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AIR MEETS SPACE: SHAPING THE FUTURE OF COMMERCIAL SPACE TRAFFIC
I. STUDY INTRODUCTION AND INITIAL RESULTS

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There are high expectations for a globally growing market of commercial space travel which is likely to turn in the next 10 to 20 years into a multi-billion Euro business. Those growth expectations are also backed up by OneWeb's order of about 700 small satellites which are likely to be brought into LEO via air launches and by a continuously growing LEO launch rate showing an increase of about 60% in the last decade. Advances in electric propulsion and spacecraft design (CubeSats) helped to significantly reduce launch costs, so that space exploitation becomes affordable for the first time also to the private sector (e.g., for school labs, micro gravity research or in the area of human spaceflight). Several key players in space business, companies like Blue Origin, Virgin Galactic, XCOR, Orbital or SNC get ready to serve the commercial manned and unmanned spaceflight market by developing their own ballistic reusable space vehicles which shall carry humans and cargo payload into suborbital and LEO space. Europe's single stage to orbit concepts, like REL's Skylon or Airbus' Spaceplane, even target for commercial manned point to point mass transportation, similar to today's travel through airspace, but with much shorter flight times. All these developments will likely stimulate demands for launch sites and spaceports, where commercial aviation and space vehicles will have to be safely managed and controlled in parallel granting easy access to potential customers. Today, management of and access to commercial aerospace is lacking a coordinated European and global approach so that the expected growing number of space vehicles passing through the air-space interface in a rather "uncontrolled" way will likely pose significant threats to human health and airspace safety. This issue is further intensified by the flood of CubeSats and Unmanned Aerial Vehicles which increase collision risks in LEO and lower airspace. Without doubt, space and airspace will move closer together in the next decade, which is why Space Traffic Management is expected to become a global undertaking. Because we think that safety in aerospace should not be jeopardised by those developments, we initiated an evaluation study together with ESA aiming at the generation of a roadmap towards a European Space Traffic Management. This is the first in a series of papers which gives an outline of the study and presents initial results from a European perspective.

I. INTRODUCTION

In order to tackle the challenges associated with the generation of a roadmap for the implementation of a European Space Traffic Management (ESTM) system, a European consortium of experts has formed. The study team comprises companies and institutes from Germany (DLR GfR mbH, DLR Space Operations and Astronaut Training and the DLR Institute for Communications and Navigation), Austria (Austro Control) and Switzerland (Astronomical Institute of the University of Bern and ROSAS) who are all well-known experts in their field. DLR GfR, acting as study lead, is a company providing reliable, safe and secure aerospace services. The company was founded in 2008 in order to operate and manage 24/7 the constellation of Galileo satellites from the Galileo Control Centre in Oberpfaffenhofen, Germany. DLR GfR has implemented a technical infrastructure, which satisfies availability requirements of 99,99% and is certified up to level "secret". As part of the company's commercial space operations, DLR GfR offers satellite platform commissioning, satellite payload in-orbit testing and long-term 24/7 routine system operations. In 2014, DLR GfR was awarded with an Air Navigation Service Provider (ANSP) Certificate for CNS (Communication, Navigation and Surveillance) by the national supervisory authority of the Federal Republic of Germany. This certificate is based on Single European Sky Regulations and allows the company to offer CNS services in all member states of the European Union. As part of the certification process, DLR GfR has established a mature Safety Management System and procedures. In addition, DLR GfR provides training focused on human factors in high reliability organisations and other areas related to Air Traffic Management (ATM). Engineers at DLR GfR constantly work on the development of innovative

Navigation Services for the aviation industry that are based on the company's core business, GNSS (Global Navigation Satellite System).

Given our broad and comprehensive view on ATM and Space Traffic Management (STM) topics, we are convinced that in the next one or two decades STM will likely become a global effort, to which Europe should contribute with its own system if it wants to play an adequate role. Because noticeable initiatives to integrate suborbital spaceplanes into the European ATM are currently lacking, we conduct, on behalf of ESA, an evaluation and roadmap study on the establishment of an ESTM system. The following five topics represent the main pillars of the study: Space Surveillance and Tracking, Space Debris, Clean Space, Space Weather and Space Traffic Control. To generate the roadmap, a holistic approach is required, starting from quantifying the safety risks in space, airspace and on ground, reaching out to the implementation of means to generate data relevant for the mitigation of certain space events in support of safe space vehicle operations, down to the point of considering the expected increase of air and space traffic and the identification of interfaces and required infrastructure to safely implement STM into a continuously evolving European ATM (aka. Single European Sky, SES, [1]). In the following we describe the scope of the study, identify the main interfaces required to build this holistic approach and highlight current gaps and deficiencies. In a forthcoming paper detailed results and the proposed roadmap for implementing ESTM will be presented.

Scope and Outline of the Study

The basic idea behind this work is to identify system requirements, elements, institutional entities and interfaces needed to build a European STM. This requires to investigate such diverse topics like capacity and requirement evaluations of relevant sensor systems (e.g., to detect and track space debris as well as re-entering objects), assessments of current technology developments (e.g., needed CNS equipment aboard spaceplanes) or aspects related to Air and Space Traffic Monitoring and Control (e.g., static vs. dynamic flight corridor handling). Therefore, the study carefully analyses the current European landscape of existing assets, technologies and interfaces, as well as national interests and programmes in the field of Air and Space Traffic Management. The goal is then to generate a roadmap for the development and implementation of the identified elements into the ESTM. The analysis also includes aspects related to the understanding of the near-Earth space environment, i.e. space debris (including man-made objects) and associated risks in LEO and on ground as well as the means to provide relevant operational data through Space Situational Awareness (SSA) networks, such as products from Space Surveillance and Tracking (SST) Centres and Space Weather Monitoring Centres. It also includes the means to appropriately mitigate and remediate the effects of the space environment on human health in LEO.

Study Objectives

The goal of this study is to provide a description of possible technical, programmatic and governmental contributions of Europe required in response to STM needs. The following main study objectives apply:

- Analyse 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 < 1000km)
- First risk quantifications associated with debris impacts and spacecraft collisions on manned suborbital flights, reflecting aspects of human health, spacecraft shielding and protection
- First risk quantifications associated with controlled and uncontrolled re-entering debris on air traffic
- Other risks for air and space traffic, including Space Weather and micro-meteoroids
- Current and future monitoring gaps and counter-measures in this regard and their level of effectiveness
- Developments required in Europe to counter the identified risks in response to the quantity and type of future air and space traffic evolution, with special focus on manned commercial suborbital space flights
- Technologies required to perform adequate mitigation and remediation measures to ensure safe traffic through air and space and their contribution to risk reduction
- Investigations on how a ESTM System can be integrated into an evolving civil aviation and ATM sector
- Roadmap definition, considering national efforts and interests as well as European collaborations with international partners.

Definition of the Term "Space Traffic Management"

The term "Space Traffic Management" usually refers to sending manned or unmanned spacecraft into space, staying in space for a certain period of time to perform a set of pre-defined operations and returning crew and/or vessel safely back to Earth. During all this time, crew and vessel are subject to active monitoring and control operations. In this regard STM appears like an overarching activity covering almost any aspect of space flight operations from then till now. For the context of this work, the above definition is way too

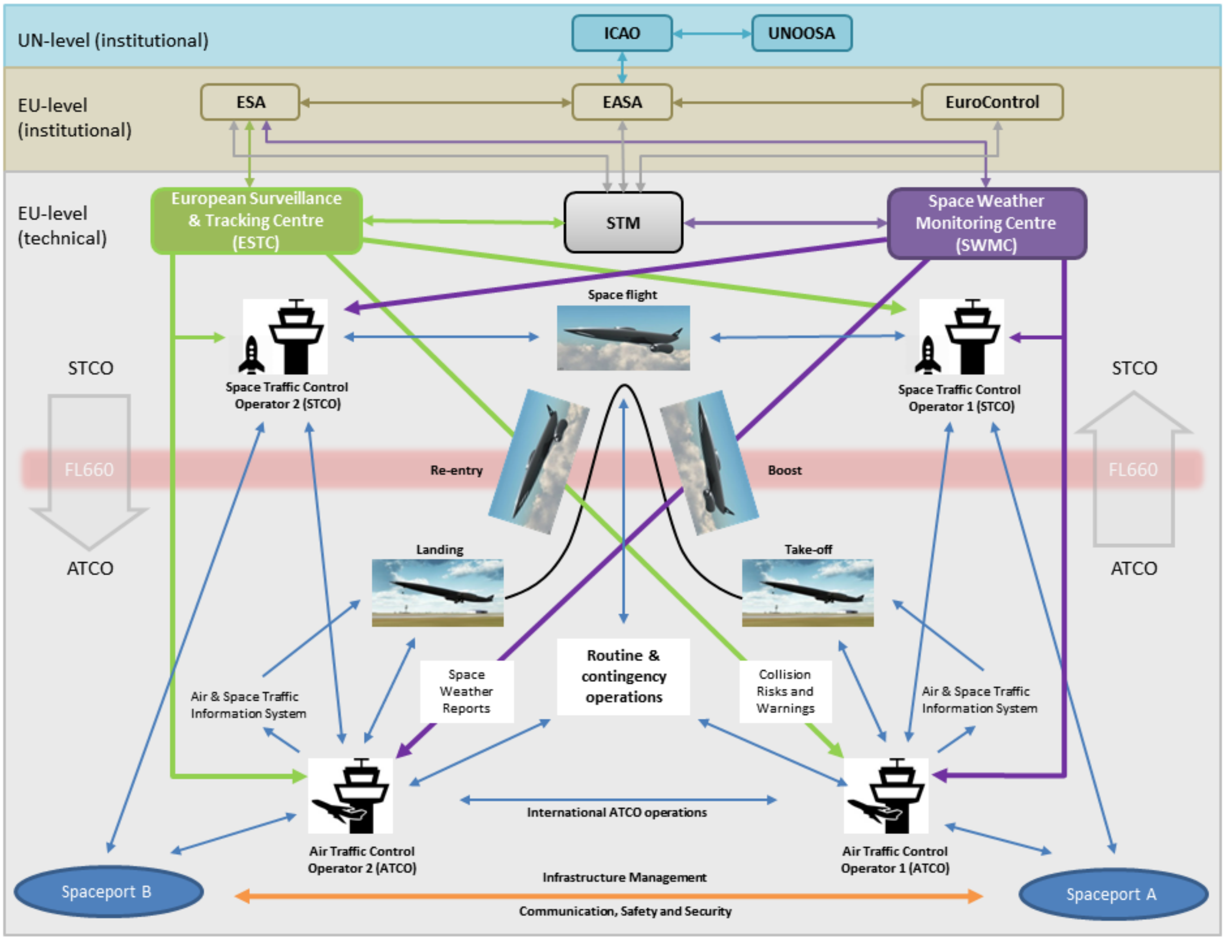

Figure 1: Reference Operations Scenario

broad, which is why STM is understood here as the: *Execution of all necessary Managing and Monitoring and Control Operations from European soil (including routine & contingency scenarios) to ensure safe ballistic point-to-point travel of manned or unmanned space vehicles through LEO and airspace under consideration of the existing European Air Traffic Management System and Infrastructure*.

II. REFERENCE OPERATIONS SCENARIO

The STM concept and roadmap is developed against a baseline, the Reference Operations Scenario (ROS), which reflects a set of typical routine and contingency operations scenarios and relevant safety operations aspects. In the present case, ROS considers suborbital point-to-point (p2p) travel from Spaceport A to Spaceport B (and return to Spaceport A) with spaceplanes having a seat capacity of at least 6 passengers and a cargo capacity of more than 800kg. Those spaceplanes are envisaged to move on ballistic trajectories at maximum altitudes between 100km and 500km. The typical time spent in or near apogee is expected to be considerably 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 on its suborbital flight to Spaceport B. It is supervised, monitored and guided from ground through airspace by the Air Traffic Control Operator (ATCO) responsible for the airspace around Spaceport A. Before take-off, 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 determinations), 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 Monitoring Centre (SWMC) and the European

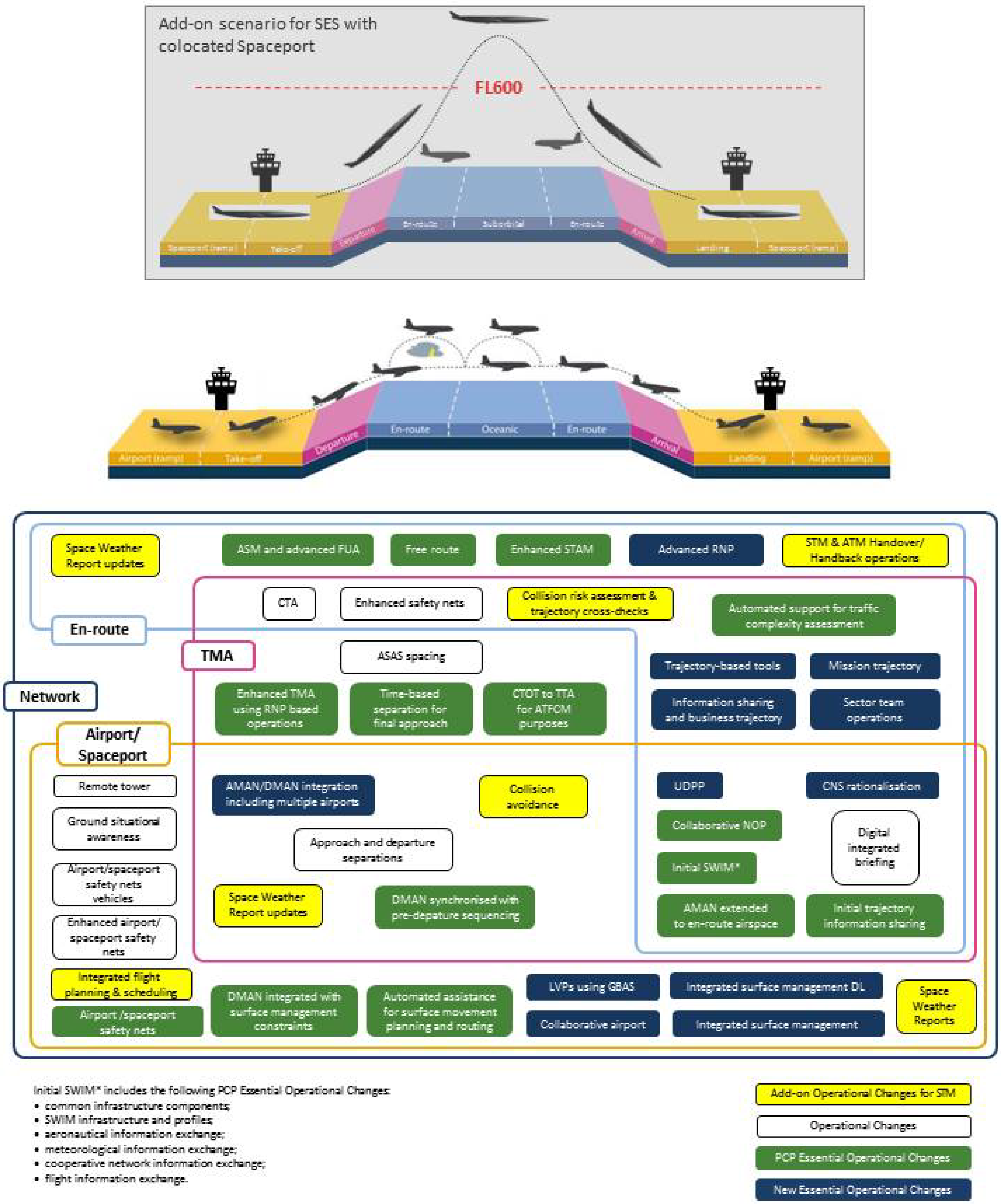

Figure 2: Supplemental operating environments for STM proposed as add-ons to SES

Surveillance and Tracking Centre (ESTC). 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 ATCO up to upper airspace, e.g., to FL600, where a handover from Air Traffic to Space Traffic Operations is performed. From now on, the STCO is responsible for guiding the spaceplane and 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 FL600 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 air space 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 is in agreement 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 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 [1]. In other words, Space Travel, be it p2p or suborbital, is currently not considered a high priority.

Compared globally, the space traffic market in the U.S. has evolved much more than in any other part of the world, yet even to an extent where FAA is already issuing Launch Site Operator Licences. In order to avoid competitive disadvantages in the multi-billion EUR space traffic market, we recommend to include the missing STM pieces in future SES iterations. A high-level overview of the required add-ons is given in Figure 2 which was taken from the European ATM Master Plan 2015 (see Figure 8 in [1]) and adapted to also show the supplemental components needed for STM. Boxes highlighted in yellow represent the proposed additional operational changes required to integrate STM into ATM.

III. INITIAL RESULTS

There are two main areas where STCOs and ATCOs will have to interface and communicate with each other. One is related to planning and scheduling of suborbital flights and integrating them into the ATM flight schedule and the other is linked to handover and handback operations when the spaceplane crosses FL600. The former includes activities such as the generation of the flight plan and schedule for the spaceplane, the corresponding backup planning for contingencies and the allocation of appropriate flight corridors for nominal and contingency cases. All these planning and scheduling operations depend critically on the risk analyses for space debris and re-entering objects performed and distributed by the ESTC and the Space Weather Bulletins (SWBs) disseminated by the SWMC. Those entities and services do not exist yet.

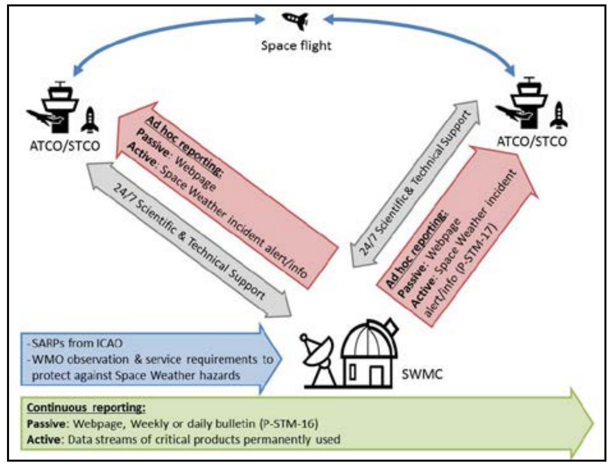

Figure 3: Information flow between SWMC and STCO

Space Weather

An essential product for Space Traffic Operations is the weekly or daily SWB, which provides all important information in a human readable manner. The STCO has to define the frequency with which the SWMC needs to deliver the bulletins according to planned space traffic operations. The second mandatory service is the ad-hoc information in case of strong and extreme Space Weather events. 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 according to the needs of the STM. Provision of measurement data from the Space Weather domain to the STM should be limited in order to prevent misinterpretations by non-experts. Based on the delivered Space Weather information, the STCO has to perform the correct measures to ensure the safety of the spaceplane, its crew and passengers. The SWMC shall not give Space Weather alerts and information directly to the flight crew. A schematic representation of the information flow is shown in Figure 3.

In the following, a list of important Space Weather products is proposed together with an evaluation of the work that needs to be done to generate them. These products could be part of the envisaged SWB:

- Real Time TEC products: The coverage of Total Electron Content (TEC) products is currently not sufficient. The highest resolution maps use data from reference networks whose stations are not equally distributed around the globe. There are huge gaps in real time measurements over mountainous or oceanic regions where no GNSS stations are available. This limitation might be overcome in the future by using additional space-based measurements and by integrating them into the existing TEC models.

In addition, more effort needs to be put into high temporal and spatial 3D reconstructions of the Ionosphere. Especially for space traffic, not only the ionisation level over a certain region is important, but also the electron density at any height during a suborbital or LEO flight.

- Long term forecast of ionospheric conditions: The forecast of ionospheric conditions and especially of TEC disturbances is a demanding task and currently of major interest to the Space Weather community. Short term (up to one hour) forecasting of TEC under quiet geomagnetic conditions is practised at a few institutions worldwide, including the SWACI service at DLR. However, a forecast of up to 24 hours and more, taking into account actual Space Weather conditions, is requested by users. It is expected that solar storm-induced geomagnetic and ionospheric perturbations will cause large errors in the existing forecasts. Hence, ionospheric storms need first to be described by an appropriate model to ensure good forecast quality.
- Geomagnetic/Ionospheric storm onset definition: In the recent NOAA Space Weather scales for geomagnetic storms the Kp-index is used as the basis to define a five-level warning system, but other physical measures, such as Dst-index, should be considered too. In this context and according to our definition, a moderate geomagnetic sub-storm is supposed to be a G2 and a G3, a strong storm is a G4 and an extreme geomagnetic sub-storm is a G5 on NOAA's geomagnetic Space Weather scale. However, the Kp-index is determined only every three hours and would most likely be insufficient to fulfil future STM safety requirements. Therefore, a better G-scale driver has to be defined with higher resolution allowing much better predictions. Here the Dst-index with one hour resolution and additional data from ACE and DSCOVR would allow for a reasonably good storm onset prediction.

Space Surveillance and Tracking

Because the entry/re-entry points to/from LEO are not always exactly known in advance (e.g., contingencies aboard the spaceplane 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 spaceplane 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 are ESTC and SWMC.

The accuracy of the spaceplane's trajectory through aerospace depends strongly on the performance of the available sensor network that is responsible for monitoring and tracking space debris and re-entering objects. Clearly, the lower the size of the objects to be tracked, the lower the risk for passengers aboard the vessel, but the higher the costs for implementing a sensitive global monitoring and tracking system. A trade-off study which evaluates these costs vs. in-flight and operational risks is currently missing, but is highly recommended to check under what circumstances commercial p2p space travel would be consistent with passenger safety requirements.

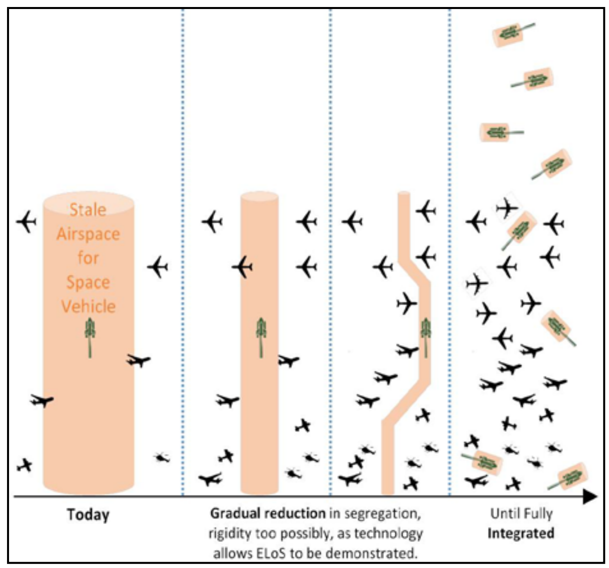

Figure 4: Dynamic Flight Corridor Handling

Integrating STM and ATM

The general concept of space vehicle integration into civil airspace 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, in-flight performance as well as operational profiles (e.g., booster usage and jettison, re-entry with burn-off elements or vertical/horizontal take-off and landing spaceplanes with limited manoeuvrability). Performance characteristics of a spacecraft, such as climb rate, speed and turn radius, are crucial for an ATCO to safely manage air traffic.

It thereby has 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 airspace is the way to go. On the one hand, reserved airspace for space vehicle launch and landings is in strong contrast to a capacity-friendly ATM concept as envisaged in the SES initiative [1]. However, if separation standards for spacecraft become prohibitively large due to their diverse operational profiles, temporary airspace solutions may be a better option. Therefore, safe integration of space travel in ATM/civil airspace is seen as the key challenge. Evolution drivers would be the amount of space travel traffic in the next two decades, ATM technology development and the maturity level of spaceplane technology. There is general agreement that full integration of STM into ATM is the end goal.

In order to realise this goal, an acceptable level of safety could be achieved by segregation, demonstrating at each stage an equivalent level of safety (ELoS) to ATM standards (cf. Figure 4) and by a couple of key technical requirements, such as spaceplanes having manoeuvring capabilities in airspace and on-board ADS-B and GNSS equipment for positional tracking.

IV. INITIAL RESULTS

We have presented initial results from an ESA-funded study aiming at the generation of a roadmap for the implementation of a European Space Traffic Management system. The main findings can be summarised as follows:

- STM (as defined in Section. I.) and suborbital space travel is currently not reflected in the latest version of the European ATM Master Plan for a Single European Sky [1]
- To close this gap, a high-level Reference Operations Scenario has been developed (cf. Figure 1), against which a potential ESTM system should be designed
- The following main technical and operational deficiencies have to be tackled to realise a STM system for Europe:
  - Integrated ATM+STM flight planning and scheduling (including dynamic flight corridor handling and interfacing with ESTC and SWMC)
  - Collision avoidance and risk assessments
  - Upgrade of Space Surveillance and Tracking networks and infrastructure to enable required services and products (e.g., ESTC, collision risks or trajectories)
  - Upgrade of Space Weather monitoring networks and infrastructure to enable required services and products (e.g., SWMC, SWBs or TEC maps).

In a second paper the roadmap and more detailed results will be presented.

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V. REFERENCES

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