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On the Implementation of a European Space Traffic Management System

I. A White Paper

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ABSTRACT

There are high expectations for a global commercial space travel market which is expected to turn into a multi-billion Euro business in the next two decades. Several key players in the space business, companies like Virgin Galactic, SpaceX, Blue Origin or SNC are preparing to serve this market by developing their own ballistic reusable space vehicles to carry humans and cargo payloads into suborbital and Low Earth Orbit (LEO) space. Europe's single stage to orbit concepts, e.g., REL's *Skylon* or Airbus' *Spaceplane*, go even further and target for manned suborbital point-to-point (p2p) transportation, similar to today's travel through airspace, but with much shorter flight times. All these developments will likely stimulate demands for new infrastructure (e.g., for spaceports, tracking & surveillance networks or control centres), requiring the implementation of adequate Space Traffic Management (STM) systems, proper Safety, Reliability and Operations Concepts and a seamless integration of space vehicles into the daily air traffic flow. Despite some initial efforts, management of and access to commercial aerospace is lacking a coordinated approach in Europe and compared to the U.S., Europe is by no means prepared to serve the developing space travel market in the near future. Without a consolidated European, yet global, commitment to commercial STM, the growing number of space vehicles expected to pass through aerospace in the coming years is going to jeopardise human health and airspace safety. In this White Paper (Paper I) we summarise key results from an evaluation study conducted by DLR GfR and partners on behalf of ESA with the objective 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 order to demonstrate that collision risks do not prevent suborbital space flights right from the start, we provide proof of concept that this kind of travel is generally feasible, given that significant advances in heat and collision shielding technologies are made. We discuss the envisioned technical, conceptual and organisational setups in response to Europe's STM needs, focussing on technology and infrastructure development, Space Debris, Space Surveillance & Tracking, Space Weather Monitoring and ATM and STM integration. For the STM system to be operational in the 2030 – 2035 time frame, the initial roadmap is presented together with the Top 10 list of STM issues that need to be tackled. In Paper II (Tüllmann et al. 2017b), we discuss Safety & Reliability aspects related to STM and propose a first risk quantification scheme together with initial values for the acceptable levels of safety of the identified hazards and risks. This mini series of papers is concluded by Paper III (Tüllmann et al. 2017c) in which we provide initial system requirements, constraints and recommendations that should be considered for a European STM setup.

Key words. Space Traffic Management – Air Traffic Management – suborbital point-to-point space flights – Space Weather Monitoring Centre – European Space Surveillance and Tracking Centre – space debris & collision risks – safety & reliability – roadmap

1. Introduction

Recent developments in the U.S. space business sector provide strong indications that in the next one to two decades commercial Space Traffic Management (STM) could turn into a multi-billion Euro business and even become a global effort. In this context, one of the most important commercial drivers for Space Traffic is considered Space Travel, focussing on manned ballistic suborbital flights (e.g., for space joyriders wishing to experience zero gravity) and manned suborbital point-to-point (p2p) space flights through Near-Earth space (e.g., for tourist or business travel). Other use cases for commercial Space Traffic would be suborbital p2p cargo transportation or satellite deployment via Low Earth Orbit (LEO). However, before we move forward, it is impertative to elaborate on what we mean when we talk about STM. Because the standard definition of the term "Space Traffic Management", as for example used by Schrogl et al. (2016), appears inaccurate for the purpose of this study, we define STM here as the:

> Execution of all necessary Managing and Monitoring & Control Operations (including routine and contingency scenarios) to ensure safe ballistic travel of manned and unmanned Suborbital Space Vehicles (SSVs) and spaceplanes through Near-Earth space and airspace under consideration of the existing European Air Traffic Management System and Infrastructure.

In this definition, the term “Space Traffic” relates to all manned and unmanned spacecraft that enter or leave Near-Earth space on either suborbital or orbital trajectories. By “suborbital” we mean either almost vertical ballistic trajectories with nearly the same start and end point or trajectories with a different start and end point which can also lead through Low Earth Orbit (LEO) for a few minutes. When the context is clear, “Space Traffic” and “Space Travel” are used synonymously.

The expectations of a growing STM market are nourished by several market evaluation studies that have been conducted over the years with the scope to analyse the potential of a private Space Travel market (e.g., NASA & STA 1997; Futron Corp. 2002, 2006; Ziliotto 2010; FAA 2010; FAA & Space Florida 2012; Booz & Company 2013; Le Goff & Moreau 2013; Airbus 2015; Crabtree et al. 2015; IATA 2015). If Europe wants to play an adequate role in commercial STM and get its equal share of this lucrative market, Europe should now start the development of its own STM system and implement it in close collaboration with international partners and in agreement to global needs.

Because there is no unanimous European approach to STM and noticeable efforts of the relevant stakeholder to integrate suborbital spaceplanes into the European Air Traffic Management (ATM) are lacking, DLR GfR conducted together with its partners on behalf of ESA, an evaluation and roadmap study on the establishment of a European STM system. The following five topics represent the main pillars of the study: (i) Space Surveillance & Tracking, (ii) Space Debris, (iii) Clean Space & the Environment, (iv) Space Weather and (v) Space Traffic Control. In order to generate the roadmap, a holistic system approach is followed, e.g., by analysing whether collision risks would actually permit commercial Space Travel, performing gap analyses of the needed infrastructure and services, providing concepts to close these gaps, deriving initial quantifications of safety risks in space, airspace and on ground and identifying interfaces to safely implement STM into a continuously evolving European ATM, also known as Single European Sky (SES, see the ATM Master Plan (2015)). In the following we describe the main findings of the study and outline how to achieve a seamless integration of the STM and ATM systems.

2. Study Objectives

The goal of this study is to provide a description of possible technical, programmatic and organisational contributions required in response to Europe’s STM needs and to identify links and interfaces to other potential stakeholders worldwide. The following main study objectives apply:

- Analysis of Air and Space Traffic monitoring capabilities available to international partners in view of complementary and collaborative developments, with a focus on very low orbital domains (altitudes ≤ 1 000 km)
- Provision of first risk quantifications associated with debris impacts and spacecraft collisions on manned suborbital flights, reflecting aspects of human health, spacecraft shielding and protection
- Provision of first risk quantifications associated with controlled and uncontrolled re-entering debris on air traffic
- Identification of other risks for Air and Space Traffic, e.g., from Space Weather or micro-meteoroids
- Identification of current and future monitoring gaps and possible counter-measures
- Recommendations for technologies required to perform adequate mitigation and remediation measures to ensure safe traffic through air and space
- Investigation on how a European STM system can be integrated with an evolving ATM
- Generation of a roadmap for implementation, considering national efforts and interests, as well as European collaborations with international partners.

It is stressed that this study is neither about political or legal issues related to STM nor market analysis and prediction.

3. Space Traffic Management

In the next 10 to 20 years STM is likely becoming an international and worldwide effort, to which Europe should contribute with an appropriate system. Intercontinental long haul flights through airspace (e.g., from Europe to the U.S. or to East Asia) could soon be progressively replaced by equivalent trips through suborbital space. Contrary to the management of airspace, which is in each nation’s sovereignty, space around Earth is free and shall be, according to the Outer Space Treaty from 1967, "the province of all mankind" (UNOOSA 1966). Therefore, it is not up to individual nations to authorise passage through the space volume located above their territory or over the polar and oceanic regions. All this calls for an international, yet global collaboration. In addition, suborbital space travel within Europe will most likely never become a profitable business as the overall gate-to-gate travel time for a suborbital flight would be comparable to that of an ordinary flight through airspace. Therefore, national solo attempts aiming to establish localised small-scale STM systems, possibly even with their own national regulations and rules, would be for neither party’s benefit. Those conflicting activities would just be significant cost drivers, delay the implementation of a European STM and the return of investments. Even more important, with ongoing harmonisation efforts for a global ATM network between Europe and the U.S. (Nelson et al. 2015) and with first initiatives from the EU and EASA elaborating on how to accommodate suborbital flights in Europe, the road is already being paved towards a global STM.

The European STM concept presented here is developed against a baseline, the Reference Operations Scenario (ROS), which shall reflect a set of typical routine and contingency operations scenarios and relevant safety operations aspects. In the present case, ROS considers suborbital p2p travel from Spaceport A to Spaceport B (and return to Spaceport A) with space vessels having a seat capacity of at least 6 passengers and a cargo capacity of more than 800kg. Those gliders are envisaged to move on ballistic trajectories at maximum altitudes between 100 km and 500 km. The typical time spent in or near apogee shall be less than 1 hour, i.e. much less than one orbital period.

In Figure 1, the ROS adopted for this study is presented, depicting a typical scenario for intercontinental space travel expected in 10 to 15 years from now. At Spaceport A, a spaceplane is waiting for departure for its suborbital flight to Spaceport B. It is supervised, monitored and guided from ground through airspace by the Air Traffic Control Operator (ATCO) who is responsible for the airspace around Spaceport A. Before takeoff, the crew aboard the spaceplane needs to receive the latest flight information, comprising of updated Space Weather Reports (e.g., warnings about radiation hazards or ionospheric corrections relevant for position determination), flight plan and trajectories (with actual departure time, backup and contingency trajectories) and flight corridor assignments (with backup and emergency flight corridors, i.e. safety buffers of blocked airspace around the spaceplane). All these products need to be automatically generated and disseminated to ATCOs and as well to Space Traffic Control Operators (STCOs) by dedicated and still to be established entities, such as the proposed Space Weather Mon-

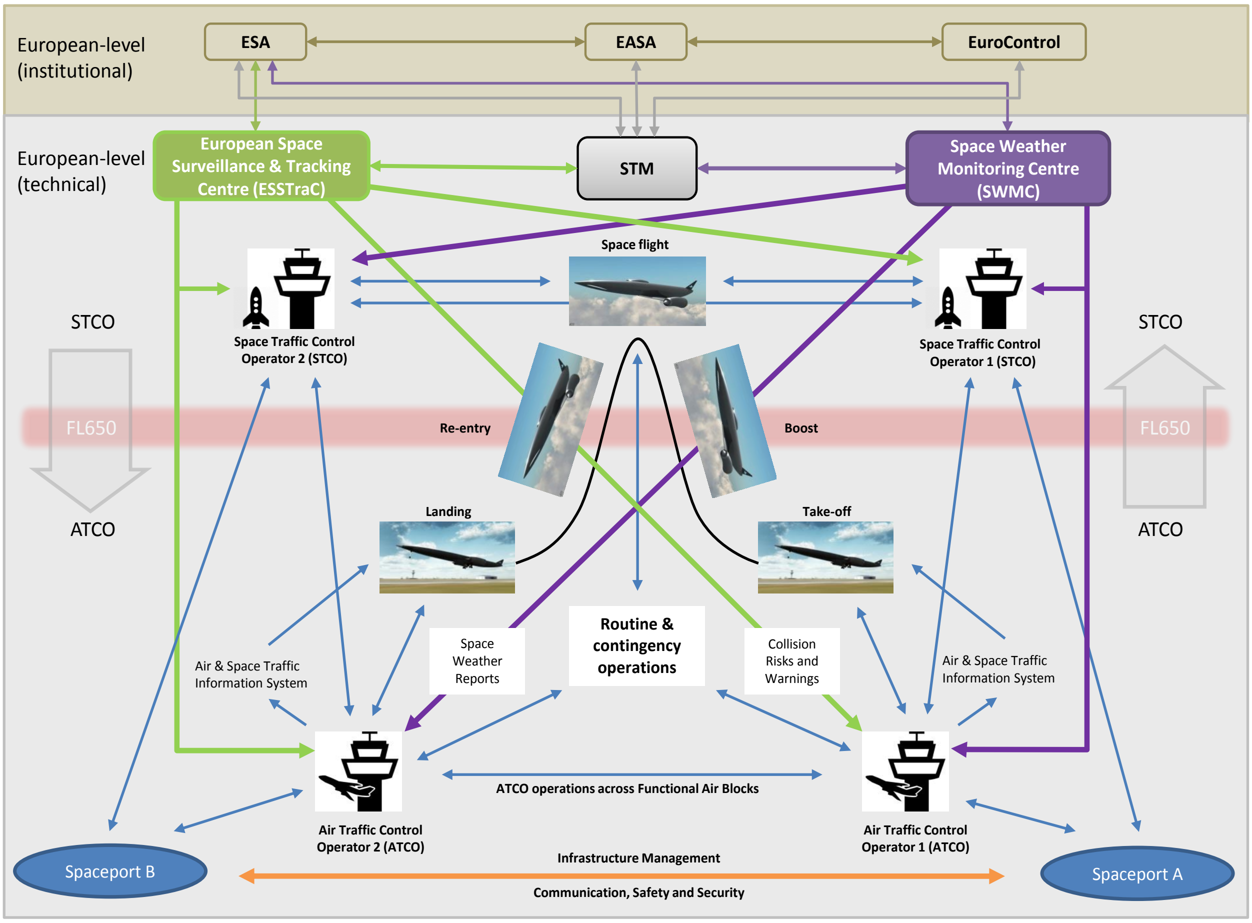

Figure 1: Adopted Reference Operations Scenario, reflecting typical routine and contingency operations for suborbital spaceflights from Spaceport A to Spaceport B with respect to monitoring and control (M&C) operations, handover and handback operations, communication (blue and orange arrows) and data and service products exchange (green and purple arrows).

itoring Centre (SWMC) and the European Space Surveillance and Tracking Centre (ESSTraC).

Once all flight data has been received and validated by the crew on board, the spaceplane is ready for take-off and is guided by the ATCO to upper airspace, e.g., to Flight Level 650 (FL650), i.e. an altitude of ~22 km, where a handover from Air Traffic to Space Traffic Control Operations is performed. From now on, the STCO is responsible for guiding the spaceplane, monitoring its trajectory and issuing corrective manoeuvres in case deviations between predicted and current flight paths increase the risk for civil aviation at re-entry beyond an acceptable level. STCOs are also in charge to provide assistance in case of contingencies aboard the vessel which require a detour or to abort the trip. In those cases, contingency flight plans and trajectories have been calculated with alternative landing sites which would allow the crew to deviate from its original flight path.

Handback operations from STCO to ATCO are executed when the spaceplane descends and crosses FL650 again. Because we are considering an intercontinental space flight, it is very likely that national borders and international space has been crossed and ATCOs and STCOs have changed. Therefore, this kind of interface requires global collaboration and a harmonisation and consistent evolution of airspace design (as e.g., currently seen between Europe and the USA). After handback it is up to the ATCO to check whether the accuracy of the re-entry position agrees with the corresponding risk figures for air traffic and to issue corrective manoeuvre instructions if indicated.

Finally, the ATCO needs to assist the pilot during landing and taxiing to the spaceport terminal. From a European ATM perspective, all aforementioned aspects and communication flows included in the ROS are new and are currently not reflected in the 2015 edition of the SES Master Plan. In other words, Space Travel, be it an intercontinental p2p trip or a suborbital ballistic joyride, is apparently not considered a high priority in Europe's strategic ATM planning.

Generally, three fundamental technological and organisational challenges need to be overcome (political or legislative constraints might be an even larger hurdle, but are not covered here). These challenges are related to the development and implementation of appropriate:

(i) Technology and Infrastructure (e.g., spaceplanes, spaceports, Clean Space, Flight Planning & Scheduling (FPS), ESSTraC, the SWMC, communication networks and data centres)
(ii) Operations concepts and procedures (e.g., for Space Weather monitoring, Space Surveillance and Tracking (SST), FPS, Search & Rescue, Clean Space, spaceports and ATM & STM integration)
(iii) Products and Services (e.g., Space Weather Bulletins (SWBs), Total Electron Content (TEC) maps, Collision Risk Analyses (CRAs), trajectories, flight plans).

In the following, we will elaborate on these gaps and deficiencies and provide a possible high-level implementation approach for a joint European Air and Space Traffic Management which may serve as add-on to the SES initiative. In addition, we investigate how to integrate ESA's Space Situational Awareness (SSA) monitoring efforts into a holistic European Space Traffic Management concept and develop a roadmap for its implementation.

3.1. Spaceplane Concepts

Several key players in space business, companies like SpaceX (*Falcon 9 + Dragon*), Blue Origin (*New Shepard*), Virgin Galactic (*SpaceShipTwo*, *LauncherOne*), Orbital (*Pegasus*) or SNC (*Dream Chaser*) actively develop and test their own reusable space vehicles. Except for the SpaceX and *Dream Chaser* designs, which are developed to deliver satellites into LEO and/or to transport crew and cargo to/from the International Space Station (ISS), the other designs shall carry up to 6 humans or cargo payloads of up to 1 metric ton into suborbital space (for zero g experience/experiments). Besides these U.S.-based companies, there are a couple of European outstanding concepts, such as DLR's *SpaceLiner* (e.g., Sippel 2010; Sippel et al. 2013), Airbus' *Spaceplane* or the ambitious hypersonic *Skylon* spaceplane developed by Reaction Engines Ltd. (REL), a privately owned British company with BAE Systems as shareholder. Especially the latter two designs deserve a closer look. Both systems feature a reusable single-stage-to-orbit approach with horizontal take-off and landing (HOTOL) capability. By design these two European concepts are different from the U.S. vertical take-off and landing (VTOL) concepts and from Virgin Galactic's hybrid design in that they behave almost like ordinary aircraft in airspace and do not depend on a mother ship that lifts them to a given altitude.

Among all those spaceplane designs, Europe has with *Skylon*, at least on paper, one of the most promising concepts to successfully enter the commercial space transportation market. This is for a couple of reasons:

1) *Skylon* could, in contrast to the U.S. approaches, simultaneously serve two different business cases, namely deployment/re-supply missions in LEO and suborbital p2p passenger/cargo transportation.
2) The payload/passenger capacity is with up to 15 metric tons (or 30 passengers) to a 300 km equatorial orbit much higher than any of the other spaceplane concepts can achieve.
3) The estimated costs to deliver the payload to LEO shall be, according to an official statement from the UK Space Agency from 28 April 2014, *"[. . .] about 1/50th of the cost of traditional expendable launch vehicles, such as rockets"*. To be more specific, to get *Skylon* a pound of mass to orbit would require between US\$690 and US\$1,230, depending on the economic forecast scenario (Emspak 2016). This price tag shall be significantly less than what SpaceX requires for its *Falcon 9* or the upcoming *Falcon Heavy*.
4) The HOTOL concept and the overall system design promises to make it much easier to integrate *Skylon* into existing and future ATM systems and although the vessel could reach a hypersonic speed of up to Mach 6 below FL650 (see Wagner et al. 2015), it would most likely still be certified according to aviation standards. In addition, no special safety requirements, regarding air traffic separation standards are expected to apply and sophisticated on-board collision avoidance systems and airspace blocking would also not be needed.
5) Compared to a pure ballistic VTOL flight, *Skylon's* aircraft-like flight performance and low g-forces of ~2.5g, might pose an invaluable psychological advantage when it comes to selling the product on the market, as most people already know how it feels like flying in an ordinary plane.

Because of these significant advantages, we expect that *Skylon*, and HOTOLs in general, will receive much broader acceptance by the general public from the very beginning, an argument also corroborated by Ziliotto (2010).

However, *Skylon* is still in its design phase and according to BBC News from November 2, 2015, REL anticipates to kick-off testing of its SABRE engine by 2020, with the first unmanned test flights to start in 2025. We therefore estimate *Skylon* to enter routine flight operations in the 2030 time frame. On the other hand, Blue Origin expects *New Shepard* to perform first commercial suborbital flights as early as 2018, indicating that commencement of public space travel is already on the verge.

3.2. Spaceports

Spaceports are the analogue to what airports are for aviation business. They are the sites where manned and unmanned SSVs are launched and, if we trust the vision of global p2p Space Travel in a not-too-distant future, spaceports are likely to become the new vibrant lifelines that connect our world. Spaceports are also the sites where spaceplanes are maintained and High-Tech industries can perform research, development and testing on space applications. However, for the Space Travel market to develop, certain assets need to be in place, such as a globally working Space Traffic Management and Control System, spaceports and a ground infrastructure which efficiently connects them with major cities and business areas. For reasons of cost efficiency it appears likely that the infrastructure needed for Space Travel will be geared towards the existing air traffic ground infrastructure as this sector has been continuously adapted to cope with ever growing market demands. Therefore, global suborbital transportation routes for cargo and passengers are expected to essentially follow traditional air traffic routes.

As the commercial space travel market matures, currently isolated spaceports are likely to move closer to more densely populated areas and business centres and could eventually merge with existing airports as safety risks related to spaceplane operations are significantly reduced. Those airports with collocated commercial spaceports are called aerospaceports. Prime candidates which could eventually host aerospaceports in the future are London, Frankfurt (for continental Europe), Tokyo, Los Angeles and New York City. These expectations are corroborated by work from Witlox et al. (2004), ISU (2008), Carta & González (2010), GaWC (2012) and Airbus (2015). Based on the findings of these studies, we identified possible mega cities and flight routes that we expect to play a key role in commercial Space Traffic by 2035. In Figure 2 the results for passenger and cargo flight routes are presented. Large circles represent mega cities that are or have the potential to become prime aerospaceports and hubs, whereas small circles denote mega cities which are likely to become secondary aerospaceports and hubs due to their significant growth potential. The bulk of those flight routes is located in the northern hemisphere and aligned along the axis North America - Europe - Asia.

Currently, the U.S. put substantial effort into the development and construction of commercial spaceports in order to cope with the anticipated growth of the suborbital space travel market. Figure 3 shows the current world-wide distribution of spaceports that have been specifically designed for suborbital space travel. The map outlines operational spaceports and planned ones with recent development activities. Other locations, like satellite and missile launch sites have been omitted. Obviously, 11 of the 20 planned and active spaceports are located on U.S. soil. Among them are all seven spaceports that are officially operating under

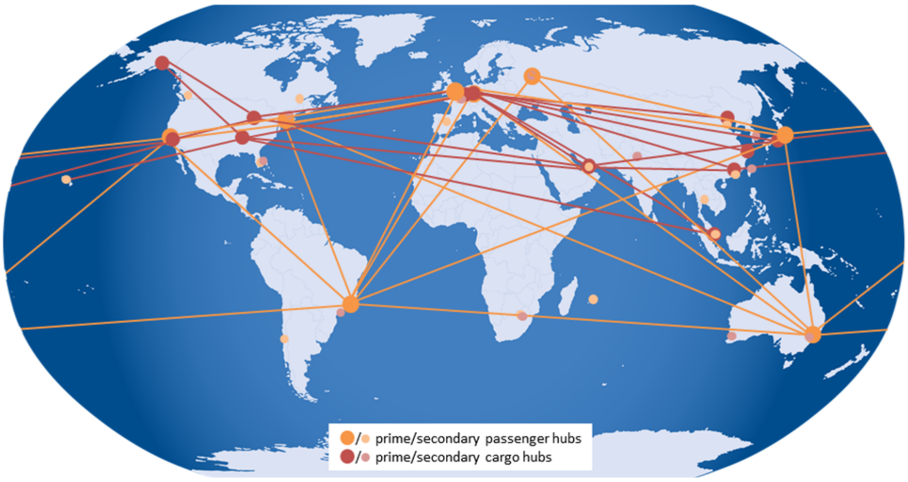

Figure 2: Potential suborbital Space Traffic routes for passenger (orange) and cargo transportation (red). Large circles represent mega cities that are or have the potential to become prime aerospaceports/hubs while small circles are for mega cities which are likely to become secondary aerospaceports/hubs due to their anticipated growth potential. Apparently most of the space traffic routes are in the northern hemisphere following the axis along North America - Europe - Asia.

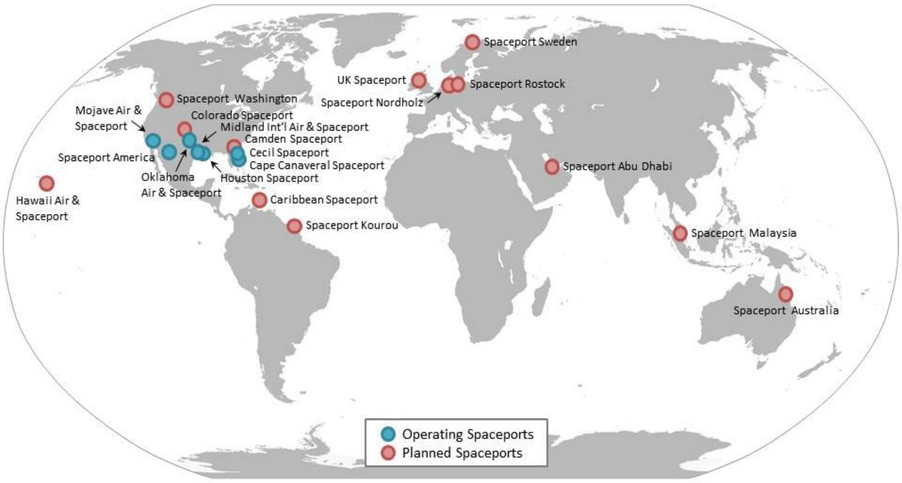

Figure 3: Global map of operating and planned Spaceports intending to serve the suborbital Space Travel market (vertical ballistic and p2p flights).

a U.S. Launch Site Operator License. Although plans for operating similar spaceports in Europe exist, no European nation is currently close to issuing similar operator licenses. The same is true for other nations which reported to plan spaceports, such as Australia, Malaysia or the United Arab Emirates.

If one compares the expected suborbital Space Traffic routes depicted in Figure 2 with the map of spaceports presented in Figure 3, there is a sufficiently good match of destinations between Europe and the United States of America. However, for continents like South America and Africa or nations like Russia and the East Asian region there is a clear deficiency and those areas appear unconnected to the global network of potential Space Traffic routes. Although it currently remains unknown what the concerned nations are planning, it is likely that they wait for the market to develop and then close the gap by providing the needed infrastructure.

Similar to the development of space vehicles for space travel purposes, the U.S. also progressed further regarding the development and operations of the necessary infrastructure than the Europeans or any other nation. In fact, there is even an oversupply of American spaceports. This is likely the result of local governments and airport authorities trying to stimulate economic growth in the area by attracting space industry to do business at their sites (see e.g., SpaceNews 2016a). The high dynamics in spaceport development is also globally reflected by the commissioning of feasibility studies, e.g., for Glasgow Prestwick Spaceport (SpaceNews 2016b) and by official announcements of strategic partnerships between spaceport and spaceplane operators, e.g., between Swiss Space Systems (S3) and Spaceport Malaysia (S3 2013), XCOR and the Caribbean Spaceport (Kloppenbug 2016) or XCOR and Glasgow Prestwick Spaceport (Spaceref 2016).[1]

3.3. *Space Traffic Monitoring Programmes*

In our view Space Traffic Monitoring represents only a single, though highly important and safety-critical, aspect any dependable STM system has to cope with. Regular suborbital p2p space

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[1] Note: By the time of writing, XCOR suspended the development of *Lynx* (SpaceNews 2016c) and S3 filed for bankruptcy (TheLocal 2016).

travel has not commenced yet and current monitoring initiatives are almost entirely restricted to surveying the space environment (see Schrogl et al. 2016) rather than monitoring Space Traffic itself. Nevertheless, the implementation of those ongoing monitoring efforts remains a precursor for initial STM service operations. In the European context ESA's SSA programme intends to monitor and track satellites and space debris, to search for Near-Earth Objects and to monitor and forecast Space Weather in order to prevent damages to spacecraft, ground infrastructure and human lives.

In the U.S., the counterparts to SSA are Space Fence (a programme that was initiated to perform space surveillance of spacecraft and space debris around Earth) and the Space Weather Prediction Centre operated by the National Oceanic and Atmospheric Administration (NAOO) which is responsible for Space Weather monitoring and forecasting. While the European space environment monitoring programme is a civilian project and still in its infancy, the U.S. military-driven system is already operational and currently undergoing a full system upgrade. Because Europe does not have the technical capability yet to detect, track, generate and to maintain a catalogue of orbital objects, Europe is completely dependent on U.S. data and their will to share it. Even for years to come, it is not expected that Europe will reach the same data quality that the U.S. are likely to achieve soon (i.e. to detect and track objects at sub-decimetre level).

Besides the lack of a system that monitors and tracks space debris, there is also a clear deficiency in Europe to monitor and track the trajectories of commercial spacecraft and except a DLR study from Drescher et al. (2016) that deals with emergency detection and response organisation for SSVs, no consolidated effort has been made so far to integrate those vessels with the existing ATM system. In addition, space debris (re-)entering the atmosphere or clouds of debris from disintegrating spacecraft (e.g., as seen during the Columbia accident in 2003) also remain largely untracked and, despite the existence of the corresponding risks posed to aviation or human safety, are deliberately accepted.

Considering the anticipated growth potential of the space travel market, frequent suborbital space rides and p2p travel seem to be on the verge of becoming reality. In order to cope with an increasing number of launches (from ground and air) and re-entries, the closure of large airspace volumes and the redirection of air traffic flows seems to be a costly and yet impractical solution. Instead, a dynamical handling of 4D space transition corridors tailored to the individual spaceplane performance and providing sufficient safety margins without causing excessive rerouteing delays and costs for the air traffic sector seems to be advisable (Bilimoria & Jastrzebski 2013). In the U.S., the merging of commercial p2p Space Traffic with the Next Generation Air Transportation System (NextGen) has also progressed much further than in Europe (see FAA 2001; DOT 2010; FAA 2016) and although SES, the major re-organisation of the European ATM, is underway and is even harmonised with the NextGen ATM concept, the European interface between space and air traffic management has been largely ignored so far. Therefore, substantial coordinated effort appears necessary if Europe wants to play a significant role in the area of Space Travel and to get a good share of this lucrative market.

3.4. Space Debris and Space Surveillance and Tracking

For further discussion and analyses, the following definitions shall apply. The term 'Space Debris' is defined as all man-made objects including fragments and elements thereof in any Earth orbit, that are non-functional[2]. The term 'Traceable Object' relates to an object which is detected and for which an orbit is determined and propagated. This includes keeping the object in a database and maintaining it. Traceable objects include space debris as well as functional satellites. 'Non-traceable Objects', however, escape detection and will therefore remain unknown to a Space Surveillance and Tracking (SST) system. Those objects are treated via statistical models, such as the ESA Master 2009 model or NASA's ORDEM 3.0 (see e.g., Krisko et al. 2015).

In order to guarantee safe and secure p2p 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 commercial manned spacecraft operations. Given the aforementioned deficiencies, we propose the establishment of the European Space Surveillance and Tracking Centre (ESSTraC), an entity that is responsible for operating the SST sensor network, creating and maintaining an orbital catalogue of traceable objects, detecting and tracking fragmentations and re-entry events, performing collision risk assessments of detectable objects, flight planning and scheduling, contingency re-planning, safety and security operations and communicating with ESA, ATCOs/STCOs and with their global counterparts. Note that layout and concept design of the SST sensor network is beyond the scope of this paper.

In line with the ROS presented in Figure 1, we envisage ESSTraC to be primarily responsible for:

- Creating and maintaining an orbital catalogue of traceable objects
- Detecting and tracking fragmentations and re-entry events
- Performing collision risk assessments of detectable objects
- 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)
- Provide regular updates to the above products (e.g., two hours before departure)
- Providing collision avoidance warnings and mitigation measures to ATCOs and STCOs
- Provide latest products to ATCOs and STCOs
- Operate and maintain global sensor networks used for object/spaceplane detection and tracking
- Communication with ATCOs and STCOs (routinely and in contingency situations)
- Perform Special Operations (e.g., provide data on request for incident investigations, perform conflict-free scheduling and execution of maintenance downtimes).

Some products provided by the ESSTraC may need some clarification. Similar to aviation, the term 'Flight Plan' refers to a unique identifier of a suborbital p2p flight that is to be scheduled and contains, among others, a unique Flight ID-number, the departure and destination spaceport, a set of corresponding departure and arrival times and some basic technical information about the spaceplane (e.g., manufacturer, type of vessel (glider or steerable), seat/cargo capacity, climb rate or minimum turn radius). The term 'Trajectory' refers to the pre-determined flight path of the spaceplane through air and space and is computed according to specifications given in the flight plan and to collision risk and space weather risk assessments. In principle, the

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[2] From: Space Debris Mitigation Guidelines of the United Nations Committee on the Peaceful Uses of Outer Space, UN General Assembly Resolution 62/217 of 22 December 2007

collision risk with other spacecraft, space debris or re-entering objects can be assessed by taking orbital catalogues of traceable objects and latest tracking information of fragmentations and re-entry events and by calculating the number of objects along the flight path for a given p2p connection at a given departure time (see Sect. 3.4.1). A trajectory would be rejected if an object would fall below a pre-defined safety distance. In such a case, new launch windows would have to be found and the trajectory of the spaceplane would need to be recomputed with different orbit parameters, in the most simplistic case by delaying departure time. In case of short-notice Space Weather alarms, e.g., during solar flares (giving reaction times of about 8 min), ESSTraC would receive a dedicated hazard warning from the SWMC and perform a reassessment of the risks and a re-calculation of the safest trajectory to the destination spaceport.

Similarly, 'backup trajectories' are alternative pre-computed flight paths based on collision risks and Space Weather warnings in case in-flight conditions or risks worsen and require a different orbit. 'Contingency Flight Plans' are special pre-defined Flight Plans that are to be executed in case of anomalies or non-nominal conditions, such as technical failures or security incidents aboard the vessel, e.g. making it necessary to redirect to an alternative spaceport. 'Flight corridors' represent a safety volume assigned to the space vessel and its 4D trajectory. The size of the safety volume could be tied to the individual in-flight performance and manoeuvrability of the vessel as well as to risk assessments for the type of vessel. In this regard, HOTOL spaceplanes are expected to have more relaxed flight corridor requirements than VTOL space vehicles, because of their airplane-like flight performance. Finally, 'Backup Flight Corridors' and 'Contingency Flight Corridors' are the same as flight corridors defined above, but for backup trajectories and for contingency flight plans, respectively.

However, before we continue to develop more detailed operations scenarios and concepts, we should demonstrate the general feasibility of a suborbital space flight with respect to collisions with space debris by considering a hypothetical flight path from Sydney (Australia) to Oberpfaffenhofen (Germany).

3.4.1. Demonstrating the Feasibility of Ballistic Space Flights

The feasibility of a hypothetical intercontinental space flight is analysed regarding collision risks by determining the minimum distance from the space vehicle's adopted ballistic trajectory to all traceable objects in the NORAD Track Two-Line Element (TLE) database (see http://celestrak.com) as a function of time and by testing whether the time slot between the two closest encounters is sufficiently long to ensure safe passage of the vessel.

For a ballistic flight from Spaceport A to Spaceport B, it is assumed that the trajectory will be similar to the one outlined in Figure 4. Here, the angle 2α denotes the shortest angle between the departure spaceport and arrival spaceport. The maximum height at apogee is assumed in this example to be 500 km, which results for an angle of $\alpha = 80°$ in a necessary launch velocity of 7,827 km s^{-1}. As an example for further analysis, a purely ballistic flight path for the shortest connection between Sydney (Australia) and Oberpfaffenhofen (Germany) is shown in Figure 5 with a corresponding angle $\alpha = 73, 34°$, not taking Earth's rotation during flight into account. In the top panel, altitude as a function of flight time is shown while in the bottom panel altitude versus travelled distance is plotted. When taking Earth's rotation into account, the flight times will be different in that the flight time from Sydney to Oberpfaffenhofen would be shorter than the flight time from Oberpfaffenhofen to Sydney.

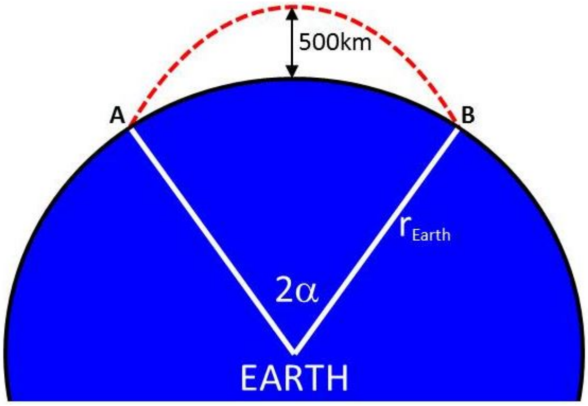

Figure 4: Schematic view of a ballistic flight.

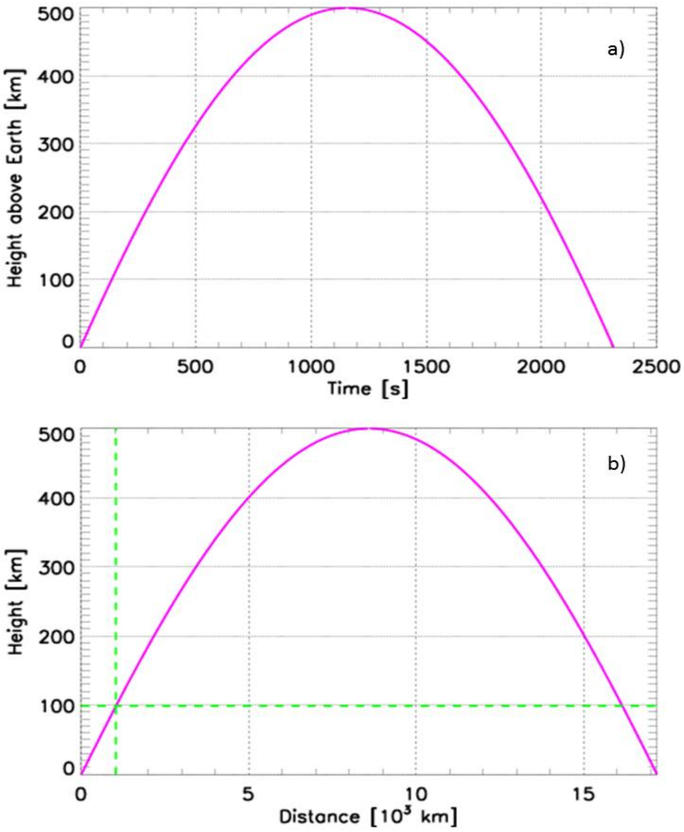

Figure 5: Pure ballistic flight path from Sydney to Oberpfaffenhofen for a spherical non-rotating Earth. Panel a): Altitude vs. time. Panel b): Altitude vs. travelled distance.

For a realistic calculation of the flight path, the space vehicle must first be accelerated to the required ballistic speed. Assuming a permanent acceleration of 3g, a value that is consistent with the *Skylon* approach of 2.5g, the required speed is achieved after 265s or after a travelled distance of approx. 1033 km. The corresponding height would be ≈100 km, which is shown by the green dotted lines in panel b) of Figure 5. The same amount of time for deceleration is allocated at the end of the flight path. For comparison, in case of an average rocket launch engine, the first 120 km in altitude would be achieved before 300 s, a value which was also valid for the Space Shuttle. At an altitude of 100 km, it is furthermore assumed that the required velocity of the ballistic flight has been achieved and that the entry point of the ballistic trajectory is hit with the correct flight vector. For the

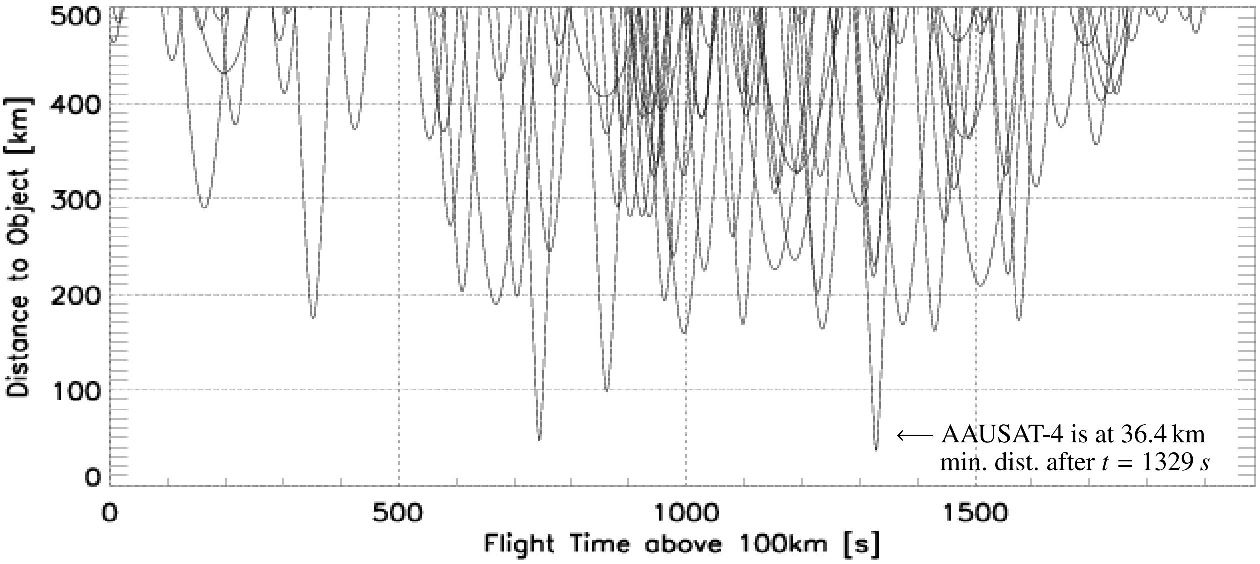

Figure 6: Distances between space vehicle and TLE-objects for the adopted flight trajectory. TLE-objects are restricted to altitudes between 100 km and 750 km, respectively, i.e. to altitudes at which TLEs re-enter Earth's atmosphere or above which the collision risk caused by TLEs is expected to be negligible.

computation of the ballistic flight path, time, height, and speed are calculated numerically and interpolated to the desired values by Chebyshev polynomials, taking into account an ellipsoidal rotating Earth.

With these assumptions, the flight time from Sydney to Oberpfaffenhofen results in 2518 s while the flight back would take 2675 s, including acceleration and deceleration, which is roughly 42 min and 45 min, respectively. The maximum flight altitude deviates from 500 km by a few kilometres due to the ellipsoidal shape of the Earth. Please note that the stated numbers are based on approximations of ellipsoidal integrals.

In order to evaluate the possibility that the space vehicle gets hit by another space object, we analyse how close such objects can actually get to the spacecraft for an arbitrarily chosen departure time from Sydney Spaceport. For this, the following assumptions apply:

- Departure time is set to 24.08.2016 at 12am (midnight)
- The flight trajectory is the one shown in Figure 5 with a temporal step size of $t = 1$ s
- Possible objects are taken from the publically available TLE catalogue as of 24.08.2016 and are called TLE-objects
- The temporal step size of their calculated ephemerides is also $t = 1$ s
- The positional accuracy of the TLE-objects is assumed to be better than 1 km in any direction
- All points where the space vehicle is below an altitude of 100 km are not considered (i.e. re-entering TLE-objects are expected to pose no threat)
- TLE-objects are filtered and rejected for a perigee height larger than 750 km, resulting in a total of 4937 TLE-objects.

The distance from the space vehicle to all TLE-objects is then calculated and stored for each second of the ballistic flight. For the adopted trajectory, the corresponding distances to the TLE-objects are plotted in Figure 6. Each distance closer than 500 km in any direction to the space vehicle is shown as a solid line for each object. In this example, the minimum distance between the space vehicle and AAUSAT-4 is determined to be about 36,4 km at flight time t=1594 s (or 1329 s after passing an altitude of 100 km).

Now, the launch of the space vehicle is delayed by one second, yielding different distances to the TLE-objects. Again, the minimum distance is stored. This is repeated for delay times of up to 600 s with a step size of one second. The result is presented in Figure 7 and nicely demonstrates how the closest TLE-object approaches the space vehicle, reaches its closest distance and increases its distance thereafter. At some point the away-moving object is replaced by another approaching TLE-object which becomes the new closest object to the spacecraft, subsequently reaching its minimum distance and increasing it thereafter. In Figure 7 this cycle continues until the maximum launch delay time is reached.

There is a launch window of almost 3 minutes (see orange line in Figure 7) where the closest distance to any object during the whole flight exceeds 50 km. If the allowed safety distance is relaxed to 30 km, the launch window during which no collisions are expected increases in this example to more than 6 minutes (see red line in Figure 7). If the launch accuracy in time and position is well below this threshold, the flight could be pre-planned for this particular flight route and at this particular date so that no avoidance manoeuvres need to be taken into account. Of course, this implies that the catalogue used for pre-planning has reasonable accuracies in position and velocity that are small compared to the initially adopted miss distance of 30 km.

In order to evaluate whether the above launch windows of collision-free space, i.e. 2 – 3 slots of ~120 s duration in a 10 min time frame, were just a chance coincidence or represent the nominal case, the minimum distances should be calculated for a period of one full day. Because such an analysis requires excessive computation time on a modern multi-core processor system, a coarser estimation was performed. As a compromise between computing time and time coverage, a time step size of 120 s for the launch delay was applied to the calculations that now cover a time period of 12 hours. At each time step, the minimum distance between the space vehicle and all TLE-objects for the complete flight path was calculated and resulted in a first statistical estimate on the distribution of closest TLE-objects. The result is shown in Figure 8.

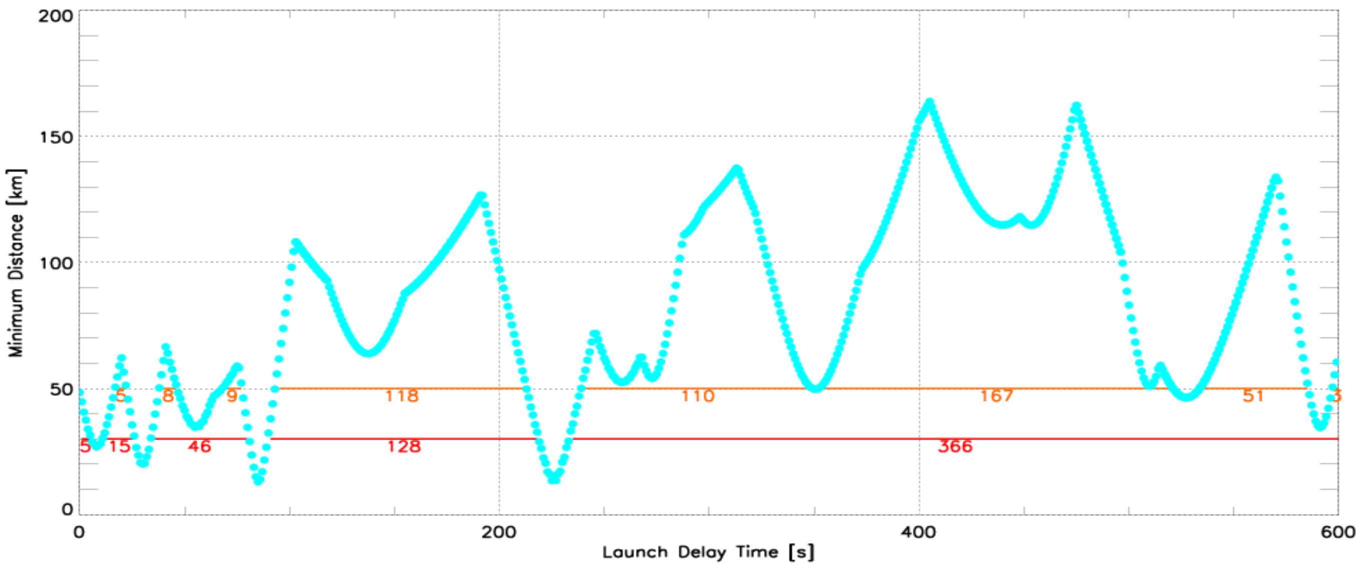

Figure 7: Minimum distance between the space vessel and all TLE-objects for the full flight with launch delay times of up to 600s.

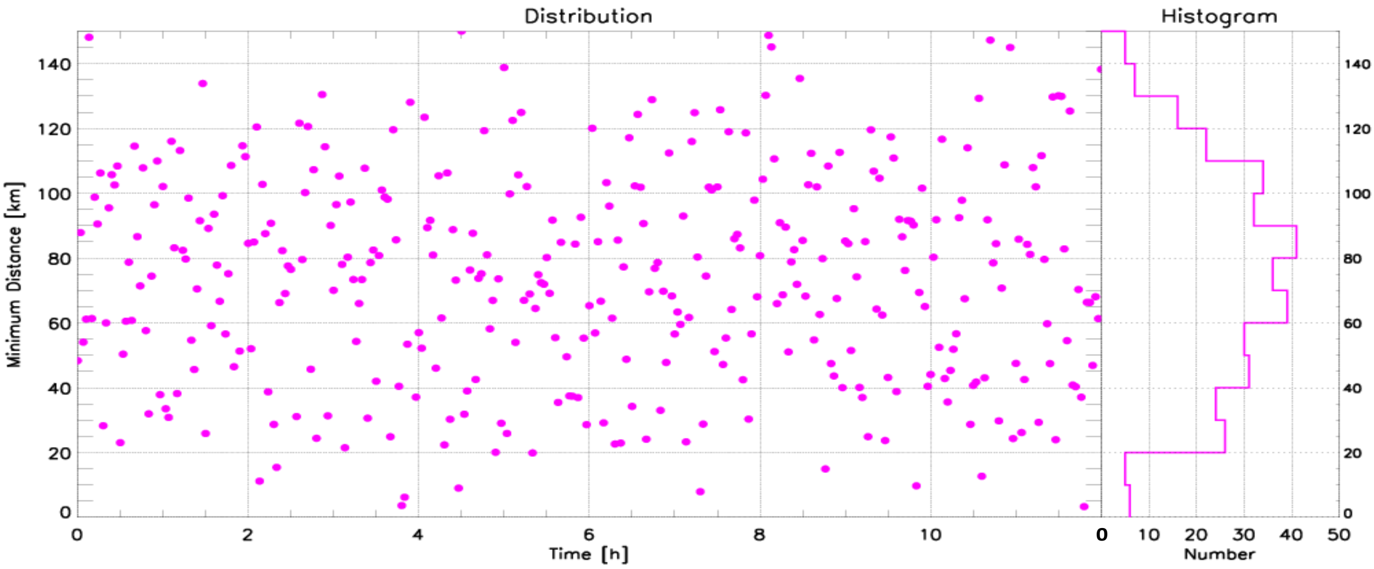

Figure 8: Minimum distances between the space vehicle and all TLE-objects in 12 hours (with launch delay times of 2min).

From the histogram it can be seen, that the minimum distances between the space vehicle and all TLE-objects for a complete flight path are statistically distributed during a period of 12 hours. Considering the results from Figure 7, in that there are several launch opportunities in a 10 min time frame, it appears reasonable to expect also multiple launch windows per day for which a safe and collision-free flight path can be pre-calculated.

It is important to point out, that this analysis relies on approximately 5 000 TLE-objects. Typically, these objects are about 5 – 10 cm in size or larger. If the same analysis is performed with objects of ≥1 cm, the number of objects which need to be taken into account would increase by a factor of 5 – 10. There are estimates that a complete catalogue of objects with sizes larger than 1cm could easily comprise a total of 200 000 – 300 000 objects.

For re-entering objects, the ground tracks can be calculated within a given accuracy. Typically, 15% – 20% of the remaining flight time are assumed (Kinkrad 2013). As a consequence, the critical time in which a re-entering object might be expected to cross the flight track of the space vehicle is about 15 min or shorter. Furthermore, the altitude of the re-entering object is not well known. As the forces acting on the object vary strongly, the object might break into several parts at an unknown altitude producing a number of objects with unforeseeable aero-dynamical behaviour. Therefore, it might be cheaper and less risky to wait for the potential overflight of the object and its debris cloud and to delay the launch of the space vehicle instead of installing enough sensors to accurately measure positions and velocities and to predict the potential flight path of the re-entering objects. Up to now, there are on average some 80 objects per year for which it is assumed that some parts might actually reach Earth's surface after re-entry.

With the above considerations, we provided proof of concept that p2p travel through suborbital and LEO space is generally feasible under certain assumptions. However, we highly recommend to conduct a dedicated follow-up study on possible launch windows, e.g., by considering more realistic trajectories, time periods longer than 12 hours or by using different flight destinations and smaller traceable object sizes.

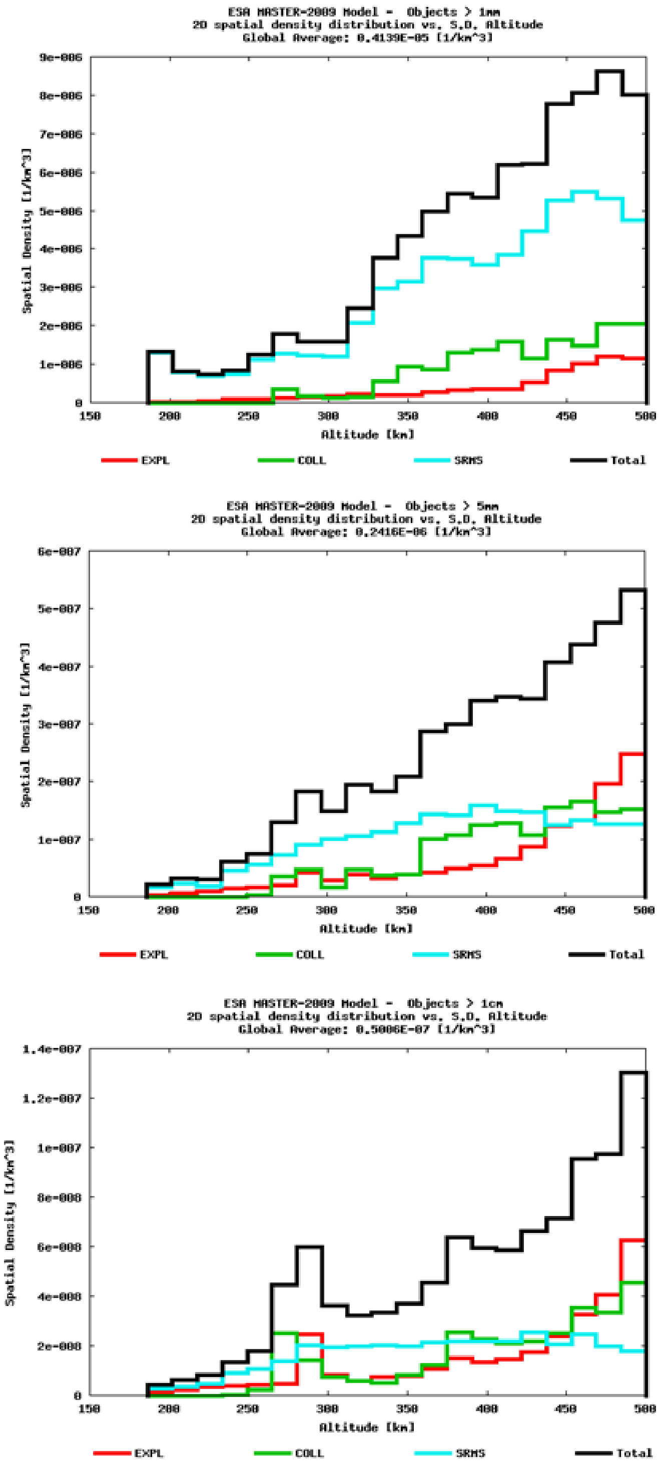

Figure 9: Spatial densities of non-traceable objects as a function of altitude (averaged over all declinations δ) for different object types, with a minimum object size of 1 mm (top), 5 mm (middle) and 1 cm (bottom).

3.5. Collision Risks from Non-traceable Objects

Collisions with space debris represent a risk that, if not properly mitigated, will almost certainly be catastrophic for humans aboard a spaceplane. In Sect. 3.4.1 we have shown that the risk caused by the traceable object population can most likely be controlled by a thorough monitoring and tracking of those objects.

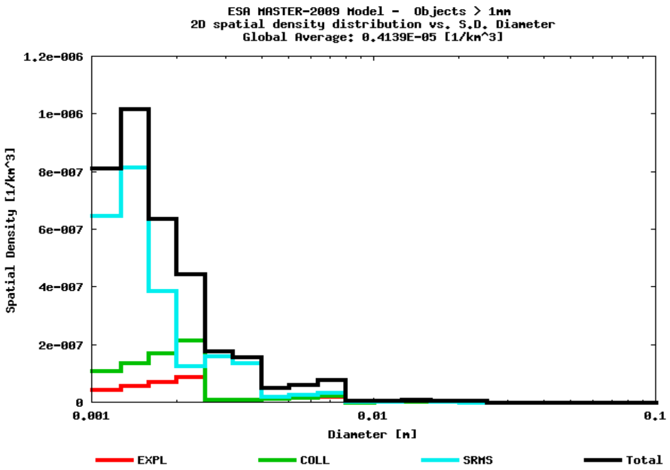

Figure 10: Spatial density of non-traceable objects as a function of object size. Densities drop significantly for object sizes larger than 1 cm.

However, what are the risks for the space vehicle and its passengers posed by the non-traceable object population? In order to estimate the risk of an impact, one needs to consider that the vessel can get hit by particles from any direction. In this regard the vessel's cross section, the inclination and latitude of its flight path, the flight time with respect to flight altitude and the spatial densities of non-traceable objects need to be analysed. Here the non-traceable object population with sizes below 1cm is of special importance as these particles have the highest spatial density among all traceable and non-traceable objects and kinetic energies that are high enough to compromise the structural integrity of the spacecraft.

In order to assess the collision risk posed by particles of the non-traceable object population, the object densities provided by the ESA MASTER 2009 model (Wiedemann et al. 2011) were analysed. Given the fact that the technical details of the possible shielding of the space vehicle are currently unknown, densities for three different minimum particle sizes were taken into account. Shields for a maximum object size of 1 mm are assumed to be rather simple, while shielding for 5 mm objects is demanding, but feasible (e.g., the Space Shuttle pressurized cabin had to withstand an impact of a particle of this size), and shielding for 1 cm particles is deemed extremely demanding. Figure 9 shows spatial densities of the MASTER population as a function of altitude (averaged over all declinations δ) for minimum object sizes of 1 mm, 5 mm and 1 cm, respectively.

The MASTER population was truncated at a maximum size of 10 cm to represent the non-traceable part (including the traceable part would, however, increase the 1 cm and larger population by 2.5% only). The altitude was selected to range from 186 km, the minimum altitude of the MASTER model, to 500 km, the maximum altitude considered for suborbital flights. In the millimetre-size regime, the population is dominated over the entire altitude range by solid rocket motor slag (SRMS).

For larger object sizes and altitudes above 450 km, explosion (EXPL) and collision fragments (COLL) become dominant. Note that the mean density drops by a factor of 17 between 1mm and 5mm, and a factor of 4.8 between 5 mm and 1 cm. This exponential increase of the number of objects with decreasing size and the dominance of the SRMS in the millimetre regime is clearly visible in Figure 10, where the spatial density of non-traceable objects as a function of object size is shown.

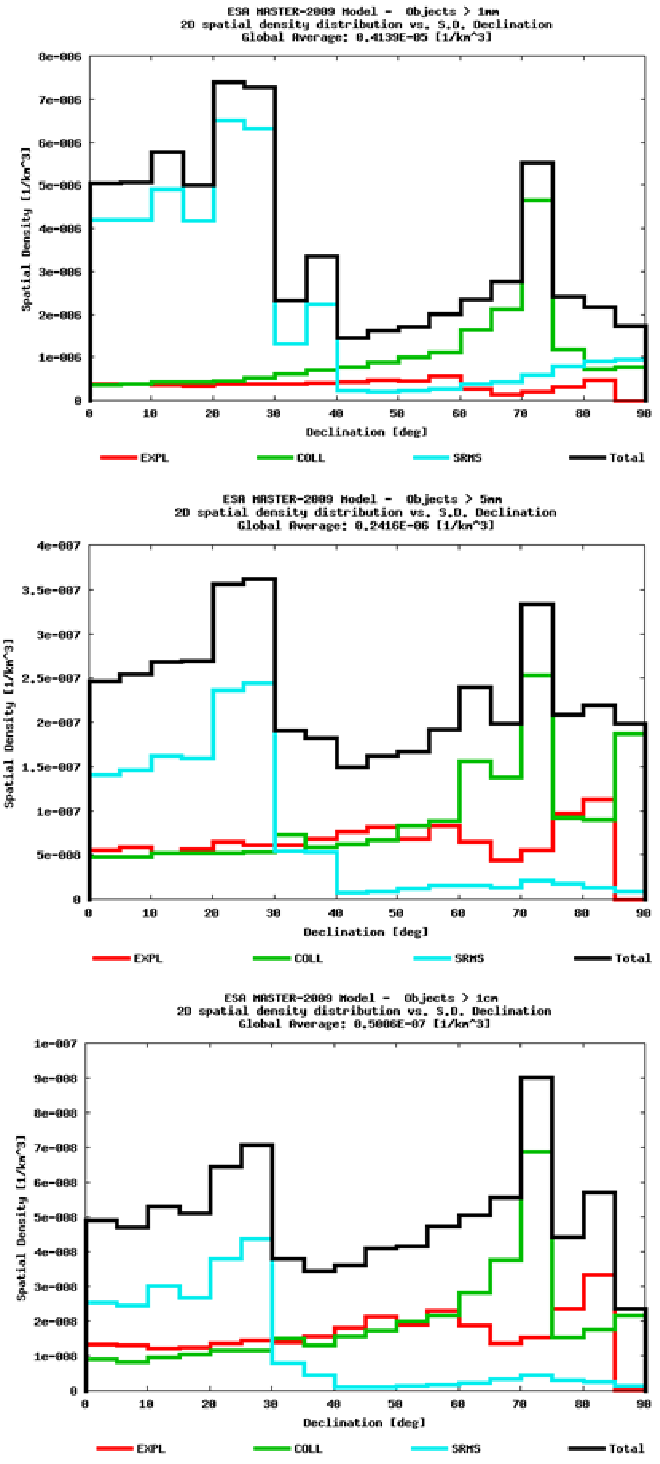

Figure 11: Spatial densities of non-traceable objects as a function of declination (averaged over all altitudes) for different object types, with a minimum object size of 1 mm (top), 5 mm (middle) and 1 cm (bottom).

Spatial densities as a function of declination (averaged over all altitudes) for the three different minimum object sizes are given in Figure 11. The object densities are not significantly depending on declination. However, at high latitudes the population is dominated by larger collision and breakup fragments (peak between 70°and 75°), while the maximum around 25° is given by smaller SRMS particles.

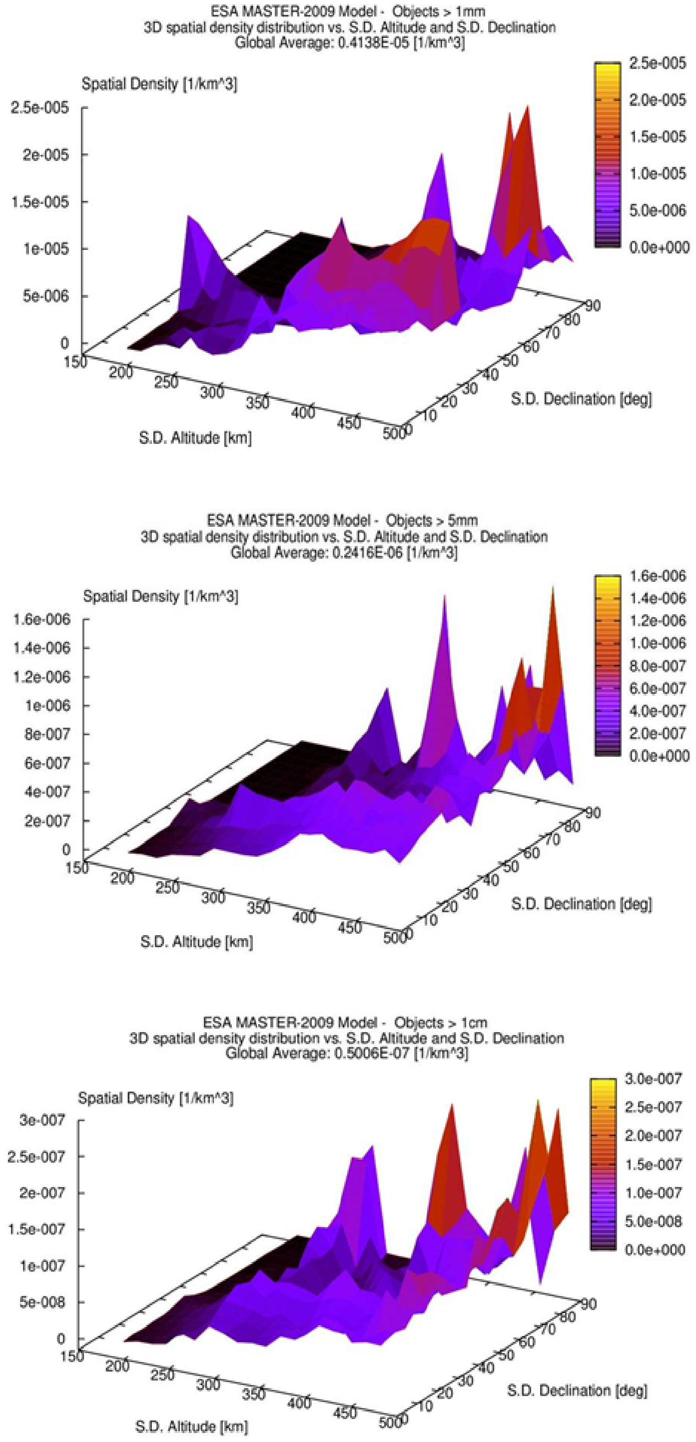

Figure 12: Spatial densities of non-traceable objects as a function of altitude and declination (total of all object types) for a minimum object size of 1 mm (top), 5 mm (middle) and 1 cm (bottom).

In Figure 12 the spatial densities of non-traceable objects (total of all object types) are presented as a function of altitude and declination for the three minimum object sizes. Note that the densities may vary by an order of magnitude for a given altitude depending on the declination δ and vice versa.

In order to estimate the number of impacts experienced by the space vehicle per unit cross section a and unit travel distance

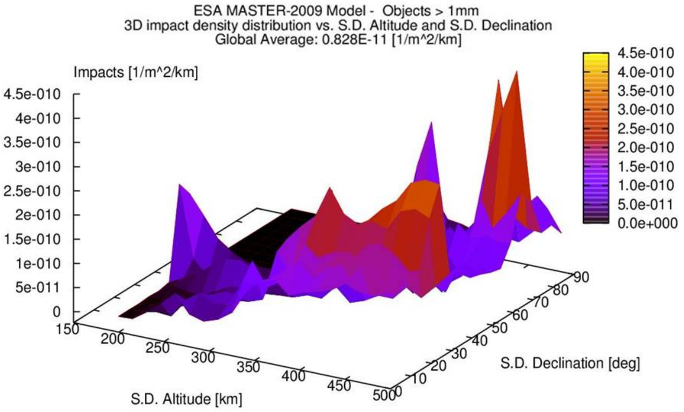

Figure 13: Number of impacts for objects >1 mm for an average cross-sectional area of 1 m^2 and a travel distance of 1km as a function of altitude and declination.

l in a particular region of space, we assume that the vehicle is traveling with a velocity v_{sv} in an environment where the particles have velocities v_p. While the space vehicle is crossing the unit volume element dV, the total number of particles in this volume element will be $(1 + v_p/v_{sv})$ times the unit spatial density ρ. The average number of impacts can then be calculated as:

$$n = \frac{a \cdot l}{dV}(1 + v_p/v_{sv})\,\rho\, dV. \tag{1}$$

The factor $(1 + v_p/v_{sv})$ is of the order of 2, as we may assume the space vehicle velocity being of the same order as the average velocity of the particles (7,8 $\mathrm{km\,s^{-1}}$ for the ballistic examples in Sect. 3.4.1, which is of the order of the circular orbit velocity in LEO). The number of impacts for an average cross-sectional area of 1 m^2 and a travel distance of 1 km was computed for the worst case of a minimum particle size of 1 mm. The number of impacts as a function of altitude and declination δ is given in Figure 13.

In regions with the highest density the number of collisions is of the order of $3 \times 10^{-10}\,\mathrm{km^{-1}m^{-2}}$. For the supposed flight example from Sydney to Oberpfaffenhofen (cf. Sect. 3.4), the total path above an altitude of 200 km is roughly 13 000 km. Assuming that the path would entirely lie in the highest density region we would expect 3.9×10^{-6} impacts per square metre from objects larger than 1 mm. Using the average collision rate of $8 \times 10^{-12}\,\mathrm{km^{-1}m^{-2}}$, we end up with 1×10^{-7} collisions for the entire journey.

In Table 1 global average spatial densities and impact rates for the non-traceable object population of three different minimum object sizes are summarized. These values are valid for altitudes between 186 km and 500 km and for declinations in the range of $0° \le \delta \le 90°$. The last row lists the number of impacts per square metre cross section for the hypothetical long distance flight.

Based on these numbers, we proceed to derive first estimates on space vehicle shielding capabilities and acceptable flight risks. We assume that collisions, i.e. hyper velocity impacts with object sizes $< x$ mm, with $x = (1, \ldots, 10)$ are lethal for an unshielded SSV. We further assume that the main collision flux stems from small-size objects (cf. Figure 10). Shielding is required if the risk arising from objects $> x$ mm is not acceptable. If no shielding is required, then no CRA for any object is required and no requirements concerning traceable objects are needed. If shielding is required, we assume that the risk arising from objects $> y$ mm $(y > x)$ is acceptable. Hence, two cases apply:

Table 1: Global average spatial densities and impact rates for the non-traceable object population and different minimum object sizes restricted to 186 km ≤ altitude ≤ 500 km and $0° \le \delta \le 90°$.

Particle size	**>1 mm**	**>5 mm**	**>10 mm**
Spatial Density ($\mathrm{km^{-3}}$)	4.1×10^{-6}	4.1×10^{-6}	4.1×10^{-6}
Impact rate ($\mathrm{km^{-1}\ m^{-2}}$)	8.2×10^{-12}	4.8×10^{-13}	1.0×10^{-13}
Impacts/15 000 km ($\mathrm{m^{-2}\ 15\,000\,km^{-1}}$)	1.2×10^{-7}	7.2×10^{-9}	1.5×10^{-9}

- Case A: Shielding of objects $< y$ mm is feasible, then no CRA for any object is required and no requirements concerning traceable objects are needed.
- Case B: Shielding of objects $< y$ mm is not feasible
  - Shielding for objects with $< z$ mm $(x < z < y)$
  - Objects with sizes between z and y need to be tracked and CRAs are needed.

As an example: If a risk for lethal collision of 1.5×10^{-7} for a SSV or a spaceplane with a 100 m^2 cross section is acceptable, then shielding for objects <10 mm is required. If shielding is technical and economically feasible, then no CRAs for any objects are required and no requirements concerning traceable objects are needed.

The impact rate for suborbital flights primarily depends on the minimum particle size to be taken into account. Conversely, the risk associated with the non-traceable population strongly depends on the maximum particle size for which the space vehicle can be shielded. The essential population to be taken into account is the SRMS particle population which dominates in the size range from 1 – 5 mm. Because this population does not show very significant variation with altitude or declination, a global average density can be assumed as a rough order of magnitude assessment of the collision risk. Given the approximations used in the previous sections and the uncertainties of the population model, the values provided in Table 1 should be considered as rough order of magnitude figures.

It is important to point out that even a small impact on an SSV or a spaceplane, which would not be harmful during the flight phase in space, may actually cause a catastrophic event during atmospheric re-entry. Classical shielding technologies used, e.g., for the ISS are not applicable because of the completely different environment during re-entry. The wing nose heat shield of the space shuttle was able to withstand impacts of objects of about 1 mm in size. On the other hand, it is not feasible to extend the catalogues of traceable objects to objects smaller than about 2.5 – 3 cm in the foreseeable future. For risk mitigation purposes, however, precise and continuous tracking of several hundred thousand objects and their corresponding orbits (which are 1 – 2 orders of magnitude more accurate than the ones in today's catalogues) appear inevitable. Therefore, the necessity to have an independent SST network, similar to the currently upgraded Space Fence system in the U.S. (SpaceNews 2016d), would by itself justify the establishment of the ESSTraC.

Even more important, there will clearly be a gap between the current shielding capabilities of about 1 mm and the minimum traceable object size of about 3 cm in future orbit catalogues. The statistical risks for a catastrophic event posed by this gap is of the order of 1×10^{-3} per flight, assuming an SSV cross-sectional area of $100\,\mathrm{m}^2$ and that the risk of colliding with an object is 1 out of 100 potentially catastrophic scenarios. For a spaceplane like *Skylon*, the corresponding risk would even increase to $\sim 8\times10^{-3}$ per flight, if we estimate its cross section to about $700\,\mathrm{m}^2$.

These risks appear unacceptably high (see also Paper II, Tüllmann et al. 2017b, for further details) and bear the danger to actually prevent p2p space travel in the future. Therefore, the gap needs to be reduced, primarily by developing new heat and collision shield concepts and technologies which could withstand impacts from objects larger than 1 mm. Here it is most important to close the gap in the lower size range, as the smallest objects pose the highest risk (cf. Figure 10). It is important to note, that the above figures come from an initial assessment of the general feasibility and require further validation before more solid conclusions can be drawn.

The future evolution of the space object population is hard to predict. It critically depends on the so-called "traffic model" (launch rates, mega-constellations, etc.). Moreover, the future use of solid rocket motors, the main contributors to the critical population, is even harder to predict. Current evolution models (using a traffic model based on historic data) predict a statistical increase of the population of objects larger than 10 cm of a factor of 2 to 3 over the coming 100 years. However, a few single collision or fragmentation events may change this picture drastically (e.g. increasing the population by a factor of 2 in a few years). If we assume, that the millimetre-size population is growing proportionally to the number of objects > 10 cm, the impact risk would increase proportionally. Therefore, a continuous monitoring of the space debris environment, in particular in the millimetre to centimetre-size range, appears mandatory to assess and manage the risks posed by collisions with space objects.

It is stressed that the detailed analysis of the shielding capability for the space vessels, the determination of acceptable risks and the cost-risk trade-off are beyond the scope of this study and should be subject to dedicated follow-up studies.

3.6. Space Weather Monitoring

The term 'Space Weather' refers to the environmental conditions in interplanetary space and their impact on Earth's magnetosphere, ionosphere and thermosphere as a consequence of interactions with the Sun, its solar wind and Cosmic Rays. These conditions can influence the operation and availability of spaceborne and ground-based systems. The natural hazards of Space Weather do not only modify atmospheric conditions, they also have the potential to catastrophically disrupt the functionality of key technologies, e.g., in the areas of communication, navigation, aviation, transportation, satellite operations, human space flight or electric power grid operations. Services based on those technologies are widely used and their interruption can have strong impacts on everyday life and result in significant economical losses. For example, mild Space Weather storms can degrade electric power quality, perturb precision navigation systems, interrupt satellite functions and are hazardous to astronauts' health. In the past, severe space storms caused perturbations in the electric power system and led to the loss of satellites through damaged electronics or increased orbital drag. For rare extreme solar events the effects could be catastrophic with severe consequences for millions of people.

3.6.1. Space Weather Conditions and their Impact on STM

Nominal Space Weather is mostly driven by the Sun and affects Earth through a variety of different physical processes and on different time scales. The ionosphere of the Earth is a highly dynamic layer of the atmosphere that is continuously exposed to extreme ultraviolet (EUV) radiation emitted by the Sun. The EUV radiation strength is related to active regions of the sun, i.e. to places where the Sun's magnetic field is disturbed. These regions emit high-energy particles and often produce different types of solar activity, such as solar flares or coronal mass ejections (CMEs). Sunspots are visual tracers of such active regions. If a group of sunspots produces an increase in the EUV flux, this group will rotate with the Sun in a period of about 27 days, leading to a 27-day variability of Earth's ionosphere. In addition, the 11-year solar cycle with its extremely varying activity maxima and minima needs to be considered, because, depending on which phase of the solar cycle is considered, the Ionosphere would be more or less strongly perturbed.

Moreover, Earth's rotation leads to a strong ionization of the ionosphere at the day side, whereas at the night side recombination considerably reduces the level of ionization. However, this strong gradient between day and night side leads to additional transport of plasma in the ionosphere and can cause further disturbance. Due to the inclination of the Sun, there is an additional seasonal effect of the ionosphere which leads to different conditions between summer, winter and equinox. Under nominal conditions, the ionosphere shows significant regional differences. Typically the ionosphere is very strong over the equator and continuously disturbed over the polar regions due to a continuous stream of charged particles following the magnetic field.

What are the consequences of nominal Space Weather for suborbital space flights?

- The flight route of every space vehicle has to be checked with respect to regions of enhanced ionization which might cause navigation or communication issues
- Likewise, the season and region on Earth, as well as daytime has to be investigated with respect to the expected perturbations (e.g., in the African region scintillation events take place very often during equinox at dusk)
- The basic ionization level in the ionosphere is different during the solar cycle and to compensate for those variations, it needs to be checked where we currently are in the cycle
- Also the propagation times of plasma patches and gradients have to be analysed to know when the navigation augmentation systems might face performance degradations.

Extreme Space Weather events can occur on different time scales next to the nominal Space Weather influences and are triggered by the continuous particle stream from the solar wind and the permanent flow of cosmic particles. These events can have severe impacts on Space Traffic operations and can lead to the complete interruption of critical services.

In Table 2, we present a risk register of the most critical risks and impacts that could occur if Space Weather conditions remain unknown to crew and passengers aboard a spacecraft operating in suborbital space or LEO[3]. In this regard, the potentially biggest threats stem from solar flares and high-energy particles as their time of arrival is relatively short (some 8 – 30 min) making it improbable to issue timely re-routeing requests for spaceplanes already en route to their destination spaceport.

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[3] In Paper II (Tüllmann et al. 2017b) the risks identified in Table 2 have been quantified and incorporated into a risk classification scheme that is proposed as a starting point for discussions and for development into the final standard.

Table 2: Risk register related to the risks in case crew and passengers aboard the spaceplane are unaware of Space Weather events

Risk	**Solar Flares**	**High-Energy Particles**	**Coronal Mass Ejection**
Origin	Sun	Sun / Cosmic Rays	Sun
Event	Electromagnetic radiation from X-ray to radio wavelengths	High-energy particles & proton showers	Energetic particles in the solar wind
Duration	1 – 2 hrs	Solar event: Up to several days Cosmic Rays: Continuous	Up to several days
Time until arrival	~ 8 min	15 min – 60 min	1 – 3 days (depending on solar wind speed)
Causes	• Enhanced ionization at the bottom of the Ionosphere (D-Layer) • Heating of the Thermosphere	Radiation	• Solar storm (extreme solar wind) • Thermosphere heating • Geomagnetic storms • Particle precipitation • Ionospheric disturbances
Impact	• Navigation (Positioning, Loss of Lock) • Radio Blackouts (GNSS Signal disturbance) • Drag effects	• Radiation damage (Passengers, Space & Air Crew) • SEU, Latchup • Interference • Degradation (damage of solar cells, microelectronics, etc.)	• Power outages • Internal/External charging • Drag effects, Navigation (Positioning), High frequency communication, geomagnetic induced currents
Forecast	No	Yes	Yes
Nowcast	Yes	Yes	Yes

Solar Flares occur as a consequence of reconnection processes of the solar magnetic field and can generate 1 – 2 hours of continuous X-ray and EUV emission. This electromagnetic radiation can reach the Earth within ~8 min and cause, in case of strong X-class flares, disturbances of communication and navigation systems. CMEs are plasma clouds of charged particles expelled from the Sun's surface that propagate with the solar wind at an enhanced velocity of up to 2 000 km s^{-1} (aka. solar storm). A solar storm interacts with the atmosphere of the Earth after 1 – 3 days and can, depending on the strength and orientation of the interplanetary magnetic field, cause serious disturbances and damages of technical infrastructure in space and on Earth. Solar storms influence also the ionized and neutral atmosphere, causing significant disturbances in the signal propagation of navigation and communication services.

Solar eruptions occur sporadic and are not predictable. They release Solar Energetic Particles (SEPs) which can reach the Earth within 15 – 60 min and can last up to several days. SEPs interact with the atmosphere and cause ground level enhancements (GLEs), a significant increase of the radiation level on Earth's surface. The frequency of all aforementioned events depends strongly on the solar activity, which follows the 11-year magnetic pole reversal cycle of the sun.

What are the consequences of extreme Space Weather for suborbital space flights?

- Solar Flares cannot be predicted due to the short arrival time scale of the X-ray and EUV radiation (~8 min). Hence, the timely re-calculation of new trajectories for spaceplanes is unrealistic and the expected positional inaccuracies have to be accepted. Real-time monitoring of the ionospheric effects with adequate descriptions of the influences on communication and navigation as well as error correction is possible.
- The impact of CMEs on the Ionosphere can be predicted with 2 – 3 hours lead time for mid-latitudes based on solar wind measurements of the DSCOVR satellite at L1 position. Earlier information on CMEs are very inaccurate regarding global arrival times and impact probabilities, but can be derived from observations with the SOHO, GOES and STEREO spacecraft.
- The prediction time scale for SEPs is with 15 – 60 min very limited. However, such events can last for several days and can produce enhanced radiation at flight altitudes affecting both air and space traffic. In case of a severe SEP event, flight routes and altitudes need to be changed and space operations need to be cancelled or postponed.

The frequency of the above discussed Space Weather events depend on the solar activity, which follows the solar cycle. The probability for extreme Space Weather events causing strong impacts on flight operations, infrastructure and temporal restrictions to not endanger human lives is estimated to be one event per solar cycle.

3.6.2. A European Space Weather Monitoring Centre

In order to mitigate the negative effects of Space Weather, an international monitoring network jointly operated by Europe, the U.S., and other space-faring nations appears mandatory. Currently, the main activity with respect to the establishment of Space Weather services in Europe is related to the implementation of independent monitoring capabilities as part of ESA's Space Situational Awareness (SSA) Programme[4]. However, despite many European initiatives to raise Space Weather awareness and to enter an initial service provision phase (e.g., originating from the FP7 programme, Horizon 2020, the working groups of the Space Weather Working Team or the Joint Research Centre of the European Commission), there is still no end-to-end Space Weather monitoring, forecasting and reporting for STM purposes as envisaged in the ROS outlined in Figure 1.

Therefore, initial ideas for a Space Weather monitoring concept are presented that is tailored to the needs of a European STM system and identifies the still missing infrastructure, inter-

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[4] See http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/SSA_Programme_overview

Table 3: Needed infrastructure for a SWMC supporting a European Space Traffic Management system

Needed Infrastructure	**Explanation**	**Products & ESA customer requirements**
TEC processing system	System for processing GNSS data streams, deriving estimates of the Total Electron Content (TEC), producing TEC maps and its derivatives. Needs NTRIP data input from global reference networks like the International GNSS Service (IGS).	TEC Map, TEC RATE MAP
Scintillation processing system	System for processing high-rate GNSS data and deriving scintillation indices	ROTI (Rate of Change of TEC index), S4, $\sigma\varphi$ (sigma phi)
Sun information from GOES and the complementary Global Ionospheric Flare Detection System (GIFDS)	GIFDS: Global measurement system based on VLF measurement to monitor and evaluate solar flares in Real-time. SEP event monitoring can be done using GOES	Real-time Flare information for Warning Messages ESA requirements: SWE-CRD-SCO-1548, SWE-CRD-SCO-1549, SWE-CRD-SCO-1558
Multilevel Warning System for GNSS Users	1. Early Warning 2. L1-Warning 3. Forecast 4. Ionospheric Alert	Early Warning Messages for GNSS users derived from solar observations. Dissemination of short and long term prediction and real-time evaluation of the ionospheric state for GNSS users
High Rate GNSS Receiver Network	A near real-time facility capable of acquiring, processing and distributing high rate GNSS data and GNSS-related data products	Delivery of the scintillation indices S4 and $\sigma\varphi$
Ionospheric Forecast System	Needed to forecast ionospheric disturbances around the world, including direct information from approaching Space Weather events.	Delivery of TEC maps over Europe up to 24 hours in advance taking possible ionospheric perturbations from geomagnetic storms into account.
Real-time TEC Time Series Plotter	Functional user interface to extract time series data from global TEC maps	ESA requirements: SWE-CRD-SCO-1548, SWE-CRD-SCO-1566
LEO satellite measurements	Radio occultation and topside measurement to increase monitoring and forecast of the ionosphere over oceans and mountain regions	ESA requirement: SWE-CRD-SCO-1565
Neutron Monitor Network	Ground based radiation measurements to identify GLEs	ESA requirement: SWE-CRD-SCO-1559
Magnetometer Network	Real-time measurements of Geomagnetic Storm Conditions.	ESA requirements: SWE-CRD-SCO-2650, SWE-CRD-SCO-2650

faces and service products[5]. Because a central European entity in response to the needed services is missing, we propose the establishment of a European Space Weather Monitoring Centre (SWMC) that shall be responsible for:

- Performing 24/7 Space Weather monitoring
- Providing Space Weather information 24/7 via dedicated web pages (passive information flow)
- Providing products needed for FPS operations via direct data streams to ATCOs and STCOs (active information flow)
- Issuing of daily and ad hoc SWBs
- Operating and maintaining 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 affect safe spaceplane operations
- Providing technical and scientific support 24/7 for services and products
- Maintenance of communication networks and web pages
- Supporting the International Civil Aviation Organisation (ICAO) on relevant Standards and Recommended Practices (SARP)
- Supporting the World Meteorological Organisation (WMO) on defining and improving observation and service requirements to protect against Space Weather hazards
- Performing Special Operations (e.g., provide data on request for incident investigations, performing conflict-free scheduling and execution of maintenance downtimes).

In addition, the SWMC could be responsible for routinely providing the following data products and services:

- Generating and disseminating near real-time global TEC maps as well as high-resolution regional maps (e.g., close to spaceports)
- Producing and circulating at least one hour forecasts of the global TEC and regional TEC (e.g., close to spaceports)
- Generating records of scintillations (small-scale high-frequency interference)
- Providing scintillation indices and near real-time scintillation monitoring based on high rate GNSS measurements
- Producing and disseminating global Change Rate Of TEC index (ROTI) maps
- Providing equivalent slab thickness for spaceport locations
- Providing information on actual and forecasted geomagnetic indices.

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[5] Initial high-level technical requirements and interfaces for a European contribution to Space Traffic Management are listed in Paper III (Tüllmann et al. 2017c) and may also serve as starting point for deriving the final set of technical STM requirements.

Table 4: Existing and needed products to secure reliable Space Weather monitoring

Product-ID	**Product name**	**Unit**	Comments	Existing / needed service	Additional information
P-STM-1	TEC map	TECu	TEC is used for Range-Error corrections (e.g. WAAS or EGNOS)	Existing (I-ESC) ESA requirement: SWE-CRD-SCO-1539	EU, global
P-STM-2	TEC error map	TECu	Can be used to estimate the formal error of map generation and therefore the accuracy of range error estimation in applications	Existing (I-ESC) ESA requirement: SWE-CRD-SCO-1539	EU, global
P-STM-3	TEC rate	TECu s^{-1}	Dynamics indicator. The TEC-rate is subject to horizontal gradients and to fast phase changes during solar flares, causing problems for satellite tracking	Existing (DLR) ESA requirement: SWE-CRD-SCO-1539	EU, global
P-STM-4	TEC gradients	TECu km^{-1}	Can be used to rate the horizontal TEC gradients, influences the solution for phase ambiguities in GNSS reference systems	Existing (DLR) ESA requirement: SWE-CRD-SCO-1539	EU, global
P-STM-5	TEC map (1h forecast)	TECu	Short term prediction	Existing (I-ESC) ESA requirement SWE-CRD-SCO-1539	EU, global
P-STM-6	TEC map (Quality of the prediction)	TECu %	To validate the quality and reliability of the short term prediction	Existing (I-ESC) ESA requirement: SWE-CRD-SCO-1539	EU, global
P-STM-7	TEC map 24h forecast	TECu	Rough medium term prediction	Existing / Needed (DLR) ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1585, SWE-CRD-SCO-1586	EU Empirical model estimating ionospheric storm impact, using statistics of past storms. Global model is needed.
P-STM-8	TEC map 24h (Quality of the prediction)	TECu %	To validate the quality and reliability of the rough medium term prediction	Existing / Needed (DLR) ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1585, SWE-CRD-SCO-1586	EU, global is needed
P-STM-9	TEC map 24h – 48h forecast	TECu	Long term prediction, data-triggered physical model	Needed ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1585, SWE-CRD-SCO-1586	EU, global
P-STM-10	TEC map 24h – 48h (Quality of the prediction)	TECu %	To validate the quality and reliability of the long term prediction	Needed ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1585, SWE-CRD-SCO-1586	EU, global
P-STM-11	Disturbance Ionosphere Index (DIX)		Characterises the level of disturbance in the ionosphere and therefore the possible performance of precise GNSS in reference networks	Needed (under development at DLR) ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1589	EU, global
P-STM-12	Geoplasma reconstruction	$e^{-} m^{-3}$	Vertical TEC information for modelling. Use for 3D Assimilation	Existing (DLR) ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1562	EU, global
P-STM-13	3D reconstruction	$e^{-} m^{-3}$	Comprehensive representation of radio wave propagation effects possible, high level ionospheric information as long as the temporal and spatial resolution fulfil user requirements	Existing (DLR) ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1561	Global

Table 4: Continued

Product-ID	**Product name**	**Unit**	Comments	Existing / needed service	Additional information
P-STM-14	Scintillation measurements	S4 and $\sigma\varphi$	Characterises small-scale perturbations in the ionosphere which have degrading influences on all GNSS signals and can lead to the complete loss of signal	Existing (I-ESC) ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1563	Local
P-STM-15	ROTI	TECu min^{-1}	Global ROTI maps can be used to detect small and medium scale ionospheric irregularities	Existing (I-ESC) ESA requirements: SWE-CRD-SCO-1539, SWE-CRD-SCO-1563	Global
P-STM-16	Weekly or Daily Space Weather Bulletin (SWB)	Info	Information on expected Space Weather conditions	Needed ESA requirement: SWE-CRD-SCO-1583	EU, global
P-STM-17	Space Weather incident reports	Info	Information on ad hoc Space Weather effects from solar flares, CMEs and high-energy proton events.	Existing / Needed (R-ESC, S-ESC) ESA requirements: SWE-CRD-SCO-1531, SWE-CRD-SCO-1533, SWE-CRD-SCO-1577	Arrival time of flares (~8 min) and high-energy proton events (~15 min). No forecast possible.
P-STM-18	Early Warning	Info	Information on Space Weather events at the Sun and impact estimation	Existing / Needed (I-ESC, S-ESC) ESA requirements: SWE-CRD-SCO-1532, SWE-CRD-SCO-1546, SWE-CRD-SCO-1566, SWE-CRD-SCO-1584	Further development to improve spatial and temporal accuracy needed.
P-STM-19	L1-Warning	Info	Information on arriving CMEs and their expected impact	Needed (under development at DLR) ESA requirements: SWE-CRD-SCO-1532, SWE-CRD-SCO-1566, SWE-CRD-SCO-1584, SWE-CRD-SCO-1589	EU, global
P-STM-20	Ionosphere Warning Scale	tbd.	Information on Space Weather effects on the ionosphere in analogy to the NOAA-SWPC Space Weather Warning Scales	Needed ESA requirement: SWE-CRD-SCO-1546, SWE-CRD-SCO-1584, SWE-CRD-SCO-1589	EU
P-STM-21	Radiation	Info	Human spaceflight – Increased crew radiation exposure risk (SWE-SRD-12560)	Existing (R-ESC) ESA requirements: SWE-CRD-SCO-1533, SWE-CRD-SCO-1567	Global, local
P-STM-22	Geomagnetic storm conditions & index	Info	Required to determine risk of internal charging leading to discharge	Existing (G-ESC,WDC) ESA requirement: SWE-CRD-SCO-1564	Global, local

Due to the complex and far-reaching nature of Space Weather events, global coverage from ground-based and spaceborne observation systems is essential for providing reliable Space Weather services and products. A gap analysis has been performed to identify the needed infrastructure for Space Weather monitoring services. The results of this analysis are summarised in Table 3 where a compilation of systems is given that are essential to ensure reliable and secure STM operations and a reference to the applicable segment-level ESA programme requirements for Space Weather is made (see ESA 2011).

A gap analysis has also been performed on existing and needed Space Weather services. Table 4 provides an overview about existing and needed Space Weather products tailored to Space Traffic Management operations. The entities which already provide these products are listed in col. 5 along with the applicable segment-level ESA requirements for Space Weather (see ESA 2011).

Radiation will be a big issue for all manned Space Traffic operations and has to be seriously taken into account. First operational models for space radiation assessment exist (e.g., Posner et al. 2010; Matthiä et al. 2014, 2015; Schrijver et al. 2015), but further development, elaboration and application of improved models is needed. In Europe, there is still a lack of space monitoring of reliable, on-line proton data in the MeV range. These data together with on-ground monitors are needed for the devel-

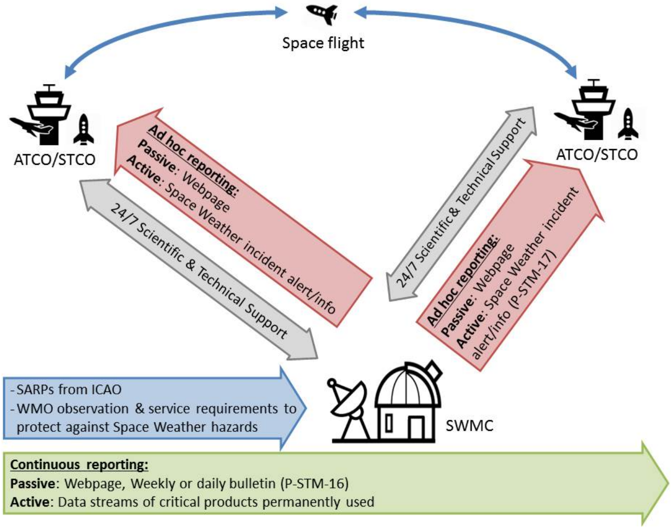

Figure 14: Information flow between SWMC, ATCOs and STCOs.

opment of reliable radiation transport models to assess radiation exposure for aircraft/spacecraft crews, astronauts and avionics.

3.6.3. SWMC Interfaces with ATCOs and STCOs

The interaction between the SWMC, ATCOs and STCOs is envisaged to be based on a passive and active information flow as outlined in Figure 14. The passive information flow shall be available 24/7 through a dedicated web page, where ATCOs and STCOs can find all information needed for secure space flight operations under nominal and weak Space Weather conditions. In case of strong and extreme Space Weather events, a Space Weather incident protocol needs to be implemented, actively distributing information via Email on Space Weather hazards. The SWMC shall also be able to provide technical and scientific support on a 24/7 basis. The SWMC shall only inform the ATCO and the STCO about Space Weather hazards and not directly communicate with the SSV pilots in order to not distort the proper information flow. The ATCO and STCO would then have to inform the crew aboard the spaceplane about appropriate measures of existing Space Weather hazards.

Based on the infrastructure listed in Table 3, the SWMC shall be capable to continuously inform about Space Weather conditions via dedicated web services providing at a minimum the products listed in Table 4. These products shall help to lower the risks and impacts listed in Table 2 from an unacceptably high safety risk level to an acceptable one (see Tüllmann et al. 2017 (Paper II) for a discussion of the proposed Safety Risk Classification Scheme). All products shall be accessible for STCOs and ATCOs so that they can download the relevant data files and use them for internal evaluation and further dissemination. In case of critical, permanently needed products, e.g., for flight scheduling and flight operations above FL650, a direct and continuous data stream to the ATCOs and STCOs could be established. Furthermore, a weekly Space Weather Bulletin (SWB, P-STM-16) shall be implemented which informs about the actual and predicted Space Weather conditions (e.g., for flight planning purposes).

The SWB should be monitored and generated by the SWMC operator electronically, focussing on products and information needed at ATCO/STCO-level. The Operator can also react on specific Space Weather incidents or irregularities by adding products or further explanations to the product. Operator-commented plots would give additional information on the broader context. The SWB should be compiled at least every week and contain data from 8 days (with one day overlap). Depending on ATCOs/STCOs needs, it shall also be possible to generate daily, hourly and on-demand SWBs, presenting the actual information and forecast together with all information from the previous day. The SWMC operator needs to monitor and analyse the solar interaction chain from Sun to Earth. In order to be more precise, the following non-conclusive list contains the different Space Weather conditions which have to be checked prior to generating a SWB:

- The interplanetary and geomagnetic conditions: Time series of the F10.7 index, the interplanetary magnetic field conditions from ACE/ DSCOVR, the solar wind velocity from ACE/ DSCOVR, the dynamic pressure as well as the geomagnetic indices Kp and Dst
- The Sun's activity: Flares, CMEs and high-energy solar particle events need to be monitored and analysed using satellite-based solar observations
- The radiation environment: The actual and expected radiation levels from Cosmic Rays (solar and galactic)
- The ionospheric weather conditions: TEC latitude time plots, global TEC maps can be presented in a latitude time plot using zonal mean TEC, TEC deviation, TEC rate, TEC gradients, TEC forecasts, scintillation monitoring, ROTI, DIX, slab thickness, ionosphere electron density and 3D TEC reconstructions.

In addition to the warnings and routine information issued continuously via the SWMC web page, a sequence of ad hoc reports shall be provided in order to inform STCOs about unusually strong Space Weather events which have a potentially high risk to strongly affect Space Traffic operations. The information would be provided by email with human (plain text) and machine readable (xml) content via an active warning system. This alert notification shall provide products P-STM-17 to P-STM-20, covering the chain of causation from Sun to Earth with forecasts (P-STM-18, P-STM-19), real-time (P-STM-17, P-STM-20) and all clear (P-STM-20) information. The Space Weather incident protocol is executed if at least one of the following Space Weather conditions is met:

- An X-class flare occurs
- A CME approaches from the visible solar disk with a speed $v > 1\,000\,\mathrm{km\,s^{-1}}$
- Enhanced geomagnetic conditions: $Kp > 6$ and $Dst < -150$
- Onset of a radiation storm with $E > 10\,\mathrm{MeV}$ and particle fluxes $> 10^4$ particles $\mathrm{s^{-1}\,cm^{-2}\,sr^{-1}}$
- Significant impact on navigation and communication due to ionospheric disturbances.

The SWMC is the entity responsible to collect and provide all products and services to ATCOs and STCOs. Additional information on envisaged tasks and responsibilities of the SWMC in the context of space flight planning and scheduling are given in Sect. 3.7.2.1.

3.6.4. Constraints on a SWMC Operations Concept

Regular and on-demand access to networks providing global Space Weather observations is vital for a SWMC. This access can only be granted if reliable international contracts with dependable partners are in place. Hence, space agencies could be ideal candidates to operate a SWMC, as they are actively involved in international collaborations and the negotiation of multilateral agreements and in that data access and usage is granted for most space agencies.

An essential product for STM operations is the weekly or daily SWB (P-STM-16) which provides all important information in a human readable manner. The STCOs have to define the delivery frequency of the SWBs according to their space flight operations needs. The second mandatory service is the ad-hoc information in case of strong and extreme Space Weather events (P-STM-17). Ad hoc Space Weather event information has to be provided in a human and machine readable format. A machine readable format ensures the direct digestion of the information into the ATM/STM system. In general, the SWMC should provide *all* Space Weather information in a preprocessed format according to the needs of the STM. Provision of science data from the Space Weather domain to the STM should be limited in order to prevent misinterpretation by non-experts. Depending on the given Space Weather information and risks, the STCO has to issue adequate instructions or mitigation measures to the crew aboard the SVVs. This requires that STCOs (and ATCOs) are properly trained in order to allow for a correct decision making process.

In addition to the ATM and STM interfaces, the SWMC also needs to have interfaces to other European and international regulatory organisations. At least two additional interfaces appear necessary, one to the ICAO and one to the WMO, as the SWMC has to provide services to second ICAO's international SARPs and WMO observation and service requirements to protect against Space Weather hazards.

As already discussed by ICAO it might actually be necessary to establish 2 – 3 regional SWMCs in Europe instead of just one single centre. In this regard a prime-backup centre approach appears reasonable, because without a SWMC acting as backup, service outages or downtimes could not be compensated (single point of failure). In order to efficiently use resources and to balance work loads, the prime centre could concentrate on daily service operations (data processing and circulation), whereas the backup centre would be responsible for the administration of all Space Weather-related aspects (e.g., acting as point of contact for official communication or conductor of negotiations for services, products and contracts). Currently, ESA's SSA programme is building up such a coordination centre, but because this programme is optional for EU member states and subject to the geo-return policy, it appears questionable whether a stable network of providing Space Weather services with long-term service contracts can be granted. Therefore, it seems advisable to establish a structural solution that guarantees continuous planning and Space Weather service provision.

3.6.5. Existing Warning Scales

The NOAA Warning Scale[6] is the most frequently used Warning scale for Space Weather Events. The scale distinguishes between three different types of events. The Radio Blackout (R-Scale), the Solar Radiation Storm (S-Scale) and the Geomagnetic Storm (G-Scale). The three scales together give a good overview about an incoming Space Weather event, but have certain issues to explain expected impacts on Earth with a sufficient good temporal and regional resolution. The most important disadvantage of the NOAA scale is, that no Ionospheric Scale exists, although this would be highly desirable for many aviation and Space Traffic applications. In the following, we will comment on some aspects of the different scales which could be improved.

The R-Scale uses GOES X-ray flux observations as driver. Since GOES can be in the eclipse of the Earth and moon, it might actually miss solar flares. The R-Scale provides information about the expected impact of flare activities on the ionosphere to customers in the area of high frequency (HF) communication or precise positioning applications. Therefore, we suggest, complementary to GOES, a ground based detection system called Global Ionosphere Flare Detection System (GIFDS) which is able to see all relevant flares starting from C-class up to X-class (Wenzel et al. 2016). Since GIFDS measures directly the flare impact in the Ionosphere, it is also ideal to measure the impact for GNSS users.

The S-Scale uses GOES energetic particle observations with energies above 10 MeV as driver. High-energy solar particle radiation during solar storms can lead to strongly enhanced radiation exposure and absorption of HF radio signals up to complete disruption of communication, which is why the S-Scale is insufficient in giving a good estimate of the expected radiation exposure in aviation or Space Traffic. In this regard, ground based measurements using the neutron monitor network are much more suitable as they detect GLEs and give better information on the expected radiation exposure. Further advantages to the S-Scale also promises the recently proposed D-index which was designed for aviation industry (see Meier & Matthiä (2014) for further details).

The G-Scale is driven by the geomagnetic Kp value, an index that is updated every three hours. The G-Scale is especially important for HF communication, e.g., for satellite navigation and positioning, to estimate the maximum usable frequencies, to predict satellite communication losses and geomagnetic induced currents. The information on geomagnetic storms is also of particular interest for STM purposes. However, the commonly used 3h-Kp index is not sufficient to fulfil operator needs, which is why a better G-scale driver has to be defined with higher temporal resolution allowing for more accurate forecasts. Here, the Dst index with one hour resolution might be a better choice. Alternatively, or complimentary to the Dst index, observations from ACE and DSCOVR could also result in a good storm onset prediction.

A very important scale for STM applications would be an ionospheric scale. Unfortunately, such a scale has not been implemented yet as its definition is very challenging due to regional dependencies, temporal dependencies and frequency dependencies of GNSS disturbances.

3.7. Integrating STM and ATM

In order to find integration points for merging STM and ATM systems, the ATM Master Plan from 2015 was broken down into high-level operational and organizational key areas and matched with the corresponding areas of the envisaged STM system. The result is presented in Figure 15, showing the overlapping set of common areas as well as the set of complementing ones for ATM and STM evolution. For implementing the Space Traffic Evolution topics ATM procedures, concepts, products and Lessons Learned must be applied as far as practical in order to build a STM system that is compatible to ATM concepts and standards.

The topics listed in the brown area represent a subset of key aspects common to both systems. Topics, such like safety and reliability (S&R, including threat mitigation for remotely piloted aircraft systems (RPAS)), data exchange strategies between ATM and STM, space debris and CRAs, Space Weather,

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[6] See www.swpc.noaa.gov/NOAAscales for details

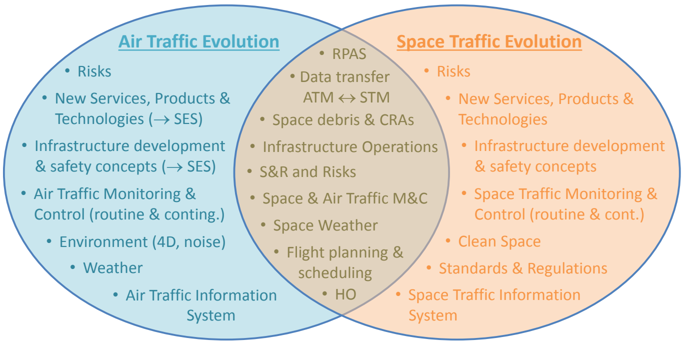


Figure 15: Common (brown) and complementing areas for ATM and STM evolution (turquoise and orange) considered for merging ATM and STM systems.

space and air traffic M&C operations, flight planning or handover/handback operations between ATCOs and STCOs touch the interface between ATM and STM and require the development of innovative operations concepts and modifications of existing risk standards to warrant a seamless ATM and STM integration and safe aerospace operations.

In the coming years, while the SES and NextGen concepts are being implemented and the commercial space travel market is still in its infancy, it is very likely that commercial p2p space flights will operate globally fairly infrequently and only from a handful of spaceports. Later, in a second stage, after space travel technology has matured, S&R performance has approached that in aviation and space travel gained public confidence, the global space travel market is likely to grow. As a result, flights through suborbital space will become increasingly more frequent and launch and landing sites move closer to more populated areas and business centres. During the final phase, p2p space travel is routine, with dozens of flights per day from dedicated aerospaceports (airports with collocated spaceports).

In the course of STM evolution it is conceivable that in stage one some of the hardware and technology, but also procedures and standards designed for space flight operations, are allowed to bypass some of the well-established ATM standards and operations procedures (provided this does not conflict with safety standards applicable at this time). During STM evolution (second stage) those hardware, procedures and standards will continuously undergo regular evaluations and updates. For example, space vehicles used for p2p space travel need to be qualified and licensed for commercial space transportation and also for flight according to aviation standards and regulations. In addition, proper flight rules for operating in or near densely-populated areas will have to be established without endangering air traffic flows. In the final stage, space vehicles and space flight operations are fully integrated with nominal ATM operations and are 100% qualified for commercial passenger transportation.

The concept of space vehicle integration into civil airspace generally calls for new route and separation standards to be laid out by ICAO in order to allow for changes in airspace and procedure design with respect to spacecraft parameters and capabilities. The challenge in this undertaking is the development of generalized spacecraft categories, which reflect design layouts, flight performance as well as operational profiles (e.g., booster usage and jettison, re-entry with burn-off elements or manoeuvrability of the vessels). However, knowing the performance of a spacecraft, such as climb rate, speed and turn radius is crucial for an ATCO to safely manage air traffic. It has therefore to be determined if a true separation standard similar to today's standards for civil aircraft can be found or if the common practice of temporarily reserved airspaces is the only way forward.

On the one hand, reserved airspace for launching and landing space vehicles is in strong contrast to a capacity-friendly ATM concept as envisaged in the SES initiative, but on the other hand, if separation standards for spacecraft become prohibitively large due to their diverse operational profiles, temporary airspace solutions might be a better option. In the communication, navigation and surveillance (CNS) domain, the communication element in the STM context can be considered as comparable to current aviation practices, i.e. radio communication or digital (space-based) communication, whereas the navigation domain for spacecraft remains to be analysed. In the context of Performance Based Navigation (PBN, see ICAO 2008), it would be highly desirable to standardise spacecraft trajectory management in an RNP-like (Required Navigation Performance) format. RNP is defined as the accuracy of the navigation performance required for operations in a particular airspace. It is expressed by the distance to the intended position (target position) that an aircraft must comply with in at least 95% of the total flight time. This navigation accuracy is based on a combination of errors of the navigation sensor, the on-board receiver, the on-board display and the aeronautical error in the horizontal plane (see e.g., ICAO 2008; Eurocontrol 2013). Following these existing navigation concepts, it should be possible to derive route spacing and traffic separation standards based on ICAO's current collision risk modelling techniques.

The element of surveillance has to find proper sensor data fusion concepts to fill the gap between orbital tracking technology and aviation surveillance systems, such as radar, multilateration or independent surveillance broadcast, which nowadays is limited to altitudes of ~60 000 ft (FL650). For spacecraft re-entry tracking the challenge will likely be to perform data transition between space tracking networks and aviation surveillance tools. Hence, it appears that the biggest challenge in integrating space vehicles into civil airspace is the navigation domain, where no standards yet exist for the space vehicle's movements in the lower atmosphere. In order to ensure the ATM system's sustainable set of standards, the most practical solution would therefore be to integrate space vehicle navigation into the existing set of RNP parameters.

3.7.1. Tasks and Responsibilities of STCOs

Similar to the role definition of ATCOs, the role of STCOs could be defined. In general, STCOs perform M&C operations for manned and unmanned space vehicles by tracking and directing them through controlled aerospace above FL650. In addition, STCOs could provide support and advisory services to crew aboard the spacecraft, such as providing ad hoc SWBs, assisting in conflict de-escalations of on-board incidents or issuing collision avoidance measures. Based on the definition of the separation concept between spacecraft and civil aircraft, the STCO's primary responsibility would be to ensure a seamless and safe integration of spaceplanes into the air traffic flow and preventing collisions between spacecraft, aircraft and debris.

In case a spaceplane crosses FL650 in either direction, corresponding handover and handback operations between STCOs and ATCOs are required. This step ensures a clean separation of responsibilities in that ATCOs are responsible for guiding spaceplanes through airspace up to FL650 and STCOs take over responsibilities above that level. This handover can be compared with and is similar to handover procedures between two airspaces controlled by different countries that are used in civil

ATM. The following list provides a high-level summary of envisaged tasks and responsibilities of a STCO:

- Communicate with interfaces (e.g., ATCOs, STCOs, SWMC, ESSTraC, pilots or spaceports)
- Perform pre-departure checks on system, flight and spacecraft status (double-check independent from ATCO)
- Check if all products from Flight Planning and Scheduling (see Sec. 3.7.2), such as flight plans, trajectories, flight corridors and their corresponding backups and contingency plans, have been uploaded and validated by flight crew
- Provide Go/No Go decisions for departure to ATCO (double-check)
- Perform handover and handback operations with ATCO once spacecraft reaches FL650
- Check accuracy of spacecraft's (re-)entry points and trajectory and issue corrective manoeuvres or the execution of backup and contingency plans if indicated
- Perform routine M&C operations as well as contingency operations
- Provide ad hoc SWBs to pilot in case Space Weather conditions change and endanger passengers and crew aboard the vessel
- Perform Special Operations (e.g., provide data on request for incident investigations, assist in conflict de-escalation in case of incidents aboard the spacecraft).

3.7.2. Possible Interfaces for STCOs

Now, that initial tasks and responsibilities for STCOs have been defined in the STM context, the following interfaces for combined ATM and STM operations are needed:

- Flight Planning & Scheduling Operations
- Air Traffic Control Operations
- Space Traffic Control Operations
- Ground Operations at Airports and Spaceports
- Spaceplane Operations.

In the context of the ROS outlined in Figure 1, a high-level task description is presented for each of these interfacing areas explaining their envisaged mutual interaction during the different flight phases, from pre-departure operations, to in-flight operations and post-arrival operations.

3.7.2.1. Flight Planning & Scheduling Operations

A completely new branch of operations requiring the design, development and validation of new requirements, procedures, elements and infrastructure in the STM context is related to Flight Planning and Scheduling (FPS). At least in the early stages of commercial space travel, FPS is expected to be very different from routine FPS operations in the aviation sector and although there are obvious similarities and many processes might be shared between STM and ATM, STM is not considered to be a scale model of today's ATM, but rather an independent add-on.

Regarding STM, FPS is related to the generation of space flight plans for p2p connections and their corresponding scheduling. FPS is subject to dynamic traffic flows in aerospace, to risk assessments made by external entities (such as ESSTraC and the SWMC), to flight corridor handling, contingency and backup planning operations. For STM and ATM to safely integrate SSVs and spaceplanes, the risks posed by those vehicles to aviation business should be in line with today's ATM risks. In other words, for commercial space travel to evolve the risk to people sharing airspace should not change, irrespective of which type of vessel is considered (see Paper II for further details). Similarly, the risks to people traveling through suborbital or LEO space aboard the vessel (e.g., resulting from Space Weather or collisions with spacecraft and debris) as well as the risk to people on ground (e.g., resulting from crashing vehicles, falling debris or re-entering objects) shall be acceptable (for initial numbers see Paper II).

In order to estimate those risks, accurate global tracking of objects entering LEO and suborbital space, such as re-entering SSVs, satellites or space debris, down to a still to be defined minimum object size and 24/7 monitoring of Space Weather events is mandatory. Based on these measurements collision risks can be quantified and decisions can be made on the best and safest trajectory that causes the least disturbance to air traffic.

Because the entry/re-entry points to/from suborbital space are not always exactly known in advance (e.g., contingencies aboard the SSV or Space Weather hazards could require unplanned manoeuvres), the spaceplane's deviation from the planned trajectory needs to be closely monitored and adjusted in case those deviations become too large to allow for a safe integration of the space vessel into the current air traffic flow. The trajectory tracking and corrective manoeuvre calculations could be performed by data processing service centres hosted at the sites that perform object tracking and Space Weather monitoring and prediction. In this context these entities would be ESSTraC and the SWMC (cf. Sects. 3.4 and 3.6.2, respectively).

Given the high frequency and complexity of FPS operations and the required timeliness of the data products, manual operations are not feasible. Therefore, we propose the development of a dedicated element, the Flight Planning and Scheduling Facility (FPSF), which automatically performs all necessary steps, from generating initial flight plans to flight scheduling with respect to risk and trajectory computations provided by ESSTraC, Space Weather warnings disseminated by the SWMC and existing air traffic flows taken from the Air Traffic Control (ATC) flight database. The envisioned high-level technical layout is provided in Figure 16.

In this concept, the FPSF is part of the STM domain and has one internal interface with Space Traffic Control (STC), a subdomain of STM, and external interfaces with ESSTraC, SWMC and Air Traffic Control (ATC) which is a subdomain of the ATM domain. The FPSF comprises two main elements, the Planning Facility and the Scheduling Facility. The Planning Facility generates a first rough Master Flight Plan (MFP) for all aircraft and spacecraft movements through aerospace planned for a given date by sorting all flight plans submitted to the ATC and STC Flight Databases according to departure time. The MFP is then processed by the FPSF's Scheduling Facility which issues requests to ESSTraC to start calculating safe (collision-free) spacecraft trajectories for the individual flight plans stored in the MFP, to determine appropriately sized flight corridors for the space vehicles and to the SWMC to generate Space Weather predictions for the given space flights.

For each issued request, ESSTraC would perform trajectory calculations from departure Spaceport A to destination Spaceport B by considering the individual performance profile of the spaceplane, assuming a set of different orbit parameters (e.g., by varying inclination or departure time), checking the number of objects (e.g., debris or aircraft) within a certain miss-distance from the spaceplane and ranking the results according to safety requirements (e.g., according to largest miss-distance or time span of collision-free space). Each of these ranked solutions would contain a validity keyword that informs about the

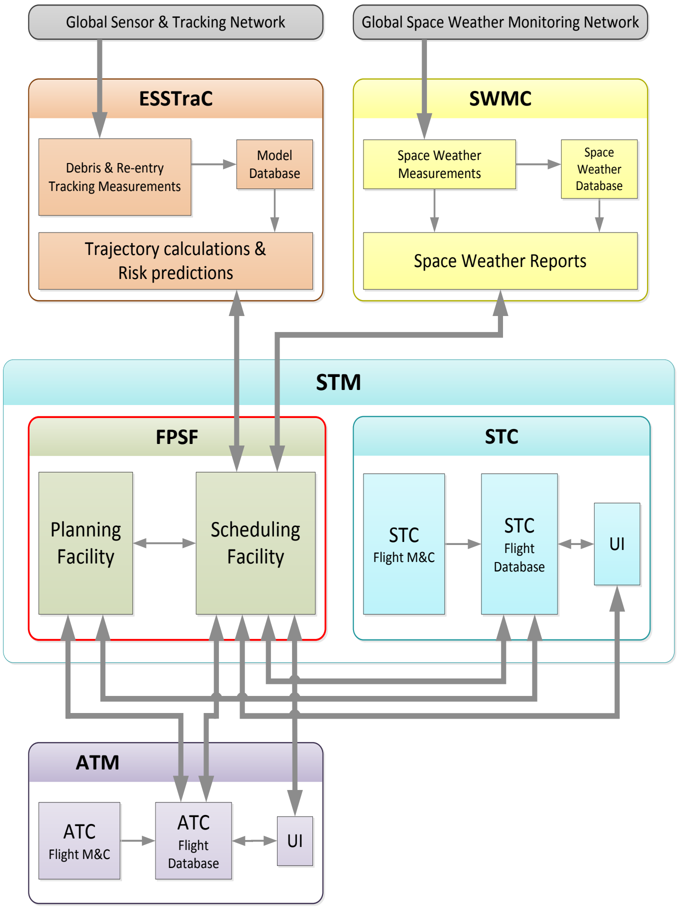


Figure 16: Layout of the Flight Planning and Scheduling Facility with its internal and external interfaces.

time slot during which the minimum miss-distance is exceeded and the calculated trajectory and departure time can be safely used (cf. Sect. 3.4.1). Based on the top-ranked trajectories for a given flight plan and the expected air traffic flow at departure and re-entry, ESSTraC will also assign an appropriately-sized flight corridor to the space vehicle, i.e. a safety buffer of blocked airspace, whose extent is dependent on manoeuvrability, climb rate and turn radius of the vessel.

Similarly, the SWMC would predict Space Weather conditions and hazardous events and issue a corresponding report to the Scheduling Facility covering the anticipated flight period plus some minutes before and after the expected departure and arrival time to compensate for potential launch delays resulting from collision risk assessments.

The Scheduling Facility now takes all data received from ESSTraC and the SWMC for a particular flight plan and determines the optimal flight path through air and space, i.e. the safest trajectory and departure time. This procedure is repeated for each entry in the MFP and the scheduling can be performed according to destination spaceport and departure time. The final MFP is then handed back to the Planning Facility which copies it to the ATC and STC Flight Databases. In case of flight delays exceeding a to be defined threshold, the Planning Facility would identify the affected flights and issue a request to the Scheduling Facility which would trigger ESSTraC to re-evaluate the flight trajectories and perform adequate adjustments in case they are needed. Finally, the updated MFP would be transferred back to the Planning Facility and to the ATC and STC flight databases, respectively.

Although the Scheduling Facility would perform continuous and fully automated updates of flight plans, trajectories, flight corridors, backup and contingency data on a 24/7 basis (requiring synchronised data transfers to/from ESSTraC and the SWMC), a User Interface (UI) is essential. The UI is needed to interact with the whole process chain, e.g., to manually insert new flight plans or to trigger on-demand trajectory calculations or optimisations).

In case of unforeseen events, such like breakup events of re-entering objects in the atmosphere (to be tracked by the Global Sensor and Tracking Network) or Space Weather hazards (to be detected by the Space Weather Monitoring Network), an alert will have to be issued by ESSTraC or the SWMC that informs the ATCO/STCO on duty and automatically triggers the re-calculation of needed flight data. This ensures that always the highest safety level for passengers aboard aircraft and spacecraft as well as for people on the ground is ensured. Once safety-compliant flight plans have been generated, they could be made accessible to ATCOs, STCOs and other personnel with a need to know, e.g., via the System-Wide Information Management (SWIM) system (see e.g., Drescher et al. 2016) developed for the SES initiative.

3.7.2.2. Air Traffic Control Operations

One important aspect in the interface between STCOs and ATCOs is the coordination and transfer of control, which should be similar to today's transfer of control of flights between adjacent area control centres. The coordination process to transfer a flight from one centre to another is quite complex and needs to satisfy a certain set of agreed rules. Coordination has to start at a predetermined amount of time before a flight reaches a boundary. This time is usually agreed by the states involved. Coordination for the transfer of control involves information about the flight identity, the point on the boundary at which the flight is expected to fly, the estimated time, the flight level and the Secondary Surveillance Radar code. The actual flight plan of the spacecraft would be also transferred automatically between STCOs, ATCOs and pilots.

In the past, the transfer of control of a flight between adjacent control centres was mainly performed directly between controllers connected through designated telephone systems. This method significantly increases the workload of the controllers, is relatively slow and error-prone. In the early 1990's, Eurocontrol developed a standard to support the exchange of flight plan data and messages in electronic format. This standard is known as On-Line Data Interchange (OLDI). It ensures that the messages exchanged between adjacent centres are always valid and up-to-date. In total, 40 OLDI messages have been developed of which today only a few are actually used for ATC operations. Of course, transfer of communication needs also to be established as part of the transfer of control procedure. The timing where transfer of control is executed could be at the point where the flight path crosses the boundary of FL650 or with reference to an agreed coordination point.

Similar to ATM, impacts from Space Weather, collision avoidance measures, weather conditions or traffic situations at the destination spaceport, can determine the actual start time of a spaceplane and therefore directly influence its flight plan. ATM distinguishes between the Estimated Off-Block Time (EOBT - which is the estimated time at which the aircraft will commence movement associated with departure), the Scheduled Off-Block Time (SOBT - which is the time that an aircraft is scheduled to depart from its parking position), and the Actual Off-Block Time (AOBT - which is the time the aircraft pushes back and vacates the parking position). If a spaceplane misses the SOBT a new time slot needs to be assigned and communicated to the pilot. In case of delays that are not covered by the safety margins stored in the validity keyword provided by ESSTraC (meaning that some space debris along the planned flight path comes too close to the spacecraft as a consequence of the delay on ground), new and probably manually triggered trajectories would need to be calculated by ESSTraC and transferred to ATCOs, STCOs and to the pilot of the spacecraft.

As part of the evolution of the European ATM, the work of ATCOs shall also be significantly facilitated. However, inserting spaceplanes into the aviation sector will likely result in additional tasks and responsibilities which, however, should not increase the overall workload beyond reasonable limits. Besides the tasks covered by ATCOs today and in the context of SES, the following supplemental STM-related activities are anticipated:

- Communication with interfaces (e.g., ATCOs, STCOs, SWMC, ESSTraC, pilots or spaceports)
- Provision of Go/No Go decisions for departure to STCOs (double-check)
- Performance of routine M&C operations for spaceplanes as well as contingency operations below FL650, including flight corridor adjustments in case of high air traffic loads
- Performance of pre-departure checks on system, flight and spacecraft status (double-check independent from STCOs)
- Performance of Special Operations (e.g., provision of data on request for incident investigations, assistance in conflict de-escalation in case of incidents aboard the spacecraft)
- Performance of handover and handback operations with STCOs once spacecraft reaches FL650
- Checking the accuracy of the (re-)entry point and trajectory of a spaceplane and issuing corrective manoeuvres or executing backup and contingency plans if indicated
- Provision of ad hoc SWBs to space pilots in case Space Weather conditions change and endanger passengers and crew aboard the vessel
- Performance of checks to see if all products from FPS, such as flight plans, trajectories, flight corridors and their corresponding backups and contingency plans, have been uploaded and validated by flight crew.

Except for the last four bullets, the envisaged ATCO operations are not much different from today's.

3.7.2.3. Spaceplane Operations

Although tasks and responsibilities envisaged for pilots operating space vehicles would share some similarities with those performed by pilots in the aviation business, there are some distinctly different activities. The following tasks and responsibilities are anticipated:

- Perform pre-departure system checks and start-up procedures (including upload and validation of flight data received from ATCO)
- Perform routine spaceplane operations in airspace up to FL650
- Communication with ATCOs, STCOs, ATC, STC and spaceport (e.g., on trajectory adjustments, runway, taxiing, parking position, etc.)
- Provide Go/No Go decisions for departure to ATCO and STCO (double-check)
- Communication with passengers and crew (in routine and contingency situations)
- Perform contingency operations, such as take-off and landing aborts, evasive manoeuvres or execution of contingency flight plans (e.g., in case of technical failures or collisions with space debris), either independently or if instructed by ATCOs and STCOs
- Perform handover and handback operations with ATCOs once spacecraft reaches FL650
- Perform routine spaceplane operations in space above FL650
- Perform trajectory checks and corrective manoeuvres if authorised/instructed by ATCOs or STCOs
- React on ad hoc collision warnings and/or Space Weather alerts received from ATCOs and STCOs and follow their instructions on risk mitigation
- Perform post-arrival operations, such as system checks, spaceplane handover to other crews or system shutdown
- Perform Special Operations (e.g., provide data on request for incident investigations, actively pursue conflict de-escalation in case of incidents aboard the spacecraft).

3.7.2.4. Ground Operations at Airports and Spaceports

Ground operations at airports and spaceports are expected to be very similar, so that this area would require the least development effort among the interfaces discussed in this section. The following activities and tasks are expected:

- Perform 24/7 ground infrastructure maintenance (terminals, launch pads, CNS equipment, etc.)
- Perform spaceplane maintenance (on request)
- Communicate with ATCOs, spaceport authorities, pilots (e.g., on scheduled maintenance work, goods supply for spaceplane, safety and security issues, etc.)
- Perform safety and security operations (e.g., regular safety checks of relevant infrastructure, RPAS mitigation, passenger screenings, etc.)
- Provide and maintain terminal and passenger information services
- Provide and maintain the Air Traffic Information System (ATIS) and Space Traffic Information System (STIS) services
- Perform Special Operations (e.g., provide data on request for incident investigations).

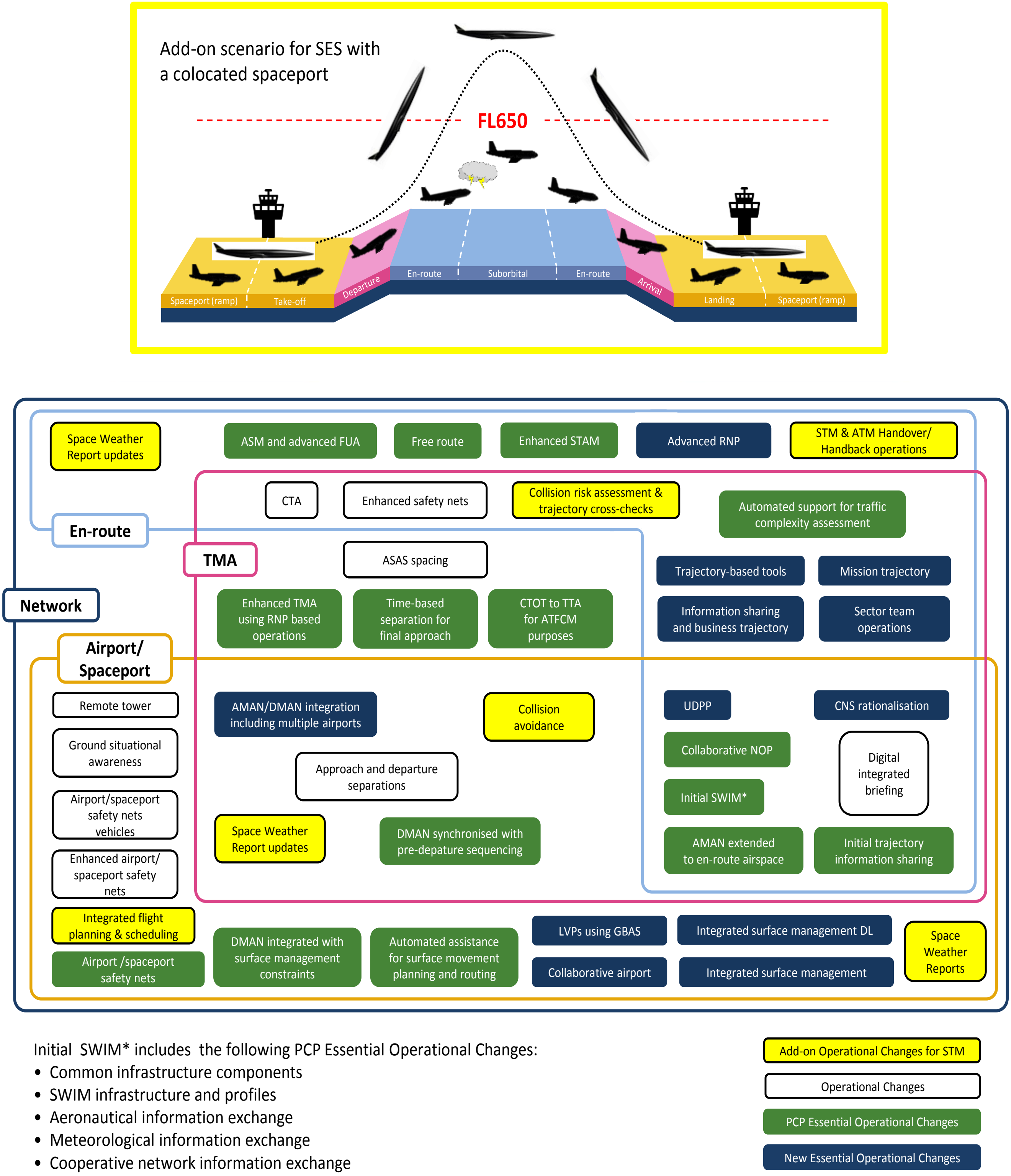
All tasks and activities described for the aforementioned interfaces are fully covered by the ROS presented in Figure 1.

3.7.3. Suggested STM Add-ons to the SES Concept

In order to visualise Europe's main deficiencies in the STM and SES context, Figure 17 was taken from the ATM Master Plan (2015, cf. Figure 8) and has been adapted to also include the supplemental add-on components and services suggested for STM purposes (see boxes highlighted in yellow).

The following add-ons to the SES Master Plan are proposed:

1) Space Weather services and products need to be added
2) Collision risk assessments and trajectory calculations are needed
3) Integrated (ATM & STM) Flight Planning and Scheduling is needed
4) Handover and handback operations between ATCOs & STCOs are needed.



Initial SWIM* includes the following PCP Essential Operational Changes:

- Common infrastructure components
- SWIM infrastructure and profiles
- Aeronautical information exchange
- Meteorological information exchange
- Cooperative network information exchange
- Flight information exchange.

Figure 17: Supplemental STM add-ons (shown in yellow) required for integrating STM with the evolving ATM system as envisaged in the SES context (this Figure was originally taken from the ATM Master Plan (2015) and modified accordingly).

Add-ons 1) and 2) require the establishment of ESSTraC and the proposed SWMC together with appropriate operations concepts and globally operating sensor networks while add-ons 3) and 4) imply a close collaboration between the ATM sector and future STM key players to develop and implement the FPSF and suitable operations procedures.

3.7.4. Flight Corridor Handling for Spaceplanes

In ATM vertical and horizontal separation standards are defined in order to facilitate safe navigation of aircraft in controlled airspace. With the help of these separation standards the ATCO ensures that the distance between aircraft in all three dimensions

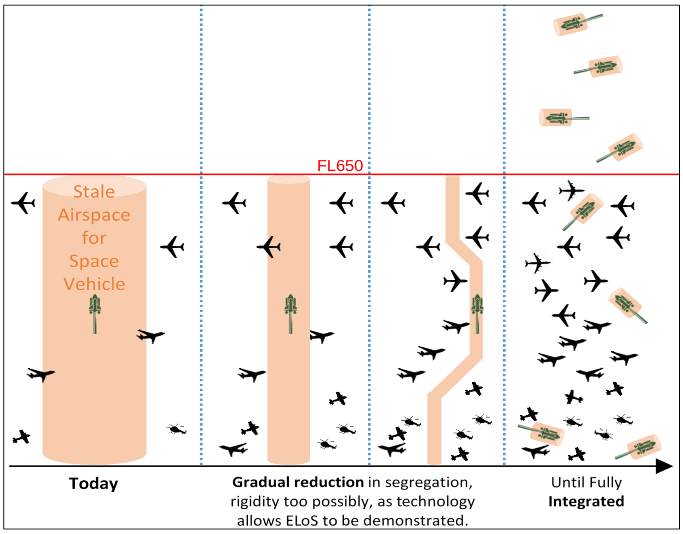


Figure 18: Evolution of Flight Corridor Handling.

does not fall below certain minima. In general, minimum separation varies with the different phases of the flight, depending on the available navigation and control systems. The basic radar separation, for example, is five nautical miles whereas national separation standards are based on the provisions given in ICAO Document 4444. In recent years, it was possible to reduce the vertical separation due to improved methods of measuring heights. For integrating SSVs and spaceplanes into civil airspace adequate separation concepts have to be defined. As shown in Figure 18, there are basically four types of separation concepts that can be applied to maintain a safe distance between conventional aircraft and ascending or re-entering spacecraft.

The first concept is applied today and involves a broad-scale airspace closure around the space vehicle. It can be compared with air corridors in ATM that are mainly used for military purposes in order to ensure safe operations in civil airspace. Air corridors that are limited in space and time are not controlled by ATCOs, they just take care that no aircraft is entering the blocked airspace. This concept is clearly the most capacity-constraining one and therefore requires major adjustments in the future when commercial p2p space travel commences.

The second concept builds up on the first approach by considering the space vehicle's vertical and lateral navigation performance during ascent and re-entry and can thereby reduce the lateral containment area based on the individual navigation performance. This could lead to considerable capacity increase depending on the predictability level of spacecraft operations in atmospheric flight phases. This is currently the critical element which prevents further progress in this area, since space vehicles are not certified or even tested to fulfil certain navigation criteria comparable to civil aviation standards (e.g. RNP values).

The third concept would be an even tighter containment area based on the in-flight navigation performance of the spacecraft which is currently uncharted territory as no relevant standards for spacecraft exit yet.

Finally, the fourth concept defines a three-dimensional co-moving space around the space vehicle as a non-penetration zone, similar to today's separation concept between conventional aircraft in controlled airspace. This concept, however, represents the case where space vessels are fully integrated into the routine air traffic flow and requires the highest level of accuracy regarding position and time. Today, this concept is far from being realized for spacecraft operations. Especially when a spacecraft scatters debris during its ascent or re-entry phase, the three-dimensional probability distribution for the spaceplane's position becomes increasingly complex and clearly reduces the chance for small containment spaces similar to those applied by current civil aviation navigation standards (see RNP concept reference ICAO 2008).

However, even fully functional spacecraft would require a navigation specification (technical and operational specifications that identify the navigation performance) which is compatible to aviation standards in order to apply concepts of route and radar separation and airspace design principles which reflect navigation accuracy and cross-track deviation probabilities. So generally speaking, the more airplane-like the in-flight performance of a spaceplane, the easier its integration into the air traffic flow.

As mentioned in Sect. 3.1, there are currently three different kinds of SSV/spaceplane concepts: HOTOLs (e.g., *Skylon* or the *Spaceplane*), VTOLs (e.g., *New Shepard*) and Hybrids (e.g., *SpaceLiner* or air launch systems like *WhiteKnight2* + *SpaceShip2*). Because the in-air performance of these vessels (like degree of steerability, climb rate, minimum turn radius), remains currently unknown, it is not possible to determine appropriate segregation requirements for these vessels to be safely integrated into routine air traffic flows. To the very least, some constraints on the handling of possible flight corridors can be given for those vehicles.

3.7.4.1. Flight Corridor Handling for HOTOLs

For HOTOLs an airplane-like in air performance with full manoeuvrability is assumed. In this regard *Skylon* would be certified according to airplane requirements (e.g., EASA CS 25) which would result in a definition of minimum separation requirements similar to aviation standards. Therefore, it is considered relatively straight forward to integrate these vessels into the day-to-day air traffic flow which would have the big commercial advantage that no air space needs to be closed and the impact on flight schedules would be minimal.

3.7.4.2. Flight Corridor Handling for VTOLs

It is assumed that this type of vessel has very limited manoeuvring capabilities (e.g., cannot perform evasive manoeuvres, one-directional flight path, no lateral steerability). Because of these constraints, the vehicle is unlikely to become certified according to aviation standards. In this case it has to be shown that risks during take-off and during ascent/descent up/down to FL650 is compliant to aviation standards. In addition, it has to be demonstrated that the launch failure probability meets aviation requirements.

The limited steerability is expected to make it hard to integrate VTOLs into the air traffic flow. To mitigate the risks, separation standards need to be based on the navigation performance and reliability of the vessel and closure of airspace might be required. Regarding risks and air space closure, VTOL concepts could benefit from sound experience with the Space Shuttle. Contrary to HOTOLs significant impacts on flight schedules and substantial costs due to airspace closure are expected.

3.7.4.3. Flight Corridor Handling for Hybrids

For hybrids it is assumed that the space vessel has some manoeuvring capabilities (e.g., can perform simple evasive manoeuvres in airspace) and glides down during descent (e.g., like the Space Shuttle). In case a carrier aircraft is used, this aircraft is expected to comply with aviation standards. Should the space vehicle also be certified according to aviation standards, the whole concept could be treated like a HOTOL, i.e. no air space blocking would be required resulting in minimum impacts on the flight schedule.

Should, however, the space vehicle not be certified according to aviation standards, it needs to be proven that the risks during take-off and ascent/descent up/down to FL650 is compliant to aviation standards and that the launch failure probability is also consistent with aviation requirements.

Integrating the vessel into the air traffic flow should be feasible. For risk mitigation purposes, separation standards for hybrids should be based on in-air performance and reliability of the landing vessel. Closure of airspace might be required. Timing and size of the airspace to be blocked should be determined by the performance and reliability of the landing vessel (ground track of the vessel should be avoided). Regarding risks and air space closure, hybrid concepts could benefit from sound experience with the Space Shuttle. Moderate impacts on flight schedules and acceptable costs due to airspace closure are expected.

Space objects, like re-entering spaceplanes or Space Debris, can pose a significant risk to airspace users and people and infrastructure on ground. These risks are discussed in Paper II (Tüllmann et al. 2017b) where the need to quantify these risks has been identified and initial values for an acceptable level of safety are proposed. It is expected that ATM and the aviation industry contribute to further studies, with the final objective to be able to make informed decisions regarding traffic re-routing or size and duration of airspace closure (if closure is in fact needed) for each predicted re-entry event, depending on object size, location and air traffic density.

3.8. Key Players and Stakeholders in STM

The increasing number of worldwide private space launches together with the flood of expected CubeSat deployments and Mega-Constellations planned by OneWeb, SpaceX or Boeing will almost certainly result in a heavy competition for limited orbit space. This in turn may provoke spacecraft accidents which are likely to cause conflicts and bring up legal issues among those parties who own the spacecraft.

Without doubt, space and airspace will move closer together in the next decades, which is why an international and globally recognised authority is needed that has the power to enact binding regulations and coordinates and stabilises access to space for civil institutions and commercial companies to mitigate conflicts and to prevent accidents which may even put human lives at stake. This international authority should also act under the auspices of the United Nations, here the UNOOSA. In this regard a well established candidate already working on STM is ICAO. Besides its current duties, ICAO could also have to take on all relevant tasks and responsibilities dedicated to civil and commercial Space Traffic Management.

In the European context, there are at least three main authorities that should be considered, i.e. Eurocontrol (performing safe ATM operations), the European Aviation Safety Agency (EASA, performing regulatory and executive tasks in the field of civilian aviation safety and environmental regulations) and ESA (which could act as prime advisory agency for EASA on technical STM-related matters). ESA could have direct technical and managerial interfaces with STM as well as with spaceports and external STM service providers, such as ESSTraC and the SWMC.

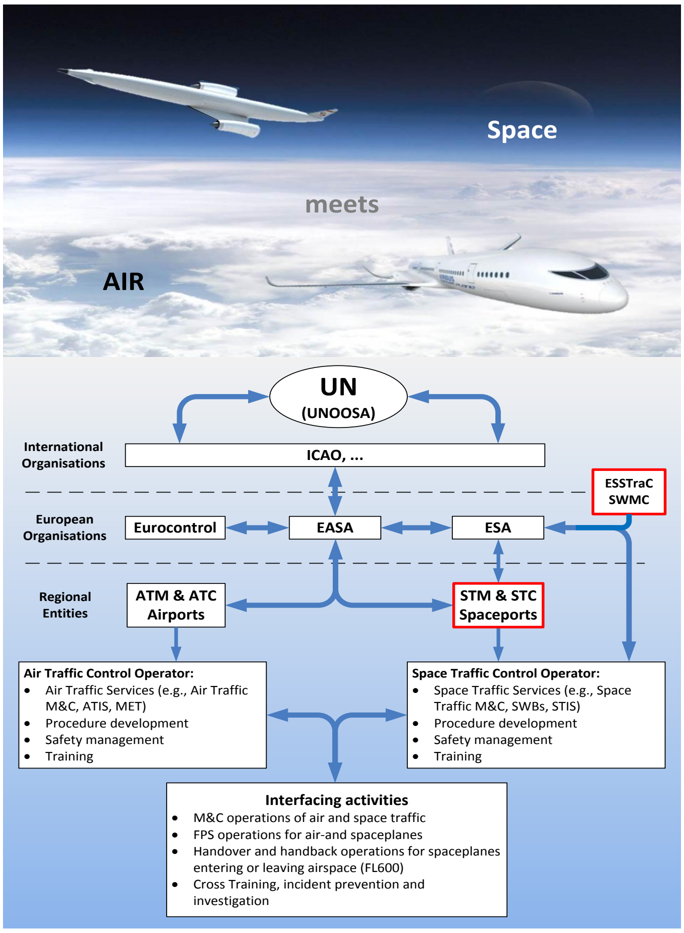


Figure 19: A possible interplay between global, European and regional STM key players in the area of Air & Space Traffic Management. Entities marked in red do not yet exist and need to be established. In this vision, ESA acts as the prime advisory agency for the EASA on all space traffic-related matters.

Space vehicles landing and starting in/from European territory will need to be included into existing European ATM systems, while spacecraft entering or leaving suborbital or LEO space need to be routinely monitored and managed by dedicated STM systems operated by Europe and international partners. Both kinds of ATM and STM control mechanisms may need regional solutions, e.g., over oceanic and polar regions or in the grey zone where Space Traffic volumes do not overlap. However, 24/7 operations at a global level are necessary as frequent handover and handback operations for spaceplanes passing through aerospace are required. An organisational breakdown with possible key players in a European Air & Space Traffic Management system is shown in Figure 19. Global, European and regional entities for air traffic control are listed and potential counterparts from a high-level assessment of the Space Traffic domain are highlighted.

In the context of expected STM activities, ESA will have a unique opportunity to open up new fields of activities thanks to its technical know-how in space business and expertise in managing international space projects. Most importantly, ESA is considered to have a key role in interfacing with the space sector in the following areas:

- Development and implementation of the ESSTraC
- Defining ESSTraC evolution

- Acting as prime advisory agency for EASA or Eurocontrol on all space-related matters
- Defining CNS core technologies and requirements
- Interfacing with other space agencies, such as NASA (e.g., on negotiating agreements for Space Weather or SST data exchange)
- Performing technical M&C of the recently established European Space Surveillance Tracking Network (ESSTN) through ESSTraC
- Providing regular and accurate space environment data in the context of SSA through the SWMC.

The following roles and responsibilities are envisaged for ESA:

- Develop a roadmap for EASA/Eurocontrol to implement the technical STM aspects into the existing ATM system
- Advise EASA/Eurocontrol on Space Traffic-related issues (e.g., oversight of regional Space Traffic authorities, companies and industry)
- Supervise ESSTraC to provide regularly accurate tracking data, CRAs and SWBs
- Steer technology development and Space Traffic evolution in Europe
- Advise EASA/Eurocontrol on Space Safety Management and technical aspects regarding the certification of Space Navigation Service Providers (SNSPs)
- Define and perform testing of space products and equipment (e.g., CNS, avionics)
- Provision of requirements and advisory to EASA/Eurocontrol on licensing and certification of commercial launchers and spaceports
- Perform investigations of aerospace Traffic accidents
- Certification of Training Products.

3.9. The Roadmap for a European STM System

In this section the initial roadmap for the implementation of the proposed European STM system is provided, reflecting all concepts, constraints and key results that have been derived in previous sections. For simplicity reasons, the whole STM implementation process is assumed to start in January 2017 and would be finished from a technical point of view when routine p2p space travel (e.g., with a *Skylon*-like spaceplane) commences. In order to at least roughly constrain the year when commercial suborbital flights could start in Europe and the STM framework needs to be in place, the following three main areas of development should to be considered.

The first one is related to technology development and to building the spaceplane (see upper panel in Figure 20). In this regard, we already pointed out in Sect. 3.1 that the most promising European spaceplane candidate is *Skylon*. According to REL, this vessel is expected to enter the flight test phase by 2025 (BBC News 2015) and could be become operational by 2030 if we assume a 5-year time frame for testing and certification.

In order to support routine and safe *Skylon* operations, the second development area, infrastructure, needs to be ready (see middle panel in Figure 20). The infrastructure consists of spaceports, support buildings and communication networks. This would set a milestone prior to 2030, so possibly something in the range from 2028 to 2030 at the latest.

The third and final area is related to the development and validation of products and services (lower panel in Figure 20), such as a STM concept, a concept for 24/7 routine and contingency Space Traffic M&C operations or Space Weather and SST products. Clearly, these products have to be ready and validated before spaceport operations and p2p Space Traffic can commence. For this, a time frame between 2026 and 2028 is adopted. If we consider a verification and validation period of about 4 years, the initial products should be ready for testing by 2022. This year would then set the milestone against which has to be developed, built and tested, a target date that looks ambitious, but possible to reach if work would actually start without delay in 2017.

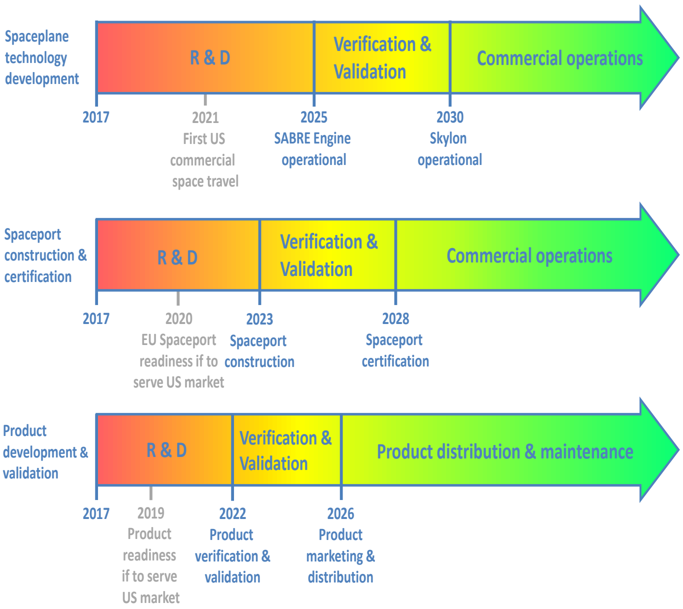


Figure 20: Milestones for a European Space Traffic market.

However, the whole scenario is more pressing if Europe were to serve additional demands of the U.S. commercial space travel market (see milestones highlighted in grey in Figure 20). Because the U.S. has a head start with respect to technology and infrastructure development, Space Travel is estimated to start in the U.S. around the 2020s, which would require European infrastructure and products to be ready by the same time, provided Europe intends to accommodate landings and take-offs of American space vessels on European soil.

Among the three areas of development outlined in Figure 10, the most critical one, without neither space flight operations nor spaceport operations are possible, is the timely development of products and services, such as the development of a STM system and its integration with the ATM. These tasks are not straight forward to implement, partly because the topic of Space Traffic is currently ignored in the Single European Sky initiative of the EU (e.g., the SESAR European ATM Master Plan in its 5th edition from 2015, does not even mention the word “Space Traffic” and “space” is mentioned only in terms of “airspace”) and partly because many interfaces are missing or need to be re-defined. In addition, reliability and safety requirements need to be defined and harmonised between the aviation and space flight sectors and a common European legislation needs to be found. Especially the latter is likely to become a very time-consuming process.

However, if we would include Air Traffic Evolution as envisaged in the ATM Master Plan and consider that upgrades of the ATM might also affect STM evolution, the whole ATM and STM implementation process could be delayed until 2035.

For reasons of clarity only a high-level version has been generated from the original roadmap which contains more than 120 tasks. This simplified version is presented in Figure 21 and focusses primarily on those aspects that have been discussed in this paper, namely Space Debris and SST (see orange bars

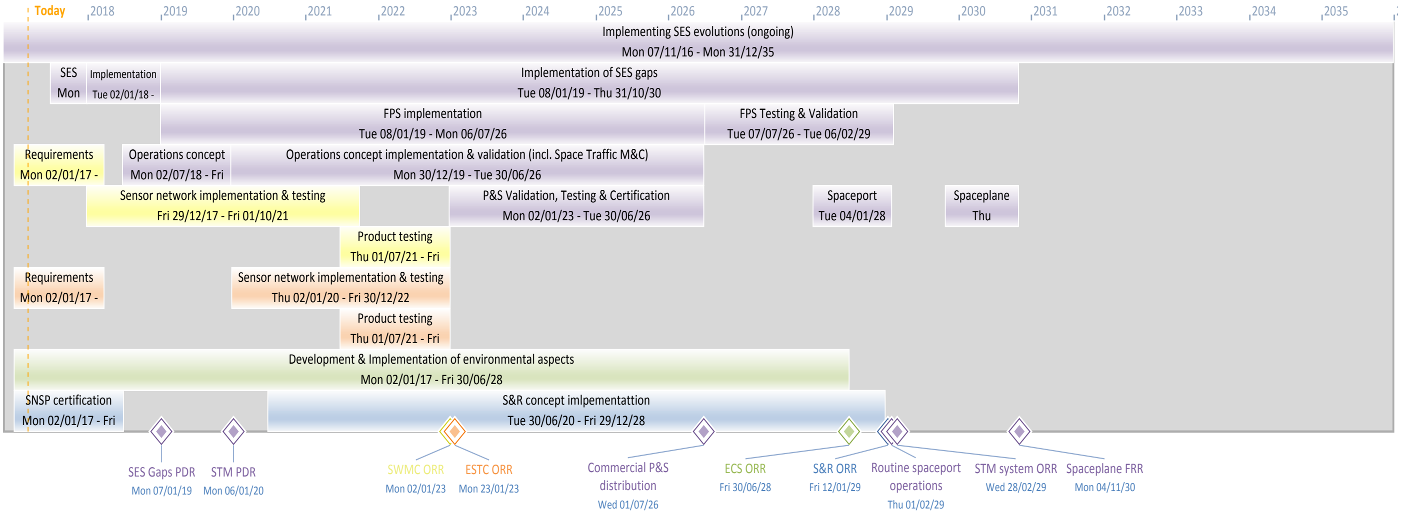


Figure 21: The high-level STM Roadmap. Environmental aspects including Clean Space (green bar) and Safety & Reliability (blue bars) are not discussed in this paper and are shown here for the sake of completeness.

and Sect. 3.4), Space Weather Monitoring (see yellow bars and Sect. 3.6), and ATM and STM integration (see purple bars and Sect. 3.7). The two entries coloured in green and blue are related to Clean Space & the Environment or to Safety & Reliability, respectively and are shown here for the sake of completeness. S&R topics are addressed in Paper II (Tüllmann et al. 2017b).

Prior to establishing a STM system in Europe, three fundamental challenges need to be overcome (political or legislative constraints are not covered in this study). These challenges are related to the development and implementation of appropriate:

1) Infrastructure and technology (e.g., spaceports, spaceplanes, data centres, FPS, Space Weather monitoring and SST systems, SWMC, ESSTraC and communication networks)
2) Operations concepts and procedures (e.g., for Space Weather monitoring, SST, FPS, regulatory, S&R and ATM & STM integration, including ATCO & STCO handover/handback operations and space traffic monitoring)
3) Products and Services (e.g., SWB, TEC maps, CRAs, trajectories, flight plans and schedules, Space Traffic Navigation Service Provider certifications and passenger services).

The areas of Space Weather, Space Debris & SST and ATM & STM integration will most likely have to deal with all three of the above mentioned aspects. The overarching task regarding ATM and STM integration is the filling of STM-related gaps identified in the SES initiative (see Figure 17) which requires to have finished the entire Space Debris & SST and Space Weather design and implementation subtask. Because the design, development and implementation of the SWMC and ESSTraC share several high-level commonalities (e.g., regarding comparable complexities of system and operations concepts or the existence of initial sensor networks and know-how), it is conceivable that both centres could become operational by 2023. In parallel the implementation of the FPS and the STM operations concepts is ongoing (to be finished by mid-2026) and after the STM system has been successfully validated, routine STM operations are expected for March 2029.

The implementation of technological solutions for ESA's Clean Space and environmental initiatives (expected to be implemented in parallel) will have an impact on the details of the STM development roadmap and, therefore, both plans should be integrated at a future date. The testing, validation and certification of products and services, spaceports and spaceplanes is subject to high uncertainties. However, given the estimated timeline for spaceplane development in Europe (cf. Figure 20), Flight Readiness Review could be in November 2030, which would constrain the dates for routine spaceport operations and product and service availability to the beginning of 2028 and mid of 2026, respectively.

Table 5: Top 10 STM-related issues listed in priority order

Priority	Issue	To be managed by
1	Define and implement binding regulations, procedures and legislation to ensure safe STM operations in Europe	EU/EC
2	UN to coordinate an international consensus on STM implementation (e.g., regarding safety requirements and standards for spaceplane operations in aerospace and STM operations)	UN
3	Define European STM safety requirements including human factors, flight, occupant and on-ground safety (with international interfaces)	EASA/Eurocontrol
4	Design and implementation of a European STM safety and operations concept that seamlessly integrates into the global context	ESA
5	Design and implementation of a European Surveillance and Tracking Centre (e.g., including sensor networks, operations, products and services)	ESA
6	Design and implementation of a Space Weather Monitoring Centre (e.g., including sensor networks, operations, products and services)	ESA
7	Design and implementation of a Flight Planning and Scheduling Facility (including international interfaces)	ESA
8	Design and implementation of an aerospace handling concept for spaceplanes and SSVs (focusing on HOTOL, VTOL and hybrid concepts)	EASA/FAA/Others
9	Design and development of needed Technologies and Infrastructure (e.g., for spaceports, spaceplanes, RPAS mitigation)	ESA
10	Design and implementation of Clean Space Concepts (e.g., related to noise reduction, environmental regulations, fuel efficiency, or space debris removal)	EU/EASA/ESA

4. Open Issues

Based on the analyses performed in this paper, we identified the most important and pressing issues regarding the implementation of a European STM system. In Table 5 the Top 10 STM-related issues are listed in priority order that have to be tackled, requiring a pan-European coordination approach.

5. Future Work

Due to their complexity, the following topics are beyond the scope of this study, but are highly recommended to be investigated in dedicated follow-up programmes:

- Design and implementation concept for ESSTraC regarding the following aspects:
    - Identify hazards for SSV and spaceplane operations, including requirements on heat and collision shielding and dependencies on ATM and spaceport operations
    - Detailed risk quantifications and trade-off studies for space debris and re-entering objects
    - Tracking concept for re-entering traceable and non-traceable objects
    - Operations Concept for ESSTraC
    - Infrastructure and product design (e.g., sensor network, near real-time trajectory calculations and dissemination, communication and data links, plus supporting reliability assessments)
- Design and implementation concept for the SWMC regarding the following aspects:
    - Detailed risk quantifications for space weather events preventing routine suborbital p2p space flights
    - Operations concept for the SWMC, supported by appropriate S&R assessments
    - Infrastructure and product design (e.g., sensor network, TEC maps, SWBs and dissemination schedule, communication and data links, plus supporting reliability assessments)
- Analysis on how a European STM system can be smoothly merged with the SES ATM concept, e.g., establish a common planning cycle for air and p2p space flight connections, including:
    - Short, mid, and long-term flight planning and scheduling (including backups and contingency products)
    - Contingency re-planning
    - Handover and handback operations
    - Realisation of Flight Corridor Handling without significantly affecting ATM operations and safety, including supporting validation by S&R
- Establishment of a European work group, working on a concept for the implementation of a global ATM/STM network, including:
    - Harmonisation of STM and ATM concepts (SES, NextGen, etc.)
    - Legal aspects (define binding regulations)
    - Interface definition
    - Roadmap generation and implementation monitoring
- Various areas applicable to S&R to enable a safe, reliable and efficient development of the STM concept, including:
    - Quantification and substantiation of the top level S&R requirements for both the SSV occupants and third parties, as well as decomposition into the different contributors and the lower severity classes.
    - S&R supporting validation and verification of technology & systems to be implemented, including initiatives designed to help, e.g. ESA's Clean Space.
    - The selection of an existing electronic tool or, the development of a dedicated one, to facilitate the reporting, collection and storage of in-service occurrences.
    - Development of a detailed certification processes for SNSPs, spaceports and other actors in the STM industry.

6. Summary

Together with its partner institutes and companies, DLR GfR has conducted on behalf of ESA an evaluation study with the objective to generate a roadmap for the implementation of a European Space Traffic Management system under consideration of the evolving Air Traffic Management system. In this context, one of the most important commercial drivers for Space Traffic is considered Space Travel, focussing on manned ballistic suborbital flights for space adventurers and suborbital point-to-point passenger (and cargo) transportation. Therefore, the term "Space Traffic Management" is defined in the context of this study as the: *"Execution of all necessary Managing and M&C operations to ensure safe ballistic travel of manned and unmanned spaceplanes through suborbital space and airspace under consideration of the existing European Air Traffic Management System and Infrastructure"*.

The most important findings and recommendations of this work can be summarised as follows:

1) In order to evaluate whether the risk of a spaceplane colliding during its suborbital flight with a piece of space debris (or other space objects) do not actually rule out suborbital p2p flights from the very beginning, we considered a hypothetical flight from Sydney (Australia) to Oberpfaffenhofen (Germany) and calculated the minimum miss distance from the space vehicle's adopted ballistic trajectory to all traceable objects in the NORAD TLE catalogue. Based on certain assumptions (cf. Sect. 3.4.1), we provided proof of concept that p2p travel through suborbital and LEO space is generally feasible as there seem to be sufficiently long time slots between the two closest encounters which would ensure safe passage of the vessel. However, dedicated follow-up studies are needed, focussing on launch window optimisations (e.g., by considering more realistic trajectories for HOTOLs, VTOLs and hybrid spaceplanes and time periods longer than 12 hours), different flight destinations and smaller traceable object sizes.
2) We identified a clear gap between current spacecraft shielding capabilities of about 1 mm and the minimum traceable object size of about 3 cm in future catalogues of traceable objects. The statistical risk for a catastrophic event posed by this gap was determined to be of the order of 1×10^{-3} per flight, assuming an SSV with a cross section of $100\,\mathrm{m}^2$ and that the risk of colliding with an object is 1 out of 100 potentially catastrophic scenarios. This risk appears already relatively high for the small-sized SSVs that shall be deployed for vertical ballistic flights, but would even increase beyond an acceptable level of $\sim 8 \times 10^{-3}$ per flight, if cross sections for *Skylon*-like spaceplanes of about $700\,\mathrm{m}^{-2}$ are considered. Therefore, this gap could turn out to be a real show stopper, provided it cannot be reduced by applying new heat and collision shielding technologies which withstand impacts from objects larger than 1 mm. Here it is most important to close the gap in the lower size range, as the smallest objects pose the highest risk.
3) Regarding STM, Europe is not well prepared to serve the developing Space Travel market in the near future, because fundamental operations concepts, products and services and infrastructure needed for safe spaceplane operations in aerospace is missing.
4) Therefore, a reference operations scenario (ROS) was defined, reflecting typical day-to-day operations for suborbital space flights, against which the European STM concept should be developed (Figure 1). We recommend that future

technical and conceptual work focusses primarily on the implementation of ESSTraC and the SWMC (and their respective monitoring networks), the FPSF, ATM & STM integration (e.g., regarding flight corridor handling) and the identified products and services (e.g., SWBs, TEC maps, CRAs, on-demand trajectory computations, FPS services).

5) Finally, the initial roadmap for implementing a European STM system has been presented (see Figure 21 for a simplified version) together with the Top 10 STM issues that need to be tackled on a European and UN level (see Table 5).

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