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On the Implementation of a European Space Traffic Management System

III. Technical Requirements

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ABSTRACT

This third paper (Paper III) concludes the mini series of papers which presents results from an ESA-funded evaluation study that has been collected by DLR GfR and its partner institutes and companies. The objective of this study is to generate a roadmap for the implementation of a European STM system within the next two decades under consideration of an evolving Air Traffic Management (ATM) system. In Paper I (Tüllmann et al. 2017a), we introduced the implementation approach by focussing on the commercial Space Travel market which is expected to develop into a multi-billion Euro business in the coming years and could become a major driver for STM in general. We provided proof of concept that this suborbital space travel is generally possible, given that significant advances in heat and collision shielding technologies can be achieved. The envisioned technical, conceptual and organisational setups were discussed regarding Space Debris, Space Surveillance & Tracking, Space Weather Monitoring, Flight Planning and Scheduling and ATM and STM integration. This work is supplemented by Paper II (Tüllmann et al. 2017b), which discussed Safety & Reliability (S&R) aspects that should be reflected in a S&R concept for the STM system. In this context relevant Safety Management Systems in aviation business were investigated to check to what extent their S&R concepts and good-practices are applicable to STM operations. A first Risk Classification Scheme was presented and initial values for the acceptable levels of safety for the identified hazards were presented and an outline of the envisaged Space Navigation Service Provider (SNSP) certification process was given. In this present work (Paper III) we focus on deriving initial technical high-level requirements and recommendations for a European contribution to Space Traffic Management and define relevant interfaces in the global context. The proposed requirements and interfaces presented here are neither complete nor final and are meant to provide a first rough guidance for space agencies, manufacturers or policy makers and shall stimulate discussions on how a European STM system could be realised.

Key words. Space Traffic Management – Air Traffic Management – suborbital space flights – Space Weather Monitoring – Space Surveillance and Tracking – safety & reliability – Safety Management – technical requirements – STM interfaces

1. Introduction

This paper (Paper III) contains the initial high-level requirements, constraints and assumptions derived from an ESA-funded evaluation study that describes the roadmap towards implementing a European Space Traffic Management (STM) system within the next two decades and integrating it with an evolving Air Traffic Management (ATM) system (see Papers I (Tüllmann et al. 2017a) and II (Tüllmann et al. 2017b) for details). The focus of the paper at hand is on technical, operational and organisational requirements related to the needed infrastructure, technology and organisational setup. This includes aspects related to the understanding of Space Debris and Space Surveillance and Tracking (SST), Space Weather Monitoring, Safety and Reliability, ATM, spaceplane technologies and the integration of the STM and ATM sectors. Political aspects and institutions as well as legislative issues are not part of this study.

Because space is "free" and is not owned by individuals or nations, STM is not just considered a European, but a global undertaking and requires international collaborations as well as thinking and planning beyond narrow national boundaries. This is especially true if Europe wants to serve international space travel markets, e.g., in the U.S. or in Asia. In this regard, a high-level layout of the anticipated global technical interfaces of the envisaged European STM system is proposed.

The overall purpose of a future STM system and its underlying operations concept should be to ensure safe space travel and air traffic operations in Europe and around the globe. Such a concept should include the requirements provided in the following chapters of this document. It is explicitly stated that this work does not intend to provide a complete set of detailed requirements, but shall rather provide initial guidance from an operations point of view and ideally stimulate discussions in the community on how to realise a European STM system.

Regarding integrated STM and ATM flight operations (see Chapter 3.7 in Paper I), a possible STM operations concept could include (but would not be limited to) the aspects listed below.
Pre-Flight Operations Phase:

- Flight planning, re-scheduling and emergency response planning, flight corridor planning (including backup solutions)

- Space Weather Bulletins dissemination
- Risk assessments and collison risk analyses (CRAs) dissemination
- Terminal information, passenger and crew briefings
- Local weather information
- Infrastructure and spaceplane maintenance
- Safety & security operations
- Flight plan dissemination (e.g., Space Weather and trajectory updates), ATM and STM operations and communication, flight and system status checks (go ahead: yes/no)
- Take-off, runway, 4D trajectories, noise reduction, fuel efficiency and re-fuelling, risks related to separation distances to sensitive infrastructure in case of accidents.

In-Flight Operations Phase:

- Routine communication and operations (e.g., handover & handback operations, trajectory cross-checks and updates, orbit adjustments, terminal and passenger information services)
- Contingency communication and operations (technical issues aboard the spacecraft, evasive manoeuvre planning and execution for collision avoidance, interfacing with Air Traffic Control Operators (ATCOs) and Space Traffic Control Operators (STCOs) on dynamic transition corridor handling or during Space Weather hazards).

Post-Flight Operations Phase:

- Infrastructure and spaceplane maintenance
- Safety & security operations
- Communication with interfaces (e.g., STCOs/ATCOs, spaceplane, Ground Ops, etc.)
- Terminal and passenger information services and crew debriefings
- Provision of data and information on request (e.g., for incident investigations).

This work captures the key requirements associated with European STM topics. They are grouped per type, i.e. according to Functional Requirements (Chapter 2), Performance Requirements (Chapter 3), Interface Requirements (Chapter 4) and Safety and Reliability (S&R) Requirements (Chapter 5). The requirements are also sorted by subject and are listed together with a reference to the topic where the requirement has been derived from.

Finally, this paper is supplemented by three annexes containing requirements for suborbital space vehicles (SSVs) and spaceplanes (Annex A), ATM requirements (Annex B) and detailed technical requirements for the Space Weather Monitoring Centre (SWMC, Annex C, see also Paper I). NOTE: The terms ‘SSV’ and ‘spaceplane’ are used synonymously throughout this document.

2. Functional Requirements

A functional requirement is a specific need or behaviour of the system from a system point of view. This chapter is grouped into the following sub-sections:

- Space Weather Monitoring (SWM)
- SST
- STM System: Certification, Regulations and Standards
- STM System: Miscellaneous (i.e. not specific to the SWM or SST or Certification, etc).

2.1. Space Weather Monitoring

One of the biggest issues in STM will be the management of the critical Space Weather environment. In fact, the conditions in space are in many aspects much more aggressive than in airspace which means, that the requirements associated with Space Weather are stricter. The list of functional requirements for Space Weather Monitoring is presented in Table 1 (see also Annex C) in this document for a list of detailed technical requirements).

2.2. Space Surveillance and Tracking

In order to guarantee safe and secure travel through suborbital and LEO space, the SSVs and spaceplanes need to avoid any catastrophic collisions during flight with other objects. This requires detailed knowledge about the trajectories of these objects as well as the definition and establishment of adequate risk and safety standards for operating commercial manned spacecraft in LEO and below. The functional requirements for SST purposes are summarised in Table 2.

2.3. STM System: Certification, Regulations and Standards

Certification, regulations and standards are considered to be fundamental pillars to support the development of the STM system. They must reflect minimum requirements and be technology-neutral to allow the necessary technological development. The relevant functional requirements for the the STM system regarding Certification, Regulations and Standards, are shown in Table 3.

2.4. STM System: Miscellaneous

In this section high level requirements for the STM concept which are not specifically aimed at SWM, Space Traffic Control (STC) or certification, regulations or standards are listed (see Table 4).

3. Performance

A performance requirement specifies the effectiveness of a capability that the system should deliver. This chapter is broken down into sub-sections for SWM, SST and miscellaneous aspects related to the STM system.

3.1. Space Weather Monitoring

The Performance Requirements for Space Weather Monitoring are listed in Table 5,

3.2. Space Surveillance and Tracking

The following requirements in Table 6 have been derived as placeholders and, as explained in Paper I, require further work in order to replace the “tbd”s with actual data, with justification.

3.3. STM System: Miscellaneous

The list of identified Performance Requirements covering miscellaneous STM system aspects are given in Table 7.

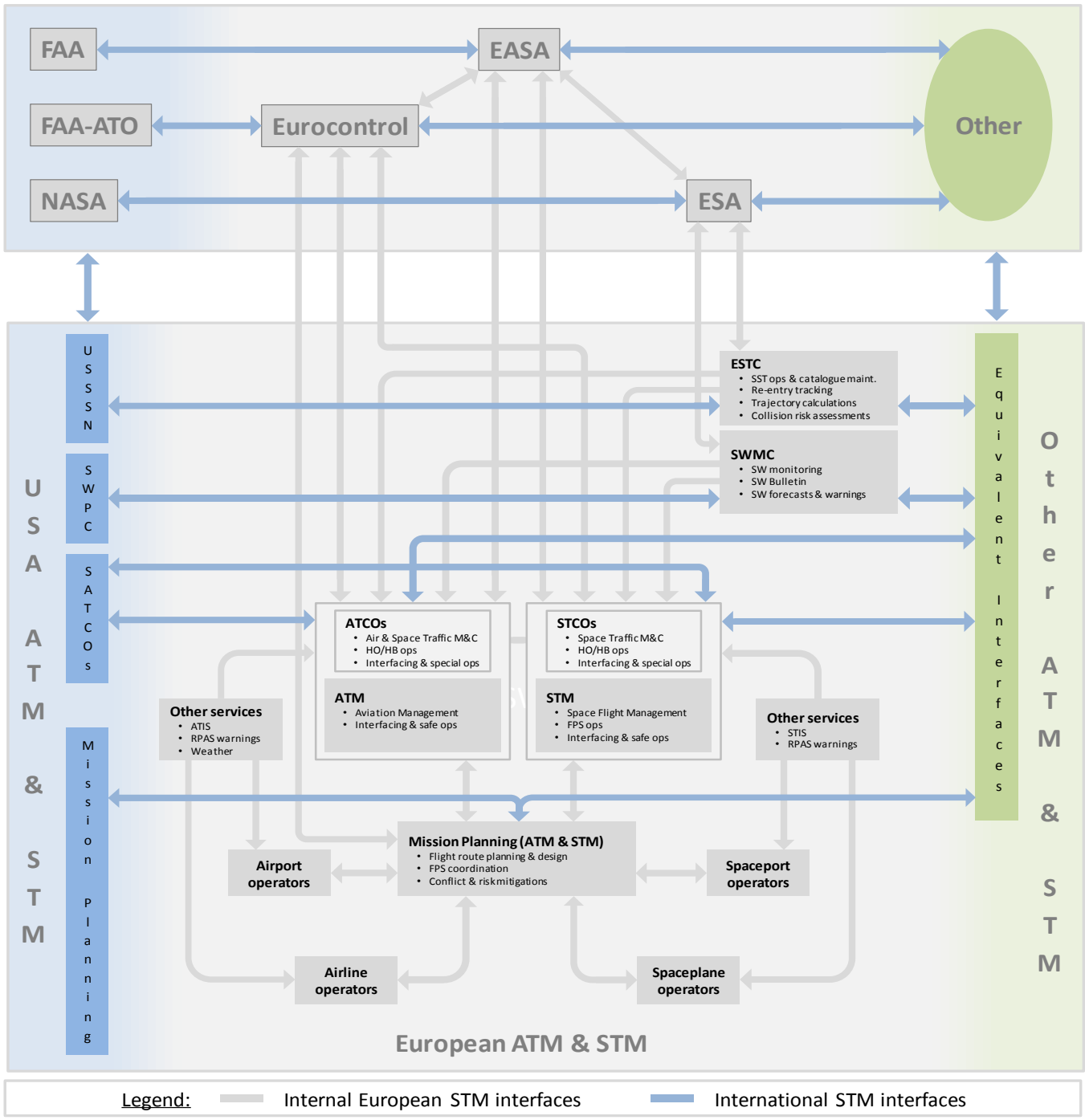

Figure 1: Possible STM interfaces in the European and global context.

4. Interface Requirements

4.1. European and Global Interfaces

Space Traffic Management, as defined in Paper I, clearly requires a global perspective and close collaboration of space-faring nations, because for commercial space flights to be most profitable large intercontinental distances are needed. This in turn calls for high safety standards, efficient planning cycles and safe and routine space flight operations to be established on a global scale. As already mentioned, there are a several operational interfaces within the envisaged European STM system, most notably those between ATCOs, STCOs, ESSTraC and the SWMC, respectively (see e.g. Figures 14, 16 and 19 in Paper I). If a European STM system is now put into the global context, further interfaces can be identified (see Figure 1), e.g. those with the ATM and STM systems of the USA (light blue part to the left) or with other, currently unknown, nations (light green part to the right).

4.2. STM and ATM Interfaces

When integrating STM and ATM, the interfaces will be a key area of focus to ensure an acceptable level of risk can be maintained. In Table 8 the corresponding requirements are listed and

those related specifically to communication (i.e. the C in the CNS domain) have been highlighted with sub-heading "COM-domain". Further requirements on the ATM domain itself can be found in Annex B.

5. Safety & Reliability Requirements

It should be recognized that safety is not aimed at achieving zero accidents, zero hazards or zero errors. The real target is to provide mitigating actions to prevent undesirable situations escalating. The key top level requirements associated with S&R in accordance to Paper II (Tüllmann et al. 2017b) are captured in Table 9. In addition, there are requirements for the Risk Classification Scheme (RCS, see Table 10), for S&R Assessment Methodology (Table 11) and for Safety Promotion (Table 12).

Appendix A: Spaceplane Requirements

The following requirements related to the design and performance of the SSVs and spaceplanes have been derived from the relevant sections in Paper I (Tüllmann et al. 2017a), as specified in the source column of Table 13. These are dependent on, and should remain consistent with, the ATM related requirements presented in Appendix B. Performance and S&R requirements for those vessels are provided in Tables 14 and 15, respectively.

Appendix B: ATM Requirements

Further to the interfacing requirements identified in Sect. 4, this chapter details the main requirements for the ATM as derived in Paper I (Tüllmann et al. 2017a). Functional and Performance-related requirements are listed in Tables 16 and 17, respectively. They are related to the Communication, Navigation and Surveillance (CNS) domain and should be considered when integrating ATM and STM systems. Note that the requirements related to the COM-domain are listed in Sect. 4. These are, of course, interrelated to the requirements for the Spaceplanes/SSVs themselves (see Annex A).

Appendix C: Detailed Technical Requirements for the SWMC Service

The detailed technical requirements for the SWMC service should include (cf. Sects. 2.1 and 3.1):

General Requirements

- The product filenames should be intuitive
- The product filenames shall be unique

Product Order Requirements

- Each product data set must be uniquely identifiable and must contain a comprehensive product description

User Account Requirements

- Security and data policies must met during the registration. Personal data and passwords have to be saved securely
- The user can see his personal data stored in the system
- The user can see his list of orders and current status

Requirements on News and Information

- Weekly bulletin on ionospheric weather
- News on the latest ionosphere related events and information
- Announcements on website availability (Timely information on maintenance)
- Information on SWMC policies and licenses
- Provision of Frequently Asked Questions (FAQ) information
- News on the latest Space Weather event and related ionospheric disturbances
- Provision of tutorial information on Space Weather and ionosphere
- Product based FAQ (for what kind of analysis can I use this product, for what not)
- Statistics on the reliability of forecasts

Website and Data Access Requirements

- Website shall be simultaneously usable for a minimum of 1 000 users
- Website shall contain a News and Information page
- Website shall contain a Product Catalogue page (cf. Table 4 in Paper I), including at least:
  - the latest images of the products
  - latest images of quality products
  - latest images of supplementary products
  - an up to date product description
  - data access information for forecast, nowcast and archived data files and direct hyperlinks
  - file and data format description, data policy and license information (at least as hyperlink)
- Website shall contain an Alarm and Warning Service page with at least the following sections:
  - General information about the warning system
  - Early Warning Message (current status, latest message and access to archive)
  - L1 Warning Message (current status, latest message and access to archive)
  - Forecast Warning Message (when available)
  - Near Real-Time Alert when available, e.g., based on flare information, perturbation indices, or scintillation measurements (cf. Sect. 3.6 in Paper I)
  - Alarm subscriptions
- Website shall contain an archive access
- Website shall contain a Logon/User Profile page
- Website shall contain a contact page for technical and 2nd-level support
- Website shall provide an User Help Desk, which operates a support data base archiving all past communication
- Website shall contain on every page a link to the user profile
- The SWMC website shall be barrier-free
- The system shall provide routine weekly reports (Website/Email)
- The system shall provide customisable reports about individual events of interest (Website/Email)
- The system shall provide a way for announcements on website availability
- The system shall provide news on the latest Space Weather event and related ionospheric disturbances (Website/Email)
- The website shall provide Frequently Asked Questions (FAQ) information
- The system shall provide information about the License, that needs to be accepted at registration
- The system shall provide certificates (HTTPS, SFTP, FTPS)
- The website shall be operative on common browsers with latest version (Firefox, Safari, Chrome, IE, etc.)

System Requirements

- The SWM system shall ensure high availability
- The SWM system shall provide a ticket system for registered users
- All interfaces shall be described in a clean and simple way

- The system must be able to manage and provide input/output data in form of files, database connections, events and streams
- The system shall be extensible for new products
- The SWM system shall archive all processed/defined products
- The system shall provide all processed/defined products at the SWMC website 24/7, despite input data pile-up
- The SWMC shall contain a monitoring system with message delivery
- System shall provide meta data describing each product type
- The SWM processing system shall continuously monitor the product quality
- The processing system shall be able to handle data streams
- Data uploads to an external FTP Server shall be considered
- An Product Order System and search engine for products shall be available
- Every product shall have an Unique Product Identifier (UPI)
- The Product Order System shall show the user the product availability
- The Product Order System shall be available on a 24/7 basis
- Each product shall have a checksum

Additional Requirements

- The SWMC shall possess a Data and Information Management System, including workflow management and an archiving system
- All data computed and disseminated by the SWMC shall be stored in a data archive (short term, mid-term and long term archive)
- The SWMC shall feature a Real Time Solar Wind receiving and processing unit for the ACE and DSCOVR satellites.

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Table 1: Functional Requirements for Space Weather Monitoring

Req.-ID	Requirement Text	Source
1	The Space Weather Monitoring Centre (SWMC) shall be responsible for the following operations and service provisions: 1) Performing 24/7 Space Weather monitoring 2) Providing Space Weather information 24/7 via dedicated web page (passive information flow) 3) Provide products needed for Flight Planning and Scheduling operations via direct data streams to ATCOs and STCOs (active information flow), such as real time Total Electron Content (TEC) products, long term forecast of ionospheric conditions, geomagnetic and ionospheric storm onset definitions and Space Weather Bulletins 4) Operate and maintain an active warning system by providing email alerts and xml notifications to STCOs and ATCOs on Space Weather events having a potentially high risk to strongly affect safe spaceplane operations 5) Provide technical and scientific support 24/7 for services and products 6) Maintenance operations of networks and web pages 7) Support the International Civil Aviation Organisation (ICAO) on relevant Standard and Recommended Practices (SARPs) issues 8) Support the World Meteorological Organisation (WMO) on defining and improving observation and service requirements to protect against Space Weather hazards 9) Perform Special Operations (e.g., provide data on request for incident investigations, perform conflict-free scheduling and execution of maintenance downtimes).	Space Weather Monitoring
2	The frequency of the SWMC products to be provided under requirement #1 shall be as follows: • Real-time TEC products: Hourly, 24/7 and on demand in case of Space Weather conditions require re-planning of the flight plan or endanger human safety aboard the vessel • Long term forecast of ionospheric conditions: Daily, hourly and on demand in case of Space Weather conditions require re-planning of the flight or endanger human safety aboard the vessel • Geomagnetic/Ionospheric storm onset definitions: Daily and hourly or on demand in case of Space Weather conditions require re-planning of the flight plan or endanger human safety aboard the vessel • Space Weather Bulletins: Weekly, daily, hourly and on demand in case of Space Weather conditions require re-planning of the flight plan or endanger human safety aboard the vessel.	Space Weather Monitoring
3	SWMC scientific support shall be ensured on a routine basis (24/7 or upon request) on the following topics: • Evaluating the actual state of the ionosphere • Standardization of data formats • Provision of Space Weather messages, bulletins and indices • Service validation and verification, quality control • Helpdesk and 2nd-level support.	Space Weather Monitoring
5	Services and products to be provided by the SWMC are detailed in Table 4 of Paper I	Space Weather Monitoring
6	Sensor/monitoring infrastructure needed for the SWMC is detailed in Table 3 of Paper I	Space Weather Monitoring

Table 2: Functional Requirements for Space Surveillance and Tracking

Req.-ID	Requirement Text	Source
14	Models for the non-traceable population in the range from 0.1 cm to 10 cm and the altitude range of 200 – 500 km must be available and need to be updated on a regular basis	Space Surveillance and Tracking
15	Statistical observations (ground-based and in-situ) of the non-traceable population in the range from 1mm to 10 cm and the altitude range of 200 – 500 km must be performed on a regular basis to validate the population models. NOTE: This requirement must be consistent with requirements #26 and #28.	Space Surveillance and Tracking
16	The European Space Surveillance and Tracking Centre (ESSTraC) shall be responsible for the following operations and service provisions: 1) Creating and maintaining an orbital catalogue of traceable objects 2) Detecting and tracking fragmentations and re-entry events and to compute corresponding risk figures for affected aircraft, spacecraft and for people on the ground 3) Performing collision risk analyses for detectable objects 4) Creating flight plans, trajectories and flight corridors consistent with collision risk requirements and their corresponding backup trajectories and contingency plans (e.g., one to seven days before departure) 5) Provide regular updates to the above products (e.g., two hours before departure) 6) Providing collision avoidance warnings and mitigation measures to ATCOs and STCOs 7) Provide latest products to ATCOs and STCOs 8) Operate and maintain global sensor network used for object detecting and tracking 9) Operate the Flight Planning and Scheduling Facility (FPSF, see Sect. 3.7.2.1 in Paper I) 10) Communication with ATCOs and STCOs (routinely and in contingency situations) 11) Perform Special Operations (e.g., provide data on request for incident investigations, perform conflict-free scheduling and execution of maintenance downtimes).	Space Surveillance and Tracking
18	ESSTraC shall make available to ATM organisations the trajectory data (positional and timing), with stated accuracy, of any traceable space object that is predicted to re-enter Earth's atmosphere. NOTE: The action taken by any ATM organisation is outside the scope of this study.	Space Surveillance and Tracking
19	ESSTraC shall make available to STM organisations the trajectory data (positional and timing), with stated accuracy, of any traceable space object that is predicted to re-enter Earth's atmosphere.	Space Surveillance and Tracking
76	In order to minimise collision risks with traceable objects, the trajectories of the spaceplane and of the space objects shall be as accurate as practical.	S&R
77	Space debris and space objects shall be traced wherever practical. NOTE: This risk mitigation is preferred to not tracing and using statistical modelling to manage the risk.	S&R

Table 3: Functional Requirements for the STM System (Certification, regulations and standards)

Req.-ID	Requirement Text	Source
46	ESA shall establish and chair a forum to define the necessary regulatory activities and enable their progression.	Safety & Reliability
47	STM regulations shall be part of a framework covering the complete suborbital space industry, i.e. STM, SSVs, spaceplanes and spaceports.	Safety & Reliability
48	A set of standards shall be defined/produced as a foundation for the STM system, which: • Are compatible with today's ATM system and globally harmonised as much as possible • Detecting and tracking fragmentations and re-entry events and to compute corresponding risk figures for affected aircraft, spacecraft and for people on the ground • Include a single set of terms and definitions related to STM (including S&R) in order to help prevent misunderstandings in future S&R work.	Safety & Reliability
64	The requirement for a Safety Management System (SMS) shall be part of the regulations for STM service providers, supported by suitable guidance on acceptable means of compliance.	Safety & Reliability
81	The requirement to report occurrences and what data must be provided shall be determined and included in the relevant STM regulations. NOTE: Occurrence data can allow actions to be taken to mitigate risks before they lead to an accident. See also requirement #82.	Safety & Reliability
83	Organisations that provide a service within the STM system shall be certified as a Space Navigation Service Provider (SNSP).	Safety & Reliability

Table 4: Functional Requirements for miscellaneous aspects of the STM System

Req.-ID	Requirement Text	Source
20	The STM organisation(s) shall reserve an exclusive and appropriately-sized space corridor above FL650 for the spaceplane (including SSVs) during its predicted passage, taking into account the expected worst-case accuracies for spacecraft and traceable objects.	Space Surveillance and Tracking
25	A collision-free flight path shall be pre-calculated including safety margins for launch delays.	Space Surveillance and Tracking
36	4D positional monitoring (e.g. CNS+A system Integration) shall be part of the STM strategy. NOTE: See also requirements #85 and #90.	Environment
73	The STM shall model and monitoring of individuals' radiation levels in order to support the pre-flight planning and risk assessment, as well as measuring in support of maintaining exposure data.	Safety & Reliability
74	The criteria to be monitored in order to predict and control radiation exposure shall include: • Total exposure duration • Timing relative to event onset and peak • Geomagnetic conditions • Flight profile • Shielding provided by vehicle • History of radiation exposure of involved person.	Safety & Reliability
82	The severity of occurrences reported (in accordance with requirement #81) shall be classified in accordance with a single, common scheme used by all reporters (see requirements #59 – #61 and #81).	Safety & Reliability

Table 5: Performance Requirements for Space Weather Monitoring

Req.-ID	Requirement Text	Source
4	The following SWMC service availability shall be maintained: • 24/7 Product generation and product provision and support services • 24/7 Provision of Standard-Products • 24/7 Monitoring Services • 24/7 Order desk and special services	SWMC

Table 6: Performance Requirements for Space Surveillance and Tracking

Req.-ID	Requirement Text	Source
12	The traceable object size shall be: (tbd) cm, i.e. the sensor system used for Space Surveillance and Tracking purposes shall be able to track objects with a diameter of (tbd) cm and above.	Space Surveillance and Tracking
17	ESSTraC shall be able to take the data in requirement #16 and compute collision risk analyses and provide regular warnings to STCOs and ATCOs as soon as they become available (near real time, tbc).	Space Surveillance and Tracking
27	All objects larger than (tbd) cm shall be kept and maintained in a catalogue.	Space Surveillance and Tracking
28	The accuracy of objects in the catalogue shall be better than (tbd) m in position and better than (tbd) m/s in velocity and (tbd) s in epoch for all times. NOTE: This requirement must be consistent with requirements #15 and #26.	Space Surveillance and Tracking

Table 7: Performance Requirements covering miscellaneous STM system aspects

Req.-ID	Requirement Text	Source
13	The trajectories of space vehicles (SSVs, spaceplanes, etc. operating in suborbital or LEO space) shall be predictable with a positional accuracy of ± 10 m and a delta velocity of $\Delta v = \pm 1\,\mathrm{m\,s^{-1}}$.	Space Surveillance and Tracking
26	The spaceplane shall have a minimum distance of 30 km (tbc) to any object listed in the orbital catalogue of traceable objects. NOTE: 30 km is the initially proposed minimum safety distance. If this cannot be guaranteed, the flight plan and associated products have to be re-calculated and updated and re-scheduled until the required safety distance has been achieved. NOTE: This requirement must be consistent with requirements #15 and #28.	Space Surveillance and Tracking
32	The STM shall be as flexible and dynamic as possible, particularly in terms of spaceplane position and predicted trajectory computation and dissemination, to maximize the efficiency and minimize environmental impact.	Environment
90	Continuous tracking and sharing of positional data with other spaceplanes, airplanes, ATCOs and STCOs shall be implemented. NOTE: See also requirements #13, #36 and #85.	Safety & Reliability, Environment

Table 8: STM and ATM Interface Requirements

Req.-ID	Requirement Text	Source
45	The following operational interfaces for combined ATM and STM operations shall be considered: • Flight Planning & Scheduling Operations • Air Traffic Control Operations • Space Traffic Control Operations • Ground Operations at Airports & Spaceports • Spaceplane Operations	Integrating STM and ATM
10	For merging STM and ATM, use of already existing infrastructure, products, services and procedures shall be made where possible (harmonisation may be required) to avoid extra costs and the ensure a homogeneous system.	Integrating STM and ATM
11	System Wide Information Management (SWIM) as developed as part of the SES initiative (see e.g., the ATM Master Plan 2015) shall be used to make the corresponding information and data identified in requirements #7 to #9 available to STM & ATM users.	Integrating STM and ATM
92	COM-domain Accurate 4D-trajectories of the planned flight shall be transferred in time to adjacent/subjacent Air Traffic Control (ATC) units, to ensure a vertical safety cylinder free of crossing air-traffic, but also to protect circulating air traffic from deployed debris. In addition, 4D-trajectory and flight plan information shall be interchanged via Ground-Ground (G-G) data networks between STC and involved ATCs. For suborbital spacecraft the capability to send and receive tactical advisories and requests is needed (e.g. to change heading or in contingency situations). Therefore, real-time voice and data communication to and from the spacecraft shall be available.	Integrating STM and ATM
93	COM-domain In case of emergency or catastrophic events, additional voice exchange between STC, ATC and a Rescue Coordination Centre (RCC) may be necessary, but will be carried out simply via G-G-networks.	Integrating STM and ATM
94	COM-domain A safe re-entry requires timely exchange of the planned re-entry 4D-trajectory via G-G data communication from STC to adjacent/subjacent ATC-units. However, due to different effects in the re-entry phase, the real re-entry trajectory might significantly differ from the planned trajectory. Therefore, near-real-time 4D-trajectory updates (calculated on-board) downlinked from the spaceplane to the ATC have to be implemented.	Integrating STM and ATM
95	COM-domain According to human factors recommended practices, additional voice-COM facilitation (in addition to digital data link) between spacecraft pilot and ATCO/STCO shall be possible.	Integrating STM and ATM
96	COM-domain At re-entry spacecraft will operate at high supersonic speeds and due to a limited amount of fuel at the point where they descend into the ATC-sector (FL 650), it is rather unlikely that ATCOs will issue tactical advisories. It is more likely to expect, that these spacecraft will be handled as a kind of priority client for which all other airspace users have to keep clear off their safety-tube. Therefore, no particular additional COM-requirements are expected during this phase, besides of Air-Ground (A-G) data link (including in band voice channel) connectivity. However, such an installation may require automated-tracking high-gain link antennas on the ground.	Integrating STM and ATM

Table 9: Top Level Safety & Reliability Requirements

Req.-ID	Requirement Text	Source
49	For each change in STM strategy (e.g. new technology or traffic management concept), a generic safety case shall be produced to validate the concept of operations by showing how an acceptable level of safety (ALoS) can be achieved.	Safety & Reliability
50	Lessons learned and best-practices in aviation S&R activities shall be read-across to the sub-orbital space industry.	Safety & Reliability
66	The top-level goal of S&R shall be to minimise injuries and fatalities to an As Low As Reasonably Practical (ALARP) level.	Safety & Reliability
67	A dedicated study shall be conducted in order to define the top level quantitative S&R requirements for the STM. As starting points, it is recommended to use 1×10^{-4} flight hour^{-1} for a catastrophic event, affecting the spaceplane and its occupants.	Safety & Reliability
68	Safety objectives shall be defined for each of the following groups of people at risk: • Spaceplane andd SSV occupants (passengers and crew) Assumption: Spaceplane and SSV passengers will not be classed as general public at first, rather they will be well-informed, (almost) crew members (see Paper II). • Third Parties (fellow airspace users and general public on the ground).	Safety & Reliability
69	Spaceplanes and SSVs shall not pose a greater risk to third parties (in the air or, on the ground) than current aviation.	Safety & Reliability
70	The probability of a collision between a spaceplane (or parts thereof) and an aircraft shall be “extremely improbable”. NOTE: It is assumed that the collision would be “catastrophic”. See also the additional requirement #71 for catastrophic consequences.	Safety & Reliability
71	Any consequence classified as catastrophic shall not be caused by: • Any single failure • Any single failure combined with a dormant condition • Software errors alone • Operator errors alone.	Safety & Reliability
72	Any consequence classified as hazardous shall not be caused by: • Any single electronic failure • Any single electronic failure combined with a dormant condition • Software errors alone.	Safety & Reliability
75	The risk of a collision between a spaceplane or SSV and space debris/space objects in space shall be assessed in both the following ways: • Traceable: Quantify the risk based on the planned suborbital flight trajectory and the spaceplane’s structural survivability. Assess continually through the mission. • Non-traceable: Estimate risk based on the best statistical information available.	Safety & Reliability
79	An equivalent level of safety (ELoS) shall be demonstrated for each degree of integration of STM and ATM. NOTE: The baseline is the accepted level of safety (ALoS) of the existing integration level.	Safety & Reliability

Table 10: Safety & Reliability Requirements for the Risk Classification Scheme

Req.-ID	Requirement Text	Source
59	A common S&R Risk Classification Scheme (RCS) shall be agreed and published, together with supporting guidance on its use. NOTE: The S&R RCS proposed in Paper I (Tüllmann et al. 2017a) is recommended as a starting point.	Safety & Reliability
60	The S&R Risk Classification Scheme (RCS) shall then be used by all service providers for: • Classifying risks • Determining probability objectives for their hazards • Assigning a severity to occurrences	Safety & Reliability
61	The S&R Risk Classification Scheme (RCS) shall be harmonised as far as practical with other schemes used in: • STM outside of Europe • Spaceplane and SSV certification • ATM • Operations of spaceports & airports	Safety & Reliability
62	The severity classifications shall consider the potential impact on people, equipment, operations and the environment.	Safety & Reliability

Table 11: Requirements for the Safety & Reliability Assessment Methodology

Req.-ID	Requirement Text	Source
53	The S&R assessment process of a STM functional system shall be defined and published, including a review of the best practices from S&R in aviation and the ECSS standards and handbooks.	Safety & Reliability
54	The S&R assessment of the equipment and the operational elements shall be integrated as far as practical.	Safety & Reliability
55	The development robustness of software and electronic hardware shall be assured as part of the S&R assessment process.	Safety & Reliability
56	S&R assessment activities shall be defined and grouped as follows: • Steady-state – valid for all missions • Mission-specific – valid for a single mission.	Safety& Reliability
57	The S&R assessments shall also be split into two broad categories, both of which shall contribute to the overall safety case of a functional system: • Predict the combination of failures/event that could lead to each risk scenario • Implement independent lines of defence against the risk scenarios.	Safety& Reliability
58	As part of the guidance material for system developers in the STM system, recommended S&R techniques shall be included. Ideally, this would reference to existing publications which could be used in the generic safety case.	Safety& Reliability
63	In the event that a hazard could lead to more than one potential scenario, the worst-case credible level shall be allocated.	Safety& Reliability

Table 12: Requirements for Safety Promotion

Req.-ID	Requirement Text	Source
51	The benefits of S&R to the efficiency of STM functional systems shall be a key part of the promotional activities.	Safety & Reliability
52	The top priorities in STM for safety shall be published, together with a summary of what is being done, or can be done, to minimise the risk of their occurrence.	Safety & Reliability

Table 13: Functional Requirements for Spaceplanes and SSVs

Req.-ID	Requirement Text	Source
84	Spaceplanes and SSVs shall be equipped with the capability to interface with/exploit the latest ATM technology as far as minimising environmental impact is concerned. NOTE: To support route efficiency and therefore minimise fuel consumption.	Environment
85	For integrating spaceplanes safely into the air traffic flow, all spaceplanes (as well as aircraft) shall be equipped with appropriate technology that allows the determination and dissemination of the vessel's current position and speed (e.g., via GNSS, ADS-B/C, etc.). NOTE: See also requirement #36 and #90.	Integrating STM and ATM
86	The structural survivability and design of the spaceplanes and SSVs shall be as robust as practical, to minimise the severity of an impact. NOTE: See also requirement #27.	Safety & Reliability
87	Any space traffic vehicle operating at orbital altitudes below 1 000 km shall have the self-shielding to enable continued safe flight and landing following collisions with credible non-traceable objects. NOTE: Objects that are not expected to occur are not "credible", i.e. presence is extremely improbable.	Safety & Reliability
97	COM-domain To ensure compatibility to normal airport operations, especially if landing at regular airports in case of diversion, the spacecraft shall be equipped with standard Air Traffic Control (ATC) VHF-voice radio communication.	Integrating STM and ATM
100	SUR-domain Spacecraft have to comply with Surveillance Performance Interoperability Regulation (SPI-IR). NOTE: This implies that spacecraft are equipped with (Mode-S) transponders, publish their position via Automated Dependent Surveillance Broadcast (ADS-B) and have the capability to downlink 4D-trajectories via ADS-C/Datalink.	Integrating STM and ATM

Table 14: Performance Requirements for Spaceplanes and SSVs

Req.-ID	Requirement Text	Source
89	The SSVs must essentially interface with ATCOs in the same way as aircraft, follow the same rules of the air (e.g. ICAO Annex 2) and be equipped with systems and technology that achieves (at least) the same level of performance within the ATM network as an aircraft.	Safety & Reliability
98	NAV-domain Spacecraft manoeuvering through ATC-sectors shall comply with Performance Based Navigation (PBN) regulations, as applicable under the specific class of airspace they are operating in. NOTE: There might be an exemption regarding the capability to fly RTA (Requested Time of Arrival), which might be complicated to achieve for Vertical Take-Off and Landing (VTOL) vehicles or spacecraft at very high speeds with low fuel. The RTA allows a vehicle to target arrival at a particular waypoint at a defined time. This is often useful for airport arrival slot scheduling. In this case, the speed is reduced in order to meet the RTA. These aspects have to be investigated.	Integrating STM and ATM

Table 15: Safety & Reliability Requirements for Spaceplanes and SSVs

Req.-ID	Requirement Text	Source
88	The Spaceplane or SV shall comply with aviation safety requirements related to catastrophic events with respect to the risk of a collision with an aircraft. NOTE: It is assumed a collision would be catastrophic for the aircraft (as well as for the spaceplane/SSV).	Safety & Reliability

Table 16: Functional Requirements for ATM

Req.-ID	Requirement Text	Source
101	SUR-domain Existing WAM/MLAT installations need antenna patterns with significant gain in higher elevation angles.	Integrating STM and ATM
102	SUR-domain Primary radars with high-elevated cone antenna patterns are needed to verify/improve 4D-trajectory prediction, especially during the "radio-black-out" phase of the descending spacecraft. NOTE: Although, technologies to overcome radio-blackout periods exist and have proven their applicability during the last of the Space Shuttle missions, it seems as a mitigation to update the spacecraft's real position/trajectory by means of primary radar. Furthermore, primary radar might also be beneficial to detect and track larger parts of debris. This might lead to an important discussion in the future as the world-wide strategy in ATM foresees the reduction of primary radar.	Integrating STM and ATM

Table 17: Performance Requirements for ATM

Req.-ID	Requirement Text	Source
91	Separation standards for space vehicles must comply with corresponding airplane standards.	Integrating STM and ATM
99	NAV-domain Touch-down and landing phases require Ground Based Augmentation System (GBAS) support rather than a legacy Instrument Landing System (ILS) for approaching spacecraft. NOTE: Due to the potentially high approaching speed and the limited ability to perform corrective manoeuvres (e.g., for VTOLs or in case of limited fuel) it seems to be beneficial to offer the best calculated (curved) trajectory to the approaching spacecraft, compared to a line-up, straight-in ILS approach. A GBAS Landing System would enable a precision approach with much greater flexibility.	Integrating STM and ATM
103	SUR-domain The existing SUR-domain infrastructure shall be improved. NOTE: Mode-S transponders cannot process altitudes above 100 000 ft (FL1000). Additionally, today's most popular ATM-systems do not process or display targets above FL650.	Integrating STM and ATM
104	ATCOs shall be trained for monitoring and control activities of space vehicles and for their routine and contingency handling in civil airspace.	Integrating STM and ATM, Safety & Reliability
105	The ATCO must also be fully trained to understand the minimum, guaranteed performance capabilities of each type of spaceplane and SSV. NOTE: To support safe integration of the STM and ATM sectors. Requirement responsibility is with both ATCOs & spaceplane/SSV manufacturers.	Integrating STM and ATM, Safety & Reliability