TOWARDS A EUROPEAN SPACE TRAFFIC MANAGEMENT SYSTEM

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ABSTRACT

We summarize the main results from an evaluation study which we conducted on behalf of ESA with the aim to identify key pillars for a European Space Traffic Management (STM) system. Our primary focus is on suborbital space transportation, specifically on point-to-point (p2p) connections for human space travel/cargo transportation (including vertical ballistic joyrides), on satellite deployment via air launch systems and on the safe integration of spacecraft with an evolving Air Traffic Management (ATM) system.

A Reference Operations Scenario (ROS) is discussed against which the potential European STM system is designed, playing a fundamental role in the ATM and STM integration process. Initial results from simulations of a hypothetical suborbital p2p flight are presented. They indicate that those flights are generally feasible regarding collision risks with *traceable* space debris/objects. Considering, however, *non-traceable* space debris/objects, a clear gap between the minimum size of detectable objects and the maximum size of objects against which spacecraft can be shielded becomes obvious. If not properly mitigated, the risk caused by this gap could become a show stopper for commercial suborbital space flights. Finally, the Top 10 list of issues is presented that need to be tackled before a European STM system is ready for implementation.

1. INTRODUCTION

There seems to be general consensus that a commercial multi-billion-Euro Space Traffic market is going to develop globally in the next two decades. This market will likely have suborbital point-to-point (p2p) space travel, suborbital cargo transportation and satellite deployment via air launches as primary use cases. Provided suborbital space traffic increases as predicted by several market evaluation studies conducted by the European Commission, NASA, the FAA or the private sector, a safe, efficient and globally (co)operating Space Traffic Management (STM) system is mandatory. Such a system should be designed according to the highest applicable safety & reliability (S&R) standards, e.g., in analogy to those defined for Air Traffic Management (ATM). In this regard, STM shall be responsible for the execution of all necessary managing and monitoring & control operations to ensure safe ballistic travel of manned and unmanned suborbital spacecraft through Near-Earth space and airspace under consideration of an evolving ATM system and infrastructure.

This STM definition is deliberately different from that given by [4] in order to cope with the new suborbital and commercial activities which could, like satellite deployment, Space Weather or Space Debris before, evolve into stand-alone branches of greater STM operations. One key aspect to warrant safe STM operations is the seamless integration of space vessels into the global ATM system. From a European perspective, the required legislation, regulations, concepts and requirements as well as the necessary infrastructure (like spaceports, spaceplanes or control centers) is either missing or not ready to serve the developing STM market in the near future. Therefore, DLR GfR mbH and its partners conducted on behalf of ESA a roadmap study on how to implement a European STM system by 2035 and how to integrate it with the existing ATM system (see [1], [2], [3] for all details).

Our study connects technical, conceptual and organisational aspects related to Space Traffic Control (STC), Space Debris, Space Weather, Clean Space and Safety & Reliability and added a variety of new aspects to the European STM landscape. In this paper, however, we focus on presenting the underlying Reference Operations Scenario (ROS), outlining a possible ATM and STM integration approach and performing an initial feasibility assessment on whether the risk of a space vessel colliding with space debris could actually prevent suborbital p2p travel by comparing it with the risk figure adopted for spaceplane occupants. The paper is concluded by identifying the Top 10 list of STM issues that need to be solved prior to implementing a STM system in Europe.

2. A REFERENCE OPERATIONS SCENARIO

The European STM concept has been developed against a ROS (presented in Fig. 1) comprising 24/7h operations of typical routine and contingency scenarios. Currently, the ROS considers suborbital p2p travel from

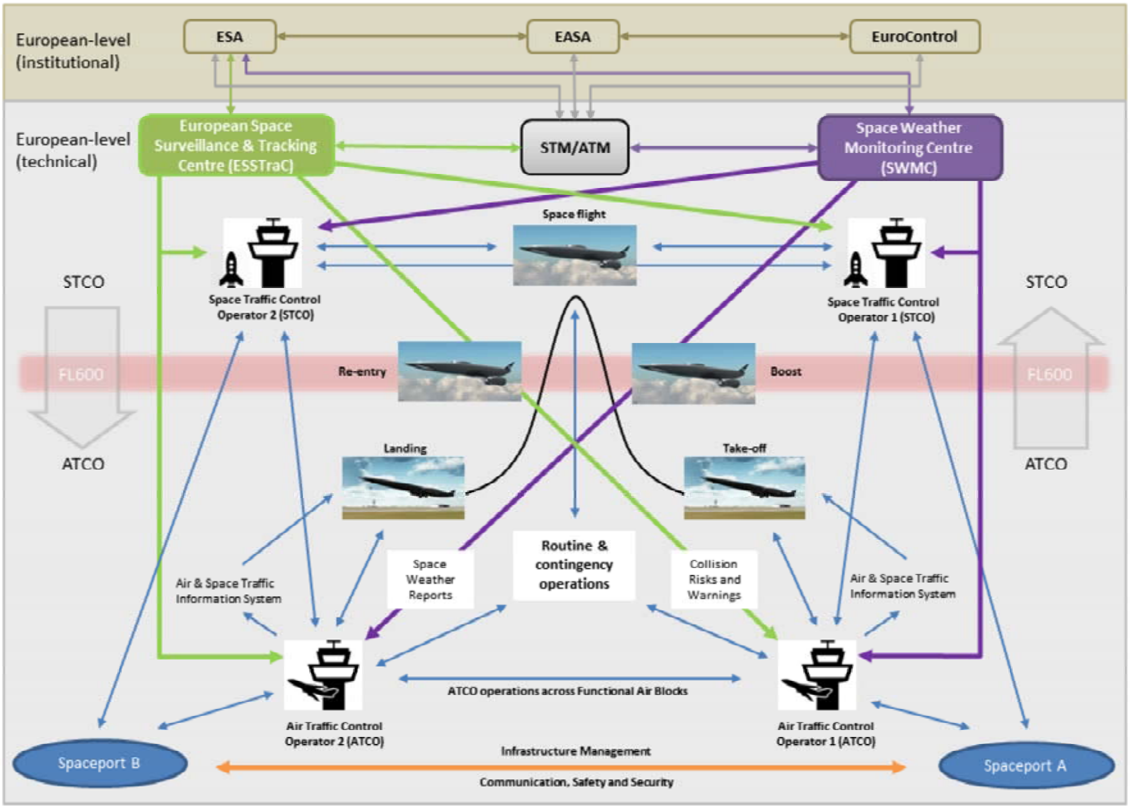

Figure 1: Reference Operations Scenario

Spaceport A to Spaceport B with return to Spaceport A and possible contingency landings at backup sites. The spaceplanes are envisaged to move on ballistic trajectories at maximum altitudes between 100 km and 500 km with the time spent near apogee being much less than 1 hour.

At Spaceport A the spaceplane is cleared for take-off and guided through airspace by the local Air Traffic Control Operator (ATCO). Shortly before the spaceplane leaves controlled airspace (FL600), handover operations are required between the ATCO and the responsible Space Traffic Control Operator (STCO), the latter being in charge of leading the space vessel safely through suborbital space. Before entering controlled airspace, there is a handback between the STCO and the ATCO who will now guide the vessel to its destination (Spaceport B).

Note, however, that internal handover operations between Air Traffic Service providers are needed in case the vessel leaves the respective control area. The same might be required for Space Traffic Service providers.

In case of contingencies which require to return to the departure spaceport or to land at an alternative site, e.g., if Space Weather conditions pose unacceptable risks to crew and passengers aboard the vessel or if the spacecraft got hit by a piece of non-traceable Space Debris (see Sect. 3.2), adequate emergency procedures need to be coordinated among ATCOs, STCOs and flight crew.

It is therefore imperative to warrant the availability of certain service products prior to launch and throughout the flight. Such products include, e.g., Space Weather reports and alerts, Collision Risk Analyses (CRAs), flight trajectories and updates as well as backup trajectories for predefined contingency cases. The service data need to be directly accessible by the controllers and the pilots aboard the air/spacecraft. Ideally, those products are part of a harmonized STM and ATM system in which the service data are circulated via a system similar to the System Wide Information Management (SWIM, [5], [6]) system which is an integral part of the SESAR joint undertaking [7].

Two new STM entities should be mandated with the generation and dissemination of these products, namely the Space Weather Monitoring Center (SWMC) and the European Space Surveillance and Tracking Center (ESSTraC, see also Sects. 3.4 and 3.6 in [1]).

Unfortunately, the operations and activities outlined in the ROS are far from being realized in Europe any time soon. This is because fundamental legislation, critical infrastructure and adequate operations concepts are missing. A significant progress in this field is further hampered by the fact that the safety-critical aspect of integrating spacecraft into today's air traffic flow is

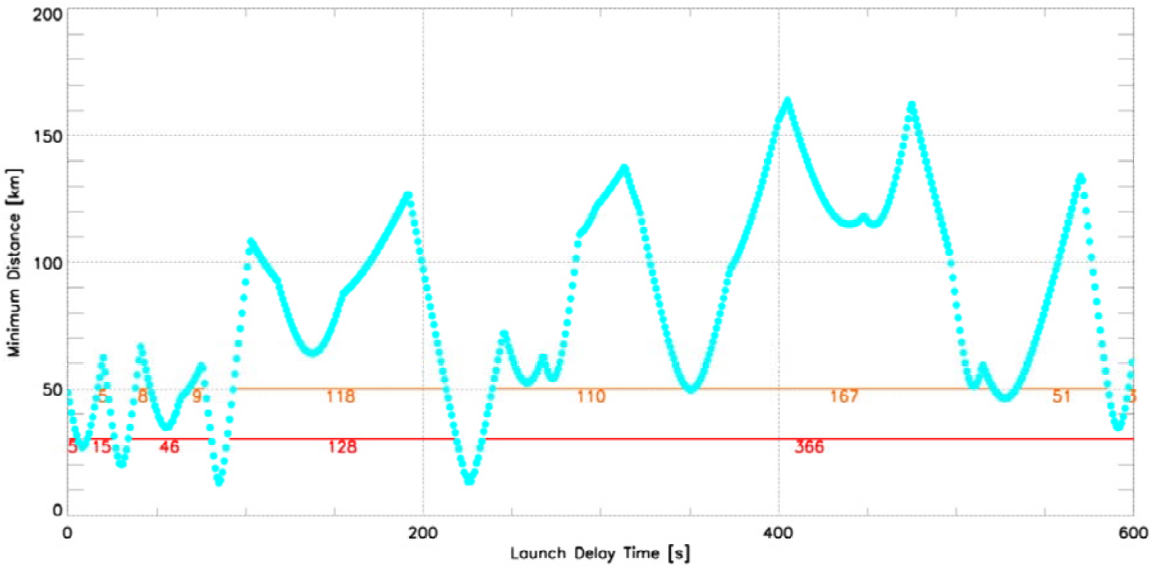

Figure 2: Minimum distance between the space vessel and all TLE-objects for launch delays of up to 600s

currently ignored in Europe's strategic ATM planning (cf. [7]). Therefore, to get Europe ready for commercial space transportation a joint effort is needed by all stakeholders, starting with the acknowledgement that suborbital flights are soon becoming reality and that the time to act is now.

3. COLLISIONS IN SUBORBITAL SPACE

Collisions with space debris or other space objects constitute a non-negligible safety risk for suborbital spacecraft and their occupants/cargo. With advanced space surveillance and tracking networks space debris and space objects (simply called traceable objects hereafter) of sizes larger than about 3cm could become trackable in the coming years. On the other hand, simple shielding technologies can protect a spaceplane only from collisions with ~1mm-sized particles. Hence, this gap requires a careful analysis to tell whether it might become a real show stopper for commercial suborbital space transportation. In the following, we try to give a first answer to this question by evaluating the feasibility of suborbital flights with respect to collisions with traceable objects, by quantifying the risk posed by non-traceable objects and comparing it with the adopted probability for a catastrophic collision.

3.1. Traceable objects

We start by considering a hypothetical ballistic trajectory from Sydney (Australia) to Oberpfaffenhofen (Germany) with a maximum altitude of ~500km. The launch time of the vessel is arbitrarily set to midnight on the 24th of August 2016. For each second of the flight, the distance from the spaceplane to all traceable objects in the NORAD Track Two-Line Element (TLE) database getting closer than 500km is determined (cf. [1] for details) and the minimum distance to the closest object is stored. Next, launch is delayed by 1s and the distance to the closest TLE object is recorded again.

In Fig. 2 minimum distances are plotted as a function of launch delay times of up to 600s. The cyan-colored data points represent the approaching TLE objects and the relative minima indicate their closest distance to the spaceplane. Adopting for simplicity reasons a minimum safety distance of 30km to the TLE objects (red line), there would be two time windows of 128s and 366s each, which the vessel would need to hit to avoid any collisions with traceable objects. If a more conservative safety limit of 50km is applied (orange line), there are three time slots, each of about 120s, for which a collision-free flight would be possible.

Ideally, this iteration is performed for launch delay times covering a period of 24 hours to see whether or not there are sufficiently frequent and long time slots.

However, due to computation power constraints, a coarser estimation was performed with a time step size of 120s for the launch delay (assuming this being a representative time slot that can be hit by the vessel) and a time coverage of 12 hours. Again, the minimum distance between the space vehicle and the TLE-objects is calculated, but now every 120s. This results in a statistical distribution of minimum distances, indicating that there could be multiple launch windows per day for which a safe flight path could be calculated in advance (see Fig. 8 in [1]).

In summary, suborbital p2p space flights appear feasible with respect to the risk of colliding with traceable objects. However, we also like to point out that additional work is needed to further substantiate our findings, e.g., by covering launch delays of 24 hours, by considering objects smaller than those listed in the TLE database and by including alternative flight destinations.

3.2. Non-traceable objects

In order to evaluate the collision risk posed by non-traceable objects, i.e. particles <3cm, the object densities provided by ESA's MASTER 2009 model [8] are analysed. As shielding capabilities of potential spaceplanes remain currently unknown, shields with three different shield strengths are considered. First, simple shields capable of withstanding collisions of particles ≤1mm in diameter (e.g., as the nose shield of the Space Shuttle). Second, shields protecting against ≤5mm-sized objects (e.g., as the shield of the Space Shuttle's cabin) and, finally, shields preventing penetrations of ≤10mm-sized objects. Although the latter are successfully deployed aboard the ISS, those Whipple-type shields are not applicable to spaceplanes due to the totally different physical conditions at re-entry. At present, adequate spaceplane shielding capable of blocking hypervelocity impacts of 1cm-sized particles does not exist and represents a severe technological challenge.

To put the assumed shielding capabilities in relation to the particle sizes and spatial densities of the ESA model, the MASTER 2009 population was filtered for a maximum particle size of 10cm (upper bound of the non-traceable object population) and altitudes ranging from 186km (the minimum altitude for which MASTER data is available) to 500km (the maximum altitude of the hypothetical trajectory).

In Fig. 3 spatial densities of the non-traceable object population are plotted as a function of object size. The distribution clearly peaks at 1–2mm-sized particles and exponentially drops towards larger object sizes. The particles are dominated by solid rocket motor slag (Al_2O_3, SRMS) and to a lesser extent by particles produced in collisions (COLL) or by explosions (EXPL). Unfortunately, the MASTER model only covers objects beyond altitudes of 186km. This means, however, that the spatial density distribution for a significant range of altitudes (from 100-186km) remains unknown and represents a gap whose risk potential remains still to be investigated.

In order to estimate the number of impacts received by the spaceplane per unit cross section a and per unit travel distance l, we assume that the vessel travels with a velocity v_{sv} in an environment where the particles move with velocities v_p. While the space vehicle crosses the unit volume element dV, the total number of particles in this volume element is $(1 + v_p/v_{sv})$ times the unit spatial density ρ. The average number of impacts can thus be calculated as:

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

The factor in brackets is of the order of 2, assuming the velocity of the spaceplane is comparable to that of the average velocity of the particles (about 7.8km s^{-1}, cf. [1]). The number of impacts per m^2 and km travel distance can now be computed as a function of altitude and declination. The result is shown in Fig. 4 for the worst case of a minimum particle size of 1mm.

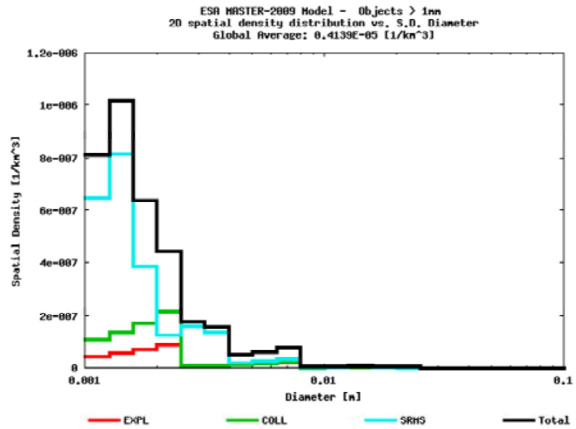

Figure 3: Spatial densities of non-traceable objects as a function of object size

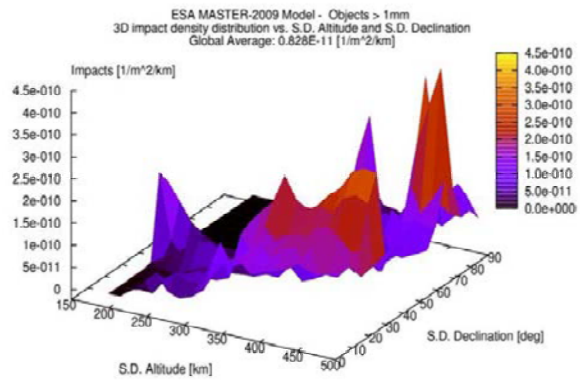

Figure 4: Number of impacts per m^2 cross section and km travel distance for objects >1 mm as a function of altitude and declination.

In regions of highest spatial densities, e.g., at altitudes around 270 and 500km, respectively, ~$3x10^{-10}$ impacts m^{-2} km^{-1} are expected. Considering again our hypothetical flight from Sydney to Oberpfaffenhofen, taking into account that the total flight path above an altitude of 200km (limitation of the MASTER 2009 model) is about 13000km and assuming that the entire trajectory would continuously lead through the highest density region (worst case), about $3.9x10^{-6}$ impacts m^{-2} from objects larger than 1mm would be expected. This value would drop to $1.1x10^{-7}$ collisions m^{-2} for the entire flight if an average impact rate of $8.2x10^{-12}$ m^{-2} km^{-1} is adopted (see Tab. 1).

In Tab. 1 global average spatial densities and impact rates for the non-traceable object population are listed for different minimum object sizes (valid for altitudes between 186–500km and for declinations 0°≤ δ ≤ 90).

Table 1: Global average spatial densities and impact rates for the non-traceable object population calculated for different particle sizes.

Particle size	> 1mm	> 5mm	> 10mm
Spatial Density [km^{-3}]	$4.1 \cdot 10^{-6}$	$2.4 \cdot 10^{-7}$	$5.0 \cdot 10^{-8}$
Impact Rate [m^{-2} km^{-1}]	$8.2 \cdot 10^{-12}$	$4.8 \cdot 10^{-13}$	$1.0 \cdot 10^{-13}$
Impacts [m^{-2} $15000km^{-1}$]	$1.2 \cdot 10^{-7}$	$7.2 \cdot 10^{-9}$	$1.5 \cdot 10^{-9}$

Table 2: Shielding capability versus maximum cross section of the spacecraft

Shielding capability (object size in mm)	Maximum cross section (m^2)
1	10
5	100
10	1000

The final row lists the number of impacts per m^{-2} cross section, using a value of 15000km for the full travel distance of the suborbital flight.
Based on these numbers, we can now put the impact risks for spaceplanes with different cross sections in relation to an acceptable level of safety (ALoS) for spaceplane occupants in order to determine the required shielding capability of the vessels (see also [2] for further details).
Due to the lack of historical data and operational experience, an initial ALoS of $1x10^{-4}$ $flight^{-1}$ is adopted for a 1h-flight which is in line with ESA's standard crew safety risk ([9], see also [10]). Because spaceplane passengers are not treated as 'general public', at least not in the early days of suborbital space flights when the industry is still maturing, they will have to accept a significantly higher personal safety risk than today's airplane passenger ($1x10^{-6}$ flight $hour^{-1}$, [11]). On the other hand, to stimulate demand for suborbital flights, the probability of catastrophic accidents has to be significantly below $1x10^{-2}$ flight $hour^{-1}$, i.e. lower than for Space Shuttle missions. Here we adopt a value of $1x10^{-4}$ $flight^{-1}$ which is placed right in the middle between risks for orbital flights and civil aviation.
If we now assume that there are 100 potentially catastrophic scenarios (with equal probability) for the spaceplane and its occupants, than the maximum probability per flight for a catastrophic collision with non-traceable objects amounts to $1x10^{-6}$. This value needs to be compared with the expected impacts m^{-2} for the full space flight (see last row in Tab. 1) to obtain the maximum acceptable cross section of the spaceplane with respect to its needed shielding capability. The results are summarized in Tab. 2.
On this basis, spaceplanes with cross sections $>10m^2$ and shields that protect against collisions with objects ≤1mm would not be permitted to launch. This restriction would primarily apply to spaceplane concepts like the SpaceLiner or Skylon rather than to spacecraft designed for vertical ballistic flights, as the former also operate at higher altitudes with increased collision risks. Currently it appears, as if the gap between today's shielding capabilities (0.1cm) and the expected traceable object size (3cm) could turn out to be a severe show stopper for commercial suborbital flights.
It is important to note, that the above estimates shall only give a first indication of the overall feasibility. The validation of the underlying assumptions, the determination of more accurate impact rates and the in-depth analysis of the risk associated with the gap is beyond the scope of this work and requires a dedicated follow-up study.
In our view it is most important to advance heat and collision shielding technologies and to focus on closing the gap at the lower particle size range, as the smallest objects pose the highest risk (cf. Fig. 3).

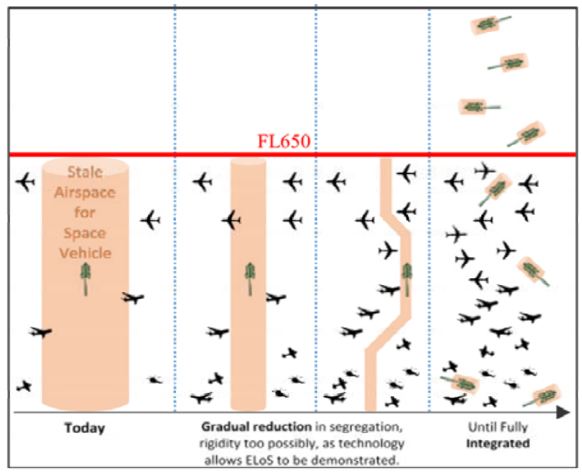

Figure 5: Evolution of flight corridor handling

4. INTEGRATING STM AND ATM

4.1. Flight Corridor Handling

The approach of safely integrating spaceplanes into the civil air traffic flow calls for new routing and separation standards. One aspect that strongly influences the definition of these standards is the spaceplane's flight performance characteristics, such as its overall maneuverability, turn radius or climb rate.
In Fig. 5 we present an evolutionary high-level flight corridor handling concept which considers four types of separation approaches which in turn require gradual improvements of the spaceplane's flight performance. The first separation approach is already part of today's ATM and demands the closure of large portions of airspace around the vessel (similar to airspace blocking for military purposes). It may turn out that this approach is only feasible in the early days of suborbital flights when there are still infrequent launches, simply because it is the most costly and capacity-constraining one. The

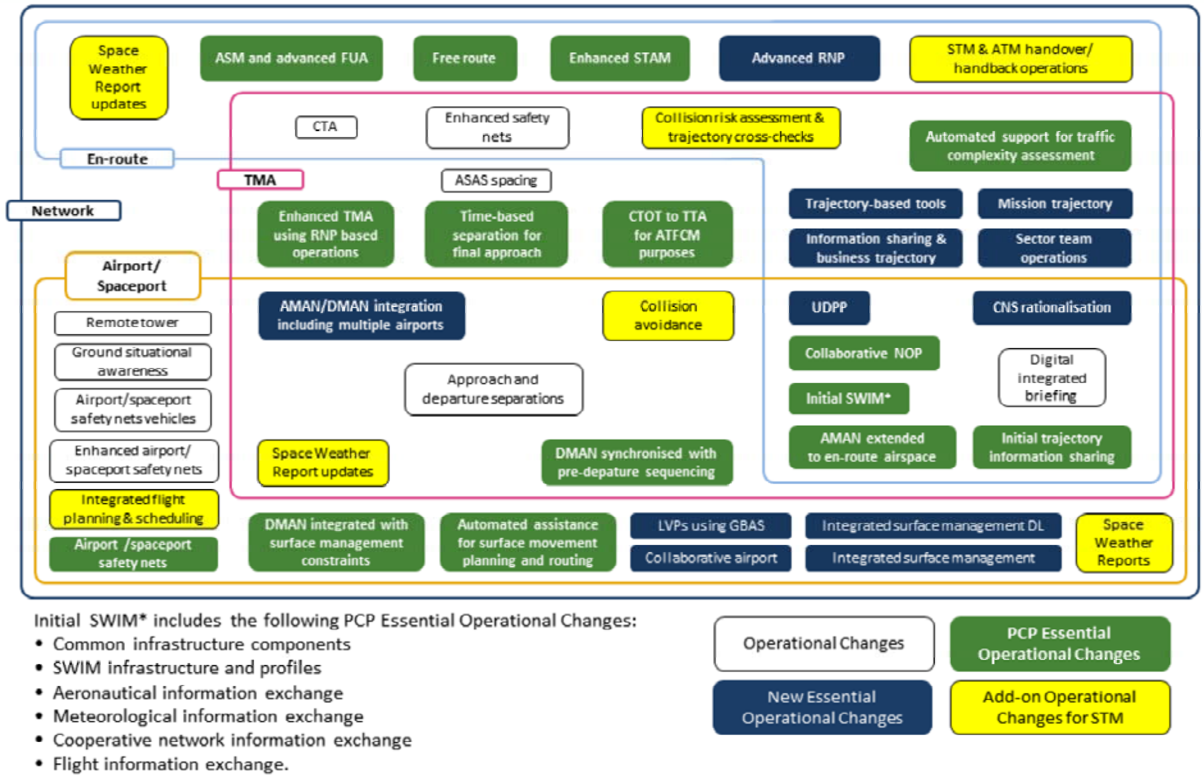

Figure 6: Supplemental STM add-ons (yellow boxes) required to integrate STM with the evolving ATM system (original figure taken from the ATM Master Plan [7] and modified accordingly).

second stage builds up on the first approach and assumes significant advancements on the vertical and lateral navigation performance during launch and re-entry of the spacecraft. This would allow for a significant reduction of the overall containment area and result, compared to the first stage, in a considerable capacity increase due to a better predictability of spacecraft operations in airspace.

The third approach requires an even tighter containment area based on the in-flight NAV performance of the vessel. However, this is currently uncharted territory as no relevant standards yet exist for suborbital spacecraft.

Finally, the fourth approach envisages bubble-like areas around the spacecraft which reflect their individual positioning accuracy and define a three-dimensional space around the vehicle as a non-penetration zone. This concept is very similar to today's separation concept between conventional aircraft in controlled airspace. However, it certainly requires the highest level of accuracy both in position and time and is far from being realized for commercial space operations.

In order to apply ATM concepts for route and radar separation and airspace design principles, e.g., with respect to navigation accuracy and cross-track deviation probabilities, the spacecraft would require a navigation specification that needs to be compatible to aviation standards. In other words, the more airplane-like the in-flight performance of the spaceplane, the easier its integration into routine air traffic flow.

For integrating spaceplanes safely into the air traffic, all spaceplanes and aircraft should be equipped with appropriate technology that allows the determination and dissemination of the vessel's current position and speed (e.g., via GNSS, ADS-B/C, etc.).

Continuous tracking and sharing of positional data with other spaceplanes, airplanes, ATCOs and STCOs as well as 4D positional spaceplane monitoring above controlled airspace should be key pillars in a joint ATM and STM strategy.

4.2. Suggested STM Add-ons to the SES Concept

At present, the topic of suborbital space transportation is largely ignored in the Single European Sky (SES) initiative of the EU [7]. In order to visualise Europe's main deficiencies in the STM and especially in the SES context, Fig. 6 was taken from [7] (their Figure 8) and was adapted to also include the supplemental add-on components and services which we identified missing from the STM point of view (see boxes highlighted in yellow). The following high-level add-ons to the SES ATM Master Plan from 2015 appear mandatory:

1) Space Weather services and products
2) Collision risk assessments and trajectory calculations

3) Integrated (ATM & STM) Flight Planning and Scheduling
4) Handover and handback operations between ATCOs & STCOs.

Add-ons 1) and 2) would require the establishment of ESSTraC and the proposed SWMC together with appropriate operations concepts and globally operating sensor networks. Regarding add-ons 3) and 4), a close collaboration between the ATM sector and future STM key players would be needed to develop and implement suitable flight planning and scheduling concepts and adequate operations procedures. Further details on ATM and STM integration are provided in [1], [2], and [3].

5. TOP 10 STM ISSUES

Based on the analyses performed in our study, the most important issues that have to be tackled for realizing a European STM system are summarized in Tab.3.

Table 3: Top 10 STM 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)	UN
3	Define a European overall safety concept regarding human factors, flight, occupant and on-ground safety (with international interfaces)	EASA/Eurocontrol
4	Development of needed technologies and infrastructure (e.g., for spaceplane engines & shielding, debris tracking, spaceports)	ESA
5	Design and implementation of a European STM/STC operations concept that seamlessly integrates into the global context	ESA
6	Design and implementation of a European Surveillance and Tracking Centre (e.g., including sensor networks, operations, products and services)	ESA
7	Design and implementation of a Space Weather Monitoring Centre (e.g., including sensor networks, operations, products and services)	ESA
8	Design and implementation of an aerospace handling concept for spaceplanes	ESA
9	Design and implementation of a Flight Planning and Scheduling Facility (including international interfaces)	EASA/FAA/Others
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

Clearly, there is a long way to go for Europe before first commercial suborbital transportation activities can commence from European territory. For Europe to get its own share of the market, it is vital to conclude on a consolidated STM implementation approach with input from all stakeholders of the aviation and space domain.

6. SUMMARY

The most important results of this work are as follows:

- Europe is not well prepared to serve the evolving space transportation market in the near future.
- A ROS was defined, reflecting typical day-to-day operations for suborbital space flights.
- We identified a gap between current spacecraft shielding capabilities (<1mm) and the minimum traceable object size (>3cm) in future catalogues of traceable objects.
- This gap could turn out to be a real show stopper if it cannot be reduced by applying new heat and collision shielding technologies (focus on small-sized particles as they pose the higher risk).

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