository. Required characteristics of a data archive, as defined for large international and national weather and climate data sets include; establishing data quality requirements for archiving, maintaining consistency in metadata, ensuring data accessibility, and maintaining data integrity. Space catalog sharing by itself is necessary but insufficient. To be useful, particularly in data fusion processes, supplied space information must also be accompanied by compatible propagator methods or force model settings, an assessment of the ranges of variability or standard deviation(s) for the attribute's estimated solution, and specification of analysis technique(s) employed to generate the information. Error estimates (for example, covariance information for the orbit solution) must be demonstrated to be realistic characterizations of actual system error as shown using established covariance realism methods. The figure below is a representation of how data could flow through an integrated shared catalog with data processing and fusion outputting SSA and STC services thus facilitating STM.



Large Constellations

Predominantly located in LEO, large constellations (LCs) are real new systems, enabled by the rise of commercial space, mass production of small satellites, and lower launch costs using mass deployment techniques. This will not stop. The size and scale of LCs is well beyond any previous space systems which can create challenges in area where they did not previously exist, and little regulation, recommendation or legal rules apply specifically to LCs or account for the scale on which they operate.

Technical Considerations:

LCs arise when continuous service is needed. In terms of traffic management, a global view is required, this is not N satellites but one system in specific orbital shells. Collective effects on LCs should be considered versus traditional per satellite management. Mass production allows a continuous versioning and improvement of models, resulting in fixed lifetimes, leading to a very low failure rate. Nevertheless, the end of mission disposal is of paramount importance, post mission disposal success rate must be as close as possible to 100%. The disposal itself is an important phase when controlled reentry is often not feasible. Semi-controlled reentry, control of the satellites until just before reentry, and design for demise are new rules that must apply. Continuous collision awareness requires their operators to continue to develop new processes, including large-scale automation, which creates new challenges, and behavior rules. National regulators will need to set rules to solve problems that have not yet occurred. Effective occupation of an orbital layer by thousands of identical satellites operated by a single operator may lead to a new cooperative way of handling the conjunction assessment, with a stronger part for the main operator, maybe taking into account all satellites in this shell, and the one(s) owned.

Policy & Legal Aspects:

Very little international agreement on specific policy exists for LCs today and existing policies were not designed for the scale of LCs It is up to each national regulating body to specify what is requested. The concept of fault is not defined, hence the a priori management of in-orbit liability is not properly regulated by international common law. Effective occupation of an orbital shell, thus preventing other operators from easily using this orbital altitude is undefined, although several interesting proposals have been made. An international dialogue, and possibly consensus, is needed. A neutral global process may aid in encouraging more effective space traffic management governance and operations.

Synthesis:

LCs have changed the paradigm of LEO space utilization; the orbit itself has now a value (as is the case for GEO). The intensive business developed in those orbital shells should be persistent, it is not the interest of a LC operator to see the operational orbital shells polluted by dead satellites or debris. Because of the number of individual satellites involved and the sustainability of their business models, LCs methods of operation might significantly influence the evolution of space standards, in a good way. There are a number of technical and policy/legal issues that need to evolve in a timely fashion; this requires swift actions as some LCs are already in operation. An international action under the ISO normative body, backed by technical insights from IADC and the political and diplomatic level in the UN, coherent with LTS needs should be strongly pushed.

Space Capacity Management

In recent years we have witnessed an exponential increase in the number of active satellites in Earth orbit, which is being driven by a growing number and diversity of space actors on Earth. The growing congestion in orbit due to active satellites and space debris has led to the conclusion that the Earth's orbital space environment constitutes a finite resource that must be managed rationally and equitably for the benefit of current as well as future generations. The management of the finite capacity of near-Earth orbital space requires both scientific and technical as well as policy and regulatory approaches to deal with all the aspects of the issue. In this chapter we examine these various aspects.

The first step toward space capacity management is to develop a scientific and technical understanding of precisely what is meant by this limited capacity, how to quantify it, and how to measure its use. Measuring the available capacity of the space environment, to drive debris mitigation guidelines to a desired environment trend. The "orbital capacity" can be understood as the number of objects compatible with a sustainable utilization of the environment. However, a consensus has not yet been reached on what a definition for sustainable environment is, in terms of population growth rate (i.e., zero-growth rate or an acceptable growth rate). The difficulty is that prediction relies on long-term simulations of the environment that depends on the definition of several parameters (e.g., launch traffic, break-up rates, disposal behavior), which are difficult to predict. Other domains can provide a good inspiration for definitions of orbital capacity and related management mechanisms. These include examples of nature from closed ecosystems, management of climate change, fisheries, and frequency management through the International Telecommunication Union.

Several metrics have been proposed such as the fragment-years that are available for consumption by human space activity in Low Earth Orbit for the next 200 years or a risk metric (also indicated as space debris index) that can be aggregated across all objects in orbit to quantify which share of the environment capacity is already in use and which could be used by future missions. On the other hand, space sustainability analyses have focused on the whole debris population, or active objects only, or the impact of large constellations. However, applying different space capacity definitions, or different aggregated space debris indices, and different hypotheses in evolutionary models or different models for in-orbit explosions and launch traffic rates can lead to widely varying results. This highlights the importance of a concerted framework for the definition, computation, monitoring, and allocation of the space environment capacity.

Life cycle assessment approaches have been developed to measure the space debris index considering not only the risk for in orbit collisions and explosions, but also other contributions as the casualty risk on ground during re-entry, or the use of an orbit slot and the revenue it may generate. A recent initiative proposed a score representing the sustainability of a mission looking at the alignment with international guidelines. The approach combined, in a unique indicator, different modules to capture different aspects of sustainability in space, considering both the impact on other operators and on the environment globally, looking both at short- and long-term effects. In general, such metrics can be defined at the environmental level (e.g., population growth) or at a single object level (e.g., number of objects, number of performed collision avoidance maneuvers, flux, fragmentation risk) and aggregated to provide a single score representative of the global environment status. In all cases, a methodology should be defined to allow for monitoring (i.e., ideally, independent assessments are possible with inputs mostly coming from available catalogues and models) and, potentially, for traffic management (e.g. having the possibility of deriving actionable measures to be applied to space missions).

While a capacity measure is needed, the resulting challenge is to define indicators and thresholds. From an operational point of view, the number of Conjunction Data Messages could be used to quantify the risk in each orbit slot. Additionally, the number of Collision Avoidance Maneuvers gives information on the threshold of collision probability accepted by the satellite operator, even if this is highly operator dependent as different operators can have different reaction thresholds. Most of the metrics proposed rely on common parameters in their assessments, such as the size (i.e., mass or cross-sectional area) of spacecraft and its orbital altitude. Some formulations consider the activity status of spacecraft and their ability to perform collision avoidance maneuvers. Further aspects that can be considered include data sharing, spacecraft design (e.g., robustness to failure), and concept of operations (e.g., station keeping strategy, disposal approach).

In conclusion, a transparent methodology needs to be developed to seek for global consensus and implementation in countries' regulatory approach. Moreover, it may be necessary to distinguish between global and local capacity. The former would correspond to the capacity of all the Earth orbits, while the latter would define the capacity of specific orbital regimes, shells, or inclinations, which could be related to space traffic management procedures. The local and global threshold not to be exceeded should be defined by international entities, as it has been done with Space Debris Mitigation guidelines and requirements, by entities such as Inter Agency Space Debris Coordination Committee and the United Nation (UN) COPUOS. To this end, the need for mechanisms to ensure the review and approval of the proposed capacity use would arise.

Regarding the policy and regulatory aspects of space capacity management, under the existing international legal framework for space activities, States bear international responsibility and liability for the space activities of entities under their jurisdiction and/or control. These obligations derive from legally binding international treaties, as well as legally non-binding (although politically binding) soft law instruments such as UN General Assembly resolutions, and other internationally accepted standards, principles, and guidelines. The treaty obligations of States are normally codified in national legislation that is implemented by the relevant national regulatory authorities. In addition to such legally binding treaty obligations, States may also choose to codify non-binding principles or guidelines, such as space debris guidelines or the Long-Term Sustainability guidelines in their national regulatory practices.

The dramatic increase in the number and nationalities of non-State actors raises challenges for national regulators regarding chain-of-custody issues and phenomena such as regulation shopping. This raises the possibility of a fragmented governance system, with different standards of behavior in one common, shared domain, which can only be avoided through cooperative governance of space activities and improved inter-regulator coordination.

Reaching a shared understanding on how space environment capacity should be uniquely defined will be the first step towards the management of this capacity. The next step would be to reach an international consensus about the metrics that should be used. In doing so, it may be necessary to distinguish between global (i.e. all the Earth orbits) and local capacity (i.e., specific orbit regimes). These are important considerations because when a State licenses a space system, it is essentially allocating a fraction of the limited, globally shared orbital carrying capacity to one of its national space actors, and it is also accepting international liability for that system on behalf of that nation's taxpayers.

The licensing process should include regulatory considerations such as: (i) what fraction of capacity is allocated and whether this can be justified as a rational and equitable allocation of such capacity; (ii) whether conditions should be imposed on a licensee to ensure that the allocated capacity is vacated after the end of licensed operations, or sooner in the event that the mission fails, and how such conditions would be enforced; (iii) whether the period of validity of a license should be limited, or whether it should remain in force as long as the allocated capacity is "used" in some way, and specifying what constitutes "use"; and (iv) whether an operating license should be transferable from the licensed operator to another operator.

Outreach

This report addresses the need for communications to a variety of stakeholder communities to enable global progress in the area of Space Traffic Management. The vision of safely coordinating the operations of satellite missions and constellations requires awareness and actions by organizations from government, commercial, academic, nonprofit and multilateral sectors.

This work adapts a Systems Architecture method to address specific questions related to communications for Space Traffic Management. The Systems Architecture approach asks several key questions, including the following:

1) Who are Primary, Secondary and Tertiary Stakeholders for Space Traffic Management?
2) What are Stakeholders Needs and Desired Outcomes in the area of Space Traffic Management?
3) What Messages are relevant to each type of Stakeholder?
4) What Channels are available to send these Messages?
5) What timeline can be proposed to apply these Channels and Messages.

The Systems Architecture definitions guide the Outreach Approach by highlighting the positions of three categories of Stakeholders. Primary Stakeholders are decision makers who actively influence the design or policy for Space Traffic Management. Secondary Stakeholders are not direct decision makers, but they have influence via funding, oversight or political interaction with Primary Stakeholders. Tertiary Stakeholders are defined as those who experience the results of the Space Traffic Management system design. Tertiary Stakeholders experience the outcomes of the Space Traffic Management system, which they may interpret as benefit or challenges.

The report identifies the following categories of Primary Stakeholders: National, Regional and Supranational Space Agencies; Space Situational Awareness and Space Surveillance & Tracking service providers; international governance bodies; and standardization bodies. The discussion on Channels highlights existing options for sharing information about technical, policy and legal aspects that can inform the design of future Space Traffic Management efforts. The report identifies a variety of settings for information about STM to be shared, especially in the categories of conferences, academic publications, Multilateral forums, space-related events, space related press and the general press. The analysis of Channels finds that many of the existing sources of information about Space Traffic Management are written in a format which assumes that the audience is generally interested and aware of Space Traffic Management. Communication among the Primary Stakeholders is the highest priority during the development of new capabilities in Space Traffic Management. Thus, there is alignment between the Primary Stakeholder audience and the active Channels. The report also finds, however, that additional effort can be applied for Primary Stakeholders to have two-way dialog with Secondary and Tertiary Stakeholders in order to understand what the Needs and Desired Outcomes are for those groups.

There is an opportunity for Primary Stakeholders to make greater use of non-traditional communication Channels to supplement the existing use of well-established Channels. Some of the high priority messages that the report identifies include reminding Stakeholders that space is a key enabler of technology to meet needs on Earth and support attainment of Sustainable Development Goals. Further, the Messages emphasize the current trends in space activity, showing the urgency to act. Additionally, the Messages note that responsibility and role of public and private actors to apply technical and non-technical approaches to address the STM challenges that are not yet resolved. The section on Timelines shows that there are regular windows of opportunity to communicate based on the annual schedule of publications, conferences, events and institutional meetings.

The report recommends harnessing these existing gathering that bring together many of the Primary Stakeholders routinely to repeat the key Messages. In addition, the analysis shows several opportunities to communicate responsively when certain events or changes occur. Overall, the report finds that ample knowledge and opportunities exist for enhancing communication among Primary, Secondary and Tertiary Stakeholders on Space Traffic Management.

Conclusion

The contributions from over 130 IAA, IAF, and IISL committee members in 14 topical areas over the last four years provides a sound foundation for further technical research, operational cooperation, regulatory discussions, and policy formulation. The breadth of the topics covered in this report accentuates the diverse nature of STM and amplifies the necessity for aggressive efforts by the community to minimize deleterious effects on current operational space systems but more importantly to create the environment for sustainable space operations for decades to come. There are likely other technical, operational, regulatory, and policy efforts that will be catalyzed by this joint report; that is the true measure of a good report, it lays the foundation for an acceleration in relevant activities in its wake.

Indeed, this current document closes formally the action taken during the opening ceremony of IAC 2018 in Bremen, but it clearly does not end the work on the vastly rich topic of STM. Numerous members have expressed the will to continue working together on some of the most pressing subjects, such as related to large constellations or space capacity management. Several subjects were also identified and not started in the frame of this document, but definitely deserve some work, leading to associated recommendations, such as the management of RF interferences or the improvement of UN registration. Last, the scope of the work shall be extended also to sub-orbital activities, transits through airspace, traffic from orbit to Moon and Mars).

No doubt IAA, IAF, and IISL will remain coordinated in near future, to tackle efficiently all the open points that deserve additional work.

Appendix
List of contributors per chapter

Overall coordination of the IAF TC26 on STM: Christophe Bonnal – France, Darren McKnight – USA
Secretary: Serge Plattard – United Kingdom **IAF-IAA-IISL Liaison**: Didier Alary – France

1. Terminology - Common understanding and Definitions

Inés Alonso – Spain
A.K. Anilkumar – India
Laurent Francillout – France
Kyran Grattan – United Kingdom
André Lacroix – Germany
Rodolphe Munoz – Belgium
Daniel L. Oltrogge – USA
Haofang Quan – China – Coordinator
Robert Rovetto – USA
Mark Skinner – USA – Coordinator
Maruška Strah – Slovenia
Igor Usovik – Russia
Elena Vellutini - Italy

2.1. New technical means of space objects monitoring

Pascal Faucher – France
Holger Krag – Germany
Samantha LeMay – Australia
Francesca Letizia – Germany – Coordinator
Jing Liu – China
Manuel Metz – Germany – Coordinator
Fabrizio Piergentili – Italy
Maria Antonia Ramos – Spain
Noelia Sanchez-Ortiz – Spain
Thomas Schildknecht – Switzerland
Smiriti Srivastava – India

2.2. Improving trackability and identification of small objects

Mohamed Ramzi Aouimeur – Algeria
Moriba K. Jah – USA
Yukihito Kitazawa – Japan
Holger Krag – Germany – Coordinator
Mike Lindsay – USA – Coordinator
David Lopez – Spain
Paolo Marzioli – Italy
Mark Skinner – USA
Nancy Wolfson – USA

2.3. Data fusion – Merging of information

Sanat Biswas – India
Katia Caceres – Spain
Emmanuel Delande – CNES
Kyran Grattan – United Kingdom
Moriba K. Jah – USA
Emma L. Kerr – United Kingdom – Coordinator
Jing Liu – China
José-Miguel Lozano-Gonzalez – USA
Romain Lucken – France
Daniel L. Oltrogge – USA – Coordinator
Alejandro Pastor – Spain
Robert Rovetto – USA
Jan Siminski - Germany

2.4. Improvement of orbital data precision and accuracy

Vladimir Agapov – Russia
Alberto Agueda-Maté – Spain
Juan-Carlos Dolado-Perez – France – Coordinator
Tim Flohrer – Germany
Moriba K. Jah – USA
Sahith-Reddy Madara – India
Vincent Martinot – France
Mike Nicolls – USA
Kumi Nitta – Japan – Coordinator
Yao Zhang – China

2.7. Hazards associated with reentry

William Ailor – USA – Coordinator
Jean-Marc Bouilly – France
Tobias Lips – Germany
Phyllis Makurunje – Zimbabwe
Pierre Omaly – France – Coordinator
Carmen Pardini – Italy
Kenichi Satoh – Japan
Tiago Soares – Netherlands

3.1. Space Capacity Management

Benedetta Cattani – Italy
Camilla Colombo – Italy – Coordinator
Emmanuelle David – Switzerland
Juan-Carlos Dolado-Perez – France
Diego Escobar – Spain
Okchul Jung – Korea
Satomi Kawamoto – Japan
Francesca Letizia – Germany
Peter Martinez – South Africa – Coordinator
Maria Antonia Ramos – Spain
Robert Rovetto – USA
Ivan Sumelzo – Spain
Aude Vignelles – Australia

3.3. Improvement of the collision avoidance process

Nicolas Bérend – France
Benedetta Cattani – Italy
Camilla Colombo – Italy
Upasana Dasgupta – Canada
Diego Escobar – Spain
Norman Fitz-Coy – USA
Toby Harris – United Kingdom – Coordinator
Matthew Hejduk – USA
Emma L. Kerr – United Kingdom
François Laporte – France
Michel Martin – Germany
Cristina Perez – Spain
Ryan Shepperd – USA
Marlon Sorge – USA – Coordinator
Mingliang Tang – China
Xu Yang – China

3.4.1. Future operations – Space tugs, In Orbit Servicing, In Orbit Manufacturing, In Orbit Recycling

John Auburn – United Kingdom
Benjamin Bastida Virgili – Germany
Riccardo Bevilacqua – USA
Luis Buinhas – Portugal
Joe Cassidy – USA
Haowen Cheng – China
Zizheng Gong – China
Dmitriy Grishko – Russia – Coordinator
Markus Jaeger – Germany
Marko Jankovic – Germany
Yide Li – China
Roberto Opromolla – Italy – Coordinator
Maria-Antonietta Perino – Italy
Javier Rodriguez – Spain
Helen Tung - Australia

3.4.2. Large constellations

William Ailor – USA
Didier Alary – France – Coordinator
Joao Branco – Portugal
Upasana Dasgupta – Canada
David Goldstein – USA
Akira Kato – Japan
Hae-Dong Kim – Korea
Yide Li – China
Martin Michel – Germany
Cristina Perez – Spain
Zaid Rana – Canada
Alessandro Rossi – Italy
Jaedong Seong – Korea
Balbir Singh – India
Marlon Sorge – USA – Coordinator
Helen Tung – Australia

3.4.6. Impact of constellations on astronomical observations

Haowen Cheng – China
Bernard Foing – Netherlands – Coordinator
Olivier Hainaut – Germany
Fatoumata Kebe – France
Tanja Masson-Zwaan – Netherlands
Charlotte Nassey – France
Marco Romero – Angola
Alessandro Rossi – Italy
Pat Seitzer – USA – Coordinator
Pietro Ubertini – Italy
Igone Urdampilleta – Spain

4.2. Technical regulations – New activities

Phillip Anz-Meador – USA – Coordinator
Yulei Fu – China
Akira Kato – Japan
Shen Lin – China
Tim Maclay – USA
Annamaria Nassisi – Italy
Ruvimbo Smanga – Zimbabwe
Francesco Santoro – Italy
Balbir Singh – India – Coordinator
Christian Unfried - Austria

4.3. Effective compliance to technical regulations

Didier Alary – France
Valentin Eder – Austria
Jose-Maria Hermoso – Spain
Satomi Kawamoto – Japan
Morgane Lecas – Austria
Stijn Lemmens – Germany – Coordinator
Peter Martinez – South Africa
David B. Spencer – USA – Coordinator
Kuan Yang – China

5. Outreach

Alberto Agueda Maté – Spain
Nate Dailey – USA
Carme Gregori – Spain
Maren Hülsmann – Germany
Noelia Sanchez-Ortiz – Spain – Coordinator
Balbir Singh – India
Lesley-Jane Smith – Germany
Maruška Strah – Slovenia
Pietro Ubertini – Italy
Danielle Wood – USA – Coordinator