Exploratory Research Plan (ERP) for Data Driven Cost Effective 5G Integrated CNS As a Service (ANTENNAE)

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Abstract

This document serves as the initial Exploratory Research Plan (ERP) for SESAR Solution 0521 of the ANTENNAE project, regarding data driven cost effective 5G integrated CNS as a service. It describes the research plan and validation activities that would allow the solution to reach Technology Readiness Level (TRL) 2. The document acts as a guideline for carrying out validation exercises, to demonstrate the feasibility of an architecture based on a CNS-as-a-service deployment on xG hybrid terrestrial

network (TN) and non-terrestrial network (NTN) for low-level (LL) and very low-level (VLL) altitude flights.

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DATA DRIVEN COST EFFECTIVE 5G INTEGRATED CNS AS A SERVICE

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1 Executive summary

This document serves as the Exploratory Research Plan (ERP) for SESAR Solution 0521 of the ANTENNAE project. It describes the research plan and validation activities that would allow the solution to advance from Technology Readiness Level (TRL) 1 to TRL2.

The Solution 0521 aims to validate the use of xG mobile wireless communication technology for very low and low altitude operations of Communication, Navigation and Surveillance (CNS) functions, by exploiting a hybrid terrestrial and non-terrestrial network for provisioning integrated CNS as a service. In the scope of this ERP, we focus on Very Low Level and Low-Level operations ranging from 50 up to 3000 m. Two scenarios will be explored:

- Beyond Visual Line of Sight (BVLOS) UAS operation in the Shannon airport area and the Limerick city (Ireland) using non-xG CNS infrastructure without any aerial user optimization,
- 3D aerial corridors considering the network deployment of a leading commercial mobile network operator in London (UK).

To assess the solution and validate it in terms of the required levels of safety, resilience, redundancy, and CNS performance, the following validation objectives were established according to the specific objectives set in the Solution Grant Agreement (GA) [6]:

- Assess the impact of the ANTENNAE solution's hybrid architecture on network performance for IAM operations,
- Assess the impact of the ANTENNAE solution RAN configuration on IAM operations,
- Assess the impact of the ANTENNAE solution as a potential framework to support A-PNT, A-SUR and JCS.

The primary validation method used across the validation exercises is wireless network system-level Fast Time Simulation. However, each exercise employs a specific validation tool and technique tailored to the expected outcomes, aligned with the validation objectives, and compatible with the appropriate analysis method. Below, are enumerated the validation experiments described in this ERP:

01. assessment of integrated CNS-as-a-Service hybrid network architecture and control policies performance,
02. cellular network optimization for aerial users,
03. evaluation of xG enabled A-PNT, A-SUR and JCS for low altitude.

Therefore, validation exercise #01 objective is to evaluate high-level network performance requirements, traffic control policies, network mobility management, integrated CNS performance requirements, and private network deployment cost evaluation by performing stochastic channel model simulations. In validation exercise #02, ray-tracing tools are used to provide realistic propagation conditions and evaluate Radio Access Network (RAN) configurations, such as antenna tilt and beamwidth, and optimize it for aerial users. In validation exercise #03, the xG-based Navigation

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and Surveillance capabilities are assessed in terms of accuracy, availability, and reliability, by modelling and simulating of xG reference signals that are used to estimate distance, position, and speed.

2 Introduction

2.1 Purpose of the document

This document defines the Exploratory Research Plan (ERP) for ANTENNAE solution (SESAR Solution 0521). The project aims to validate the applicability of 3rd Generation Partnership Project (3GPP) standards and xG technologies for delivering Integrated Communication, Navigation and Surveillance (ICNS)-as-a-service capabilities at low altitudes, considering both Terrestrial Network (TN) and Non-Terrestrial Network (NTN) systems.

In this sense, this document provides a detailed plan for the experimental and validation exercises planned to meet the research and innovation (R&I) needs to take the project from Technology Readiness Level (TRL) 1 to TRL 2. These exercises are motivated by the need to respond to research questions concerning the impact, possibilities and performance of the solution with regard to Low-Level (LL) and Very Low-Level (VLL) airspace, U-space, Unmanned Aircraft Systems (UAS), Vertical Take-Off and Landing (VTOL) Capable Aircraft (VCA), 3GPP TN and NTN.

Exercises are defined not only in terms of the validation objectives they are designed to meet, but also in terms of the methodology used, the limitations encountered, and the analysis methods envisaged once the data have been collected.

2.2 Intended readership

This document is addressed to a broad audience of stakeholders, ranging from ANTENNAE project partners and SESAR JU stakeholders to stakeholders involved in regulating and developing European airspace. The audience includes, but is not limited to:

- **ANTENNAE project and solution partners:** collectively develop content and track its progress,
- **SESAR Joint Undertaking:** follow the progress of the project in its capacity and for its feedback on the present document,
- **Air Navigation Service Providers (ANSPs):** understand the purpose of the solution and potentially prepare for its integration,
- **ATM and U-space service providers:** understand how the ICNS solution supports both ATM and U-space,
- **Standardization bodies:** establish new standards adapted to the new use of Airspace and U-space, CNS technologies,
- **Airport/Airfield and Vertiport owners/providers:** monitor developments in low-level (low altitude) air traffic,
- **Airspace users:** adapt to the arrival of low-altitude operations and to understand how they will be integrated into the airspace,
- **Aerospace industry:** understand advances in ICNS regarding the development and regulation of low-altitude operations,

- **Scientific community:** keep abreast of innovative advances in CNS technologies.

2.3 Background

The feasibility of the ICNS concept was first studied in the SESAR **FACT** (Future All Aviation CNS Technology) project, where 4G and 5G networks were evaluated for this purpose [8]. ICNS has also been studied as part of the **SESAR PJ14-W2-76** (Integrated CNS and Spectrum) industrial research [9]. As the ANTENNAE solution (SESAR Solution 0521) also aims to validate the applicability of existing 3GPP standards, it relies on available standards regarding data service, navigation and surveillance. The Integrated CNS concept was introduced as part of the **European Drone Strategy 2.0** [10]. In Europe, EUROCONTROL works on the relevant matters [18]. At the International Civil Aviation Organization (ICAO) level, a dedicated Integrated CNS and Spectrum Project was established [19].

At present, several SESAR projects are running in parallel with ANTENNAE, involving some of the project's collaborators, enabling collaboration and exchange between the different teams. The **EALU-AER** (Enhanced Automation for U-space/Air Traffic Management (ATM) integration) project [11] is part of the deployment of U-space and integration between U-space Traffic Management (UTM) and ATM, through the development of an infrastructure platform structured around Shannon airport in Ireland. The experimental results and achievements of the project might therefore be used to develop the exercises presented in this document, enabling simulations as close to reality as possible.

Continuing on the subject of U-space, the **SPATIO 2.0** project aims to address the separation between UAS, particularly in the context of strategic and tactical conflict resolution, to enable dynamic, efficient and safe capacity management and avoid collision.

The **FCDI** project's [12] main objective is to improve the communication infrastructure's cost efficiency, by enabling a more extensive use of public networks, allowing communication infrastructure scalability and sustainability with an extended usable spectrum and the use of existing public infrastructures. In addition, FCDI will enable global communication infrastructure interoperability by allowing the use of alternative communication protocols and by accommodating specific technical, commercial and regulatory needs.

Other projects, apart from SESAR, stand out for their synergy with Solution 0521. **ETHER** project [13] develops solutions for a Unified Radio Access Network (RAN) and for the energy-efficient, Artificial Intelligence (AI)-enabled resource management across the terrestrial, aerial and space domains, while creating the business plans driving future investments in the area. To that end, ETHER introduces and combines a series of key technologies under a unique 3D multi-layered architectural proposition that brings together: a User Equipment (UE) antenna design, a robust unified waveform, energy-efficient seamless horizontal and vertical handover policies, network orchestration, a flexible payload system, joint communication, compute and storage resource allocation, and energy-efficient semantics-aware information handling techniques.

The **AiRMOUR** project [14] was a Horizon EU project (2021–2023) focused on integrating Urban Air Mobility (UAM) into emergency medical services. It explored how drones and air taxis could support healthcare logistics, such as transporting doctors or medical supplies. Real-life demonstrations took place in Finland, Norway, and Germany, with simulations in Luxembourg and Dubai. The project produced tools and guidance for cities and operators, including a UAM guidebook, GIS planning tools, and public acceptance studies. It was coordinated by VTT Technical Research Centre of Finland and funded by the EU's Horizon 2020 programme.

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The **INSTINCT** project [15] is an ongoing effort (2024-2026) funded by the SNS JU (HORIZON-JU-SNS-2023-STREAM-B-01-02) focused on joint sensing and communications for future immersive and intelligent connectivity, where TID is a partner. The project involves research activities aimed at integrating localization, tracking, mapping, monitoring, imaging, incident detection, and semantic capabilities into connectivity services. Some of these activities include radio propagation simulation via ray tracing tools, such as Sionna RT, which leverage accurate GIS data from dense urban areas in the UK.

The **ORIGAMI** project [16] is an ongoing initiative (2024–2026) funded by the SNS JU (HORIZON-JU-SNS-2023-STREAM-B-01-01), aimed at advancing next-generation mobile network architectures by addressing key challenges related to highly resilient global connectivity and efficient integration of computing resources. The project introduces three core architectural innovations: Global Service-Based Architecture (GSBA), Zero-Trust Exposure Layer (ZTL), and Compute Continuum Layer (CCL), along with multiple Network Intelligence (NI) solutions enabled by these advancements. This project is coordinated by TID.

The **6G-MIRAI** project (2025–2028) [17], funded by the SNS JU under HORIZON-JU-SNS-2024-STREAM-B-01-05, aims to develop reliable, AI-native wireless communication systems that fully leverage the latest technological advances in the physical layer—particularly cell-free massive MIMO—and next-generation virtualized and disaggregated RANs. Key research areas include the development of realistic channel and hardware models to support AI-native air interfaces, practical AI-driven physical layer designs, and scalable AI-based network coordination. The project seeks to establish a close collaboration between leading industry stakeholders and academic institutions across the EU and Japan, aligned with the EU-Japan Digital Partnership. TID is a member of the project consortium.

2.4 Structure of the document

The present document is divided in 6 chapters according to the following structure:

- **Chapter 1 – Executive summary**: summarises the key elements and concepts of the SESAR solution ERP,
- **Chapter 2 – Introduction**: presents the purpose and scope of the document. It also introduces the document's target audience and the background on which the project is based. A glossary of terms and a list of acronyms are provided for ease of reading,
- **Chapter 3 – Context of the exploratory research plan**: provides the context in which the ERP is written, in terms of scope, R&I needs, performance and maturity level,
- **Chapter 4 – Exploratory research plan**: Covers the approach envisaged by the ERP to progress towards the targeted maturity level. It details the involvement of the various stakeholders, the validation objectives and relative assumptions, and the list of associated validation exercises and planning,
- **Chapter 5 – Validation exercises**: Contains details of the validation exercises, describing their scope and setting them in the context of the solution in terms of stakeholders and objective validation, as well as providing their limitations. The section also defines the tools used to carry

out the exercises, the data collection elements and the schedule for each activity within the exercises,

- **Chapter 6 – Reference**: provides a list of the reference documents used in the preparation of this document.

2.5 Glossary of terms

Term	Definition	Source of the definition
5GA	In Rel. 18, the 3GPP envisions to enhance the performance of the current 5G standard enabling new use cases, bringing energy efficiency, intelligent Radio Access Network (RAN) automation, non-terrestrial networks, Multiple Input Multiple Output (MIMO) evolution, and including services that focus on uplink communication and connect people moving at high velocities.	3GPP Third Generation Partnership Project [20]
Air Traffic Management	The dynamic, integrated management of air traffic and airspace including air traffic services, airspace management and air traffic flow management – safely economically and efficiently – through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions.	ICAO 4444 [21]
Exploratory Research	Explores new concepts beyond those identified in the European ATM Master Plan or emerging technologies and methods. The knowledge acquired can be transferred into the SESAR industrial and demonstration activities.	European ATM Master Plan [22]
Integrated CNS	A unified system that enables interdependency between communication, navigation, and surveillance (CNS) technologies, taking full advantage of cross-domain synergies to improve service quality, spectrum efficiency, and CNS capabilities.	ANTENNAE project initial definition
Low-Level Altitude	Altitude within 8 300 metres or 27 230 feet above Mean Sea Level (MSL) 10 000 ft MSL is an upper limit for low-altitude IAM operations.	ANTENNAE project initial definition

Very Low-Level Altitude	Altitude below 150 meters or 500 feet AGL	ICAO UTM Framework Edition 4 [23]
Unmanned Aircraft System (UAS)	Unmanned aircraft system (UAS) means an unmanned aircraft and the equipment to control it remotely	Commission Delegated Regulation (EU) 2019/945 of 12 March 2019 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems, European Commission, 2019, C/2019/1821 [24][25]
U-space	U-space airspace means a UAS geographical zone designated by Member States, where UAS operations are only allowed to take place with the support of U-space services U-space service means a service relying on digital services and automation of functions designed to support safe, secure and efficient access to U-space airspace for a large number of UAS	Commission Implementing Regulation (EU) 2021/665 of 22 April 2021 on a regulatory framework for the U-space (C/2021/2671) [26] SESAR Smart ATM U-space and urban air mobility [27]

Table 1: glossary of terms

2.6 List of acronyms

Term	Definition
3GPP	3rd Generation Partnership Project
5G	5th Generation of Cellular Network
ADS-B	Automatic Dependant Surveillance-Broadcast
ADS-C	Automatic Dependant Surveillance-Contract
AI	Artificial Intelligence
ANSP	Air Navigation Service Provider
AOA	Angle Of Arrival
AOC	Air Operator Certificate
AOD	Angle Of Departure
A-PNT	Alternative Position Navigation and Timing

A-SUR	Alternate Surveillance
ATM	Air Traffic Management
BS	Base Station
BVLOS	Beyond Visual Line Of Sight
CA	Collision Avoidance
CAP	Capacity
CEF	Cost Efficiency
CISP	Common Information Service Provider
CNS	Communication Navigation Surveillance
ComReg	Communication Regulation
DAA	Detect And Avoid
DES	Digital European Sky
DMRS	Demodulation Reference Signal
DRL	Deep Reinforcement Learning
ENV	Environment
ERP	Exploratory Research Plan
eSIM	Embedded SIM
EXE	Exercise
FR2	Frequency Range 2
GA	Grant Agreement
GNSS	Global Navigation Satellite System
GUE	Ground User Equipment
HE	Horizon Europe
HEMS	Helicopter Emergency Medical Services
HPBW	Half-Power Beam Width
IAM	Innovative Air Mobility

ICAO	International Civil Aviation Organization
ICNS	Integrated CNS
ID	Identifier
JCS	Joint Communication and Sensing
KPA	Key Performance Area
KPI	Key Performance Indicator
LEO	Low Earth Orbit
LL	Low-Level
LoS	Line-of-Sight
MNO	Mobile Network Operators
N/A	Not Applicable
NLoS	Non-Line-of-Sight
NTN	Non-Terrestrial Network
OFDM	Orthogonal Frequency-Division Multiplexing
OSED	Operational service and environment description
PI	Performance Indicator
PRS	Positioning Reference Signal
R&I	Research and Innovation
RAN	Radio Access Network
RB	Resource Block
RedCap	Reduced Capability
RSSI	Received Signal Strength Indicator
RTK	Real-Time Kinematic
SAF	Safety
SAR	Search and Rescue
SBAS	Satellite-Based Augmentation System

SEC	Security
SESAR	Single European Sky ATM Research
SESAR 3 JU	SESAR 3 Joint Undertaking
SIM	Subscriber Identity Module
SINR	Signal-to-Interference-plus-Noise Ratio
TDOA	Time Difference Of Arrival
TN	Terrestrial Network
TOA	Time Of Arrival
TRL	Technology Readiness Level
TTT	Time-To-Trigger
UAS	Unmanned Aircraft Systems
UE	User Equipment
USSP	U-space Service Provider
UTM	U-space Traffic Management
VCA	VTOL Capable Aircraft
vHPBW	Vertical Half-Power Beam Width
VLL	Verry Low-Level
VTOL	Vertical Take-Off and Landing
xG	x^{th} Generation of Cellular Network

Table 2: list of acronyms

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3 Context of the exploratory research plan

3.1 Exploratory research plan context

The development of this ERP takes place with the aim of bringing the ANTENNAE solution (SESAR Solution 0521) from TRL1 to TRL2 maturity level. The solution aims to validate the applicability of 3GPP standards to deliver low-altitude CNS functions using xG terrestrial and non-terrestrial networks according to ICNS-as-a-service model, in the context of the emergence of U-space within European airspace.

The experimental conditions described in this document must therefore meet a number of characteristics essential to the evaluation of the solution. These characteristics derive directly from the research questions detailed in Section 3.3.

The specific requirements of a ICNS network for VLL and LL altitudes will be examined. The ability to ensure continuity of coverage using both TN and NTN, and the management policies arising from this hybridization, will be examined. Network configurations enabling such operation will be evaluated. The solution also looks at the possibilities offered by ICNS in terms of Alternative Positioning, Navigation and Timing (A-PNT), Alternate Surveillance (A-SUR) and Joint Communication and Sensing (JCS) for low-altitude operations.

Setting up validation exercises and experiments therefore requires defining a scope of application subject to several assumptions. The main ones concern xG networks, for which we assume deployment, resilience and security, as well as certification for UAS. Full details of the assumptions are given in section 4.4, particularly with regard to network integration and U-space.

The ANTENNAE solution (SESAR Solution 0521) targets **xG (i.e. 5G, 6G, etc.)**, **which encompasses 5G and further standards**. For this reason, we will prefer the use of the term xG over 5G in this document. However, occasional references to 5G remain, as it is currently the generation defined and deployed under 3GPP mobile communication standards.

3.2 Scope

In this section we will provide the scope definition of the exploratory research plan. The ANTENNAE solution general objective in the Grant Agreement (GA) [6] proposes to develop 5G network system level simulations to develop and demonstrate a cost-effective integrated communication, navigation and surveillance services setup for Innovative Air Mobility (IAM) operations in low-level altitude. This general objective unfolds in several specific objectives, which are enumerated below:

1. Low altitude-specific network configuration & management policies to deliver cost-effective CNS-as-a-service in low altitude operations, across all stakeholders.

2. Hybrid network architectures comprising terrestrial & non-terrestrial network segments for increased availability & resilience.

3. RAN optimization solutions for antenna configurations, such as tilt and beamforming, and spatial-domain interference mitigation to achieve coexistence of ground and aerial users.

4. A-PNT and A-SUR system performance validated, and positioning & integrity algorithms specified for low-altitude operation.

5. Validation of identified Key Performance Indicators (KPIs) for a 3GPP 5G-aligned network for CNS-as-a-Service for low altitude operations.

These specific objectives are first turned into the list of research questions and Research and Innovation (R&I) needs in Section 3.3, and further in the three research plan validation objectives briefly listed below, but we elaborate more on these plan validation objectives in Section 4.3:

- Assess the network high-level performance,
- Validated network control policies and network configurations,
- Assess the terrestrial network RAN configuration and policies,
- Evaluate the xG-based A-PNT, A-SUR, and JCS systems performance.

Therefore, to fulfil the objectives in the research plan we describe three validation exercises using fast time system level simulations as the main validation technique, as the general and specific objectives as described in the GA were planned to be validated through system level simulations.

In the course of the project development three validation exercises will be carried out, which are detailed in Chapter 5. The goal of **validation exercise #1** proposed is to address all the higher layers network performance evaluations, such as the coverage continuity, mobility management, network control policies and if the network achieved KPI are enough to support CNS as a service. For modelling the physical and link layer with more accuracy we propose to use ray-tracing tools in the **validation exercise #2** and investigate the impact of antenna tilt and beamforming on the cellular network performance and optimize the RAN configuration. A different setup is proposed for **validation exercise #3**, which will be used to assess the network capabilities for A-PNT and A-SUR, i.e., if it is possible to meet the accuracy, timing and availability performance requirements.

Further details of the validation exercises and activities can be found in Chapter 5 and in the STELLAR platform.

3.3 Key R&I needs

ANTENNAE solution (SESAR Solution 0521) is at the core of the development of U-space and Innovative Air Mobility operations in European airspace. Performance requirements in terms of communication, navigation and surveillance are becoming increasingly complex and demanding, especially in a low-altitude context. It is therefore essential to find new ways of providing CNS functions in a context of traffic growth and development. By proposing the use of an ICNS service unifying the three fragmented domains via dedicated xG networks based on emerging 3GPP standards, the solution raises a major question: **is xG offering enough resources to provide ICNS-as-a-service capabilities for U-space users?**

Several research questions arise from this problem statement, helping to structure efforts in order to address all identified challenges and to advance the SESAR solution to a higher maturity level:

- What are the low altitude-specific network configuration & management policies to deliver cost-effective CNS-as-a-service in low altitude operations across all stakeholders?
- Using the hybrid TN-NTN connectivity framework, which network configurations can achieve sufficient and continuous coverage for VLL and LL IAM operations?
- What mobility algorithms and network management policies will support aerial user network mobility?
- Which RAN optimization solutions for antenna configurations will allow coexistence between aerial and ground users?
- Are the 3GPP 5G/xG standards capable of offering A-PNT, A-SUR and Joint Communication and Sensing (JCS) system performance, and positioning & integrity algorithms specified for VLL and LL IAM operations?

These questions serve as the axes around which the exercises and validation objectives, detailed in Chapter 4, are structured. In Table 3, we summarize the R&I needs, correlating with the research questions.

KPAs	R&I needs/Research Question
R&I-01	What are the low altitude-specific network configuration & management policies to deliver cost-effective CNS-as-a-service in low altitude operations across all stakeholders?
R&I-02	Using the hybrid connectivity framework, which network configurations can achieve sufficient and continuous coverage for VLL and LL IAM operations?
R&I-03	What mobility algorithms and network management policies will support aerial user network mobility?
R&I-04	Which RAN optimization solutions for antenna configurations (e.g., tilt, beam pattern) will allow coexistence between aerial and ground users?
R&I-05	Are the 3GPP 5G/xG standards capable of offering A-PNT, A-SUR and JCS system performance, and positioning & integrity algorithms specified for VLL and LL IAM operations?

Table 3: ANTENNAE solution R&I and research questions summary

3.4 Estimated performance contributions

ANTENNAE solution (SESAR Solution 0521), although not labelled as a U-space or IAM solution, focuses on LL and VLL airspace within 4 000 ft AGL, where the majority of the IAM operations are expected to take place. Using AGL instead of MSL as an altitude reference for the majority of the IAM operations is justified by the fact that some cities are located in highly elevated geographical areas, while the technical capability of many VCA will allow such operations, and the ground infrastructure, particularly enabling CNS, operates using AGL measures. Operational altitude within 4 000 ft (about 1200 m) includes VLL altitudes, which is 500 ft (150 m) where the majority of the U-space operations are expected. Operations at these altitudes are expected to be performed mostly by UAS and VCA,

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although not exclusively. General aviation, Search and Rescue (SAR), and Helicopter Emergency Medical Services (HEMS) operations, first responders, and many others may happen at those altitudes or penetrate them for take-off or landing. The impact of the solution will therefore be predominantly on these aircraft types, even though by extension on U-space rather than ATM.

At solution level, this means that **U-space KPAs are more relevant than ATM KPAs**, which are highly focused on commercial aviation. We have therefore chosen to use the DES performance framework – U-space companion document [3] for providing the estimated performance contribution. These performances are listed in Table 4.

KPAs	PIs	PIs Definition	Estimated impact
Capacity (CAP)	**U-space Capacity Focus Area**		
	U.CAP1	U-space maximum number of drones (Number of drone operations per unit of time).	**Low:** By providing easier access to CNS services, the deployment of Solution 0521 would help to facilitate an increase in U-space capacity, although this is not the primary objective of the solution. The solution also aims to ensure that services can continue to operate even in the event of high aircraft and/or UAS density, making it compatible with capacity increases that may also be envisaged in the future.
Cost Efficiency (CEF)	**U.CEF4**	USSP Cost of additional ground infrastructure	**Medium:** As the use of xG increases, Solution 0521 will inevitably require the deployment of new ground infrastructures or networks. The private or public nature of these infrastructures remains to be defined. A surplus of data is also expected with the use of the xG networks and the increased accessibility to the U-space it will bring, in comparison with the default U-space deployment requiring data processing and storage hardware and software. The operating costs are primarily driven by the maintenance of the added infrastructure, including hardware and software, which demand updates and technical support, also increasing the labour costs.
Safety (SAF)	**U.SAF1**	Total number of estimated accidents	**Medium**: Solution 0521 expects to meet all existing safety standards, in addition to providing

		with U-space contribution per year	alternatives to traditional methods of navigation and surveillance through A-PNT and A-SUR, respectively. In addition to providing redundancy, these techniques would address known Global Navigation Satellite System (GNSS) vulnerabilities and the risk of congestion on the 1090 MHz frequency.
Security (SEC)	**SEC1**	A security risk assessment has been carried out	**Medium**: The security **KPA won't be measured directly from the validation exercises**. A security assessment will be carried out following the SecRAM 2.0 methodology [5], to identify potential security risks associated with the use of ICNS-as-a-service. It should also be noted that the use of A-PNT could reduce the security risks associated with GNSS vulnerabilities.
	SEC2	Security requirements have been derived	
	SEC3	Risk Level – 2 possible levels: medium/low	
Environment (ENV)	**Emissions Focus Area**		
	U.ENV1	Actual Average CO_2 Emission per flight	**Low:** Despite the need to deploy new infrastructure, the 0521 solution would largely reuse existing ones, limiting the CO_2 emissions that its implementation would generate. Then, the additional coverage offered by the hybrid 5G TN-NTN may enable more efficient aircraft flight routes. Additionally, enabling the use of electricity-powered UAS to perform cargo delivery missions and VCA-based cargo and passenger operations can reduce the number of car trips and helicopter flights.

Table 4: Solution 0521 estimated performance contributions

3.5 Initial and exit maturity levels

Project/ Proposed SESAR solution(s) ID	Proposed SESAR solution(s) title	Initial maturity level	Exit maturity level	Reused validation material from past R&I Initiatives

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SESAR Solution 0521	Data driven cost effective 5G integrated CNS as a service (ANTENNAE)	TRL1	TRL2	Not Applicable

Table 5: maturity levels table

The initial maturity level of Solution 0521 is TRL1. The solution is now in a phase of applied research, shifting away from the domain of scientific research and placing it at the heart of a concrete context: the development of U-space in European airspace.

As shown in Table 5, the aim is to achieve TRL2 through the various validation exercises detailed in this document and the analysis arising from their results. As expected of a TRL2 project, the research questions are refined, as described in Section 3.3.

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4 Exploratory research plan

4.1 Exploratory research plan approach

The ANTENNAE solution (SESAR Solution 0521) research plan aims to describe the validation activities that will be carried out during the project. Such validation activities mainly involve simulation and modelling of 3GPP wireless networks to validate the solution proposed architecture based on a CNS as a service deployment on xG hybrid terrestrial and non-terrestrial network for low level and very low-level altitude flights. At last, the simulation and modelling exercises proposed in this research plan will help to proof the viability of the CNS as service concept utilizing public commercial ground xG networks and satellite communication combined to increase U-space and IAM resilience, safety, and situation awareness.

The validations exercises will address the specific objectives enumerated in the GA [6] and described in Section 3.3, which were also linked to the research and innovation needs. The specific objectives can be combined into validation objectives due to the overlapping scope of some specific objectives: **assess the impact of the ANTENNAE solution's hybrid architecture on network performance for IAM operations** (OBJ-ANTENNAE-TRL2-ERP-001), which comprises of a network performance evaluation to benchmark the main metrics, such as coverage, packet drop, latency, and capacity; **assess the impact of the ANTENNAE solution network RAN configuration and policies on IAM operations** (OBJ-ANTENNAE-TRL2-ERP-002), that consists on assessing networking configuration and traffic control policies that can enable performance and cost-efficiency**; assess the impact of the ANTENNAE solution as a potential framework to support alternative Navigation and Surveillance techniques (A-PNT, A-SUR and JCS)** (OBJ-ANTENNAE-TRL2-ERP-003), which will cover the experiments of alternative navigation and surveillance techniques in a xG hybrid terrestrial and non-terrestrial network environment. Figure 1 illustrates the validation exercise assessments using U-space CNS applications as example.

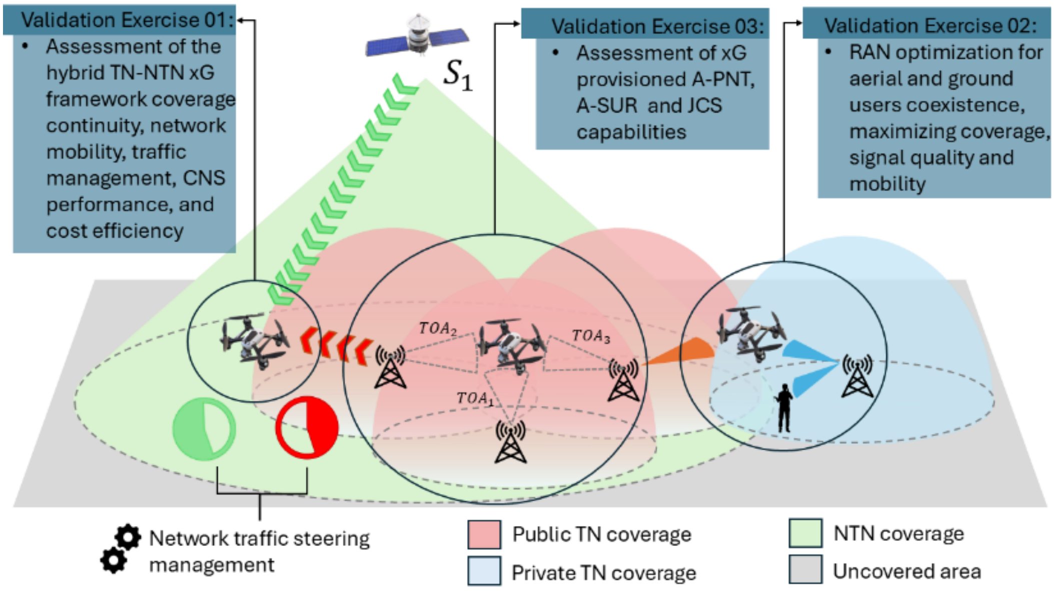

Figure 1: Illustration of validation exercises assessment mechanisms

The aforementioned validation objectives will be fulfilled by three validation exercises. The validation exercise #01 focus on system level performance evaluation, which comprehends several important aspects of the network, such as coverage, mobility management, traffic steering, Communication, Navigation, and Surveillance performance, which are under the umbrella of validation objective OBJ-ANTENNAE-TRL2-ERP-001. The validation exercise #02 provides the requirements for OBJ-ANTENNAE-TRL2-ERP-002, by using ray-tracing tools to emulate the propagation conditions expanding the research outcomes to the physical layer and its configurations to provide CNS services to aerial users via RAN configuration optimization, while still assuring the adequate quality of service to ground users. Finally, OBJ-ANTENNAE-TRL2-ERP-003 requirements will be fulfilled by validation exercise #03, that simulates ground and non-terrestrial network alternative navigation and surveillance capabilities. The goal of the latter is to assess the feasibility of the alternative techniques for navigation and surveillance on xG hybrid network as potential.

The validation exercises share data between them, but no interdependency exists between them. Once the scenarios are chosen, the input data are sourced, and simulation and modelling parameters are defined, the validation exercises can be executed simultaneously or without a mandatory order. This initial phase of scope definition is crucial to the validation exercises and a risk assessment is necessary to mitigate the impacts on each validation exercise, as detailed in Chapter 5. Besides, internal validation with all the project participants, with the project advisory board, and invited experts will help ensuring the development and progress of the validation exercises. The outcomes of each validation exercise will support the solution qualitative analysis, which will be highlighted in the other solution deliverables, and elevate the solution to TRL2.

In Sections 4.3 and 4.5, all the validation objectives and validation exercises are listed, as well as their respective success criterion and variables. The results of the validation exercises are directly related the network performance, although if the performance is found adequate, the solution will directly impact several KPAs. Thus, the main contributions of this research plan include the following KPAs: **Safety**, due to the improved situational awareness, increasing robustness, resilience ,and redundancy; **Cost Efficiency**, resultant from the low-cost of xG commercial off-the-shelf (COTS) devices and widespread services; **Capacity**, that will increase due to the growing number of UAS in operation; **Environment**, that will result from a larger network coverage, reducing the flight routes and the CO_2 emissions.

4.2 Stakeholders' expectations and involvement

The implementation of Solution 0521 will have an impact on many stakeholders. Whether these stakeholders are directly involved in permitting the implementation of the solution, or are impacted by it at a later stage, it is necessary to examine why the research and the results of the validation exercises are important to them. These points are discussed in Table 6.

Stakeholder	Involvement	Why it matters to the stakeholder
European Institutions (SESAR, European commission)	Responsible for the future of European airspace, the European institutions are behind the project, its organization and financing.	As project coordinators, the institutions must be kept informed of project progress. It is therefore essential for them to ensure that the project is running properly, that it is relevant to the

		ATM master plan, and that it is coordinated with other projects. European institutions are directly involved in the development of the solution, and the results obtained will enable the solution to be definitively included in the plans for the future of European airspace. **KPAs of interest**: All.
U-space Service Providers (USSPs)	In charge of ensuring an efficient and safe management of UAS in U-space, USSPs are at the forefront of interest in the solution. They must therefore be kept informed of any advances in CNS technology for U-space and VLL.	By proposing to use xG networks to implement an ICNS-as-a-service model, Solution 0521 offers a means of providing CNS technologies LL and VLL altitudes, particularly suited to the U-space context. The same applies to the use of xG as a potential framework for supporting alternative CNS techniques. The results of the validation exercises will give clear indications of the possibilities of moving towards the use of xG for CNS technologies. Even if they do not have an immediate impact on USSPs, they will enable them to prepare and anticipate future use. **KPAs of interest**: Capacity, Cost Efficiency, Safety, Security.
Common Information Service Provider (CISP)	The CISPs are responsible for collecting data from the various stakeholders operating in the airspace and transmitting it to the USSPs. They must therefore be kept informed of any advances in CNS technology for U-space and VLL.	The solution, based on the concept of ICNS, provides a means of offering CNS services, particularly suited for LL and VLL operations, which may occur within the U-spaces. ISPs are on the front line regarding the use of xG for CNS technologies, and the results of the validation exercises are therefore of prime importance so that they can consider and prepare for future use. **KPAs of interest**: Capacity, Cost Efficiency, Safety, Security.

Air Navigation Service Providers (ANSPs)	Responsible for the organization and structure of airspace, they must ensure the maintenance of an airspace offering adequate capacity, safety, flexibility and responsiveness. The integration of new vehicles into the airspace and the associated standards will be carried out under ANSP supervision.	To perform their duties, ANSPs require functional CNS services and thus benefit from with advances in CNS technologies. Once again, the results of the validation exercises will give clear indications of the possibilities of moving towards the use of xG for CNS technologies and will enable ANSPs to prepare and anticipate future use. **KPAs of interest**: Capacity, Safety, Security.
Standards Organizations	Standards organizations are responsible for developing new standards for European airspace, aviation and aeronautical equipment, which are then applied by regulators. As such, their expertise is essential to any project requiring changes to regulations.	New standards will need to be developed in order to implement the solution. These new standards will concern both the use of xG for ICNS and the implementation of U-space. The results obtained by Solution 0521 can give precise indications for the establishment of future standards, so it is in the interest of standardization bodies to follow their outcomes closely. **KPAs of interest:** Capacity, Safety, Security.
Regulators	Regulators are in charge of developing and applying regulations to ensure the safety and efficiency of air traffic. Their role is to ensure that new technologies comply with existing airspace requirements, in order to guarantee quality of service.	The modernization of European airspace and the application of the new standards required by the solution will be carried out by regulators. It is therefore in their interest to follow the development of ICNS, U-space and related technological solutions. The results of the validation exercises can provide regulators with information to anticipate the regulations to be developed for deployment of the solution. **KPAs of intertest**: Capacity, Safety, Security.
Telecommunication operators (Satellite operators and	Companies enabling access to xG networks by deploying and	As Solution 0521 is centred around the use of xG networks and satellite broadband services, the participation of

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Mobile network operators)	maintaining the required infrastructure.	telecommunications operators will be essential to its implementation. The results of the simulations will therefore be of prime importance to them. In fact, by providing indications of the coverage and network infrastructures required for deployment in both urban and rural LL and VLL areas, their exploitation will enable an initial techno-economic analysis of the interest of operators in getting involved in the project. **KPAs of interest**: Capacity, Security.
Network Managers	Network Managers are in charge of managing ATM network functions, as well as resource sharing within European airspace. Any new use of these resources will therefore be under their control.	As the solution relies on the use of 5G to deliver a number of important services, Network Managers will have a key organizational role to play in its deployment. The results of the validation exercises are important for network managers, in order to anticipate future functions that could be implemented and the new resource management related to the new use of xG networks. They would therefore be particularly interested in exercises involving hybridization between xG, NTN and private TN networks, as well as those linked to TN-TNT handovers. **KPAs of interest:** Capacity, Cost Efficiency, Security.
Airspace users	All users of European airspace, from airliners to UAS and military aircraft, must comply with all existing regulations.	As the first to be affected by the implementation of a solution, keeping abreast of its progress and the new features it will bring can facilitate its subsequent implementation. The results of the validation exercises can give them a first insight into the potential offered by the solution.

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		KPAs of interest: Capacity, Cost-Efficiency, Safety, Security.
UAS Operators	Accountable for all the drone operations it performs. It is the equivalent of the airline for the pilot in manned aviation. It could be civil, military, an authority (special) or a flight club.	UAS operators are the beneficiaries of CNS services. The results of the validation exercises will elaborate on the benefits of using the ICNS and enable them to anticipate potential future uses. **KPAs of interest**: Capacity, Safety, Security.
UAS manufacturers	UAS manufacturers have a responsibility to design aircraft that comply with the safety and performance standards required to operate in European airspace.	As this solution directly concerns UAS, manufacturers are well advised to keep abreast of its progress. The development of ICNS using 5G will make a major contribution to the implementation of U-space and IAM operations in general. By keeping abreast of the validation exercises results, the UAS and VCA manufacturers can also prepare for the necessary adaptations to come. **KPAs of interest**: Cost-Efficiency, Safety, Security.
Scientific community	By regularly contributing new advances in the fields related to the development of the solution, the work of the scientific community indirectly helps and participates in its development.	For the scientific community, the validation activities shown in this document can serve as a basis for future innovation and research relevant to U-space and IAM and aviation in general. **KPAs of interest**: All.

Table 6: stakeholders' expectations and involvement

4.3 Validation objectives

In this section we detail the solution validation objectives required for exploratory research plan. For better understanding, we propose Table 7, which links the solution validation objectives to the R&I needs and research questions in Section 3.3. In addition, included a table to summarise validation objectives' variables, which can be found after the validation objectives and validation success criteria tables for each validation objective. The validation objectives' variables are classified into the **dependent** (the ones that are measured and tested in an experiment), **independent** (the variables manipulated in the experiment) and **control** (the constant variables that should not interfere with the

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results) variables. The remainder of this section details each solution validation objectives and its respective success criteria and variables.

Objective Identifier	Validation Objectives	R&I Need
OBJ-ANTENNAE-TRL2-ERP-001	Assess the impact of the ANTENNAE solution's hybrid architecture on network performance for IAM operations	R&I-01, R&I-02, R&I-03
OBJ-ANTENNAE-TRL2-ERP-002	Assess the impact of the ANTENNAE solution RAN configuration policies on IAM operations	R&I-03, R&I-04
OBJ-ANTENNAE-TRL2-ERP-003	Assess the impact of the ANTENNAE solution as a potential framework to support alternative Navigation and Surveillance techniques (A-PNT, A-SUR and JCS)	R&I-05

Table 7: ANTENNAE Solution validation objectives

The validation objective **OBJ-ANTENNAE-TRL2-ERP-001** refers to the assessment of network performance indicators. This validation objective requires a careful definition of the validation scenarios and the development of the necessary features to simulate such scenario as a pre-validation phase. In the post-execution phase, we are interested on investigating the network coverage extension and continuity in the scenario, for both TN and NTN, as well as the performance attained against the required CNS services performance requirements, such as latency, availability, capacity, and messages per second.

[OBJ]

Identifier	OBJ-ANTENNAE-TRL2-ERP-001
Objective	Assess the impact of the ANTENNAE solution's hybrid architecture on network performance for IAM operations
Title	Network performance assessment
Category	<performance>, <operational feasibility>
Key Environment conditions	Nominal conditions, IAM, European cities, drone operations, satellite communication
TRL level	TRL 2

[OBJ Suc]

Identifier	Success Criterion
CRT-ANTENNAE-TRL2-ERP-001-001	Solution 0521 meets the performance requirements for the terrestrial and non-terrestrial network coverage at different altitudes (RSSI greater than -94dBm for terrestrial network [28] and RSSI greater than -96dBm [29] for non-terrestrial network) for 99.9% of the flight route [30]

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CRT-ANTENNAE-TRL2-ERP-001-002	Solution 0521 meets the performance requirements for surveillance message delivery rate greater than 99% for 1 message per second [31]
CRT-ANTENNAE-TRL2-ERP-001-003	Solution 0521 meets the performance requirements for BVLOS operation for urban and remote areas of data rate > 5 Mbps and end-to-end latency < 100 ms (for 720p video streaming, plus C2, telemetry, and situational aware report) [32]
CRT-ANTENNAE-TRL2-ERP-001-004	Solution 0521 meets cost efficiency targets (operational cost per Gbps < 0.05USD [33]) comparing fair queuing and cost-aware network control traffic policies for both commercial MNO network and hybrid private and commercial network

Table 8 details the validation objective OBJ-ANTENNAE-TRL2-ERP-001 variables and classify them according to the roles they will play in the validation exercise as independent, control and dependent variables. These variables will be assessed quantitatively to provide a better understanding of the performance offered by the hybrid TN-NTN network proposed in the solution and the network control policies. Hence, we qualitatively analyse the impact of the solution in the proposed KPAs and PIs. In Section 5.1.8, we come back to these variables, but from a simulation output and data collection perspective.

Variable	Type
Aircraft altitude	Independent
Handover method	Independent
Network traffic load	Independent
Network access cost	Independent
Terrestrial network placement	Control
Terrestrial network configuration	Control
Satellite Network configuration	Control
Aircraft receiver configuration	Control
Terrestrial network channel model	Control
Non-terrestrial network channel model	Control
RSSI (Received Signal Strength Indicator)	Dependent
Handover failure	Dependent
Signal-to-Interference-plus-Noise Ratio (SINR)	Dependent

Capacity	Dependent
Latency	Dependent
Packet Delivery rate	Dependent
Network usage cost	Dependent

Table 8: OBJ-ANTENNAE-TRL2-ERP-001 objective variables

In the validation objective **OBJ-ANTENNAE-TRL2-ERP-002** we want to evaluate the network performance in terms of RAN configuration policies. The result of this evaluation is intended to assess not only the performance of CNS services as a technological solution but also its viability from the technological and business perspectives. Therefore, in this validation objective not only the scenarios need to be defined but also which network policies will be evaluated. Such evaluation can be supported by system-level simulations and ray tracing, the former focusing on higher-layer functions, such as traffic scheduling and mobility management, and the latter applied to radio propagation modelling in the RAN. In Table 9, we summarize and classify the input and output variables involved in this validation objective.

[OBJ]

Identifier	OBJ-ANTENNAE-TRL2-ERP-002
Objective	Assess the impact of the ANTENNAE solution's RAN configuration policies on IAM operations
Title	RAN configuration policies assessment
Category	<Performance>, <Operational feasibility>
Key Environment conditions	Nominal conditions, IAM, European cities, drone operations, satellite communication
TRL level	TRL 2

[OBJ Suc]

Identifier	Success Criterion
CRT-ANTENNAE-TRL2-ERP-002-001	Solution 0521 delivers RAN configuration policies that decrease outages (SINR less than -5 dB [34]) for UAS in aerial corridors at VLL altitude (below 150 meters) by more than 70% compared to traditional 3GPP baselines (down-tilted antennas and fixed vertical HPBW [35]).
CRT-ANTENNAE-TRL2-ERP-002-002	Solution 0521 provides RAN configuration policies that enhance data rates for UAS in aerial corridors at VLL altitude (below 150 meters) by more than 50% compared to traditional 3GPP baselines (down-tilted antennas and fixed vertical HPBW [35]).

CRT-ANTENNAE-TRL2-ERP-002-003	Solution 0521 provides 3GPP-compliant handover configurations that decrease ping-pong handovers (time of stay < 1s [36]) for UAS in aerial corridors at VLL altitude (below 150 meters) by more than 50% compared to 3GPP recommendations (set-1 and set-5 [36]), while keeping Radio Link Failures below 0.01% on the flight route.

Variable	Type
Aircraft altitude	Independent
Antenna beamwidth	Independent
Antenna tilt	Independent
3GPP Handover parameters	Independent
User-cell associations	Independent
RAN site's location	Control
Signal quality (SINR)	Dependent
Users' data rate	Dependent
Radio Link Failures	Dependent
Ping pong handovers	Dependent

Table 9: OBJ-ANTENNAE-TRL2-ERP-002 objective variables

Validation objective **OBJ-ANTENNAE-TRL2-ERP-003** addresses the solution 0521 potential A-PNT and A-SUR capabilities. The first successful criterion is to define the techniques that will be evaluated in the validation exercises. Once the techniques are defined and implemented, then the assessment of these techniques follows, focusing on accuracy and availability, as detailed in Table 10.

[OBJ]

Identifier	OBJ-ANTENNAE-TRL2-ERP-003
Objective	Assess the impact of the ANTENNAE solution as potential enabler of alternative navigation and surveillance techniques (A-PNT, A-SUR and JCS)
Title	Alternative CNS assessment
Category	<Performance>, <Operational feasibility>
Key Environment conditions	Nominal conditions, IAM, European cities, drone operations, satellite communication
TRL level	TRL 2

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[OBJ Suc]

Identifier	Success Criterion
CRT-ANTENNAE-TRL2-ERP-003-001	Solution 0521 meets the performance requirements for the alternate positioning method accuracy (geometric position accuracy < 30 m and altitude accuracy < 45 m, with at least 95% probability) [31]
CRT-ANTENNAE-TRL2-ERP-003-002	Solution 0521 meets the performance requirements for the alternate positioning method availability (detection of 3 or more [37] different ground BS PRS > 99% [30])
CRT-ANTENNAE-TRL2-ERP-003-003	Solution 0521 meets the performance requirements for surveillance message delivery rate greater than 99% for 1 message per second

Variable	Type
Aircraft altitude	Independent
Scatterers Velocity	Independent
PDSCH Configuration	Control
PRS Configuration	Control
Terrestrial network placement	Control
Terrestrial network configuration	Control
Satellite Network configuration	Control
Aircraft receiver configuration	Control
Terrestrial network channel model	Control
Non-terrestrial network channel model	Control
Position RMS Error	Dependent
Speed RMS Error	Dependent
Number of detected Ground BS	Dependent
Number of detected NTN BS	Dependent
Percentage of detectable Reference Signals	Dependent

Table 10: OBJ-ANTENNAE-TRL2-ERP-003 objective variables

4.4 Validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
SPA-ANTENNAE-TRL2-ERP-01	U-space and IAM development stage	U-space and IAM services are successfully operational and regulated by the correspondent authorities	For the solution 0521 operation it is essential that safety and operational rules are well established, leveraging business models	When and where U-space operations are not regulated and fully developed, special flight concessions might be necessary. **Impact:** High
SPA-ANTENNAE-TRL2-ERP-02	Data availability	Availability of the data required for the exercise realization (propagation models, ground infrastructure position, satellite constellation configuration, etc.)	It is required to define the input parameters and scenario definitions of the validation exercises	If some data is not available a contingency might be looking at literature for state-of-the-art system models **Impact:** Low
SPA-ANTENNAE-TRL2-ERP-03	Ground Network	The solution 0521 might require the deployment of additional CNS infrastructure on the ground to support safe operations	Operation in remote areas might not be fully covered by commercial MNOs	Not deploying ground infrastructure (where and when needed), will require that U-space operations rely only on NTN **Impact:** Low

Table 11: validation assumptions overview

In Table 11, the validation assumptions are defined in a concise way and in accordance with the *DES Common Assumptions document* [4]. Because the forecast-independent, aggregation and CBA assumptions are not directly applicable to the validation proposed in this document, we defined *Specific Performance Assumptions*. These assumptions cover environment, operation, equipment availability, and regulatory assumptions which will make

4.5 Validation exercises list

[EXE #01]

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Identifier	TVAL.01.1-ANTENNAE-0521-TRL2
Title	Assessment of integrated CNS-as-a-Service hybrid network model and network control policies performance
Description	The objective is to assess the performance achieved by the hybrid TN-NTN network architecture in the proposed scenario through extensive system level simulations and network control policies, considering different UAS altitudes. Statistical performance analysis will be conducted to validate if the performance is above minimum threshold stablished for U-space and IAM, in terms of coverage, channel capacity, latency, etc.
KPA/TA addressed	<Capacity>, <Cost Efficiency>, <Environment>
Addressed expected performance contribution(s)	Improved CNS capabilities for U-space and IAM operations
Maturity level	TRL2
Use cases	From the OSED [2]: • Hybrid connectivity • Safety applications: Communications
Validation technique	Fast Time Simulation
Validation platform	MATLAB implemented mobile wireless networks system level simulation
Validation location	Shannon Airport – Limerick City, Claire and Limerick, Ireland
Start date	01/08/2025
End date	31/12/2025
Validation coordinator	COLLINS
Status	<In progress>
Dependencies	N/A

[EXE #01 Trace]

Linked Element Type	N/A

<SESAR Solution>	SESAR Solution 0521
<Project>	ANTENNAE
<Sub-Operating Environment>	N/A
<Validation Objective>	OBJ-ANTENNAE-TRL2-ERP-001

Table 12: validation exercise #01 layout

[EXE #02]

Identifier	TVAL.01.2-ANTENNAE-0521-TRL2
Title	Cellular network optimization for aerial users
Description	The objective is to explore the use of advanced RAN optimization techniques for 5G deployments, including handover management optimization and antenna configuration elements such as tilt and beam patterns to provide enhanced coverage to connected UAS in aerial corridors. 3D ray tracing simulations will be run to simulate realistic U-space scenarios and assess the performance of Radio Access Network configuration policies.
KPA/TA addressed	<Capacity>, <Cost Efficiency>
Addressed expected performance contribution(s)	Improved network coverage and seamless connectivity for U-space operations.
Maturity level	TRL2
Use cases	From the OSED [2]: • Cell Shaping and Coverage Optimization for Aerial Users • Mobility Management for Aerial Users
Validation technique	Fast Time Simulation
Validation platform	Ray tracing-based system level simulations with Sionna RT.
Validation location	London, United Kingdom
Start date	01/08/2025
End date	31/12/2025

Validation coordinator	TID
Status	In progress
Dependencies	N/A

[EXE #02 Trace]

Linked Element Type	N/A
<SESAR Solution>	SESAR Solution 0521
<Project>	ANTENNAE
<Sub-Operating Environment>	N/A
<Validation Objective>	OBJ-ANTENNAE-TRL2-ERP-002

Table 13: validation exercise #02 layout

[EXE #03]

Identifier	TVAL.01.3-ANTENNAE-0521-TRL2
Title	Evaluation of xG enabled A-PNT, A-SUR and JCS for low altitude
Description	In this validation exercise the xG network capacity of performing A-PNT, A-SUR, and JCS will be assessed. Thus, system level performance analysis by modelling the xG reference signals and channel will result in the evaluation of the accuracy, availability, and reliability of such methods.
KPA/TA addressed	<Capacity>, <Cost Efficiency>, <Environment>
Addressed expected performance contribution(s)	Improved Navigation and Surveillance capabilities for IAM and U-space operations
Maturity level	TRL2
Use cases	From the OSED: • Safety applications: Navigation and Surveillance
Validation technique	Fast Time Simulation
Validation platform	MATLAB implemented xG-based A-PNT, A-SUR, and JCS simulations
Validation location	Shannon Airport – Limerick City, Claire and Limerick, Ireland

Start date	01/08/2025
End date	31/12/2025
Validation coordinator	Collins
Status	In progress
Dependencies	N/A

[EXE #03 Trace]

Linked Element Type	N/A
<SESAR Solution>	SESAR Solution 0521
<Project>	ANTENNAE
<Sub-Operating Environment>	N/A
<Validation Objective>	OBJ-ANTENNAE-TRL2-ERP-003

Table 14: validation exercise #03 layout

4.6 Validation exercises planning

Figure 2 provides a screenshot of the validation exercises on STELLAR platform. The validation exercises planning is detailed in Chapter 5. The validation exercises are still under approval of SJU/STELLAR but they reflect what is described in this ERP, according to Section 4.5 and Chapter 5.

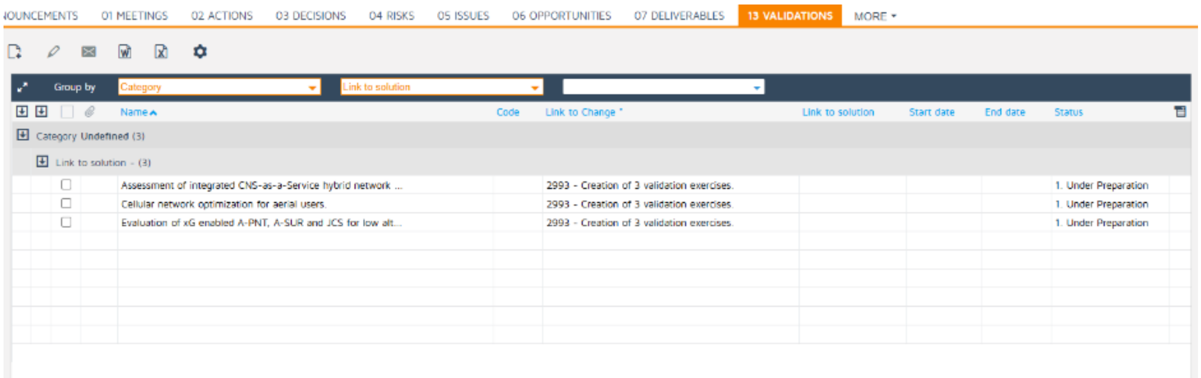

Figure 2: screenshot of all the validation exercises on STELLAR

4.7 Deviations with respect to the SESAR 3 JU project handbook

No deviations with respect to the SESAR 3 JU project handbook have been identified till the current version of this document.

5 Validation exercises

5.1 Validation exercise #01 plan

5.1.1 Validation exercise description and scope

In this section, we will describe the network performance evaluation validation exercise, relating to offering the ICNS for various aircraft types. The actors in this exercise include aircraft, air traffic controller, xG base stations and surveillance data. The current CNS operating mode of UAS runs using fragmented communication, navigation and surveillance technologies. These often are based on legacy commercial aviation policies and procedures, which do not meet the new requirements of next generation aircraft including UAS. These can be highly manoeuvrable, power-limited and light aircraft that fly at low altitude with strong need for CNS resilience and safety services.

This has driven to the concept of CNS functions integration, called Integrated CNS, which aims to improve spectrum use efficiency and reduction of airborne equipage, while maintaining the required level of resilience, redundancy and safety.

In ANTENNAE solution (SESAR Solution 0521), the CNS integration will be made through hybrid TN-NTN xG mobile wireless networks. The intended architecture is tailored for aeronautical use that requires coverage in remote areas, service redundancy and high-availability time. The xG (currently 5G) networks provide high-data rate and low-latency connectivity with high-availability and its pervasiveness in densely populated areas makes it a strong candidate to provide VLL and LL connectivity. However, in remote areas, such as rural areas, xG terrestrial coverage might not be sufficient and increasing altitude the signal receive power might decrease due the focus on ground users. Thus, the non-terrestrial network is used as backup in urban areas and main connectivity system in remote areas, increasing the reliability and expanding the coverage.

The proposed validation exercise considers a system level wireless network simulation that leverages simulators developed in related projects and common considered features adopted for this solution. This simulator integrated with such features will provide data about the hybrid terrestrial and non-terrestrial network, allowing the evaluation of several functions of the network and whether the performance resulting from this exercise is sufficient to ensure CNS as a service provisioning with the required levels of safety.

The key validation objectives are:

- provide qualitative assessment for the terrestrial and non-terrestrial coverage in the validation scenario,
- provide qualitative evaluation for the terrestrial and non-terrestrial handover criteria, considering inter/intra networks,
- provide quantitative evaluation that can assess if the CNS performance requirements will be met by the hybrid terrestrial and non-terrestrial network architecture.

The evaluation scenario is based on a related project flight test scenario. The EALU-AER project realizes flight tests with UAS around Shannon Airport and Limerick City, Ireland, envisioning the development of a Beyond Visual Line Of Sight (BVLOS) flight infrastructure and assess the viability of such operation.

Considering this physical scenario, in this validation exercise we also exploit a Low Earth Orbit (LEO) satellite constellation and the 4G/5G public commercial mobile networks. Tailoring this hybrid architecture with network management policies and possibly private deployed 5G base stations we aim to achieve high CNS as a service performance with cost efficiency.

The validation technique is based on varying certain network parameters and the pseudo-random number generator seed. This technique enables the assessment of different aspects of the network and to investigate how such aspects interact among each other. Exploiting such interactions allows us to identify trade-offs and trends. Additionally, by changing the seed and realizing a large enough number of scenarios we can increase the confidence of the results. Figure 3 shows two scenarios, which the aircraft altitude changes to capture the network coverage at different heights and how each network provides coverage.

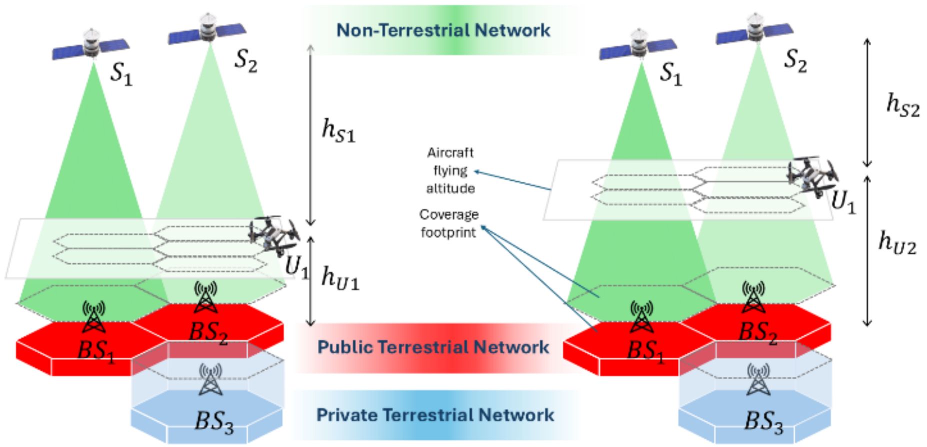

Figure 3: Validation exercise #01 simulation method

The main platform used in this validation exercise is discrete event simulator developed in MATLAB. This wireless network simulator has common elements to every wireless network simulation, such as channel model, antenna model, and transceiver devices. Each realization of the simulation has a fixed duration, which is divided in time slots and at each time slot an event may happen. For example, the aircraft position is updated at each time slot, according to the velocity and the time slot unit. To comply with the solution requirements, several features will be implemented, such as, 5G ground base station, 3GPP UAS channel model, and 3GPP antenna model. Figure 4 exemplifies the simulation process split into different phases and considering the hybrid terrestrial and non-terrestrial network configuration proposed by the solution, which can be assessed through the simulator for different performance indicators, in this case the coverage continuity is depicted as a RSSI heatmap for each altitude to be evaluated in the scenario.

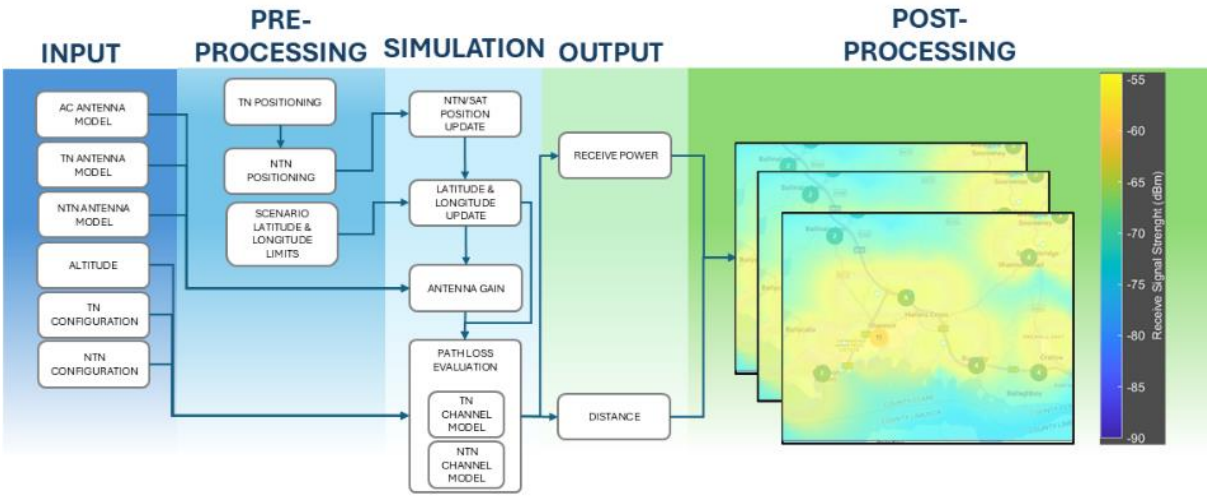

Figure 4: Validation exercise #01 simulation pipeline

At the end of the validation exercise the solution is expected to reach TRL 2.

5.1.2 Stakeholder's expectations and benefit mechanisms addressed by the exercise

Stakeholder	Involvement	Why it matters to the stakeholder
European Institutions (SESAR, European commission)	Participation in bilateral meetings, validation exercise progress tracking, feedback on the preliminary and final validation results	As project coordinators, the institutions must be kept informed of the overall project progress. It is therefore essential for them to ensure that the project is running properly, that it is relevant to the ATM master plan, and that it is coordinated with other projects. European institutions are directly involved in the development of the solution, and the results obtained will enable the solution to be definitively included in the plans for the future of European airspace.
U-space Service Providers (USSPs)	Workshops, conferences and publications	The results of this validation exercise will evidence the feasibility of ICNS technologies relying on xG networks for connectivity, which might change the U-space management, increasing safety and efficiency.
Regulators	Assess the safety requirements considered in the validation exercises,	The results of the validation exercises can provide regulators with information to

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	feedback on the preliminary and final validation results	anticipate the regulations to be developed for deployment of the solution.
UAS operators	Provide UAS operation insights, feedback on the preliminary and final validation results	UAS operators may use the results of this validation exercise to guide their operational choices in terms of CNS technologies. Instead of relying on proprietary radios and expensive private dedicated links, the operators might be able to reduce costs and weight based on the resultant quality of service provided by findings of this validation exercise.
Telecommunication operators (xG mobile network and Satellite operators)	Provide network data, analyse business viability, Workshops, conferences and publications	By providing indications of the coverage and network infrastructures required for deployment in both urban and rural LL and VLL areas, their exploitation will enable an initial techno-economic analysis of the interest of operators in getting involved in the project.
Scientific Community	Workshops, conferences and publications	For the scientific community, this validation exercise can serve as a basis for future innovation and research.

Table 15: stakeholders' expectations

The Stakeholders particularly involved and benefited from the validation exercise #01 are listed in Table 15. This is the subset of stakeholders directly involved or impacted by the results of this validation exercise; a complete list of Stakeholders related to the solution can be viewed in Table 6.

5.1.3 Validation objectives

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria
OBJ-ANTENNAE-TRL2-ERP-001	Success criteria (same as in Section 4.3)	Fully Covered	Same description as validation objective OBJ-ANTENNAE-TRL2-ERP-001 from Section 4.3	Same description as success criteria for validation objective OBJ-ANTENNAE-

				TRL2-ERP-001 from Section 4.3

Table 16: validation objectives addressed in validation exercise #01

From the solution validation objectives, in Table 16 we list the ones that will be met in this validation exercise.

5.1.4 Validation scenarios

In this section we describe the reference and solution scenarios, highlighting the differences and contributions of our solution. Although the same geographical area is considered, the solution scenario proposes the use of a hybrid terrestrial and non-terrestrial network to provide improved continuous coverage and CNS capabilities, as described in the solution OSED [2].

5.1.4.1 Reference scenario(s)

In the scope of ANTENNAE solution (SESAR Solution 0521), we leverage the research carried out in another SESAR JU Project, EALU-AER, which propose to deploy and demonstrate an end-to-end U-space infrastructure to enable UAS BVLOS operations. The project exploits flying routes between two areas in Ireland, the Shannon airport area in County Claire, Ireland, and the Limerick city area in Limerick County, Ireland. Shannon Airport is one of the largest airports at Ireland and next there is the Future Mobility Campus Ireland (FMCI) vertiport. Limerick, which is the third largest city in Ireland, representing Limerick area, therefore, an urban area and can be explore for commercial activities. These two areas are connected through the Shannon River estuary, which can be considered unpopulated/sparsely populated area, making it easier to obtain Operational Authorisation to fly over that area, minimising the ground risks. The flights are about 20 km long, but the flying altitude varies from 36 metres (120 ft) to 134 metres (440 ft) AMSL. The U-space airspace will be mixed between Controlled airspace (Class-C) and uncontrolled airspace (Class-G), being the closest airport the international Shannon Airport, which literally will be just adjacent to the area of UAS operations. Visual and instrumental procedures might be affected by the definition of this U-space.

Figure 5: Area between the Shannon Airport and the Limerick County, Ireland. The flight test operations are run in the Shannon River estuary area (*in yellow*), which offers low risk due to the scarce population, from the Shannon Airport vertiport to a few points of interest in Limerick city.

The airborne equipment consists of LTE transceiver, 2.4 GHz proprietary radio, Satellite communication transceiver, GNSS receiver, CNPC-1000 Collins Aerospace radio. Besides the public commercial LTE Base Stations (BSs) and satellites, several CNPC ground stations and a Collins Aerospace Skyler radar are deployed for improved communication and surveillance. The main communication service explored are C2 and telemetry, which for BVLOS require service reliability and low latency. The navigation relies only on GNSS for positioning and timing when visual operation is not possible. The Skyler radio, ADS-B data from the aircrafts nearby, and UA remote ID are combined for enhanced surveillance, detecting cooperative and non-cooperative aircrafts. All these functionalities are however fragmented in several equipment onboard and using different portions of the spectrum, which are all gathered by operation control centre and pilot.

5.1.4.2 Solution scenario(s)

The ANTENNAE solution (SESAR Solution 0521) envisions a hybrid terrestrial and non-terrestrial network solution. Therefore, for public commercial mobile network operator, the ANTENNAE solution sourced the location of the 5G base stations operated by the largest MNOs in Ireland (Vodafone, Three, Virgin, Eir) in the n78 band at the Commission for Communication Regulation (ComReg) Ireland online platform which makes information public [38].

Additionally, ANTENNAE will explore the same ground network framework used in 3GPP TR 36.777 [39]**Error! Reference source not found.** for the commercial cellular network which consists of 25 m BS with down tilted transmitting at power of 43 dBm. The aerial users' altitude ranges from 50 m up to 3000 m. For altitudes up to 300m, the 3GPP TR 36.777 provides path loss, small scale fading, statistical Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS), and antenna models for urban macro-BS, rural macro-BS and urban micro-BS. The only differences from the proposed validation exercises to this framework investigated by 3GPP is the central frequency, which is the n78 (3.6 – 3.8 GHz) and 20 MHz bandwidth, more suitable for the geographical area the solution targets, and the altitude range which we will extrapolate to altitudes above 300 m applying the same channel model in this case. Every cell is installed with an antenna that irradiates the radiation pattern as described by the 3GPP in Table 7.1-1 of [40]. The propagation channel model proposed by 3GPP for aerial UEs in the Annex B of [39].

For NTN, the LEO satellite constellation configuration is based on a LEO satellite deployment operating in the Ka-band at 20 GHz. Due to the severe path loss, the link performance is compensated with a 400 MHz bandwidth to offer high data rates. The constellation is comprised of 308 satellites on a circular orbit with an altitude of 550 km and 24 orbital planes with an inclination of 53º. Each satellite travels with 27400 km/h speed to complete the orbit loop in 90 to 100 minutes. The weather effects on the satellite and HAPS links are not considered and the propagation channel model used is Free-Space Path Loss (FSPL) plus atmospheric attenuation, as defined by ITU-R P.618.8 [41], and 3GPP NTN channel models [42].

This hybrid deployment is motivated by the necessity of providing connection in remote areas and increasing safety for aerial users. The former is a consequence of the MNOs providing better connectivity where it is more profitable, e.g., where there is a dense population which may result in more potential users. The latter is to comply with the aviation safety principles that advocate systems' redundancy and resilience which are being considered in the design of the proposed solution. Thus, NTN will provide connectivity for two main reasons, improve connectivity in remote areas and serve as redundant connection.

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5.1.5 Exercise validation assumptions

Not Applicable. No additional assumptions compared to the ones in Section 4.4.

5.1.6 Limitations and impact on the level of significance

The validation exercise #01 presents several limitations. The reference scenario mixes urban and rural/remote area. The area of Limerick City is densely populated, consequently providing a better ground network coverage. The Shannon airport and estuary area less populated and the ground network coverage might be scarce. This fusion urban and remote area makes the validation exercise more comprehensive and challenging, but the results obtained might not be applicable to different scenarios, although it is believed that the results will provide relevant insights for related projects. Therefore, the assessment will try to be generic and extensive as possible to avoid possible biases resulting from the chosen scenario and independent variables.

5.1.7 Validation exercise platform / tool and validation technique

In this section we detail the platform used in this validation exercise and the validation technique.

5.1.7.1 Validation exercise platform / tool characteristics

Due to the low TRL aimed for Solution 0521, the validation exercises will rely on wireless networks simulation, leveraged by a simulation framework developed in related projects, such as ETHER. The main platform used for prototyping such simulations is MATLAB, which allowed to design a flexible simulation framework, only requiring the development of specific features regarding the solution architecture. The base code of this simulator framework provides a discrete event simulator focused on wireless network events and basic wireless network devices. Using object orientation paradigm (OOP), we are able inherit from these base classes that provide basic and common functionalities shared across several entities and build new classes on top of it, reusing code and enabling continuous growth.

The features implemented in the simulation framework are related to xG functionalities and the hybrid network connection. Whenever available these features were implemented following standards and official documentation. For example, the 3GPP defines channel models for LL operating UAS [38] in different scenarios which are being used in our simulator to calculate the path loss and small-scale fading. Below, we list the features implemented in our simulation framework in addition to the original features common to wireless system level simulation capabilities:

- UAS mobility model,
- Shannon airport area BS locations,
- 3GPP Urban Macro BS, Urban Micro BS and Rural Macro BS channel model,
- 3GPP antenna model,
- 3GPP Handover events,
- LEO Satellites mobility model.

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For the validation exercises proposed in the solution we will exploit wireless network system level simulations. These simulations can be divided into three phases, pre-processing, simulation, and post-processing. In the preprocessing phase the scenario is set for the simulation phase. During this step all the ground stations are placed in the ground, as well as the initial position of the NTN elements. These network elements are created and their attributes, such as frequency of operation, transmit power, and bandwidth, are defined. Also, the aerial user trajectory is calculated considering the mobility model and network parameters, such as speed, direction, and receiver sensitivity.

The parameters in the pre-processing phase are usually changed to evaluate the impact of different scenario conditions and network configurations. For instance, we may start with a low speed and linearly increase it to a maximum high-speed value and then assess how the network responds to the fast changes in the aerial user position in terms of handovers (handover failures, ping-pong handovers and handover interruption time). Another example, the altitude may increase from a minimum altitude level to a maximum altitude level, with regular steps, simulating different aerial corridors/tracks, to evaluate the minimum, maximum, and average received power from the TN in each point in a square grid covering the whole area of interest. Finally, if random events are included in the simulation, the seed of pseudo-random number generator can also be changed to induce different random events.

In the simulation phase, a time slotted discrete event simulation approach is taken. The simulation is limited by a given number of timeslots and at each timeslot events might take place, and new events might be scheduled. For example, considering the aerial user speed, at each time slot its position will change according with the mobility model, speed, and timeslot duration. Also, networks events are scheduled, e.g., measuring the received power, handover to a different base station, or send a packet.

The post-processing phase may vary according to the simulator design. On some occasions, the post-processing phase might include only the statistical and graphical analysis of the experiment output, and the data generated in the simulations. However, in this validation exercises multiple aspects of the network can be evaluated with the same output data. The pre-processing phase includes a layer of network function to be assessed depending exclusively on the network measurements taken in the previous step. This approach allows modularity, which leads to code reuse, leverages code extension, facilitates code debug and fixing, and enables collaboration among multiple developers.

The network events are primarily oriented by received power and SINR, which are calculated considering the proper propagation channel models and the noise and sensitivity requirements. Thus, if the calculated received power is below the sensitivity or certain SINR level, the signal cannot be decoded. Consider handovers, for instance, if the received power from a ground base station B is greater than the received power from a ground base station A, which is serving the aircraft at a given timeslot, then a handover from ground base station A to ground base station B is triggered. In this example, if the receive power from all ground base stations for all the simulated timeslots is available, then any handover decision and handover method can be evaluated. With the same data we can evaluate the coverage based on receive power and interference levels across the whole aircraft trajectory.

Figure 6 details the simulation framework architecture used in this validation exercise. The architecture is based on a modular approach, which relies on the input layer to receive data from other types of simulators, such as mobility simulator, and data regarding the scenario to be simulated, such as ground network elements position. The intermediary layers, pre-processing, simulation, and output will virtually generate the scenario, model and realizes the events at each timeslot, and store the

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observation (results) of each event in an organized way in a data structure to be processed by the upper layers.

The post-processing layer acts as a simulator itself. Some network capabilities that do not require discrete event simulation and that do not interfere with any of decision taken during the simulation, if any, can be simulated based on the data from the output layer. As aforementioned, the handover is an example of network function that takes place without interfering with the aircraft mobility or receive power measurements. Similarly, a higher layer simulator can be attached using the data output from the post-processing layer, which already considers lower layers decisions.

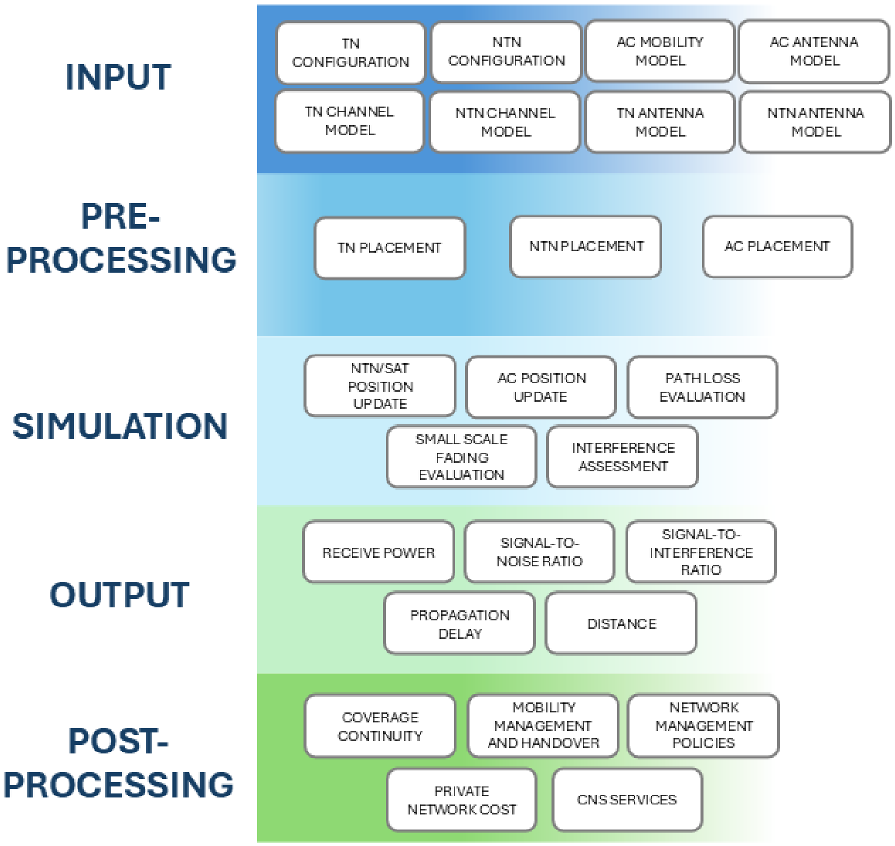

Figure 6: exercise #01 simulation framework architecture

5.1.7.2 Validation exercise technique

The validation technique applied is to simulate extensively different scenarios varying some input parameters. First, this technique allows to evaluate different aspects of the simulated scenario, for example, how good is the network coverage at different altitudes which will range from a minimum to a maximum value. Second, the pseudo-random number generation seed may be changed to differ the random distributions that are sampled during the simulation, thus by using the same seed we keep the reproducibility of the experiments and by the law of large numbers we ensure that if enough experiments were realized the results will converge to the true mean. Third, by jointly varying different parameters it is possible to not only investigate individual parameter trends, but also trade-offs resultant of the interaction between two or more parameters. Finally, this type of analysis will provide enough data to substantiate the findings derived from this validation exercise.

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Due to the modular design of the simulator, several different aspects of the network can be simulated by changing the post-processing function. Below we detail each one of the post-processing modules.

5.1.7.2.1 Coverage continuity analysis

The coverage analysis is of great importance for assuring CNS continuity and operational safety for UAS and IAM operations. Such analysis allows those involved in the operation to plan the best CNS connectivity solution for each mission considering the geography, availability, and CNS technologies necessary. Thus, we prioritize the coverage continuity analysis in our validation exercises, by varying the aircraft altitude and the network it is connected we can calculate RSSI for each latitude and longitude in the area of study. After collecting the RSSI for each coordinate, we can analyse the coverage by plotting a RSSI heatmap over the area and in a further analysis propose methods to fill the coverage gaps with more ground stations. The initial data set to perform this validation is the mobile operators ground base stations coordinates (longitude and latitude), the satellite constellation data and the reference scenario characteristics. After the preliminary results and validation with other participants, if it is detected that the coverage is insufficient, we might propose the deployment of private ground base stations which also requires to analyse the trade-off between cost and coverage improvement to achieve service viability.

5.1.7.2.2 Network mobility management and handover

The goal of network mobility management is to allow the seamless switch of source base station when the users is moving out of range of its current source base station. This process, also called handover, involves the detection of the adequate base station to handover and transference time, the transference of resources between the current and the future base station, and the mitigation of potential failures that might hinder the overall network performance, such as handover failures, long handover delays and ping-pong handovers. The 3GPP defines several handover triggering events [43], as shown in Table 17.

Event	Description	Triggering Condition
A1	Source cell becomes better than a threshold	$R_{SC} \geq T$
A2	Source cell becomes worse than a threshold	$R_{SC} \leq T$
A3	Neighbour cell becomes better than source cell by an offset	$R_{NC} \geq R_{SC} + O$
A4	Neighbour cell becomes better than a threshold	$R_{NC} \geq T$
A5	Source cell becomes worse than a threshold T1 and neighbour cell becomes better than a threshold T2	$R_{SC} \leq T_1$ $R_{NC} \geq T_2$
A6	Neighbour cell becomes better than a secondary source cell by an offset (only applicable when Carrier Aggregation is active)	$R_{NC} \geq R_{SSC} + O$
B1	Other access technology cell becomes better than a threshold	$R_{RAT} \geq T$

B2	Source cell becomes worse than a threshold T1 and other access technology becomes better than a threshold 2	$R_{SC} \leq T_1$ $R_{RAT} \geq T_2$

Table 17: 3GPP xG handover triggering events

For this analysis we will compare the RSSI between the source and the candidate base stations and the SINR throughout the process with the minimal SINR threshold used for synchronization. If the SINR falls below the minimal synchronization SINR threshold the handover fails and the connection needs to be reestablished, which is time consuming processes. Besides, the handover between TN and NTN will also be evaluated.

5.1.7.2.3 Network traffic steering management

To design a cost-effective and safety-oriented solution it is essential to define the traffic management policies either to reduce the cost of operating the network or to avoid traffic interruptions. Thus, exploiting the virtualization and flexibility features available in xG networks, we will assess network control policies for access traffic steering, switching and splitting, for cost minimization and capacity maximization. To this end, we will analyse the performance of resource scheduling algorithms, such as weighted fair queueing, based on capacity, cost, and a base traffic load in terms of resultant cost and throughput. The network access cost and underlying traffic load are artificially defined for experimental purpose with the objective of emulating a real network where aerial users will coexist with other users and the MNOs will charge for different services according to capacity and latency required, impacting the viability of ICNS as a service.

5.1.7.2.4 CNS safety applications

Each one of the CNS applications presents different requirements to the network in terms of capacity, message periodicity, latency, and reliability. Hence, we will compare the network resultant performance from the simulations with the CNS performance requirements. This analysis will determine which conditions are necessary for our solution enable CNS as a service. Additionally, given the minimum necessary CNS performance requirements per aircraft and the performance provided by the hybrid TN-NTN network architecture, we will be able to estimate the volume of aircrafts supported by the solution.

5.1.7.2.5 Private Network Cost

The public network capacity and coverage may not be enough to support all the C, N, S services traffic. Thus, the deployment of private network infrastructure can support to attain the required communication, navigation and surveillance performance metrics. In parallel, other aeronautical networks resources should be efficiently used to mitigate congestion, lack of data transmission capacity, and high communication delays.

xG terrestrial and non-terrestrial networks enable aerial users collocated virtually with the ground users to share the network capacity by enabling slicing, which is managed according to the business models agreed between the MNOs and the UAS operators. Network slicing technology can enable the MNOs to passively or actively reserve part of the network resources (e.g. bandwidth in terms of data rate) to specific users that require assured or guaranteed QoS, such as, low-latency or high data rate. In urban densely populated areas, the MNOs count on the number of subscribers and traffic volume to ensure their return of investment on XG network infrastructure. In essence, the lack of investment on XG network infrastructure in rural and remote areas lead to low and sparse coverage, which may not support minimum requirements of CNS services.

The deployment of private xG networks (ground BSs, network core, fronthaul, and backhaul) to support UAS and IAM operations are required to meet the aerial users CNS performance requirements. This deployment also requires licensing for operation and is subject to spectrum availability. Thus, deploying and maintaining additional network infrastructure will be assessed in this validation exercise from the network performance perspective.

5.1.8 Data collection and analysis

5.1.8.1 Data and data collection methods

The simulation requires as input the network elements' location, such as ground base stations and satellite's locations. The base station information was sourced at the ComReg Ireland [38], which is made available at no cost in their website. All the 4G and 5G base stations operating in Ireland for commercial purpose are registered in the ComReg data platform, but in this validation exercise the scope is reduced to the base stations in the area defined in the Section 5.1.4. The other data regarding the ground network, such as height, transmission power, and antenna and channel models, are specified in the 3GPP standards [42]. To assess the network traffic management policies, we also need to define the network traffic load, the underlying base data traffic flowing through the network, and the network access cost, how expensive is to send data through a network. For the NTN, the constellation is based on an early deployment of Starlink and such data widely available, for more details see Subsection 5.1.4.2. Besides, the reference scenario determines the geographical characteristics of the simulation, which are the areas of County Claire and County Limerick, particularly the Shannon River estuary area close to Shannon airport and Limerick City centre.

The result of the simulations will be compared among the different scenarios configurations. Therefore, we can determine which scenario configurations are more adequate for the solution and establish lower and upper bounds. For example, between the input variables, we will vary the aircraft altitude and handover method, with goal of assessing coverage and mobility management, respectively. Table 8, in Section 4.3, contains a list of input independent and control variables that may influence the validation exercise.

Due to the convenient matrix workflow, we will also use MATLAB for processing and analysing the simulation results. Table 18 details the main metrics extracted from the simulator as output and how they will be used in the analysis. Each output metric is related to an indicator, that are the outcome of this validation exercise. This list of metrics does not exclude the addition of other metrics to the final analysis if they help understanding the results and support the final conclusions.

Metric	Direction	Indicator
RSSI	Increase	Coverage
Handover Failure	Decrease	Reliability
SINR	Increase	Reliability, Scalability
Capacity	Increase	Data Availability, Scalability

Packet drop rate	Decrease	Data Availability, Scalability
Latency	Decrease	Data Availability
Network Usage Cost	Decrease	Cost efficiency

Table 18: Exercise #01 metrics and indicator details

For refinement of the concept and review of the results, we plan at least 3 iterations with the whole solution consortium. By using the Agile methodology for development, we plan that in the 3 sprints, we can discuss and interact among the partners. At the end of each development cycle, the task leader will present the validation exercise detail and results originated of the simulation, aiming to motivate discussions, review the results and obtain suggestions of improvement and fine tuning.

As the validation exercise will be carried out using MATLAB, the required license for professional commercial use of this tool is already provided. Thus, the validation exercise will incur in no extra costs for the solution or stakeholders involved.

The experimental data will be recorded in MATLAB "*.mat" files, which can store the data structures generated during the simulation. Upon request, such structures can be converted to different file types, such as "*.csv", "*.json" or "*.hd5". The plots of the results will be generated in both "*.fig" MATLAB format and "*.png" format.

5.1.8.2 Analysis methods

After the exercise execution, i.e. ending of the simulations for the different input parameters, the data will be processed in the most convenient way to visualize it, for instance, mean plus confidence intervals, bar plot, box plot, geo plot and heat maps. These data will be analysed with the other solution participants several times to ensure the mitigation of bugs and simulation biases before the conclusions are drawn. Once the simulations are validated, the results will be used to establish bounds to each metric, and according to the solution performance compared to the bounds we can start the qualitative analysis. At the end of the validation exercise we will propose the answers to our initial hypothesis and observation conclusions supported by the results in a report which will be discussed internally and with experts. Below we list what we expect as results:

- **Coverage analysis**: the RSSI/receive power data is processed and displayed in a heatmap plot, thus for each altitude and for each sampled coordinate (latitude and longitude) of the scenario we assess the RSSI level compared to the receiver sensitivity level and the interference with the synchronization threshold defined by 3GPP.
- **Mobility management**: To compare the different handover techniques, we can compare the different techniques performances by using bar plots, for example, the handover triggering events in the "x" axis and the handover failures in the "y" axis. The goal is to find the technique and the parameters that offer the best performance for the scenario.
- **Network control policies**: Three metrics will be evaluated: capacity, network usage cost, and packet drop rate. These metrics will be shown as cumulative distribution function, box plots, line and bar plots of the mean plus confidence intervals.
- **CNS safety applications**: The CNS requirements for each technological domain are plot against the resultant performance of the solution, for example, reliability.

- **Private network cost**: Given the capacity and coverage deficit, we need to determine where the private operated infrastructure is necessary. With the objective of minimizing the total cost, and consequently the number of ground BSs, we will evaluate the impact of increasing the number ground BSs in the capacity and coverage performance requirements.

5.1.9 Exercise planning and management

The validation exercise #01 started at month 7 (the 1st of March 2025) and to finish at month 18 (the 1st of February 2026). The validation exercise comprises of the wireless network simulation of the scenario explained in Section 5.1.4, which includes the ground network and non-terrestrial network. During this period, we will conduct the validation exercise activities, including the discussion of the scenario, simulation and results with the validation team and also asking the advisory board and invited experts their insights about the results. The key milestones of the validation exercise are:

- Collect the input data and pre-processing parameters,
- Use 3GPP channel models and antenna models,
- Develop the Satellite simulation capabilities,
- Integrate the 3GPP and satellite features to the simulator,
- Plan and run the simulations,
- Post-process the simulation results,
- Write a simulation results report.

5.1.9.1 Activities

Table 19 summarizes the phases, activities, and the actors responsible to carry them out.

Phase	Activities	Responsible
Preparatory	Scenario definitions and concept development; Simulation's features design and development; Features integration in the simulator; Sourcing input data	Exercise leader
	Scenario and simulations refinement proposing	Validation Team
Execution	Execution of the simulation; Execution of the post-processing and data visualization	Exercise leader
Post-execution	Analysis and discussion; Validation exercise report;	Exercise leader, Validation Team, Advisory Board and Invited experts

Table 19: Exercise #01 Planning activities

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Below, we list the validation exercise #01 activities (ACT-X) that need to be performed and their respective phases (PREP01, EXEC01, POST01):

- ACT-1-PREP01: Look up for the correct input parameters, such as transmit power and bandwidth,
- ACT-2-PREP01: Obtain and clean the data set with the ground station location in Ireland,
- ACT-3-PREP01: Obtain the Satellite network parameters,
- ACT-4-PREP01: Implement the terrestrial and non-terrestrial features in the simulator, such as channel model, antenna model and small-scale fading,
- ACT-5-PREP01: New features integration to the simulator,
- ACT-6-PREP01: Scenario analysis and discussion,
- ACT-1-EXEC01: Simulation Execution,
- ACT-2-EXEC01: Simulation results post-processing,
- ACT-1-POST01: Analysis and discussion of the simulation results,
- ACT-2-POST01: Validation exercise report.

5.1.9.2 Roles and responsibilities in the exercise

Table 20 details the roles and responsibilities of the institutions participating in the validation exercise.

Actor	Role/responsibility
Exercise Leader **(COLLINS)**	Prepare the platform and scenarios to be carried out; Develop the required features for the solution scenario; Integrate the features and scenario to the simulator; Run the simulations; Process the results and provide data visualization resources; Adjust the simulator according to the other participants suggestions.
Validation Team **(TID, VTT)**	Suggest and propose modifications to the simulator; Analyse and discuss the results.
Advisory Board and Invited experts	Be involved in the discussions and provide feedback/insights.

Table 20: exercise #01 Role and Responsibilities

5.1.9.3 Time planning

Table 21 presents the validation exercise #01-time planning, showing the distribution of work allocated by activity over the entire duration of the exercise.

Activity	Month											
	Mar 25	Apr 25	May 25	Jun 25	Jul 25	Aug 25	Sep 25	Oct 25	Nov 25	Dec 25	Jan 26	Feb 26
ACT-1-PREP01												
ACT-2-PREP01												
ACT-3-PREP01												
ACT-4-PREP01												
ACT-5-PREP01												
ACT-6-PREP01												
ACT-1-EXEC01												
ACT-2-EXEC01												
ACT-1-POST01												
ACT-2-POST01												

Table 21: detailed exercise #01-time planning

5.1.9.4 Identified risks and mitigation actions

Table 22 summarizes the risks and mitigation actions identified for the validation exercise #01.

Risks	Impact (1-low, 2-medium, 3-high)	Likelihood (1-low, 2-medium, 3-high)	Criticality (calculated based on likelihood and impact)	Mitigation actions
Risk 1	1	2	3	Proactive briefings and analyses. Simplification of test cases, iterative and incremental approach to simulations.
Risk 2	3	1	3	Continuously monitoring the industry advancements and incorporating the upcoming

				innovations in the best possible way. In the final versions of the deliverables the status quo will be presented.
Risk 3	1	2	3	Keeping continuous dialogue with relevant stakeholders as part of CDE activities; focusing on industrial collaborations to discuss and access relevant information on key technological aspects.

Table 22: exercise #01 risks and mitigation actions

Below, we describe the risks listed in Table 22:

- Risk 1: The creation of test cases and test scenarios for the Concept of Operations takes longer than planned due to insufficient data available on operation parameters of aircraft,
- Risk 2: A significant breakthrough in the development of a 5G integrated CNS methodology or similar technology by another party, which may make certain exploratory research plans outdated,
- Risk 3: The continuation of the lack of data and information about the key technical aspects e.g., NTN frequency bands, RATs RedCap may make the level of expected maturity of the network architecture lower than planned.

5.2 Validation exercise #02 plan

5.2.1 Validation exercise description and scope

In this section, we describe the validation exercise on RAN optimization for aerial users. This exercise is complementary to the network performance evaluation (Section 5.1), but due to the different requirements these exercises need to be executed separately. The complexity of xG RAN, particularly 5G as the current state of work, and the different requirements of aerial and ground users ensue the necessity of investigating opportunities for RAN optimization to enhance coverage and communication quality for the U-space. For a complete and deeper analysis, 3D ray tracing tools will be applied to generate radio propagation data, allowing the experimentation of different antenna configurations, including variations in the beam patterns and tilts, as well as configurations related to mobility management. Compared to the previous validation exercise in Section 5.1, this validation exercise adds an extra layer in the pre-processing phase, for scenario modelling and ray tracing simulation.

Some research efforts have been dedicated to enable UAS connectivity via cellular networks while maintaining optimal performance for ground users. Short-term solutions, such as time and frequency separation, offer only limited scalability for managing cellular-connected UAS effectively. While these methods can temporarily improve connectivity by allocating specific time slots or frequency bands to UAS, they lack the capacity to handle a large and growing number of unmanned aircraft in the sky [44]. These existing solutions assume UAS operations without spatial restrictions, requiring networks to ensure connectivity across the entire 3D space. However, akin to terrestrial vehicles and aircraft, UAS are expected to operate within designated aerial paths or corridors. With most UAS traveling along corridors, MNOs might focus on providing reliable connectivity within these specific areas rather than across the entire sky. The establishment of aerial corridors is expected to be driven by safety and logistics considerations, not communication needs, offering limited flexibility for altering UAS trajectories and instead underscoring the need for specialized 3D cellular service to provide sufficient coverage and capacity along predefined corridors.

In ANTENNAE solution (SESAR Solution 0521), cellular network configurations will be optimized to better serve aerial corridors while minimizing the impact of communications for ground users. Validation exercise #02 will target the optimization of antenna configurations in the 5G RAN to optimize coverage, seamless connectivity, and user transmission rates. Figure 7 illustrates a general overview of the RAN optimization scenario in this validation exercise.

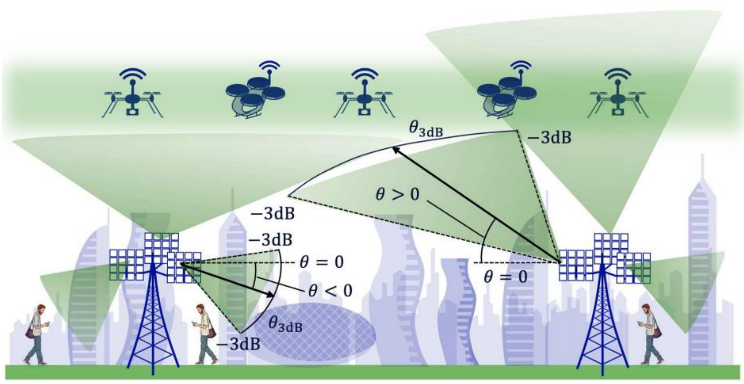

Figure 7: Schematic representation of the RAN optimization scenario in validation exercise #02.

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The key validation objectives are:

- Provide a qualitative assessment for the optimization of antenna configuration parameters in the 5G RAN to optimize coverage and signal quality jointly for UAS in aerial corridors and ground users.

- Provide a qualitative evaluation of mobility management optimization techniques in the RAN for the joint optimization of seamless connectivity and reliability for both UAS in aerial corridors and ground users.

As a validation platform, we will use ray tracing tools to perform site-specific radio channel modelling of the experimental scenario to simulate the propagation of the electromagnetic front-waves irradiated from antennas with specific properties. This data is represented in the form of cluster of rays, which includes angle of departure, angle of arrival, propagation delay, delay spread, and received power, for the main ray and its multi-path components. From this data, we will model the antenna parameters, such as the transmission power, antenna model, antenna tilt and beamforming algorithm, which will serve as inputs to the system-level simulator to estimate other metrics, such as coverage and signal quality metrics (e.g., SINR), or achievable data rates.

Regarding the validation techniques, we will assess state-of-the-art data-driven optimization techniques to modify antenna parameters, such as antenna tilt, beamwidth, or handover-related parameters, in order to enhance coverage, capacity and reliability for connected UAS in aerial corridors.

At the end of the validation exercise, the solution is expected to reach TRL 2.

5.2.2 Stakeholder's expectations and benefit mechanisms addressed by the exercise

Table 23 summarises the Stakeholders involved in this validation exercise and the validation exercise's results benefits.

Stakeholder	Involvement	Why it matters to the stakeholder
European Institutions (SESAR, European commission)	Participation in bilateral meetings, validation exercise progress tracking, feedback on the preliminary and final validation results	As project coordinators, the institutions must be kept informed of the overall project progress. It is therefore essential for them to ensure that the project is running properly, that it is relevant to the ATM master plan, and that it is coordinated with other projects. European institutions are directly involved in the development of the solution, and the results obtained will enable the solution to be definitively included in the plans for the future of European airspace.

U-space Service Providers (USSPs)	Workshops, conferences and publications	The results of this validation exercise will evidence the feasibility of ICNS technologies relying on xG networks for connectivity, which might change the U-space management, increasing safety and efficiency.
Regulators	Assess the safety requirements considered in the validation exercises, feedback on the preliminary and final validation results	The results of the validation exercises can provide regulators with information to anticipate the regulations to be developed for deployment of the solution.
UAS operators	Provide UAS operation insights, feedback on the preliminary and final validation results	UAS operators may use the results of this validation exercise to guide their operational choices in terms of CNS technologies. Instead of relying on proprietary radios and expensive private dedicated links, the operators might be able to reduce costs and weight based on the resultant quality of service provided by findings of this validation exercise.
Telecommunication operators (xG mobile network and Satellite operators)	Provide network data, analyse business viability, Workshops, conferences and publications	By providing indications of the coverage and network infrastructures required for deployment in both urban and rural LL and VLL areas, their exploitation will enable an initial techno-economic analysis of the interest of operators in getting involved in the project.
Scientific Community	Workshops, conferences and publications	For the scientific community, this validation exercise can serve as a basis for future innovation and research.

Table 23: Exercise #02 stakeholders' expectations

5.2.3 Validation objectives

Table 24 summarizes the validation objectives to be met with this validation exercise.

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria

OBJ-ANTENNAE-TRL2-ERP-002	Success criteria (same as in Section 4.3)	Fully Covered	Same description as validation objective OBJ-ANTENNAE-TRL2-ERP-002 from Section 4.3	Same description as success criteria for validation objective OBJ-ANTENNAE-TRL2-ERP-002 from Section 4.3

Table 24: Validation objectives addressed in validation exercise #02

5.2.4 Validation scenarios

This section outlines both the reference and solution scenarios for validation exercise #02, highlighting the specific contributions of our approach. Both scenarios consider the same geographical region and RAN deployment; however, the solution scenario incorporates data-driven optimization techniques for antenna deployment configuration—including tilt and beam patterns—as well as mobility management settings that affect handover behaviour.

5.2.4.1 Reference scenario(s)

For this validation exercise, we will consider a reference scenario relying on production data from the RAN owned by a leading commercial mobile network operator in the UK. The portion of the network considered will consist of 10 deployment sites varying in height from 22 to 56 m and operating a carrier in the 2 GHz band spectrum. Each site will be equipped with at least three sector antennas, for a total of 30 cells. The geographical area selected for our validation exercise will span approximately 1400 m by 1275 m, within the area of London, between latitude [51.5087, 51.5215] and longitude [−0.1483, −0.1296]. Within this area, ground users will be randomly located outdoor (i.e., excluding areas inside buildings) at a height of 1.5 m, with a density of 10 Ground User Equipment (GUE) per cell on average [35]. We will also consider four 3D aerial corridors within the area, each 900 m in length, 40 m wide, and positioned at heights between 140 m to 160 m. The UAS-to-GUE ratio will be set to 50% following the 3GPP Case 5 in [35]. Figure 8 illustrates a 3D model of the selected area in London, identifying some of the cell site's locations, and showing a representation of the aerial corridors. Optimizing the cell antenna parameters within this urban scenario is a non-trivial task, as different areas present different signal propagation patterns. This brings the challenge of tailoring the deployment to the location characteristics while accounting for interference and load balancing. The need to provide reliable connectivity along UAS corridors further complicates the problem, requiring configurations that are not easily designed heuristically.

Figure 8: Area of London considered, with some of the cell deployment sites indicated by black markers and 3D UAS corridors in blue.

We will consider the following reference solution for antenna deployment optimization: a traditional, all-downtilt 3GPP baseline configuration, where all base stations are down-tilted (e.g., [−12º, -4º]) with all vertical Half-Power Beam Width (vHPBW) are set to 10º [35].

Likewise, for mobility management optimization we will consider 3GPP-compliant solutions for the reference scenario. In 3GPP, mobility management relies on predefined threshold sets to regulate handover decisions. Among the reference configuration suggested by the 3GPP in simulation recommendations, we will specifically focus on *set-1* and *set-5* [36], as they represent two extreme cases in handover optimization:

- *Set-1* is designed to reduce ping-pong handovers by delaying handovers, applying a uniform configuration across all radio cells with a Time-to-Trigger (TTT) of 480 ms and an A3-offset of 3 dB.
- *Set-5*, on the other hand, aims to minimize HOF by accelerating handovers, setting TTT to 40 ms and A3-offset to -1 dB, again uniformly across all cells. While this configuration allows the UE to switch to a stronger serving cell more quickly, it increases the likelihood of ping-pongs, as rapid transitions may cause frequent unnecessary handovers.

It should be noted that 3GPP evaluations apply these settings uniformly across all cells in their performance evaluations rather than adapting them per cell, primarily to simplify network-wide mobility management and reduce optimization complexity. However, this approach is often suboptimal, as it lacks adaptability to site-specific radio conditions and UE mobility patterns, motivating the need for adaptive, data-driven optimization techniques. As such, we will employ these methods as a reference for comparing the performance with the data-driven methods evaluated in the solution scenario.

5.2.4.2 Solution scenario(s)

The ANTENNAE solution (SESAR Solution 0521) envisions the use of data-driven methods for optimizing the cellular network deployment and the mobility management configuration. We will evaluate the use of state-of-the-art data-driven optimization techniques in the same geographical setup as the reference scenario described above, i.e., relying on production data from the RAN owned by a leading commercial mobile operator in the UK, in a specific area of London.

For antenna deployment optimization, we will assess the use of advanced data-driven techniques that will be used to optimize antenna tilts and half-power beamwidth. These optimization techniques will serve to optimize coverage and data rates both for UAS in aerial corridors and ground users jointly. In this context, Bayesian optimization has previously proven useful in addressing coverage/capacity trade-offs, optimal radio resource allocation, and mobility management [45]; however, it faces limitations due to the number of decision variables it can efficiently handle, which limits the amount of sites and the number of antenna parameters that can be jointly optimized. The ANTENNAE solution envisions the use of more recent data-driven techniques, such as those based on High-Dimensional BO (HD-BO), for optimizing cellular networks at a larger scale, thus overcoming the limitations of traditional vanilla Bayesian optimization techniques.

For mobility management optimization, it is critical to account for speed variations between different connected users (e.g., UAS vs ground users), since a parameter set optimized for one speed may not be suitable for another. For instance, in 3GPP-based handover scenarios high-mobility users may travel deep inside a target cell before the TTT expires, increasing the likelihood of handover failure due to degraded SINR. Conversely, these users may also experience unnecessary handovers (ping-pongs) when passing through small cells too quickly. These challenges are intensified for connected UAS, as they experience rapid fluctuations in received signal strength and strong interference from neighbouring cells, further worsening connectivity issues. The ANTENNAE solution envisions the use of data-driven mobility management optimization techniques for optimizing the triggering of handovers for both UAS in aerial corridors and ground users. We will assess the use of state-of-the art optimization techniques, such as those based on HD-BO and Deep Reinforcement Learning (DRL), in order to optimize handovers in two different ways: by modifying 3GPP-compliant parameters (e.g., TTT, A3-offset) and through more flexible solutions that can dynamically define user-cell associations at a finer granularity.

5.2.5 Exercise validation assumptions

Not Applicable. No additional assumptions compared to the ones in Section 4.4.

5.2.6 Limitations and impact on the level of significance

This validation exercise reflects UAS operations limited to VLL (up to 150 m), which might not be the same as IAM or UAM operations. Also, the validation scenario is focused on a dense urban area in London, which organically offers better ground network coverage, albeit with higher capacity demand. Nevertheless, this scenario represents the most challenging problem in terms of optimization and scalability, due to the higher number of cell sites and the number of configuration parameters to be optimized. While the results may not be directly applicable to rural areas with sparser network deployments, they are expected to be sufficiently comprehensive and realistic to serve as a representative assessment of the potential of RAN optimization solutions for UAS operations in aerial corridors. Note that the reference scenario will consider cell site deployments and configurations from a major commercial MNO operating in the analysed geographical area.

5.2.7 Validation exercise platform / tool and validation technique

In this section we detail the platform used in this validation exercise and the validation technique.

5.2.7.1 Validation exercise platform / tool characteristics

This validation exercise will rely on **site-specific radio propagation modelling, by using 3D ray tracing** techniques. Specifically, **simulations will be conducted using Sionna RT [46]** as a main radio propagation modelling engine.

For the simulations in Validation exercise #02, we will build the simulation framework depicted in Figure 9Figure 9. A 3D representation of the reference scenario (Figure 8) will be constructed from OpenStreetMap, including terrain and building information (GIS data). Base stations will be positioned and configured as per the real MNO's cellular network topology. Then, these two data sources will be combined to create a radio propagation environment, using Blender. After that, large-scale channel gain (not including the antenna gain) between the base stations and the users will be obtained using Sionna RT [46], i.e., via 3D ray tracing. Simulations will be conducted at the operating carrier frequency of 2 GHz, and the material itu_concrete will be used to model the permittivity and conductivity of all buildings. The final radio propagation map (i.e., final channel gains) will be obtained by Sionna RT, after combining antenna gain patterns with the omnidirectional ray tracing channel gains. After that, validation metrics will be computed for the validation exercise, such as metrics related to signal quality (e.g., SINR), user's data rate, or mobility-related performance metrics (e.g., radio link failures). The validation platform will support the simulation of multiple antenna configurations (e.g., tilt, HPBW) and handover configuration parameters (e.g., TTT, A3-offset, user-cell associations).

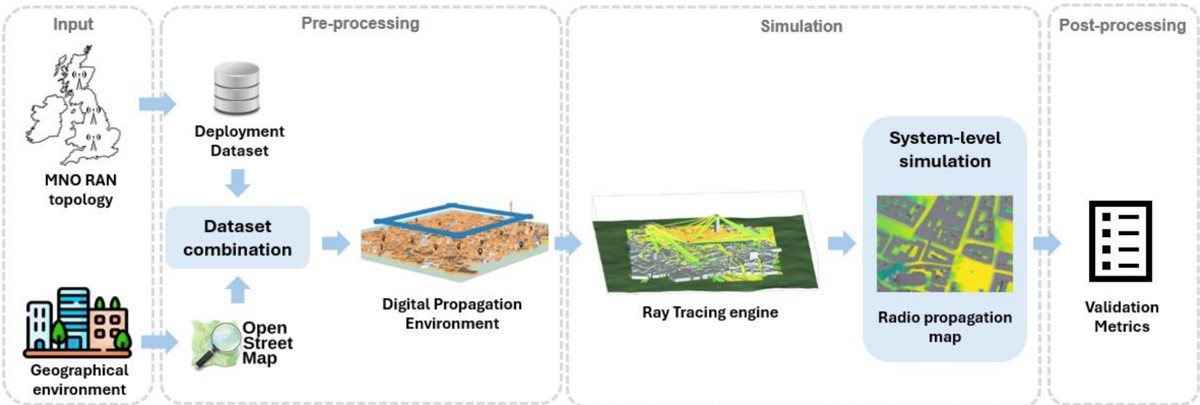

Figure 9: Simulation framework for Validation exercise #02

5.2.7.2 Validation exercise technique

In validation exercise #02, we will use 3D ray tracing as a validation technique to simulate accurate site-specific model propagation. What distinguishes ray tracing from other empirical radio propagation models is not only its granularity but also the underlying physical principles that govern its predictions. From a high-level perspective, ray tracing formally models radio propagation phenomena inspired by models from optics and acoustics. As a result, they have become a useful tool to simulating radio propagation under realistic geometric and material constraints. In this context, the Sionna RT engine [46] models wave propagation behaviour through the discrete emission of rays and simulate their interactions with 3D environments. These types of techniques rely on principles of geometrical optics, where key propagation phenomena—reflection, diffraction, and scattering—are governed by local geometry and surface characteristics. Specifically, the propagation effects can be categorized as follows:

- **Direct rays:** Travel directly from transmitter to receiver without interacting with obstacles (i.e., Line of sight)
- **Reflected/Transmitted Rays:** Interact with surfaces via reflection or transmission, governed by Snell's Law and Fresnel coefficients.
- **Diffracted Rays:** Bend around edges, modelled using Geometrical Theory of Diffraction (GTD) and Uniform Theory of Diffraction (UTD) to capture shadow boundaries and edge geometries.
- **Scattered Rays:** Arise from interactions with rough surfaces (e.g., building facades, vegetation), incorporating both specular and diffuse components.

In contrast to stochastic methods, ray tracing determines signal behaviour on a per-path basis, explicitly accounting for surface normal, material boundaries, and angles of incidence. Under the Shooting and Bouncing Rays (SBR) framework, rays are emitted in discrete directions from the transmitter, and their interactions are recursively computed across surfaces and edges. This allows for accurate site-specific radio propagation modelling across the analysed RAN optimization scenario, for example, to simulate more accurately communications under non-Line-of-Sight conditions.

5.2.8 Data collection and analysis

5.2.8.1 Data and data collection methods

Simulations will be conducted for the reference (Section 5.2.4.1) and solution (Section 5.2.4.2) scenarios at the operating carrier frequency of 2 GHz, and the material itu_concrete will be used to model the permittivity and conductivity of all buildings. Several aspects will be modified for the simulations, including input conditions of the digital propagation environment (e.g., antenna configurations) and other aspects affecting system-level simulations, such as user's mobility and handover-related configuration parameters.

The simulation scene will include real data of antennas deployed by a commercial MNO in the UK. The geographical area selected for this validation exercise covers approximately 1400 m by 1275 m, and is located within London, between latitude [51.5087, 51.5215] and longitude [−0.1483, −0.1296] (Figure 8). It will include 10+ cell sites varying in height from 22 to 56 m. Each site is equipped with three sector antennas with a transmit power of 46 dBm.

The experiments devised in validation exercise #02 will target a systematic assessment of how 5G RAN deployment and mobility management can be optimized to increase communication's performance in mixed settings with terrestrial and aerial users. In these simulations, ground users will be distributed uniformly across the selected area at a height of 1.5 m, with an average of 10 ground users per sector. UASs will be uniformly distributed along predefined aerial corridors arranged as specified in Figure 8, with an average of 70 UASs per corridor.

Some of the simulated scenarios will include variations in the altitude of aerial corridors. For example, from 50 m to 150 m. This will permit us to assess the capability of the tested data-driven optimization solutions to transfer the learned policies to scenes with aerial users at different heights.

We describe below the key aspects considered in the various optimization use cases assessed in this validation exercise.

5.2.8.1.1 Cell Shaping and Coverage Optimization

Data-driven optimization solutions will be tested for varying configurations in antenna deployments. Specifically, the optimization will consider changes in the antenna tilt and the vertical half-power beamwidth, which can be configured in 5G multi-antenna systems with the objective of maximizing coverage and data rates jointly for ground and aerial users. These two aspects will be systematically varied to understand how different configurations influence signal coverage, interference patterns and data rates within the network, as well as to assess the potential improvement of data-driven optimization solutions with respect to the reference scenario (Section 5.2.4.1).

5.2.8.1.2 Mobility management optimization

As a complementary optimization task, mobility management will involve the handling of user-cell associations in the validation scenario. In addition to the previous antenna settings, several other system-level parameters will be optimized orthogonally. These include handover-related parameters defined in 3GPP specifications, which govern the process of handovers and user-cell associations; these are the TTT and A3-offset parameters, which determine how users transition between different radio cells. By analysing the effect of these parameters, the tested data-driven optimization techniques will identify configurations that enhance mobility performance for both ground users and UASs in aerial corridors.

5.2.8.1.3 Validation metrics

For the validation, we define a set of metrics associated with the aforementioned RAN optimization tasks: antenna deployment and mobility management optimization. Table 25 shows the main metrics we will extract from the validation platform (Section 5.2.7) and how we will use them for this validation exercise. Each metric includes an indicator that reflects the expected outcome in the validation exercise. This list of metrics does not exclude the addition of other complementary metrics to the final analysis that may support the final validation conclusions.

Metric	Direction	Indicator
SINR	Increase	Coverage, signal quality
Users' data rate	Increase	Capacity, Communication quality
Radio Link Failures (%)	Decrease	Reliability, communication quality
Ping-pong handovers (%)	Decrease	Reliability, communication quality

Table 25: Exercise #02 metrics and indicator details

5.2.8.1.4 Tools and data collection methods

The tools needed to implement the validation platform are all open. This includes the ray tracing engine (SIONNA RT), the computer graphics software (Blender), and the open GIS database from OpenStreetMap that the validation platform includes.

Simulations will be run in a secure cloud-based computing platform, as they involve confidential data from the MNO's network topology, and the validation results will be saved in this computing environment in the form of csv files for tabular data, and png files for the graphical results.

For the planning and execution of this validation exercise, we will perform several iterations with the other partners of the ANTENNAE consortium. We will follow the Agile methodology for development, with 3 sprints that will serve as checkpoints to discuss and interact among the partners. At the end of each development cycle, the task leader will present the validation exercise detail and results originated of the simulation, aiming to motivate discussions, review the results and obtain suggestions of improvement and fine tuning.

5.2.8.2 Analysis methods

After the simulation experiments, the resulting validation metrics will be processed using the most suitable methods for visualization. These may include tables with aggregated statistical indicators, bar plots, box plots, or cumulative distribution functions to show full metric distributions. In addition, results may be disaggregated by relevant percentiles or differentiated by cell site. Where applicable, maps will be used to depict resulting cell partitioning schemes for coverage across both ground user areas and UAS corridors. The data will be jointly analysed with other consortium participants through multiple review rounds to minimize potential simulation biases before drawing conclusions. Once validated, the simulation results will be compared between the reference and the solution scenarios, and they will be used to perform a qualitative assessment. At the end of the validation process, we will compare the results against the expected indicators defined for the exercise (Table 25) and will compile all evidence-based conclusions in a report to be discussed internally and with external experts.

The expected results include:

- **Antenna deployment optimization**: Signal quality (SINR) and user data rates will be compared between the reference and the solution scenarios, the latter incorporating data-driven optimization techniques. Key validation metrics, such as outage probability (i.e., the probability that ground and aerial users receive SINR below a predefined threshold), and the geometric mean of user data rates, will support the qualitative analysis at the full-scene level. This will enable assess coverage and communication’s quality in the validation scenario.

- **Mobility management optimization**: Data-driven mobility optimization policies will be evaluated against the 3GPP baseline methods from the reference scenario. The analysis will focus on qualitative comparisons of ping-pong handover occurrences and radio link failure rates. This will allow the assessment of communication’s reliability in the validation scenario.

5.2.9 Exercise planning and management

The validation exercise #02 started at month 7 (the 1st of March 2025) and is planned to finish at month 18 (the 1st of February 2026). This validation exercise involves the simulation of the reference and the solution scenarios in Section 5.2.4 though 3D ray tracing techniques, with the goal of assessing RAN optimization techniques through site-specific radio propagation simulations. The execution of this validation exercise will include the discussion of the requirements and input/output parameters for the validation scenario, the implementation of the validation platform using 3D ray tracing, and the implementation of the data-driven optimization methods envisioned in the solution scenario (Section 5.2.4.2). It will also involve discussions and interpretation of results with other partners in the consortium, the advisory board and invited experts. The key milestones of this validation exercise are:

- Collect the input data and pre-processing,

- Develop simulation platform based on 3D ray tracing,
- Develop data-driven optimization algorithms for antenna deployment configurations,
- Develop data-driven optimization algorithms for mobility management configurations,
- Plan and run the simulations,
- Post-process and interpret the simulation results,
- Write a simulation results report.

5.2.9.1 Activities

Phase	Activities	Responsible
Preparatory	Scenario definitions and concept development; Simulation design and development; Sourcing input data	Exercise leader
	Scenario and simulations refinement proposing	Validation Team
Execution	Execution of the simulation; Execution of the post-processing and data visualization	Exercise leader
Post-execution	Analysis and discussion; Validation exercise report;	Exercise leader, Validation Team, Advisory Board and Invited experts

Table 26: **Exercise #02 Planning activities**

Below, we list the validation exercise #02 activities (ACT-X) that need to be performed and their respective phases (PREP02, EXEC02, POST02):

- ACT-1-PREP02: Look up for the simulator's input parameters, such as radio cell parameters and material properties in the digital propagation environment,
- ACT-2-PREP02: Obtain and clean the datasets, including GIS data the RAN topology details from a commercial MNO in London,
- ACT-3-PREP02: Develop simulation platform based on 3D ray tracing, using SIONNA RT,
- ACT-4-PREP02: Write the simulation scripts for the experiments on antenna deployment optimization,
- ACT-5-PREP02: Write the simulation scripts for the experiments on mobility management optimization,
- ACT-6-PREP02: Scenario analysis and discussion,

- ACT-1-EXEC02: Run the simulations,
- ACT-2-EXEC02: Simulation results post-processing,
- ACT-1-POST02: Result analysis and discussion with other participants,
- ACT-2-POST02: Validation exercise report.

5.2.9.2 Roles and responsibilities in the exercise

Actor	Role/responsibility
Exercise Leader **(TID)**	Prepare the validation platform and scenarios to be carried out; Develop the required features for the solution scenario; Integrate the features and scenario to the simulator; Run the simulations; Process the results and provide data visualization resources; Adjust the simulator according to the other participants suggestions.
Validation Team **(COLLINS, VTT)**	Suggest and propose modifications to the simulator; Analyse and discuss the results.
Advisory Board and Invited experts	Be involved in the discussions and provide feedback/insights.

Table 27: Exercise #02 roles and responsibilities

5.2.9.3 Time planning

Table 28 presents the validation exercise #02-time planning, showing the distribution of work allocated by activity over the entire duration of the exercise.

Activity	**Month**											
	Mar 25	**Apr 25**	**May 25**	**Jun 25**	**Jul 25**	**Aug 25**	**Sep 25**	**Oct 25**	**Nov 25**	**Dec 25**	**Jan 26**	**Feb 26**
ACT-1-PREP02												
ACT-2-PREP02												
ACT-3-PREP02												
ACT-4-PREP02												
ACT-5-PREP02												
ACT-6-PREP02												
ACT-1-EXEC02												

ACT-2-EXEC02												
ACT-1-POST02												
ACT-2-POST02												

Table 28: Detailed exercise #02-time planning

5.2.9.4 Identified risks and mitigation actions

Table 22 summarizes the risks and mitigation actions identified for the validation exercise #02.

Risks	**Impact** (1-low, 2-medium, 3-high)	**Likelihood** (1-low, 2-medium, 3-high)	**Criticality (calculated based on likelihood and impact)**	**Mitigation actions**
Risk 1	1	2	3	Proactive briefings and analyses. Simplification of test cases, iterative and incremental approach to simulations.
Risk 2	3	1	3	Continuously monitoring the industry advancements and incorporating the upcoming innovations in the best possible way. In the final versions of the deliverables the status quo will be presented.
Risk 3	3	2	3	Employing black-box performance functions circumventing closed-form mathematical modelling and optimization. Resorting to scalarization to turn

				multiple objectives into a combined one. Partitioning the network into clusters of nodes to run smaller, distributed instances of the models for computational scalability.

Table 29: exercise #02 risks and mitigation actions

Below, we describe the risks listed in Table 29:

- Risk 1: The creation of test cases and test scenarios for the Concept of Operations takes longer than planned due to insufficient data available on operation parameters of aircraft.
- Risk 2: A significant breakthrough in the development of a 5G integrated CNS methodology or similar technology by another party, which may make certain exploratory research plans outdated.
- Risk 3: Large-scale RAN optimization mathematically intractable and/or convergence issues with stochastic optimization methods.

5.3 Validation exercise #03 plan

5.3.1 Validation exercise description and scope

In this section, we will describe the alternative navigation and surveillance technologies validation. There are several reasons that motivates the use of alternative navigation and surveillance, for instance, GNSS is sensitive to ionospheric and tropospheric effects, loss of satellite visibility, and jamming. Additionally, IAM and UAS application require very accurate positioning and thus rely on the aid of other technologies, such as Real-Time Kinematic (RTK), specially for take-off and landing flight phases, since vertical GNSS accuracy is less precise and more critical in such phases.

Consequently, if GNSS is not available and navigation information is compromised, the surveillance data is also unreliable which can put the aerospace safety at risk. Traditionally, aviation relies on Automatic Dependant Surveillance-Broadcast (ADS-B)/Automatic Dependant Surveillance-Contract (ADS-C) for surveillance, but currently in UAS operation these functions are not mandatory and would increase the aircraft payload and power consumption. Commonly, UAS operate using Direct Remote ID, which is broadcast via Bluetooth or Wi-Fi to other UAS operating at close range, but such aircrafts might be invisible to the ATC. Therefore, is necessary to increase navigation, positioning and timing resilience and accuracy as well as increasing situational awareness by providing reliable surveillance data.

To circumvent these issues, alternative techniques were proposed to complement the legacy Navigation and Surveillance technologies. A-PNT are the systems that can act as backup solution for GNSS to aid determining the location, direction and time reference. Likewise, A-SUR approaches are techniques that can improve surveillance robustness by integrating multiple digital communication technologies to avoid the congestion of surveillance channels. Supporting A-SUR, JCS aims to use data transmission waveforms to determine objects position and timing conferring radar capabilities to mobile wireless communication technologies.

In Release 16 [47], the 3GPP defined measurements of timing difference using the reference signal for distance and positioning measurement using the theory of hyperbolas. In this technique, the source ground base station plus a set of neighbour ground base stations send synchronized in time the Positioning Reference Signal (PRS), and the device measures the Time of Arrival (TOA) of each signal, and the Time Difference of Arrival (TDOA) between all TOAs. With the TDOAS is possible to generate the hyperbolas and the UE is assumed to be located at the hyperbolas' intersection. By collecting this position of all the aerial users and exploiting the xG open APIs it is possible to create a database for alternate surveillance. Figure 10 illustrates the xG positioning method.

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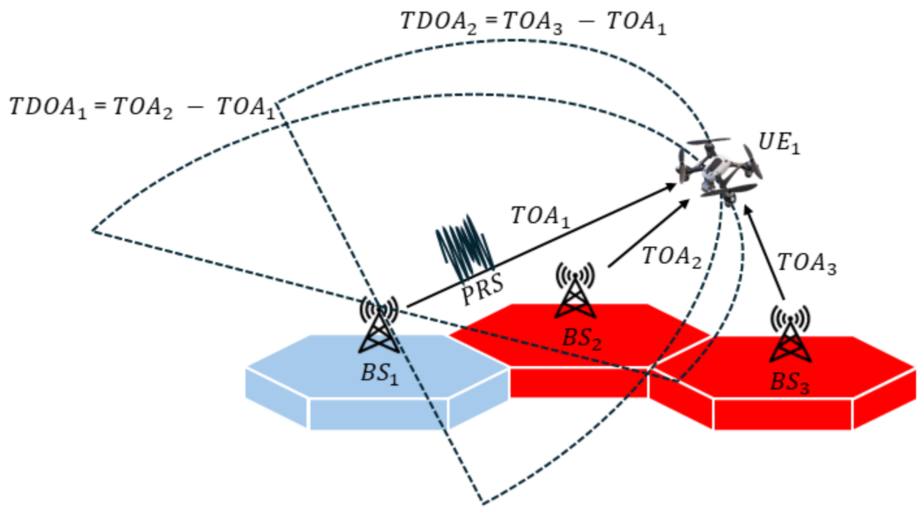

Figure 10: xG multilateration technique

Similarly, we can use LEO satellites for the same principle. In real deployments the LEO satellites do not mandatorily operate with regenerative payload, but in this validation exercise it is assumed that the LEO constellation is formed by xG regenerative payload satellites. The combination of ground and space-based alternative navigation and positioning increase the robustness of U-space operations and prevents from GNSS jamming and spoofing. Additionally, these functions are feasible only using the factory-installed transceivers in the UA, eliminating the need for extra equipage, reducing weight and power consumption.

Another capability of modern xG networks is to use the signals not only for communication but also for sensing with JCS techniques. With JCS technique, by exploiting channel matrix estimation techniques that helps inferring the signal Angle Of Departure (AOD), Angle Of Arrival (AOA), and Doppler shift, to determine the position and speed of surround objects that scattered the signal, including non-cooperative aerial users that might eventually be in the airspace. The lack of primary radar and surveillance infrastructure aiming low-altitude and very low-altitude operations motivates the use of such techniques to provide cost-efficient radar-like services to improve the safety level. Particularly in BVLOS operation environments with non-cooperative aerial users, the JCS may increase the situational awareness by complementing direct Remote ID, which is mandatory for UAS, and ASD-B, Collision Avoidance (CA), and Detect And Avoid (DAA), that are not. Also, the realization of a xG-based surveillance framework will leverage traffic control automation, due to the integration of AI, network APIs, and edge computing.

The main objectives of this validation exercise are to propose, validate and assess multilateration positioning, 5G-positioning based Alternate Surveillance, and JCS using 5G ground stations techniques. To obtain these results, we will consider the ground base station layout and LEO satellite constellation in the areas of Claire and Limerick Counties, Ireland, close to Shannon Airport vertiport and several potential commercially exploitable points in Limerick City. With this data as input, we can simulate the xG positioning function using MATLAB Simulink toolboxes and assess the availability, accuracy and reliability of a potential alternative navigation and surveillance services. By varying the altitude and position we can assess the alternative navigation and surveillance techniques comparing with the

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current technologies and validate the xG hybrid terrestrial and non-terrestrial network as an enabler of such services. Figure 11 depicts the simulation platform and validation technique.

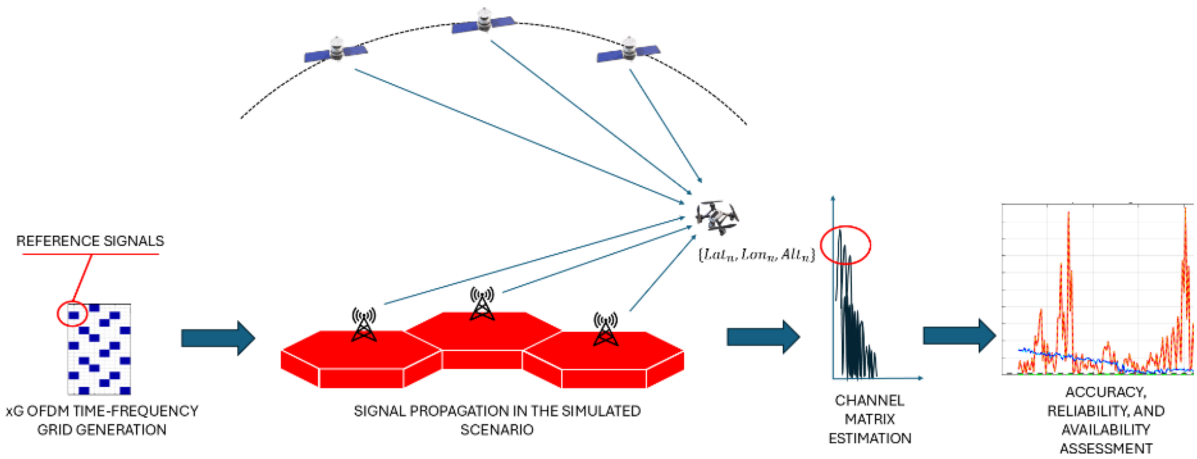

Figure 11: Simulation platform diagram and simulation technique

At the end of this validation exercise, the solution will reach at TRL2.

5.3.2 Stakeholder's expectations and benefit mechanisms addressed by the exercise

Table 30 below summarizes the expectation s of the Stakeholders impacted by the validation exercise #03, according to what was describing at Table 6.

Stakeholder	Involvement	Why it matters to the stakeholder
European Institutions (SESAR, European commission)	Participation in bilateral meetings, validation exercise progress tracking, feedback on the preliminary and final validation results	As project coordinators, the institutions must be kept informed of the overall project progress. It is therefore essential for them to ensure that the project is running properly, that it is relevant to the ATM master plan, and that it is coordinated with other projects. European institutions are directly involved in the development of the solution, and the results obtained will enable the solution to be definitively included in the plans for the future of European airspace.
U-space Service Providers (USSPs)	Workshops, conferences and publications	The results of this validation exercise will evidence the feasibility of ICNS technologies relying on xG networks for connectivity, which might change the U-space

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		management, increasing safety and efficiency.
Regulators	Assess the safety requirements considered in the validation exercises, feedback on the preliminary and final validation results	The results of the validation exercises can provide regulators with information to anticipate the regulations to be developed for deployment of the solution.
UAS operators	Provide UAS operation insights, feedback on the preliminary and final validation results	UAS operators may use the results of this validation exercise to guide their operational choices in terms of CNS technologies. Instead of relying on proprietary radios and expensive private dedicated links, the operators might be able to reduce costs and weight based on the resultant quality of service provided by findings of this validation exercise.
Telecommunication operators (xG mobile network and Satellite operators)	Provide network data, analyse business viability, Workshops, conferences and publications	By providing indications of the coverage and network infrastructures required for deployment in both urban and rural LL and VLL areas, their exploitation will enable an initial techno-economic analysis of the interest of operators in getting involved in the project.
Scientific Community	Workshops, conferences and publications	For the scientific community, this validation exercise can serve as a basis for future innovation and research.

Table 30: Exercise #03 stakeholder's expectations and benefit mechanisms

5.3.3 Validation objectives

Table 31 describes the validation objectives to be met by validation exercise #03.

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #01	Exercise validation objective	Exercise success criteria

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OBJ-ANTENNAE-TRL2-ERP-003	Success criteria (same as in Section 4.3)	Fully covered	Same description as validation objective OBJ-ANTENNAE-TRL2-ERP-003 from Section 4.3	Same description as success criteria for validation objective OBJ-ANTENNAE-TRL2-ERP-003 from Section 4.3

Table 31: Exercise #03 validation objectives

5.3.4 Validation scenarios

In this section we will detail the reference and solution scenario focusing on Navigation and Surveillance functions. In the reference scenario, legacy manned aircraft Navigation and Surveillance technologies are the most common operating method even for U-space operations, although such technologies start to present a few shortcomings, as GNSS jamming and ADS-B congestion, to name a few. Thus, emerging alternative Navigation and Surveillance techniques need to be early assessed for integrating the future of aviation.

5.3.4.1 Reference scenario(s)

As previously mentioned in Section 5.1.4.1, the most used navigation technology is GNSS. However, it presents some shortcomings, such as low vertical accuracy, susceptibility to jamming, sensitivity to atmospheric phenomena, and loss of satellite visibility. Thus, some solutions have been conceived to overcome such challenges, such as RTK and Satellite-Based Augmentation System (SBAS), to improve GNSS accuracy and reliability. Besides these methods, either the operator must rely on visual flying or near-real-time/real-time video in case of beyond visual line of sight.

In terms of Surveillance, the current operating scenario is even more restricted. Some earlier attempts of providing surveillance capabilities to U-space, such as in project FACT, used ADS-B. This raises three concerns, first ADS-B 1090MHz frequency is prone to congestion and would not support the increase in demand the U-space would imply, second ADS-B is not mandatory in most UAS even in the commercial ones, and third ADS-B ground infrastructure focuses on high altitude aircrafts operating at class A, B and C airspaces which might be a handicap for low altitude and uncontrolled airspace operations.

Since ADS-B is not widely available for such class of aircrafts, the UA manufacturers need to provide a direct Remote ID which is broadcast by the aircrafts using Wi-Fi or Bluetooth transceivers. Due to the low range these communication standards can achieve, such method is not sufficient to increase situational awareness or even to create a U-space traffic management or control centre. Another surveillance technology is ACAS Xu, which combines several inputs such as ADS-B, radar, and active mode S/C interrogation. Although powerful, this framework is also not widespread in UAS operations, depends on expensive gear, and still under prototyping and regulation.

Geographically the scenario used in this validation exercise is the same as the one described in Section 5.1.4.1.

5.3.4.2 Solution scenario(s)

U-space and IAM solutions need to weigh the power consumption, equipment weight, and cost of acquisition and operation, in addition to the safety, redundancy, and resilience levels required to any airborne equipment. Additionally, spectrum is a scarce and expensive resource, thus certificating and regulating new technologies is onerous and should be avoided. Hence, solutions exploiting existing infrastructure, integrated and lightweight are more suitable for U-space and IAM operations.

The positioning proposed by 3GPP for xG mobile wireless networks in Release 16 [47], which lists U-space operations and missions as a use case, utilizes special signals and coordinated transmissions from multiple ground base stations to measure the TDOA and estimate the aerial user position by calculating the interception of hyperbola. Thus, ANTENNAE will investigate the accuracy, availability and reliability of 3GPP xG positioning function as an A-PNT technique which may be able to support pilots and operators in case of a GNSS fault. Additionally, LEO satellites can also provide positioning data given the constellation and aircraft altitudes. These positioning methods could also work alongside legacy GNSS positioning for crosschecking in case of any security threats and accuracy augmentation.

Surveillance functions can also be performed by using xG technology. Not only can xG provide positioning functions, but through channel estimates is possible to explore JCS. Due to the high frequencies in Frequency Range 2 (FR2), the ground base stations can capture information about the surrounds by analysing the time delays and Doppler shifts in the transmitted waveform can be interpreted as the positions and velocities of scattering objects in the surroundings. This method provides a low-cost radar functionality that can be leveraged as complementary or for areas where the use of radars is not mandatory.

Besides JCS function, direct remote ID surveillance can be expanded by using an exposed positioning Application Programming Interface (API) in the xG network to create a surveillance framework. With this framework, it would be possible to estimate the coordinates of the aircrafts in the area that are associated with any xG network and create a near-real-time/real-time visualization interface. With the xG networks unique identifications, such as Subscriber Identity Module (SIM) and embedded SIM (eSIM) keys, and the Direct Remote Identifier a basic U-space control centre can be deployed when operations require. The assessment of these alternative surveillance functions is subject to latency, availability, accuracy, and reliability.

5.3.5 Exercise validation assumptions

In addition to the assumptions in Section 4.4, in validation exercise #03 we also consider the assumptions in Table 32.

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
SPA-ANTENNAE-TRL2-VLE-03-01	xG Positioning API	Although no modification is needed in order to have positioning functions on xG service, to access the positioning information it	With the xG positioning API open it is possible to retrieve an	As xG positioning is considered complementary or redundant to GNSS the impact is low,

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		is necessary to have access to the aircraft xG network user identifier and to the xG positioning API	aircraft positioning information	and it is possible to operate using only GNSS **Impact:** Low
SPA-ANTENNAE-TRL2-VLE-03-02	FR2 operation for sensing	FR2 frequencies provide almost specular propagation, which, similar to light, mitigates the multipath effect being more suitable for sensing applications	Due to the reduced range of a few hundreds of meters, the FR2 deployment is still very incipient	The JCS method would work with lower FR1 frequencies, though with reduced accuracy **Impact:** Low
SPA-ANTENNAE-TRL2-VLE-03-03	xG aerial users' identification	Cooperative aerial users would be already identified, but non-cooperative aerial users will possibly not be identified	Due to privacy issues regarding the network identifier, some aerial users might not disclose their direct remote ID or xG network to the network operator	Non cooperative users still can be identified as an object for collision avoidance purposes, however neither as aerial users nor which type of aircraft **Impact**: Low

Table 32: validation exercise #03 assumptions

5.3.6 Limitations and impact on the level of significance

The validation exercise #03 presents several limitations. The first limitation is the scenario under investigation, though it mixes dense and sparse xG ground BS deployments which might be seen as urban and rural areas, different configurated areas might be more challenging for A-PNT and A-SUR techniques. For example, in the case of A-PNT, not having enough number of ground BSs or Satellites might reduce accuracy or make it inviable. Likewise, JCS sensing range can be limited in urban canyon or hilly areas where there are none or few BSs at building rooftops or hill tops. If the coverage is found insufficient to provide the A-PNT and A-SUR required performance, we analyse this as a scenario limitation and that still worth to investigate the technology capabilities by deploying private ground BSs but also considering the cost-efficiency as a key metric for the assessment. Regarding the JCS function, the antenna configuration plays an important role in the accuracy. Directional and electronically steerable antenna arrays are suitable for this purpose, but different configurations are usually found in real network deployments. Different countries and local authorities might also have different regulations about user privacy which would require seeking authorization to identify the aerial users in a future xG-based surveillance platform.

5.3.7 Validation exercise platform / tool and validation technique

In this section we detail the platform used in this validation exercise and the validation technique.

5.3.7.1 Validation exercise platform / tool characteristics

The validation exercise will assess the proposed alternative Navigation and Surveillance methods through extensive system level simulations using MATLAB and the 5G Toolbox, which allows us to prototype such functions. The 5G Toolbox emulates the 5G signals according to the chosen PRS configuration for all ground base stations in the scenario, which will result in the position calculation for alternative navigation. Additionally, for JCS function assessment the Phased Array Toolbox is required to provide antenna array simulation according to the carrier frequency in use.

This first step of the simulation is to specify the main network parameters, such as number of ground BSs, the ground BSs' placement, channel, noise, and the reference signals configuration. To avoid collision and interferences, the reference signals time and frequency properties must be configured to avoid overlap between the neighbour ground BSs, and all ground BSs can be heard by the aerial users.

Once all the physical elements were configured, the second phase is the signal processing phase in which the simulation should generate the signals. Two signals need to be allocated to enable the positioning and speed estimation, the PRS and the Physical Downlink Shared Channel (PDSCH). The PDSCH is the channel that delivers data from the BSs to the users, occupying a time-frequency portion of the downlink grid of Resource Blocks (RBs) within a slot. Additionally, the PDSCH contains the Demodulation Reference Signals (DMRS) that are used for channel estimation to enable coherent demodulation of the transmitted data and for the sensing function to estimate the user speed and position. The PRS is a highly configurable and bandwidth-efficient reference signal optimized for time-based positioning. The correct configuration of both signals in the resource grid helps to minimise interferences.

The signal generation begins with the modulation of the reference signals configured in the previous phase. The modulated signal propagation through the channel is simulated and it involves calculating and applying the propagation delay, small-scale fading, large-scale fading, and noise to the modulated signal. With these features we can simulate the inaccuracies of applying the alternative navigation and surveillance techniques in a real environment, where the signal bounces and scatters when reaching different objects and surfaces, randomly oscillating the signal time-of-arrival and receive power.

Once the delayed, faded and noise-added signal is received, some filtering techniques may be applied to clean the signal and improve the performance of the estimation techniques. After filtering, if applicable, the simulation finishes with the calculus of the aerial user position/speed, which might include estimating the signal Doppler shift, angle-of-arrival, propagation delay, and path loss. The whole simulation process is depicted in Figure 12.

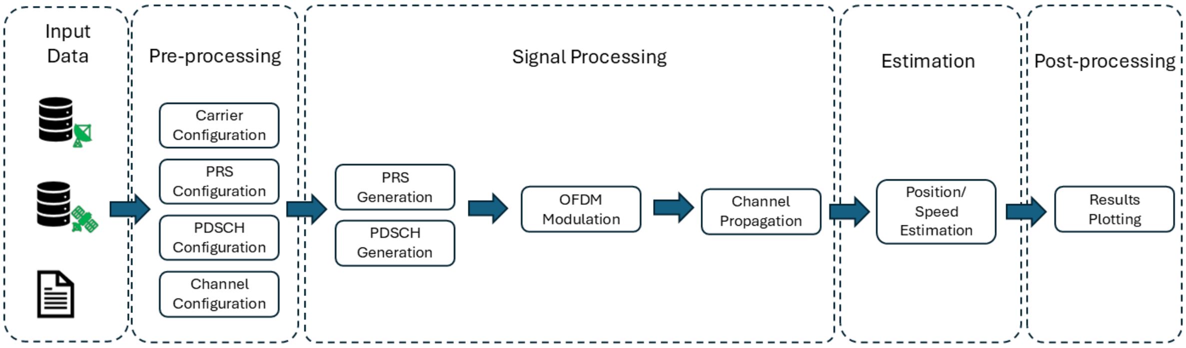

Figure 12: exercise #03 simulation diagram

5.3.7.2 Validation exercise technique

Channel simulation involves the realization of several probability density functions, that depend on the pseudo random number generator which motivates the use of Monte Carlo simulations. Hence, as each realization of the simulation is independent of the remaining realizations and identically distributed by the law of the large numbers it is possible to obtain a result that converges to the true expected value with a sufficient number of realizations. Additionally, by fixing the pseudo random number generator seed it is possible to repeat the simulation in the same conditions, given the same input parameters as well.

The input parameters can also be varied to analyse different dependent variable trends. Finding trade-off between the dependent and independent variables is important to assess the feasibility of the solution and the conditions necessary to its application in a certain environment. Finally, we can cross-compare the performance resultant obtained from the validation exercise with baseline navigation and surveillance functions.

In terms of alternative navigation and positioning, the main metric to be evaluated is the accuracy. By comparing the position estimated by the xG positioning protocol with the actual aerial user position in the simulation, we can calculate the accuracy error and evaluate against the GNSS and other methods accuracy. Additionally, we are interested on investigating the latency of the method, how long the positioning information takes to be available since the positioning signal was sent, and availability, if there are coverage limited areas, i.e., where less than three ground BSs are available. Likewise, we can validate the A-SUR techniques, which either depend on the positioning data reliability or JCS-based radars accuracy.

5.3.8 Data collection and analysis

5.3.8.1 Data and data collection methods

The main input data needed to perform validation exercise #03 are the terrestrial network topology, non-terrestrial network specification and xG network configuration. The terrestrial network topology and satellite configuration are the same as validation exercise #01, as described in Sections 5.1.4 and 5.1.8. Particularly, the scenario simulated in this validation exercise corresponds to area of the Shannon River estuary between Claire and Limerick counties, Ireland, delimiting the geographical area which will be investigated. In this area a latitude and longitude grid will be defined, and each point of this grid will be evaluated for different altitudes.

The 5G network configuration parameters need to be tuned according to the number of BSs and sectors in the simulation scenario to mitigate interference, particularly the PRS timing. Multiple adjacent ground BS should not transmit the PRS simultaneously, thus the transmission must be coordinated by using muting patterns to avoid interference. Thus, it is necessary to establish which ground BS are neighbour with each other and define the PRS muting configuration.

For the evaluation we will use the MATLAB 5G, Communication, and Phased Array System toolboxes. The 5G toolbox provide the 5G functions in which regards to frame definition, Orthogonal Frequency-Division Multiplexing (OFDM) time-frequency resource grid, physical channels and reference signals configuration. With the signals configured and modulated, the Phased Array System and the Communication toolboxes are used to simulate the phased array transmission and the channel propagation. Finally, the signals are demodulated and the estimation algorithms provide either channel matrix or the user position, which can be post-processed into user's coordinates and speed, compared to the real data will allow us to measure the accuracy, for example. Table 33 details the simulation output metrics.

Metric	Direction	Indicator
Position RMS Error	Decrease	Accuracy
Speed RMS Error	Decrease	Accuracy
Number of detected Ground BS	Increase	Availability
Number of detected NTN BS	Increase	Availability
Percentage of detectable Reference Signals	Increase	Reliability

Table 33: validation exercise #03 metrics and indicator details

For better development of the validation exercise we will take the Agile methodology approach. We plan several interactions with the solution consortium, advisory board, and invited experts. With the consortium we plan interactions at the end of each development sprint, with 3 sprints planned till the end of the validation exercise. In these interactions we plan to engage in discussions and have feedback from the other participants to assure the validation exercise is being executed as planned.

As previously mentioned, the validation exercise will be carried out using MATLAB. All the licensing required for professional commercial use of this tool is already provided as well as the necessary toolboxes. Therefore, there is no extra cost for the solution or stakeholders involved.

The experimental data will be recorded in MATLAB "*.mat" files, which can store the data structures generated during the simulation. Upon request, such structures can be converted to different file types, such as "*.csv", "*.json" or "*.hd5". The plots of the results will be generated in both "*.fig" MATLAB format and "*.png" format.

5.3.8.2 Analysis methods

According to the activities planned for this validation exercises, at the end of each sprint the results will be analysed and validated collaboratively with the other participants and guest experts. Due to the randomness inherent to the channel simulation, the adequate visualization method is to calculate the mean and confidence interval of each metric and compare with ground truths. Additionally, we are interested on investigating the spatial performance of the solution, to which we might use heatmaps to find the points where the performance is below acceptable levels. Below we list what we expect as results:

- **Accuracy**: In this analysis we will compare the achieved positioning and speed estimation error (RMSE) mean and confidence interval around the mean with the known legacy navigation technologies accuracy, such as GNSS.

- **Availability**: Each BS, either from TN or NTN, will have the PRS correlation measured that will result in the number of available BSs for positioning function. In addition, for each position in the grid, calculating the number of available BSs will help finding which areas would be more suitable to exploit xG positioning and JCS sensing and where the coverage needs to be improved with the deployment of extra BSs.

- **Reliability**: Given the total number of transmitted reference signals, some signals cannot be successfully decoded due to harsh channel conditions or to the long distance between the user and the BS. The remaining reference signals that are successfully decoded evidence the reliability of the alternative navigation and surveillance system.

5.3.9 Exercise planning and management

As the previous validation exercises, the validation exercise #03 started at month 7 (the 1st of March 2025) and to finish at month 18 (the 1st of February 2026). Throughout the validation exercise execution, we will source the input parameters and scenario data, develop the simulation scripts, process and analyse the preliminary results. Recurrent interactions with the other participants, advisory board, invited experts are planned to discuss the results and identify points of improvement. The key milestones of the validation exercise are:

- Collect the input data and pre-processing parameters,
- Develop the scripts for testing alternative positioning and navigation techniques,
- Implement the A-SUR functionality,
- Develop the JCS simulation script,
- Run the simulations,
- Generate plots and illustrative diagrams,
- Write a report assessing the results.

5.3.9.1 Activities

Table 34 details the validation exercise #03 phases, the activities and the responsible for each activity.

Phase	Activities	Responsible
Preparatory	Scenario definitions and concept development; Simulation design and development; Sourcing input data	Exercise leader
	Scenario and simulations refinement proposing	Validation Team
Execution	Execution of the simulation; Execution of the post-processing and data visualization	Exercise leader
Post-execution	Analysis and discussion; Validation exercise report;	Exercise leader, Validation Team, Advisory Board and Invited experts

Table 34: Exercise #03 planning activities

The activities for the validation exercise #03 are described in the list below:

- ACT-1-PREP03: Look up for the correct input parameters, such as transmit power and bandwidth,
- ACT-2-PREP03: Obtain and clean the data set with the ground station location in Ireland,
- ACT-3-PREP03: Obtain the Satellite network parameters,
- ACT-3-PREP03: Write the simulation scripts for A-PNT,
- ACT-4-PREP03: Write the simulation scripts for A-SUR,
- ACT-5-PREP03: Write the simulation scripts for JCS,
- ACT-6-PREP03: Scenario analysis and discussion,
- ACT-1-EXEC03: Run the simulations,
- ACT-2-EXEC03: Simulation results post-processing,
- ACT-1-POST03: Result analysis and discussion with other participants,
- ACT-2-POST03: Validation exercise report.

5.3.9.2 Roles and responsibilities in the exercise

Table 35 details the roles and responsibilities of the institutions participating in the validation exercise.

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Actor	Role/responsibility
Exercise Leader **(COLLINS)**	Prepare the platform and scenarios to be carried out; Develop the required simulation scripts for the solution scenario; Run the simulations; Process the results and provide data visualization resources; Adjust the simulator according to the other participants suggestions.
Validation Team **(TID, VTT)**	Suggest and propose modifications to the simulator; Analyse and discuss the results.
Advisory Board and Invited experts	Be involved in the discussions and provide feedback/insights.

Table 35: exercise #03 Role and Responsibilities

5.3.9.3 Time planning

Table 36 presents the validation exercise #03-time planning, showing the distribution of work allocated by activity over the entire duration of the exercise.

Activity	Month											
	Mar 25	Apr 25	May 25	Jun 25	Jul 25	Aug 25	Sep 25	Oct 25	Nov 25	Dec 25	Jan 26	Feb 26
ACT-1-PREP03												
ACT-2-PREP03												
ACT-3-PREP03												
ACT-4-PREP03												
ACT-5-PREP03												
ACT-6-PREP03												
ACT-1-EXEC03												
ACT-2-EXEC03												
ACT-1-POST03												
ACT-2-POST03												

Table 36: detailed exercise #03-time planning

5.3.9.4 Identified risks and mitigation actions

Risks	Impact	Likelihood	Criticality (calculated	Mitigation actions

	(1-low, 2-medium, 3-high)	(1-low, 2-medium, 3-high)	based on likelihood and impact)	
Risk 1	1	2	3	Proactive briefings and analyses. Simplification of test cases, iterative and incremental approach to simulations.
Risk 2	3	1	3	Continuously monitoring the industry advancements and incorporating the upcoming innovations in the best possible way. In the final versions of the deliverables the status quo will be presented.
Risk 3	1	2	3	Filter extensive ADS-B database from COLLINS to identify representative low altitude trajectories. Build relationships with other SESAR projects (e.g. SPATIO 2.0) to exchange information on U-Space operations.

Table 37: exercise #03 risks and mitigation actions

Below, we describe the risks listed in Table 37:

- Risk 1: The creation of test cases and test scenarios for the Concept of Operations takes longer than planned due to insufficient data available on operation parameters of aircraft,
- Risk 2: A significant breakthrough in the development of a 5G integrated CNS methodology or similar technology by another party, which may make certain exploratory research plans outdated,

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- Risk 3: Availability of reference trajectory data for low latitude operations, especially highly manoeuvrable IAM vehicles.

6 References

6.1 Applicable documents

This ERP complies with the requirements set out in the following documents:

SESAR solution pack

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Performance management

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Security

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Project and programme management

[6] 101167288, ANTENNAE Grant Agreement, 25 June 2024.

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[30] 3rd Generation Partnership Project, 3GPP TS 22.125, Uncrewed Aerial System (UAS) support in 3GPP (Release 19), June 2025.

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