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Interoperable data exchange for safe and efficient launch and re-entry operations in an international environment

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Abstract

The frequency of commercial space launch and re-entry operations is increasing worldwide. Current regulations and procedures ensure safe operations by temporarily closing large volumes of airspace where risks to aircraft would exist in case of non-nominal events during launch or re-entry operations. To maintain the safety of air traffic as the number of space operations rises, effectively providing the right information to the right stakeholders at the right time is key. Through a cooperative agreement, the FAA and DLR are sharing their unique capabilities using the Commercial Space Integration Lab and Air Traffic Validation Center, located in the USA and Germany respectively, to improve situational awareness through real-time data exchange. The project seeks to answer whether U.S. and European ANSPs can respond adequately to a non-nominal event during a launch or re-entry operation that presents a hazard to the airspace system. It leverages existing international data standards and infrastructures by using a data exchange approach based on System Wide Information Management (SWIM). Within the project an initial assessment of the processes, roles and responsibilities for implementing launch and re-entry events in the air traffic systems on both sides of the Atlantic, as well as the requirements for basic functions and performance parameters of a SWIM-based integration, have been completed. The project developed a demonstration model across all system levels as far down as to the ANSPs, namely to the air traffic controllers. Through a series of demonstrations, covering launch scenarios from the U.S. with possible effects on European airspace and vice versa, the project evaluated the technical and operational feasibility of the concept. The key data parameters identified during the analyses shall enable information sharing among various users within the U.S. and European global airspace system. It has been shown, that the systems on both sides of the Atlantic could be connected via standardized protocols und used successfully for exercises in different scenarios. Further research on the best integration of the processes in international ATM networks and Domains will be the follow-on.

Keywords: Commercial Space Integration, Space Traffic Management, Air Traffic Management, Launch and Re-entry Operation, SWIM

1. Introduction

The DLR (Deutsches Zentrum fuer Luft- und Raumfahrt / German Aerospace Center) and the FAA (Federal Aviation Administration) initiated the 2018 DLR-FAA Data Exchange Project (DEP) in support of identifying and validating solutions for safely and efficiently integrating commercial space launch and re-entry operations into the global airspace system. The collaborative nature of this work has been formalized through a Memorandum of Cooperation (MoC) in the development of commercial space transportation, which has been signed October 24, 2019 by the DLR and the FAA Office of Commercial Space Transportation (FAA AST).

Launches to orbit and re-entries from orbit are operations of global scope and scale. The vehicles cross territorial, national and airspace boundaries on their way to and from space. While it may take a vehicle just a few seconds to move across these boundaries, the effects on the airspace below can linger for minutes or even hours in the event of a non-nominal occurrence.

Timely, efficient and effective data sharing across participating entities is a critical enabler to effectively prepare and execute their responsibilities for safe and efficient airspace management, particularly in non-nominal scenarios.

2. Problem description

The number and type of commercial space launches and re-entry operations is continuously increasing at a global level. In order to ensure the safety of air traffic, the spacecraft is separated from other aircraft over a wide area. This is not only to ensure sufficient separation between the respective vehicles, but also to take into account a higher probability of failure compared to air traffic standards. Thus, air traffic (and also people and infrastructure on the ground) must be protected from potential debris in the event of a non-nominal situation.

In principle, a non-nominal event can occur during the entire flight phase, for example, anywhere along the ascent trajectory. Risk calculations provide information on how high the resulting damage probability is and what consequences are to be expected. The occurrence of potential damage events can be prevented by closing off large segments of airspace along the flight trajectory and the potential debris trajectory.

However, this has a massive impact on air traffic operation and would lead to enormous disruptions such as flight delays and necessary detours (including a required increase in fuel consumption and CO_2 emissions). Moreover, large areas of oceanic airspace cannot be closed but merely designated as danger areas. In order to reduce the need for prophylactic airspace closures, they instead will be limited to areas for where there is insufficient time to guide aircraft out of the risk zone when a non-nominal event occurs. Airspace restrictions required for this purpose will be communicated in advance via Notice to Airmen (NOTAM) and will include areas around the spaceport and along the initial flight path, as well as around the area expected for the return of burned-out rocket stages or fairing. The size of these areas will be calculated in advance as part of safety analyses using detailed models. For all other areas, it must be determined whether any debris generated in the event of an incident would result in an unacceptable risk to other air traffic participants. For this case, concepts have been developed to allow air traffic control to warn and guide potentially affected aircraft out of an affected area in the event of an incident.

On the FAA side, the loss of the Space Shuttle Columbia during its re-entry in 2003 was a trigger for the development of such procedures [1]. The evaluation of this accident had shown that aircraft had flown several times through the danger area of the debris cloud that had been created, and that there was neither sufficient information on the part of air traffic control to recognize the dangers nor established procedures to be able to react to them. The procedures subsequently developed and implemented were a prelude to improved dynamic integration of space events into air traffic management in the United States. Models and procedures for calculating Aircraft Hazard Areas (AHAs) were improved and their computational speed increased, so that information about an AHA can be derived from the last available position report of a spacecraft and transmitted to air traffic control. For some time, work has been underway to convert the initially established manual processes, which were based among other things on telephone transmissions of AHA descriptive coordinates, into digital processes and to accelerate them [2][3]. Part of the reason for this is to respond to the massive increase in launch frequency at U.S. spaceports.

Other nations and spaceports, such as the European Spaceport at Kourou, also use similar processes where, if necessary, affected air traffic control facilities are notified by telephone about areas affected by a non-nominal event such as an on-trajectory explosion of the space vehicle.

However, with the increase of commercial space launch and re-entry operations, the frequency of space flights traversing the airspace also used by others is growing. The former special event of a space launch has become daily business. Due to the nature and physical requirements of space operations, the impact of a non-nominal situation cannot always be limited to national boundaries and jurisdictions. This must be considered when adapting processes that simultaneously permit a rapid response capability to incidents to ensure safety, while maintaining the necessary airspace capacity for air traffic. Efficient and reliable provision of all information required for this purpose is crucial. Due to the global nature of spaceflight events, national solutions are not sufficient in this respect today. Affected and involved stakeholders must be included in future concepts for addressing this issue in a cross-border and interoperable manner.

3. Conceptual approach

Addressing this challenge, the DEP set itself the goal to demonstrate a way of integrating Space Traffic Management (STM) into Air Traffic Management (ATM) by exploring space data exchange on an international level between operators and air navigation service providers (ANSPs) to increase situational awareness and the ability to respond to non-nominal events during space operations thus improving efficiency and safety.

The concept to be developed addressed the following key questions:

What data should be exchanged for commercial space launch and re-entry operations?

- Address the safety of launch and re-entry operations, with a specific focus on air traffic safety
- Identify the information needed by the different involved stakeholders
- Capture an international perspective, assuming cross-border operations.

In what timeframe (prior, during & after commercial space launch and re-entry operations) does the data need to be exchanged?

- For each of these timeframes, different information requirements exist
- During the operation, time criticality is an issue which needs to be addressed
- Timely availability of data might allow for a more efficient use of airspace during launch and re-entry operation

What is the utility of the data exchanged?

- With information being available, how can it utilize the planning and decision making process?
- Who will be able to utilize the information?
- Can we use the information to act on it – effectively and efficiently?

3.1. Data selection and communication format

Starting with the data exchange itself, first of all the data or respectively information that was to be shared and exchanged had to be identified. The way these data can be shared had to be addressed in parallel, as the type and categories of data might influence communication methods and formats.

Existing (standardised) methods of data sharing for aeronautical information were used as a starting point. Here, System Wide Information Management (SWIM) is becoming an increasingly important and applied standard. The FAA research and development (R&D) environment provides SWIM capabilities which were available to be used within the project. Furthermore, DLR already demonstrated dynamic and secure data exchange of airspace restrictions based on SWIM solutions, together with the Embry-Riddle university, using the Florida NextGen Testbed in Daytona [4]. The prototypical data exchange demonstration setup therefore expanded on this experience and used the available capabilities. It should already be noted that SWIM might only be a part of later implemented solutions, as sharing mission critical data will most likely require other dedicated ways of data communication. Nevertheless, SWIM is providing very specific capabilities which were of good use for testing the concept developed in this framework.

The data sharing method dictated to some extent the format to be used and led to two specific SWIM-messages: Launch Reentry Vehicle Tracking and Status Service (LRVTSS) and Aircraft Hazard Area Message Service (AHAMS), which have been developed as extensions to previous existing definitions.

The LRVTSS basically provides vehicle status and positioning information. It is used to follow the trajectory of the spacecraft and it can further be used to extract the last known state vector of the vehicle in case of a non-nominal event. Essential information included within the LRVTSS is data about the vehicle type and ID, vehicle and flight status information and position, altitude and speed. Table 1 shows the complete list of data types used within the LRVTSS, Figure 1 shows an example of the related R&D SWIM message format.

The AHAMS provides information about potential hazard areas. They can be used to distribute information during planning and execution of a flight. This is reflected also in the different types of AHAs: Planned, Contingency and Refined. In this sequence they are usually getting more precise (and therefore also smaller) with respect to the actual flight event. The AHAMS contains information about the position of the hazard area (coordinates) and also its vertical dimension (upper / lower limits), the time it has been calculated (generated) for and when the AHA is expected (!) to be cleared again. The message also contains additional information about the related vehicle and mission they are generated for.

Table *2* shows the complete list of data types used with the AHAMS, Figure 2 shows an example of the related R&D SWIM message format.

Table 1: Launch Reentry Vehicle Tracking and Status Service Data Types

Launch Reentry Vehicle Tracking and Status Service	
Number	**Data Type**
1	Vehicle Name
2	Mission Type (Launch/Re-entry)
3	Vehicle Type ID
4	Vehicle Type Element
5	Vehicle Status (Nominal/Non-nominal)
6	Sensitivity (All, Restricted, Department of Defense A/R/D)
7	Position (Latitude-Long)
8	Airspeed (Knots)
9	Altitude (Meters)
10	Timestamp (Vehicle and Message)
11	Velocity (NED in m/s)
12	Flight Status
13	Flight Identification
14	Operator


```
<?xml version="1.0" encoding="utf-8"?>
<VehiclePositionMessage xmlns:fixm=
"http://www.fixm.aero/nas/3.0" xmlns:tss=
"us:gov:dot:faa:commercialspace:LRVTSS" xmlns:xsi=
"http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="LRVTSS_Message.xsd"
><fixm:flight timestamp="2020-12-16T15:16:59.412Z"
><fixm:enRoute><fixm:position positionTime=
"2020-12-16T15:16:59.412Z" reportSource="SURVEILLANCE"
><fixm:velocity><fixm:vector uom="METERS_PER_SECOND">
-476.3238224 -755.6571695 4080.39546
</fixm:vector><fixm:nasAirspeed uom="knots">4030
</fixm:nasAirspeed></fixm:velocity><fixm:targetAltitude ref=
"MEAN_SEA_LEVEL" uom="METERS">310406
</fixm:targetAltitude><fixm:targetPosition><fixm:pos>
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</fixm:pos></fixm:targetPosition></fixm:position></fixm:enRou
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</fixm:gufi><fixm:operator><fixm:operatingOrganization><fixm:
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</fixm:operatingOrganization></fixm:operator><tss:MissionType
>Launch</tss:MissionType><tss:VehicleTypeID>VehicleRocket
</tss:VehicleTypeID><tss:VehicleTypeElement>Booster
</tss:VehicleTypeElement><tss:VehicleStatus>Nominal
</tss:VehicleStatus><tss:Sensitivity>R
</tss:Sensitivity></fixm:flight></VehiclePositionMessage>
```


Figure 1: R&D SWIM LRVTSS Message Example

Table 2: Aircraft Hazard Area Message Service Data Types

Aircraft Hazard Area Message Service	
Number	**Data Type**
1	AHA Type (Planned, Contingent or Refined)
2	AHA Generation Time
3	Mission Type (Launch/Re-entry)
4	Vendor ID
5	Flight ID
6	Vehicle Type
7	Vehicle Type Element
8	All Clear Time
9	Sensitivity
10	Begin and End Time
11	Upper and Lower Limits (Feet)
12	Position (Latitude-Long)
13	Timestamp (AHA Generation and Message)


```xml
<?xml version="1.0" encoding="utf-8"?><AHA_Message xmlns:gml=
"http://www.opengis.net/gml/3.2" xmlns:aixm="http://www.aixm.aero/schema/5.1.1"
xmlns:aha="us:gov:dot:faa:commercialspace:AHAMS" xmlns:xsi=
"http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation=
"AHA_Message.xsd"><hasMember><aixm:Airspace gml:id="ABC12"><gml:identifier
codeSpace="urn:uuid:">...</gml:identifier><aixm:timeSlice><aixm:AirspaceTimeSlice
gml:id="ID001"><gml:validTime><gml:TimePeriod gml:id="VID000003"
><gml:beginPosition>2020-12-13T11:19:24.560Z</gml:beginPosition><gml:endPosition>
2020-12-13T11:19:24.560Z
</gml:endPosition></gml:TimePeriod></gml:validTime><aixm:interpretation>BASELINE
</aixm:interpretation><aixm:sequenceNumber>1
</aixm:sequenceNumber><aixm:correctionNumber>0
</aixm:correctionNumber><aixm:featureLifetime><gml:TimePeriod gml:id="VID000004"
><gml:beginPosition>2020-12-13T11:19:24.560Z</gml:beginPosition><gml:endPosition>
2020-12-13T11:19:24.560Z
</gml:endPosition></gml:TimePeriod></aixm:featureLifetime><aixm:type>OTHER:AHA
</aixm:type><aixm:designator>ABC12</aixm:designator><aixm:name>LAUNCH DANGER ZONE
</aixm:name><aixm:geometryComponent><aixm:AirspaceGeometryComponent gml:id="C001"
><aixm:theAirspaceVolume><aixm:AirspaceVolume gml:id="V001"><aixm:upperLimit uom=
"FT">UNL</aixm:upperLimit><aixm:upperLimitReference>SFC
</aixm:upperLimitReference><aixm:lowerLimit uom="FT">00000
</aixm:lowerLimit><aixm:lowerLimitReference>SFC
</aixm:lowerLimitReference><aixm:horizontalProjection><aixm:Surface gml:id="S001"
srsName="..."
><gml:polygonPatches><gml:PolygonPatch><gml:exterior><gml:Ring><gml:curveMember><gm
l:Curve gml:id="CUR001"><gml:segments><gml:GeodesicString><gml:posList>
34.259308613888095 -59.54376181946782 34.34898724635531 -59.024874505020705
36.4223396684997 6 -59.55701163678554 6 36.33266103603255 -60.075308471655035
34.259308613888095 -59.54376181946782
</gml:posList></gml:GeodesicString></gml:segments></gml:Curve></gml:curveMember></g
ml:Ring></gml:exterior></gml:PolygonPatch></gml:polygonPatches></aixm:Surface></aix
m:horizontalProjection></aixm:AirspaceVolume></aixm:theAirspaceVolume></aixm:Airspa
ceGeometryComponent></aixm:geometryComponent><aixm:extension><aha:AirspaceExtension
 gml:id="Airspace1_TS1_AHA_EXT1"><aha:AHAType>Planned
</aha:AHAType><aha:AHAMessageType>AA
</aha:AHAMessageType><aha:AHAGenerationTimeStamp>replace_generationtimestamp
</aha:AHAGenerationTimeStamp><aha:EnterNASTime>replace_enternastimestamp
</aha:EnterNASTime><aha:MissionType>Launch</aha:MissionType><aha:VendorID>
OperatorA</aha:VendorID><aha:FlightID>ABC12</aha:FlightID><aha:VehicleTypeID>
VehicleRocket</aha:VehicleTypeID><aha:VehicleElement>Booster
</aha:VehicleElement><aha:AllClearTime>replace_allcleartimestamp
</aha:AllClearTime><aha:Sensitivity>A
</aha:Sensitivity></aha:AirspaceExtension></aixm:extension></aixm:AirspaceTimeSlice
></aixm:timeSlice></aixm:Airspace></hasMember></AHA_Message>
```


Figure 2: R&D SWIM AHAMS Message Example

3.2. Data exchange timeframe and information needs

After the content and format of the data exchange has been determined, the timeframes in which the information should be exchanged and made available to the different stakeholders have to be defined. Three major timeframes have been identified with respect to launch and re-entry operations – prior, during and after the operation takes place. Those data exchange timeframes and the respective information needs which have been identified are shown in Table 3.

Table 3: Data exchange timeframes

Data exchange timeframes and information needs		
PRIOR	**DURING**	**AFTER**
• Mission Briefing • Mission Name • Operator • Launch Site • Launch Date • Launch Time • Planned Trajectory • Key Mission Event List • Contingency Hazard Areas (CHAs)	• Actual Trajectory • Key Mission Event • Refined Hazard Area (RHA) in case of a non-nominal event	• Data analysis focusing on the speed of the data exchange (timelines) and the SWIM connection (producer-consumer) • Lessons Learned

Information exchange PRIOR to launch and re-entry operations does not have to rely on the introduced data formats only. Nevertheless, the information content is in a way the same as defined for the previously defined message formats.

DURING the launch and re-entry event, the information exchanged is based on the LRVTSS and AHAMS message in addition to some other information, e. g. key mission events like the staging of the rocket.

AFTER the operation has taken place, the performance of the data exchange can be evaluated. Also, information should be shared which allows an analysis with respect to the performance indicators relevant for this kind of operation.

3.3. Utilization of exchanged data

The purpose of the described data exchange has already been elaborated at the end of paragraph 2 during the problem statement. The provision of information should allow for an improved situational awareness, preparing all involved stakeholders to take actions when required to maintain the safety of air traffic during launch and re-entry operations. The timely provision of near-real-time data throughout the execution of the launch and re-entry shall allow for fast and efficient measures in case of non-nominal situations to ensure the safety of uninvolved third parties, focusing here on the air traffic and potentially affected airspace users.

Therefore, the selection of information and the allocation of related data to the described data exchange timeframes shall ensure the provision of all required information to traffic flow management, air traffic control centers and air traffic controllers. This should result in an improved situational awareness for ATM stakeholders, allowing them to make informed decisions and act as fast and as effective as possible.

With the transfer of information through a digital exchange, data should be made available in real-time, secure and reliable. It should cover as a minimum the vehicle position, its status and related hazard area information.

Those capabilities allow to integrate such information into air traffic monitoring and control systems, allowing for further automation and decision support. By this the described data exchange is a prerequisite and foundation for higher degrees of automation.

3.4. *Technical setup of a functional data exchange prototype*

To realize a functional prototype of the real-time data exchange, FAA and DLR developed a setup facilitated by available infrastructures and (prototype) tools. Using specific capabilities of the FAA-AST Commercial Space Integration Lab at the FAA William J. Hughes Technical Center (WJHTC) and the DLR Air Traffic Validation Center of the Institute for Flight Guidance, systems were connected for real-time data communication, transmitting LRVTSS and AHAMS data packages, using the FAA R&D SWIM installation at the WJHTC. The DLR systems were connected via VPN with the WJHTC SWIM.

As the demonstration scenarios, described later in section 4, required data flows with different directions, allowing to cover operations from the U.S. with potential effects on European airspace and operations from Europe with potential effects on U.S. airspace, the technical setup and the initiated data flows varied accordingly. Typically, the space vehicle trajectory was simulated using a real-time simulation replay or an excel trajectory re-player. The state vector information was processed and LRVTSS messages generated and transmitted. CHAs for planned trajectories were calculated beforehand and provided through information exchange prior to the simulated operation. Refined Hazard Area (RHA) coordinates were calculated based on actual state vector data and transmitted via an AHAMS message.

On the FAA side, Hazard Risk Assessment and Management (HRAM) capabilities were used to calculate the resulting RHA, in association with functionalities provided by the Space Data Integrator (SDI) prototype, which was also used for visualization of the vehicle trajectory, flight progress information, related AHA and other related status information.

On the DLR side, a generic Spacecraft Hazard Area Server produced RHA information when required.

On the receiving end of the data exchange, the information was processed, verified and visualized. Through the visualization, using either the FAA SDI or the DLR Space Operations Dashboard (SOD, Figure 3), participating stakeholder – like an ATC center supervisor - were able to follow the flight progress and potentially affected areas (CHAs); in case of a non-nominal event, stakeholders could assess the affected region of the resulting RHA and decide on initiating appropriate mitigation measures.

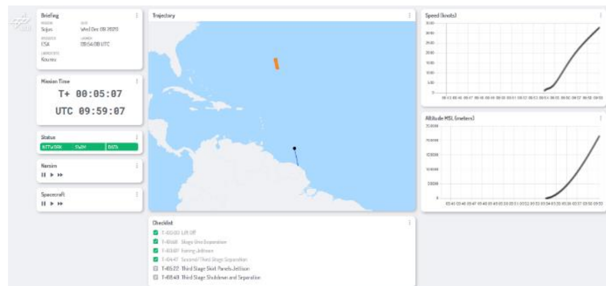

Figure 3: Space Operations Dashboard (SOD)

As part of the DLR setup, RHA information could be forwarded from the SOD workstation, when confirmed by the Supervisor, to an air traffic Controller Working Position (CWP). The technical setup involved a coupling with the DLR air traffic control simulator (Air Traffic Management and Operations Simulator – ATMOS), allowing an air traffic controller to react on getting the RHA displayed at his (prototype) radar display (Traffic & Trajectory Visualization - TTV), where he was controlling simulated air traffic. Similar evaluations addressing the utilization of the data exchange has been performed by FAA using a traffic simulation tool.

Figure 4 shows the data flow which has been established for the U.S.-to-Europe scenarios.

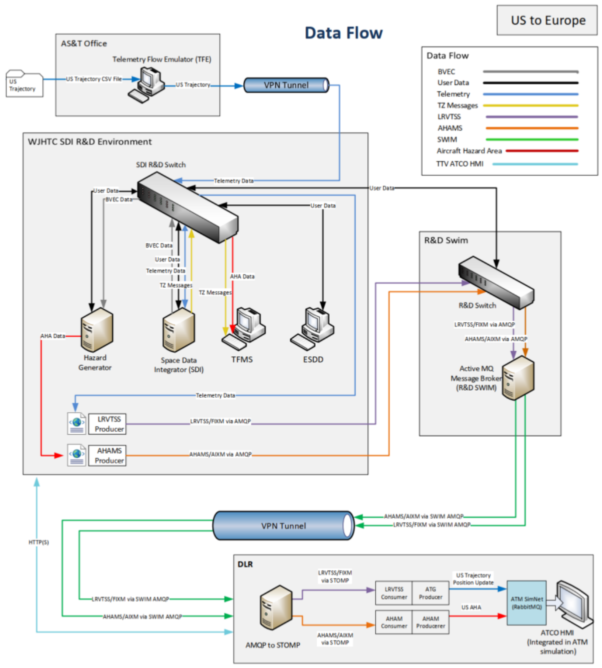

Figure 4: U.S. to Europe Data Flow

4. Experiments and Demonstration

4.1. Scenarios

For demonstrating the data exchange, a number of scenarios have been designed. Those scenarios were then used to simulate the launch event and execute the data exchange using the system setup which has been described in 3.4.

The scenarios consisted of three different flight profiles:

- Simulated launch from Cape Canaveral spaceport Florida for an assumed cargo or crew supply to the ISS
- Simulated launch from Kourou spaceport at French Guiana into a polar / sun-synchronous orbit
- Simulated suborbital A-to-B flight from Europe (Germany) to the U.S. west coast based on the DLR SpaceLiner concept [5]

The flight profiles were combined with a number of event scenarios, representing both nominal and non-nominal flights. Table 4 shows the matrix of the different flight profiles combined with nominal and non-nominal flight progress scenarios.

Four different non-nominal event scenarios have been generated:

- Loss of Signal (LOS), with a re-acquisition of the signal later in the flight
- Diversion (for the suborbital flight – similar to a change of landing site for a horizontal re-entry vehicle)
- Abort (with crew capsule landing)
- On-trajectory explosion

Table 4: Aircraft Hazard Area Message Service Data Types

	US-to-EU	EU-to-US
NOMINAL	**Rocket Launch** (Crewed) Cape Canaveral	**Soyuz** (Cargo) Kourou **SpaceLiner** (Crewed) Germany – US West Coast
NON-NOMINAL	**Loss of Signal** (Crewed) **On-Trajectory Explosion** (Cargo) **Abort** (Crewed) Cape Canaveral	**Loss of Signal** (Cargo) **On-Trajectory Explosion** (Cargo) Kourou **Diversion** (Crewed) Germany – US West Coast

During the scenario runs, data was exchanged in real-time via the described message formats. To cover also the „analogue“ part of communication, which is an essential part of the process to maintain situation awareness and communicate decisions fast and in real-time, certain roles were defined and brought together via a telephone conference. Depending on the scenario team members were representing the Joint Space Operations Group (JSpOG) on the U.S. side of the operations, representatives of the launch and/or reentry vehicle operator, air traffic network operations supervisor and also Air Traffic Control Officers (ATCO) (for parts of the scenarios at which the utilization of exchanged information was analysed up to the ATCO CWP).

In the following, using the *US-to-Europe On-Trajectory Explosion* scenario, the execution of the individual scenarios is explained and the resulting implementation and demonstration of the concept is described in more detail:

In the named scenario a generic space vehicle launch from Cape Canaveral is simulated. The launch trajectory traverses the Atlantic Ocean, with potential debris hazards over European airspace in case of a non-nominal event late in the launch. For the scenario it is therefore assumed that European ANSPs, especially en-route ATCOs are to be involved in the event. The airspace directly around the launch site gets temporarily restricted during the launch window. Airspace further downrange below the flight trajectory is not restricted, hence air traffic is operating normally.

During pre-mission analysis, CHAs have been calculated, providing indications of potentially impacted areas in case of non-nominal events for the whole launch. During launch, telemetry and status information is monitored by the FAA, using the SDI. Within the developed concept, that information is as well shared on the European side, using SWIM for data exchange, showing information on the SOD.

569 sec into the scenario/launch an on-trajectory explosion occurs. This generates debris, which will pass through the atmosphere and controlled airspace down to the ground. The hereby caused Loss of Signal (LOS) and changed status is recognized by the SDI as well as the SOD. The event triggers an RHA calculation, performed with FAA tools. The RHA is specific to the last received state vector and the atmospheric condition at the day of operation. It is therefore smaller than the CHA. The RHA is transmitted via AHAMS message to the SOD on the European side (with DLR in this simulation representing the European ATM stakeholders), where the situation is getting evaluated. Before the debris reaches altitudes of controlled airspace, ANSP decision makers are able to relay the RHA information to the responsible Area Control Centres (ACCs) and from there to the ATCO CWPs. The ATCOs can now react to the received information and the RHA displayed on their radar screen and clear the related airspace. By the time the debris falls through the controlled airspace, air traffic control should already have directed the air traffic out of the RHA.

4.2. Exercises

To evaluate the developed concept, a number of exercises have been performed, applying the described scenarios with the technical implementation for real-time data exchange.

Through a number of technical exercises, the functionality of the data exchange, required CHAs and RHAs calculations, message generation and reception, data processing and visualisation has been verified.

Functional exercises then evaluated the feasibility of the concept and the procedures accompanying the technical data exchange. For each scenario all required roles were occupied by team members from DLR and FAA. Each scenario had a detailed script covering all involved roles, the expected data exchange events and the procedures being performed, including the communication via the running hotline. Each scenario started with the final minutes of the launch countdown and ran through the complete launch operation prior to orbital insertion (or the scripted event), except the SpaceLiner scenarios which started mid-flight to avoid unnecessary waiting times of an otherwise uneventful 90-minute flight progress.

During the performance of each exercise, data transmissions have been recorded and events have been logged, allowing for analysis of data transfer times and reaction times based on available information provided via hotline and data exchange.

4.3. Demonstration

Following the performed exercises, the project concluded with so-called internal and external demonstrations, addressing the extended FAA and DLR teams as well as interested international stakeholders. During the so-called external demonstration, a total of 40 participants from European air navigation service providers, aviation authorities, space agencies and spaceports (Germany, France, Italy, United Kingdom, Sweden, Norway, Finland as well as Eurocontrol) participated, during which several scenario re-runs have been performed and stakeholder feedback has been collected.

As part of the project, to reach out for the public, additional demonstration for students in STEM based courses (Science Technology Engineering Math) have been performed on both sides (U.S. and Europe) using the developed setup.

Due to the fact that the exercise execution and the described demonstrations had to be performed between end of 2020 and mid-2021, the technical setup had to be adapted to accommodate for COVID-19 related restrictions, preventing the project team to use FAA and DLR infrastructures as planned. The system setup had to be changed in a way that allowed the team to operate and execute the exercises out of the Home Office. **Fehler! Verweisquelle konnte nicht gefunden werden.** gives an impression of this alternate exercise execution setup.

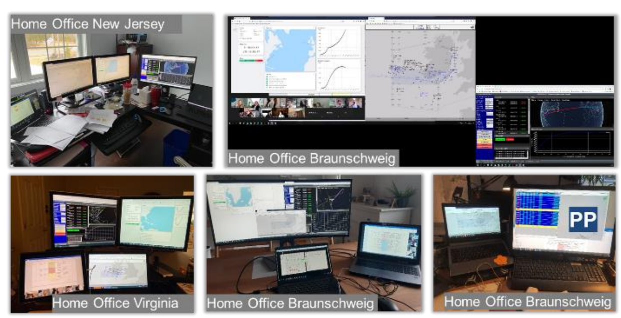

Figure 5: Exercise execution setup

5. Results and Discussion

5.1. Exercise execution and data transmission

Detecting a non-nominal situation usually starts with a LOS. The situation is getting evaluated, which has been covered in the simulation through communication on a hotline between launch operator, JSpOG and Launch operations supervisor. In this process, LOS time and last state vector gets confirmed by the launch operator. The calculation of a RHA is initiated already in parallel, based on the last state vector and transmitted via an AHAMS message to the connected facility on the other side. Times generating the RHA and receipt of the RHA at the other facility are shown in Table 5.

Table 5: Time difference between LOS and RHA reception (time stamps in hh:min:ss)

	US-to-EU			**EU-to-US**	
	LOS	On-Trajectory Explosion	Abort	LOS	On-Trajectory Explosion
LOS detected	13:54:30	14:54:30	15:19:29	15:28:15	15:58:20
Generate RHA	13:55:23	14:55:31	15:20:05	15:29:08	15:58:47
Receipt of RHA	13:55:25	14:55:32	15:20:06	-	-
Time Difference	**55 s**	**62 s**	**37 s**	**-**	**-**

The duration of the sequence between the LOS and the receipt of the RHA on the part of the participating stakeholders varied between 37-62 seconds. Within this timeframe, the generation and transmission of the RHA itself only consumed an amount of 1-2 seconds.

During the exercises and the following data analysis an issue regarding the message reception through SWIM has been discovered. Lost messages between producer and consumer occurred. On several scenarios, the SWIM R&D system dropped every third message. If the AHAMS message was part of the dropped messages, a time stamp for the RHA reception could not be generated (thus the missing times in Table 5 for the EU-to-US scenarios). Those SWIM issues have been investigated in the follow up of the exercise runs and the error could be isolated, identified and corrected. Later test showed correct data handling using the SWIM setup.

Further data analysis showed that data transmission worked equally fast into both directions (<1 sec), data processing from LOS to RHA reception was comparable for both directions and for all tested scenarios.

It has to be emphasised that – after issues in the SWIM R&D system setup have been solved – the communication using SWIM worked well throughout the data exchange demonstration. Nevertheless, in general, data communication setups for mission critical data have to be evaluated against all relevant reliability and security criteria. The important result from the perspective of the DEP is, that by using adequate technical means to exchange launch and re-entry operational data, relevant information can be provided in real time to ATM stakeholders involved in mission critical decision making.

In addition, it must be noted that RHA calculation usually started immediately with the LOS being detected and that the calculation time itself depends on the tool and algorithms used to determine the RHA. Very fast prediction algorithms usually tend to be less accurate, but uncertainties are always compensated “to the safe side”, resulting in potentially larger areas to be protected.

As frequent short disruptions in the data stream might occur during real operations, additional buffer times might be considered to distinct a LOS event from those effects. Nevertheless, a timely initiation of the RHA calculation is critical to provide required data asap when needed.

5.2. Utilization of RHA information at ATCO CWP

To analyse the potential of utilizing data exchange all the way to the air traffic controller, DLR has developed a concept to visualize information at ATCO CWP. This should enable the controller to initiate appropriate measures to protect aircraft from falling debris. The concept has been implemented and evaluated at DLR’s Air Traffic Validation Center and used during the DEP exercises.

If airspace is, due to falling debris, temporarily restricted for aircraft, controllers need three information: First, where the HA is located; second, when the area is active; third, which aircraft are at risk. The Human Machine Interface (HMI) developed makes this information accessible through four additional elements on the radar screen: a button to display the CHA, a representation of the RHA, time indications relating to the RHA and an algorithm that identifies aircraft at risk and highlights them. Figure 6 shows a screenshot of the ATCO HMI used during the DEP exercise runs, with the airspace controlled by the ATCO in a darker blueish grey and the transmitted RHA shown as a dotted line segment (here for the abort-scenario together with a restricted airspace segment covering the drop zone of a capsule in case of a launch abort during a crewed launch).

Evaluation of the visualisation concept has been performed in parallel experiments, which have confirmed the general approach, functionality and layout decision, but also pointed out the need for further research. This has to address specifically the coordination processes between controllers, as it may results in new requirements for such a concept [6].

During the DEP exercises, US-to-EU scenarios resulting in an RHA location south of Ireland (partly) within the simulated Shannon sector, the participating air traffic controller (a former ATCO now working as research associate at DLR) had no issues clearing the related airspace segment and keeping it clear of air traffic during scenario runs. It has to be pointed out that due to the non-nominal situation occurring late in the flight, the resulting RHA was rather long but relatively narrow in size (see Figure 6), causing less issues in keeping it clear of air traffic but resulting in relatively long trajectory extensions to circumnavigate the affected region. These effects were noted but were not in the focus area of the DEP. It is recommended nevertheless to evaluate such effects during follow up activities.

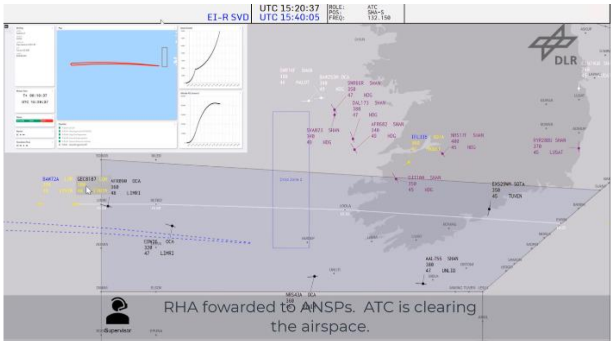

Figure 6: DLR ATCO HMI (TTV) showing transmitted RHA (dotted line segment on the lower left)

On the FAA side, potential utilization benefits of the exchanged data and transmitted RHA by air traffic control has been performed offline using recorded data sets with a traffic simulation tool. Based on the location of the RHA and simulated traffic for the chosen exercise scenario, the potential to clear the affected airspace segment from present aircraft has been evaluated.

5.3. *Stakeholder demonstration feedback*

The developed concept, the functional prototypes and the exercise setup and scenarios have been demonstrated via an online event on July 15th 2021. While the demonstration had been previously planned as an on-location event, COVID-19 travel restriction made it necessary to perform the demonstration online. Through screen sharing and video representation of the previously performed exercises, stakeholders were asked to provide feedback to the concept itself and to point out potential follow up steps based on the achieved results.

Several questions were used to channel stakeholder feedback, like:

- What data should be exchanged for commercial space L&R operations?
- In what timeframe does the data need to be exchanged?
- Who needs the data in a nominal and in an off-nominal case?

In general, the developed concept and its elements received positive feedback, especially the digital data exchange via SWIM and the ability to provide CHAs as initial information, updated then by an RHA when calculated. Similarities between the CHAs and the SESAR concept of Dynamic Manoeuvring Areas (DMA) were pointed out.

The use of SWIM for the provision of time critical data was discussed, some stakeholders consider dedicated data communication protocols to be preferred, but SWIM use is as likely being a key component of ATM at all altitudes for diverse airspace users.

Stakeholder feedback also indicated an interest into more detailed analysis of the traffic impact of the exercise scenarios performed in the DEP simulations, determining how many aircraft had to be diverted due to drop zones or an incoming RHA.

Furthermore, the stakeholder feedback included suggestions and recommendations within and beyond the scope of the DEP itself, such as:

- A determination and creation of regulations with exact term definitions is necessary to create international equality and situational understanding for the integration of STM into ATM.
- Models are needed to accurately calculate RHAs, CHAs and the Instantaneous Impact Point (IIP), where the focus should be on the timing. These must be unambiguous and known to all influenced traffic users.
- Conduct validation as well as quantification of the DEP concept to underscore feasibility. An implementation of the concept in shadow mode was advocated.
- Determining the exact response time available to the debris case is of high interest.
- The difference between oceanic and traditional radar control must be considered for real world use. The implementation of (satellite based) ADS-B is future-oriented and preferable.
- The framework of the DEP could be expanded: Affected interactors with launches beyond aviation should be considered, such as shipping. Who else can benefit from the data and results obtained from the DEP? The feedback confirmed this issue.

Addressing the international coordination, the exchange with potentially involved and affected stakeholders showed that there is yet a lack of awareness and data on the difference of directly and indirectly impacted stakeholders. For example, in a scenario that does not directly affect Europe (no debris falling through European airspace), how is traffic entering the concerned airspace region from Europe affected and how does European ANSPs and airspace users need to be involved.

As pointed out during the discussion, the definition and establishment of communication interfaces between STM & ATM in the European framework will be required. Here, projects in the European SESAR framework like ECHO will likely contribute to addressing these issues.

6. Conclusions

The results of the demonstrations highlighted the need for pre-mission planning and near-real-time mission status updates for increased preparedness, increased situational awareness, and an increased ability to maintain a common operating picture across the participants.

The exercises and demonstrations preformed within the project have shown that commercial space data can be exchanged and utilized for launch and re-entry operation and air traffic management. They also confirmed the importance to provide all relevant information to the stakeholders in the potential need to make decisions related to the safety and efficiency of operation – in the air and in space.

While the scenarios created for the purpose of evaluation and demonstration of the developed concept were based on connecting U.S. and European stakeholders, the concept is transferable to many other missions and launch and re-entry operational situations. This becomes obvious for example, when considering launches affecting airspaces controlled by multiple ANSPs within a European environment or also on a global level.

The implemented data exchange using SWIM showed the feasibility of the chosen technical approach for connectivity and data distribution. While time-criticality and reliability requirements are high for the examined purpose, using only SWIM based communication might proof to be sufficient and dedicated communication protocols and infrastructures might be required. Nevertheless, SWIM may also be used to provide information to other airspace users, enhancing information currently provided through NOTAMS, and adding dynamic functions.

Follow up activities have been identified on the basis of the achieved results. For example, the data exchange has to be implemented into existing or new processes, e. g. within European network operation and air traffic control itself. When exchanging information about hazard and risk contours, international harmonization of risk assessment methods and hazard area calculation becomes more important and might even become a pre-requisite for interoperability, especially when considering licensing of launch and re-entry operations. For cross-border operations, international agreements on how such a concept can be applied to real operations have to be elaborated, including and involving all related stakeholders.

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