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Abstract

This document presents the Exploratory Research Plan (ERP) for the ATMACA project, outlining validation activities to advance the solution from TRL1 (Basic Principles) to TRL2 (technology concept formulated and/or application formulated). ATMACA framework develops a secure Data Link Context Management (DLCM) application, providing mobility, session, connection, and context management capabilities, with operational applications such as Controller-Pilot Datalink Communication (CPDLC) and Green Route Operations (GRO). These are complemented by human-centred Human Machine Interfaces (HMIs) that enhance usability and situational awareness for both pilots and air traffic controllers (ATCos). The ERP defines the strategy for designing, preparing, and executing six validation exercises covering simulations, emulations, human-in-the-loop studies, and a flight trial. It also establishes the link to the Exploratory Research Report (ERR), which will consolidate results and demonstrate the feasibility and performance contributions of the ATMACA solution in line with SESAR's Digital European Sky vision.

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ATMACA

AIR TRAFFIC MANAGEMENT AND COMMUNICATION OVER ATN/IPS

ATMACA

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1 Executive summary

The Exploratory Research Plan (ERP) is a comprehensive roadmap designed to guide the experimental validation of the technological solution. It includes detailed methodologies for scenario creation, specifying criteria for simulations and emulations, and integrating monitoring tools necessary for the implementation phase. The ERP will also describe the way in which one or more validation exercises or activities are to be prepared and executed to achieve the validation objectives of the ATMACA project as an exploratory research project.

The ERP document describes the preparation of the validation activities to demonstrate the transition of ATMACA solution from TRL 1 (basic principles observed) to TRL 2 (technology concept formulated), setting the basis for future higher-level validation and prototype development in subsequent project phases [15]. A summary of the information and elements contained in the ERP is provided below:

- **Purpose and scope of the validation exercises**

The validation exercises focus on evaluating the ATMACA solution across the Key Performance Areas (KPA) of Human Performance (HP), Operation Efficiency (OPS), Digitalisation (DIGI), Cost-Efficiency (CEF), Environment (ENV), Security (SEC) and Safety (SAF) [17][18]. The validation will follow an iterative Human-Centred Design approach aimed at demonstrating and validating both the framework tools and the Human Machine Interface (HMI) concept, thereby supporting the solution's development from concept to functional prototype level.

- **Statement regarding the initial and exit maturity level**

ATMACA will augment technology already developed by some of the project partners in the field of Air Traffic Management (ATM) [37] while delivering a datalink communication protocol, a framework with the Data Link Context Management (DLCM), and a novel HMI solution for supporting human operators in the use of the Datalink applications. The project is set to progress from its current TRL 1 (Basic Principles Observed) to developing its knowledge base, defining a technology concept, and advancing to TRL 2 (Basic Technology Research / Research to Prove Feasibility).

- **Summary of the validation approach, objectives and scenarios**

The development and validation of the ATMACA solution are aligned with the design and execution of appropriate validation and demonstration activities and to show that it is operationally and technically feasible, deployable in the relevant operating environment, and capable of delivering valuable/tangible performance benefits in line with the ambitions set out in the ATM Master Plan [13], at an acceptable cost for its stakeholders emphasising the ATM stakeholders.

- **List of the validation exercises**

1. Validation exercise #1. Green Route Operations (GRO) Concept Validation

This exercise assesses the operational performance and functional capabilities of GRO [22] as an advanced operational application within the ATMACA solution framework. WIND TEMperature (WINTeM) networking and trajectory optimisation algorithms will be executed using historical flight data from French airspace. The resulting wind optimal

trajectories will be compared against the original flight paths to quantify potential efficiency gains enabled by GRO integration.

2. Validation exercise #2. Simulation of Datalink Communication Protocol

This exercise is designed to validate the core functional capabilities of the ATMACA datalink communication protocol [19][20][21] under simulated conditions: protocol-level simulations using OMNeT++ to assess key performance metrics against existing protocols and industry standards.

3. Validation exercise #3. Emulation of Datalink Communication Protocol

This exercise is designed to validate the core functional capabilities of the ATMACA datalink communication protocol under near-operational conditions: emulation involving virtualised network nodes and the integration of the DLCCM [24] and Controller-Pilot Datalink Communication (CPDLC) [23] applications, to assess the protocol stack and applications behaviour in a representative air-ground communication environment.

4. Validation exercise #4. Early-Stage Evaluation of Low-Fidelity HMI

This exercise is intended to conduct an early-stage usability evaluation of the ATMACA solution's HMIs [25] through an iterative assessment of low-fidelity wireframes. Structured feedback from representative end users, including Air Traffic Controllers (ATCOs) and pilots, is used to improve layout, interaction flows, and role-specific functionalities, ensuring alignment with operational workflows and human performance considerations.

5. Validation exercise #5. Role-Based Human-in-the-Loop HMI Simulation

This exercise aims to evaluate the ATMACA solution's HMIs [25] through a human-in-the-loop simulation using SAERCO's Air Traffic Control (ATC) simulator in realistic ATC scenarios. ATCOs interact with simulated flights by issuing CPDLC messages via the HMIs, enabling the assessment of controller workload, situational awareness, and communication effectiveness in a role-specific and controlled environment.

6. Validation exercise #6. Datalink Communication Flight Trial

This flight trial aims to demonstrate the operational capabilities of the ATMACA solution following the integration of its key operational components. Conducted onboard a Turkish Airlines (THY) aircraft, the trial will assess end-to-end mobility management, session continuity, and handover performance across multiple ATC nodes. Communication will be handled via role-specific HMIs or onboard terminals, with ground-based stations simulating operational ATC environments. The full HMI will not be integrated during the trial.

2 Introduction

2.1 Purpose of the document

The ERP document describes the preparation of the validation activities to achieve ATMACA solution for TRL2. It identifies the context of the experimental research plan in terms of scope, Key Research and Innovation (R&I) needs, expected performance contributions, and initial and exit maturity levels.

The ERP presents the experimental research plan approach, the stakeholders' expectations and involvement, validation objectives, assumptions, exercise list, and exercise planning.

2.2 Intended readership

This document is intended for various stakeholders in the ATM community at large, especially those involved in the SESAR Programme. These include:

- ATMACA consortium members who will need to prepare and execute the validation activities.
- SESAR 3 JU programme management, and related SESAR 3 projects.
- Other SESAR solutions partners.

External to the SESAR project, other stakeholders are to be found among:

- ATM Stakeholders:
- Air Navigation Service Providers (ANSPs).
- ATM infrastructure and equipment suppliers.
- Aircraft manufacturers and equipment suppliers.
- Airspace users.
- Airport owners/providers.
- Affected National Supervisory Authorities (NSAs).
- Affected staff organisations.
- Regulatory and standardisation organisations: European Aviation Safety Agency (EASA), International Civil Aviation Organisation (ICAO), European ATM Standards Coordination Group (EASCG), EUROCONTROL, European Organisation for Civil Aviation Equipment (EUROCAE).
- Entities involved in Aeronautical Telecommunication Network (ATN) research.
- Academic research and Industry research who wish to learn about the validation activities behind the ATMACA solution.

2.3 Background

Aeronautical communication networks face unique challenges due to their dynamic, high-mobility environments. Aircraft frequently transition between diverse coverage areas, networks, ground stations and communication technologies, including satellite and radio links. These transitions must meet stringent safety, reliability, and performance requirements, making robust communication systems essential for supporting operational services.

The background for the ATMACA solution is sustained by the review of current and planned communication networks and protocols within the ATN over the Internet Protocol Suite (IPS) that

support aeronautical applications and services. This review has been carried out in the project deliverable D2.1 “Review of Current and Future ATM Communication Networks” [16]. Central to this review are the various aeronautical datalink technologies, such as VHF Data Link (VDL), Satellite Communications (SATCOM), and LDACS, that enable reliable information exchange between aircraft and ground systems. Within the SESAR program, the Future Communication Infrastructure (FCI) [39] has been developed as an IP-based system designed to support ATN/IPS multilink capability, enabling seamless mobility between heterogeneous datalink systems to enhance efficiency, capacity, safety, and reduce environmental impact. These technologies support a wide range of aeronautical datalink applications and services critical to ATM.

Transitioning to more specific challenges, a major focus of ongoing research lies in the study of mobility management protocols, which are vital for maintaining session continuity as aircraft transition between different access networks. Despite significant progress, current mobility solutions present limitations, and several open problems and challenges remain, particularly in achieving robust, scalable, and secure mobility management for future ATM systems.

2.3.1 The gap in mobility management

Mobility management [43] is a critical requirement for the ATN in a multilink environment; however, existing solutions remain inadequate for addressing the unique operational challenges of aeronautical communications under SESAR. Since current IP-based protocols were not originally designed to support seamless mobility across heterogeneous links, they often suffer from performance issues such as handover delays, packet loss, latency, and signalling overhead. Most existing approaches concentrate on terminal mobility and basic handover mechanisms but fail to fully support the broader mobility tiers, user, session, and service mobility. In addition, limited effort has been devoted to aligning mobility mechanisms with application-specific requirements, which is essential for ensuring the continuity, quality, and CEF of critical aeronautical services.

To address these challenges, three protocols have emerged as the most promising candidates: Proxy Mobile IPv6 (PMIPv6), Ground-based Locator/Identifier Separation Protocol (GB-LISP), and the Session Initiation Protocol (SIP). These protocols have been analysed in detail in a previous deliverable (D2.1) to assess their advantages and limitations [16]. Mobility management in ATN/IPS must ultimately satisfy all four mobility tiers, terminal, user, session, and service mobility, while also meeting fundamental prerequisites such as registration, configuration, dynamic address binding, and continuous location management. Although PMIPv6, GB-LISP, and SIP each address specific aspects of mobility, none of them individually provides a comprehensive solution for the complex demands of aeronautical multilink environments.

2.3.2 ATMACA protocol to fill the gap

The ATMACA project addresses the limitations of existing mobility solutions in multilink aeronautical communication environments by introducing a new datalink communication protocol, the ATMACA protocol. This protocol is specifically designed for the ATN and integrates key features such as:

- Session and connection management for reduced latency and uninterrupted service continuity.

- Context management, incorporating flight plan, airspace, and operational data to enhance situational awareness.
- Built-in Quality of Service (QoS) mechanisms to guarantee service quality for time-sensitive applications.
- Robust security, including mutual authentication, Role-Based Access Control (RBAC), and context-based authorisation.
- Comprehensive mobility support, covering terminal, user, session, and service mobility.
- Flexibility and scalability to adapt to evolving aeronautical communication needs.

The ATMACA protocol draws inspiration from SIP (for flexible session management)[26][41][42] and Diameter (for authentication and structured data handling) [30]. By extending and adapting these protocols, ATMACA delivers seamless session continuity, secure and efficient mobility management, and future-proof adaptability tailored to the complexities of aeronautical communications.

2.3.3 ATMACA solution as a way forward

The ATMACA project proposes an innovative solution for ATM and communication over ATN/IPS. It integrates three core elements:

- a specialised datalink communication protocol with session, connection, context, and mobility management,
- advanced operational applications, including the Context Management Application (CMA)
- an enhanced HMI for pilots and controllers.

The ATMACA framework is designed as a scalable and future-proof system that:

- ensures secure, reliable, and efficient communication.
- supports application integration and interoperability through CMA.
- incorporates context-based applications such as CPDLC and GRO to optimise controller–pilot interactions and trajectory management.
- features advanced HMIs for ATC towers, radar systems, ATM stations, and flight decks, capable of handling high data loads.
- is compatible with commercial off-the-shelf (COTS) equipment and System-Wide Information Management (SWIM)-enabled systems [36][40], ensuring interoperability with current and future Communication, Navigation and Surveillance (CNS)/ATM infrastructures.

By addressing the challenges of mobility in IP-based air–ground communications, ATMACA reduces handover delays, guarantees continuous service in complex airspace, and contributes to increased capacity, operational efficiency, safety, and sustainability in line with SESAR’s Digital European Sky vision.

ATMACA aims to deliver four key operational improvements in ATM:

- Streamlined ATC and communication handovers, reducing delays and ensuring continuity.
- Flexible flight session management, enabling more adaptable flight operations.

- Seamless datalink operations management, supported by an intuitive HMI that enhances situational awareness for both pilots and controllers.
- Trajectory prediction and optimisation, supporting GRO for more efficient and environmentally sustainable flight planning.

The main goal of the ATMACA project is to develop and validate a scalable, interoperable, and cost-effective air–ground datalink communication and digital flight management environment covering all flight phases from gate to gate, including airports, Terminal Manoeuvring Areas (TMAs), en-route, and oceanic airspace. Development is closely linked to validation and demonstration activities to prove that the solution is operationally and technically feasible, deployable in real environments, and capable of delivering tangible performance benefits in line with the ATM Master Plan, at an acceptable cost for stakeholders.

2.4 Structure of the document

Section 2 describes the purpose of the document, the intended readership, background, structure of the document and glossary of terms, and the list of acronyms. Section 3 describes the scope, key R&I needs, expected performance contributions, and initial and exit maturity levels. Section 4 describes the experimental research plan approach, the stakeholders’ expectations and involvement, validation objectives, validation assumptions, validation exercise list, and validation exercise planning. Section 5 provides a detailed description of the six validation exercises. Section 6 lists the references used in developing this ERP.

2.5 Glossary of terms

Term	Definition	Source of the definition
Air Traffic	All aircraft in flight or operating on the manoeuvring area of an aerodrome.	ICAO Annex 11 - ATS [31]
Air Traffic Control Service (ATC)	A service provided for the purpose of: Preventing collisions: 1) between aircraft, and 2) in the manoeuvring area between aircraft and obstructions. Expediting and maintaining an orderly flow of air traffic.	EU 2015/340 [27]
Air Traffic Controller (ATCo)	A person authorised to provide ATC services.	EUROCONTROL ATM Lexicon [28]
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 sufficiently – through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions.	ICAO 4444 – ATM [32]

Air Traffic Service	A generic term meaning variously, flight information service, alerting service, air traffic advisory service, ATC service (area control service, approach control service or aerodrome control service).	ICAO Annex 11 – ATS [31]
Controller-pilot Data Link Communications	A means of communication between controller and pilot, using data link for ATC communications.	ICAO Global Operational Data Link Document (GOLD) [35]
Data Link Communication	A form of communication intended for the exchange of messages via a data link	ICAO Annex 11– ATS [31]
Data Link Initiation Capability	A data link application that provides the ability to exchange addresses, names and version numbers necessary to initiate data link applications.	ICAO Doc 9880 – Part I [33]

Table 2-1: glossary of terms

2.6 List of acronyms

Term	Definition
ACC	Area Control Centre
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-C	Automatic Dependent Surveillance - Contract
ANS	Air Navigation Service
ANSP	Air Navigation Service Provider
AOC	Airline Operations Centre
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
ATMACA	Air Traffic Management and Communication over ATN/IPS
ATN	Aeronautical Telecommunication Network
CEF	Cost Efficiency
CMA	Context Management Application
COTS	Commercial Off-The-Shelf
CNS	Communication, Navigation and Surveillance
CPDLC	Controller-Pilot Data Link Communication
DAT	Data Authority Transfer
DIGI	Digitalisation
DLCM	Data Link Context Management
DLIC	Data Link Initiation Capability
DoS	Denial-of-Service
EASA	European Aviation Safety Agency
EASCG	European ATM Standards Coordination Group
EFB	Electronic Flight Bag
ENV	Environment

EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
EUROCONTROL	European Organisation for the Safety of Air Navigation
EXE	Exercise
FCI	Future Communication Infrastructure
FEEF	Fuel Efficiency
FIR	Flight Information Region
FRD	Functional Requirements Document
GB-LISP	Ground-based Locator/Identifier Separation Protocol
GRO	Green Route Operations
HMI	Human Machine Interface
HP	Human Performance
ICAO	International Civil Aviation Organisation
ID	Identification
IFR	Instrumental Flight Rules
IPS	Internet Protocol Suite
KPA	Key Performance Area
KPI	Key Performance Indicator
NSAs	National Supervisory Authorities
OPS	Operational Efficiency
OSD	Operational Service and Environment Definition
OSI	Open Systems Interconnection
PMIPv6	Proxy Mobile IP version 6
PRD	Predictability
QoS	Quality of Service
RBAC	Role-Based Access Control
SAF	Safety
SATCOM	Satellite Communications
SEC	Security
SESAR	Single European Sky ATM Research Programme
SESAR 3 JU	SESAR 3 Joint Undertaking
SIP	Session Initiation Protocol
SWIM	System-Wide Information Management
TEFF	Technical Efficiency
THY	Turkish Airlines
TMA	Terminal Manoeuvring Area
TRL	Technology Readiness Level
UC	Use Case
VFR	Visual Flight Rules
VHF	Very High Frequency
VO	Validation Objective

Table 2-2: list of acronyms

3 Context of the exploratory research plan

3.1 Exploratory research plan context

The ERP aims at presenting the different experiments planned to validate the functional and non-functional requirements of the ATMACA solution, advancing it from TRL1 (Basic Principles) to TRL2 (technology concept formulated and/or application formulated). The goal is to demonstrate feasibility and operational relevance through a set of validation activities that combine simulations, emulations, human-in-the-loop studies, and a flight trial.

3.1.1 Geographical, Operational and Technical Environment

The validation activities will be conducted across diverse airspace environments - simulated, emulated, or real-world flights - representative of real operational conditions:

- Airports, including ground movements, gate operations, and runway/taxiway procedures.
- TMAs, high-density traffic zones where seamless mobility and communication continuity are critical.
- En-route airspace, long-range cruise phases requiring robust datalink continuity across ANSP boundaries.
- Oceanic and remote region areas with limited terrestrial connectivity where satellite and multilink operations play a key role.

This broad geographical coverage ensures that the ATMACA solution is validated under conditions ranging from dense, complex air traffic to sparse, long-haul segments.

The Operational Service and Environment Definition (OSED), D2.3 [18], describes in detail the operational environment. It compares previous and new operating methods, illustrating how ATMACA enhances current practices through four representative use cases:

- Seamless flight handovers and session transfers between ATCos and sectors.
- Persistent IP-based communication sessions with enhanced continuity and context.
- Unified and consistent datalink operations featuring enhanced HMI for controllers and pilots.
- Support for GRO via real-time trajectory optimisation and environmental data integration.

The technical environment integrates both existing and advanced systems to demonstrate feasibility and interoperability:

- ATN/IPS infrastructure, IP-based multilink communication networks spanning satellite, terrestrial, and cellular technologies.
- Specialised ATMACA protocol providing session, connection, context, and mobility management capabilities at the application layer.
- Operational Applications, including the CPDLC, and GRO support tools.
- SWIM, enabling seamless information exchange with other CNS/ATM systems.

- HMIs, advanced, role-specific interfaces for ATC and cockpit environments.
- Validation Platforms, simulation environments and testbeds replicating gate-to-gate flight operations.

3.1.2 Key Assumptions

As stated in OSED, D2.3, the key assumptions are divided into operational, safety, performance, and other related assumptions as described below [18].

Operational assumptions

- ATMACA will be fully compatible with existing and legacy data link systems, ensuring seamless integration with avionics, ground infrastructure, and COTS equipment.
- Onboard hosting will be supported by an Electronic Flight Bag (EFB) Class 3 or equivalent dedicated unit, with continuous real-time data provision from avionics and sensors; ATC hosting systems are also assumed available.
- The protocol will enable gate-to-gate operation (airports, TMAs, en-route, oceanic) with multilink coverage and scalability to growing traffic demands.
- End-user acceptance (pilots, ATCos) is assumed, with intuitive HMIs validated through user-centred assessments.
- The solution builds upon and is fully compatible with SWIM [36][40] and FCI frameworks [39].

Safety assumptions

- Safety-critical exchanges (e.g. ATC clearances, emergencies) will be prioritised, with failover mechanisms ensuring reliability.
- The protocol will integrate aviation cybersecurity standards (encryption, authentication, authorisation).
- Coexistence with other safety-critical systems is assumed, without interference.
- Full alignment with EASA regulations and standards, supported by rigorous safety validation and risk assessments.

Performance assumptions

- Protocol will ensure low-latency, high-reliability communication, with bandwidth aggregation, dynamic link selection, and failover.
- SWIM-based data management will provide real-time, synchronised updates between aircraft and ground systems.
- Uplink/downlink of safety-critical information will meet SWIM purple profile requirements (security, safety, reliability, accessibility).

Other assumptions

- ATMACA is assumed to remain compliant with regulations, undergoing certification and approval before deployment.

- The onboard hosting system will be standalone, avoiding modifications to certified avionics unless formally approved.
- The trial organisation is assumed to have clearly defined roles, responsibilities, and processes in place to effectively manage both clients and provided services.
- Pilots and ATCos will receive training to operate ATMACA, with roles unchanged - human oversight remains central. The system is expected to reduce workload and enhance efficiency in information exchange.

Together, these environments and assumptions ensure validation covers the full operational spectrum, from dense airspace to remote segments, while proving ATMACA's feasibility as a secure, interoperable, and scalable future communication solution.

3.2 Scope

The ERP focuses on the ATMACA solution as described in D2.3 OSED. The proposed solution introduces a robust service framework centred on four key capabilities: Session Management, enabling the persistent and contextual handling of air-ground and ground-ground communications; Connection Management, ensuring reliable, secure, and redundant connectivity for operational continuity; Mobility Management, supporting seamless mobility across users, devices, services, and sessions, enabling uninterrupted operations; and Multilink Communication, optimising communications through redundancy and load balancing across multiple networks. The solution also includes the concept of "flight sessions", which uniquely binds a flight to its communications, contextual data, and historical exchanges, ensuring context continuity through all operational phases and across ATC units.

Within this scope, the ERP will validate ATMACA's ability to deliver seamless, secure, and interoperable datalink communication across all flight phases (gate-to-gate) in dynamic European airspace environments, including airports, TMAs, en-route, and oceanic segments. The validation activities will target the ATMACA operational concept, the functional and non-functional requirements and the prototype of the solution.

The ERP will use simulations, emulation, laboratory-based tests, and controlled demonstrations to assess the ATMACA solution across the set KPAs, measured via KPIs. Validation activities will address four representative scenarios described in section 3.1.1. Experiments will consider high-mobility, multilink communication environments where aircraft transition between radio, satellite, and ground networks, while ensuring compliance with ICAO, EASA, and SESAR standards. The ERP encompasses the needs and roles of pilots, controllers, ANSPs, airlines, and airports, ensuring that the research reflects real operational challenges and benefits.

The main high-level research questions that are planned to be answered with the validation activities are described in section 3.3 Key R&I Needs. The six validation exercises related to the high-level research questions are described in section 4.5 Validation exercises list.

3.3 Key R&I needs

The outstanding R&I needs focus on developing, validating, and integrating a holistic mobility management solution tailored for aeronautical multilink networks. This requires addressing challenges in mobility across all tiers, seamless handovers, QoS assurance, robust security, integrated context

management, and human–machine interaction. The proposed research questions will guide experiments and validation activities, ensuring that ATMACA delivers a scalable, secure, and future-proof communication framework aligned with SESAR’s Digital European Sky vision. The major high-level research questions to be addressed during the validation activities are:

RQ1: Mobility Performance:

How can mobility management in multilink ATN/IPS environments be optimised to minimise handover delay, packet loss, latency, and signalling overhead?

RQ2: Seamless Handover:

What mechanisms are most effective for supporting intra-domain and inter-domain mobility, including both horizontal and vertical handovers in aeronautical networks?

RQ3: Unified Mobility Framework:

How can terminal, user, session, and service mobility be integrated within a single, coherent framework for aeronautical communications?

RQ4: Integrated Management Functions:

In what ways can session, connection, mobility, and context management be combined to reduce architectural complexity and improve cost efficiency?

RQ5: Trajectory Prediction and GRO Integration

How can real-time flight and weather data, improve trajectory prediction accuracy and enable environmentally efficient flight operations?

RQ6: Security & Trust:

How can authentication, RBAC, and context-aware authorisation be embedded into mobility protocols to ensure robust security and trustworthiness?

RQ7: Human–Machine Interaction:

How can advanced, human-centred HMIs enhance situational awareness, usability, and workload management for pilots and controllers under high traffic and data load conditions?

RQ8: Interoperability & Scalability:

What approaches ensure seamless interoperability with SWIM-enabled systems and legacy CNS/ATM infrastructures, while maintaining scalability for future operational demand?

3.4 Estimated performance contributions

The ATMACA project is expected to deliver measurable performance contributions across multiple KPAs of the SESAR DES performance framework. These contributions will be validated through the six planned experiments/validation activities, using both qualitative (impact level) and, where possible, quantitative Key Performance Indicators (KPIs).

KPA	Expected Improvements	KPIs
Cost Efficiency (CEF)	<ul style="list-style-type: none"> Reduced ATCo interventions and communication workload via automation. Cost savings from more efficient use of airspace and improved operational predictability. 	CEF1: Direct ANS Gate-to-gate cost per flight. CEF2: Flights per ATCo-hour on duty. CEF3: Technology cost per flight.

Environment (ENV)	<ul style="list-style-type: none"> Reduction in CO₂ emissions by reducing fuel burnt through GRO. 	ENV1: Average CO ₂ emission per flight.
Operational Efficiency (OPS)	<ul style="list-style-type: none"> Improved trajectory predictability and adherence. Reduction in flight time variability through optimised trajectory management. Seamless inter-domain mobility reducing delays in communication and coordination. 	<p>FEEF1: Average fuel burnt per flight. TEFF1: Gate-to-gate flight time. PRD1: Average difference between actual & flight plan or Reference Business Trajectory (RBT) durations. PRD2: Variance of difference between actual & flight plan or RBT durations.</p>
Safety (SAF)	<ul style="list-style-type: none"> Reduced communication errors through seamless handovers and session continuity. Increased resilience of datalink services through integrated mobility and context management. Built-in authentication and security mechanisms ensuring message integrity and confidentiality. 	SAF1: Total number of estimated accidents with ATM contribution. (Yearly Count of events - Not directly measurable.)
- Digitalisation (DIGI)	<ul style="list-style-type: none"> Deployment of a new IP-based datalink protocol with integrated session, connection, context, and mobility management. Compatibility to ensure seamless integration into the ATM environment. 	<p>DIGI1: Adoption of digital services. DIGI2: Interoperability with legacy/COTS systems. DIGI3: Automation of datalink services.</p>
Security (SEC)	<ul style="list-style-type: none"> Robust security through RBAC and context-aware authorisation. 	<p>SEC1: A security risk assessment has been carried out. SEC2: Security requirements have been derived. SEC3: Risk level per security assessment is lowered after risk treatment.</p>
Human Performance (HP)	<ul style="list-style-type: none"> Enhanced situational awareness for ATCos and pilots via role-based HMIs. Reduced workload through automated handovers and context management. Improved usability and acceptance of new tools. 	<p>HP1: Consistency with human capabilities and limitations. HP2: Suitability in supporting human actors. HP3: Adequacy in supporting human actors. HP4: User acceptability and feasibility for changes.</p>

Table 3-1: estimated performance contributions of the ATMACA project

The estimated performance contributions in Table 3-1 demonstrate that ATMACA has the potential for high impact in KPAs. The KPIs of these contributions will be validated through a combination of simulation, emulation, human-in-the-loop studies, and flight trials.

3.5 Initial and exit maturity levels

As stated in the Grant Agreement (101167070) [11], at project start, the ATMACA solution is assessed at TRL1, corresponding to the Concept Formulation stage. This assessment is based on:

- The theoretical foundations already established through the patent “Air Traffic Communication and Management System and Method” (Turkish Patent and Trademark Office, no. 2016/20184).
- Results from ongoing academic research and literature review, which demonstrated feasibility of using ATN/IPS for air–ground communications.
- Initial conceptual design work outlining how a specialised IP-based protocol could overcome the disadvantages of existing CPDLC over VDL2.

The outcomes of this stage confirm that the ATMACA solution has a defined theoretical basis, innovative features for IP-based aeronautical communication, and initial conceptual models (e.g. protocol design, preliminary HMI layouts, and environmental trajectory optimisation concepts).

By the end of the project, the ATMACA solution is expected to reach TRL2, corresponding to the Proof-of-Concept stage. At this level:

- The concept will be validated analytically and experimentally, using simulation, emulation, and early flight trials.
- Human-centred requirements will be defined, and HMIs evaluated through low-fidelity prototyping and human-in-the-loop simulations.
- Early implementations of the ATMACA protocol will be exercised with representative operational data emulated CPDLC scenarios.
- A proof of concept will be demonstrated, showing that the proposed ATMACA solution can satisfy communication continuity, mobility management, and environmental efficiency requirements under representative ATM conditions.

The exit maturity gate is scheduled for Month 22 (MS9), at which point KPA/KPI-based assessments will confirm achievement of TRL2.

As planned in D1.1 “Project Management Plan” [14], the maturity assessment follows SESAR 3 Multiannual Work Programme (2022–2031) criteria for TRL2. The proposed ATMACA project is compliant with the ATM Master Plan and/or Strategic Research and Innovation Agenda (SRIA). The solution architecture for IP-based communication, meeting all necessary application performance criteria as listed in RTCA/EUROCAE DO-290/ED-120 [38][29] and others in 2004, has been documented (SYS.TRL2.1). The ATMACA project includes opportunities to support CNS infrastructure for CPDLC, DLDM, Digital Strip, Digital Voice, Departure Clearance, and digital ATS message exchange (SYS.TRL2.3). The results of the ATMACA project aim to achieve the design of the Green Route Optimisation Application and TRL2 environmental assessment. The verification objectives covered by TRL2 validation activities address the relevant and primary SESAR Solution Research and Development needs. The proposed ATMACA project defines and documents operational and technical assumptions that may impact the integration of the ATM solution into the European ATM system (PRG.TRL2.2). Based on the results of the work package, potential operational environments where the SESAR

Solution should be deployed have been identified (OPS.TRL2.2). Additionally, the ATMACA project has supported the definition of the SESAR technological solution through the results provided by paper/analytical/modelling/simulation studies (SYS.TRL2.2). D1.5 “TRL Monitoring Report” provides a concise yet comprehensive view of the project’s readiness evolution and its alignment with the overall technical objectives of ATMACA [15]. The table below (Table 3-2) describes the maturity levels of the ATMACA solution under research.

Project/ Proposed SESAR solution(s) ID	Proposed SESAR solution(s) title	Initial level maturity	Exit level maturity	Reused material from past R&I Initiatives validation
0153	Air Traffic Management and Communication over ATN/IPS (ATMACA)	TRL1 – Concept formulated (based on patent 2016/20184, academic research, literature review)	TRL2 – Proof of Concept (validated analytically and experimentally through simulation, emulation, HMI studies, and flight trial)	Results from SESAR studies on ATN/IPS, CPDLC limitations, and VDL2 shortcomings; insights from SESAR exploratory research deliverables; existing models for mobility management (PMIPv6, LISP, SIP); historical trajectory datasets (for GRO validation)

Table 3-2: maturity levels table

4 Exploratory research plan

4.1 Exploratory research plan approach

The ERP is structured to advance the ATMACA solution from its initial maturity level of TRL1 to the target maturity level of TRL2. At TRL1, ATMACA has already established its theoretical foundations through prior research, a registered patent (2016/20184), and initial conceptual design work. The ERP now defines a pathway of validation activities that will provide both analytical and experimental evidence of feasibility, human-centred requirements, and early proof-of-concept demonstrations.

The planned validation exercises progressively reduce uncertainty by moving from analytical simulations to emulations, human-in-the-loop assessments, and finally a flight trial. Together, these activities are designed to confirm that the ATMACA protocol, HMIs, and applications such as GRO and CPDLC, can function under representative operational and technical conditions.

At each step, self-assessments will be carried out to measure alignment with TRL2 criteria (as per SESAR performance framework), identify gaps, and adjust activities accordingly.

- Exercise #1 (GRO Concept Validation): Validates environmental and efficiency contributions using historical trajectory data and optimisation models. Provides early analytical evidence to support ENV and OPS KPAs.
- Exercise #2 (Protocol Simulation): Assesses protocol-level functions supporting CPDLC operations, where Data Authority Transfer (DAT) forms an integral part of the application, ensuring session continuity during both DAT procedures and terminal mobility management within a controlled simulation environment, providing evidence of technical feasibility against DIGI and SAF KPAs.
- Exercise #3 (Protocol Emulation): Builds on simulation outcomes by emulating near-operational conditions to evaluate CPDLC and DLCCM with integrated session and context management functions. The exercise focuses on user, session, terminal, and service mobility to demonstrate continuity of service, coordinated CPDLC message handling, under representative air-ground operational scenarios, providing evidence of feasibility across SEC and SAF KPAs.
- Exercise #4 (Low-Fidelity HMI Evaluation): Validates early ATMACA HMI design concepts through end-user evaluations, ensuring human-centred requirements, usability, and situational awareness are addressed. The exercise focuses on refining interface layout, workflow logic, and interaction design to support HP and SAF KPAs.
- Exercise #5 (Human-in-the-Loop HMI Simulation): Conducts role-based simulations with ATCos under realistic traffic conditions to assess workload, situational awareness, usability, and communication flow using ATMACA HMI prototypes. The exercise validates human-system interaction in representative operational settings, strengthening evidence across SAF and HP KPAs.
- Exercise #6 (Flight Trial): Provides the final proof-of-concept demonstration of end-to-end mobility management, session continuity, and application performance under live flight

conditions. The exercise validates ATMACA’s operational feasibility and confirms TRL 2 maturity across CEF, SAF, HP, and DIGI KPAs.

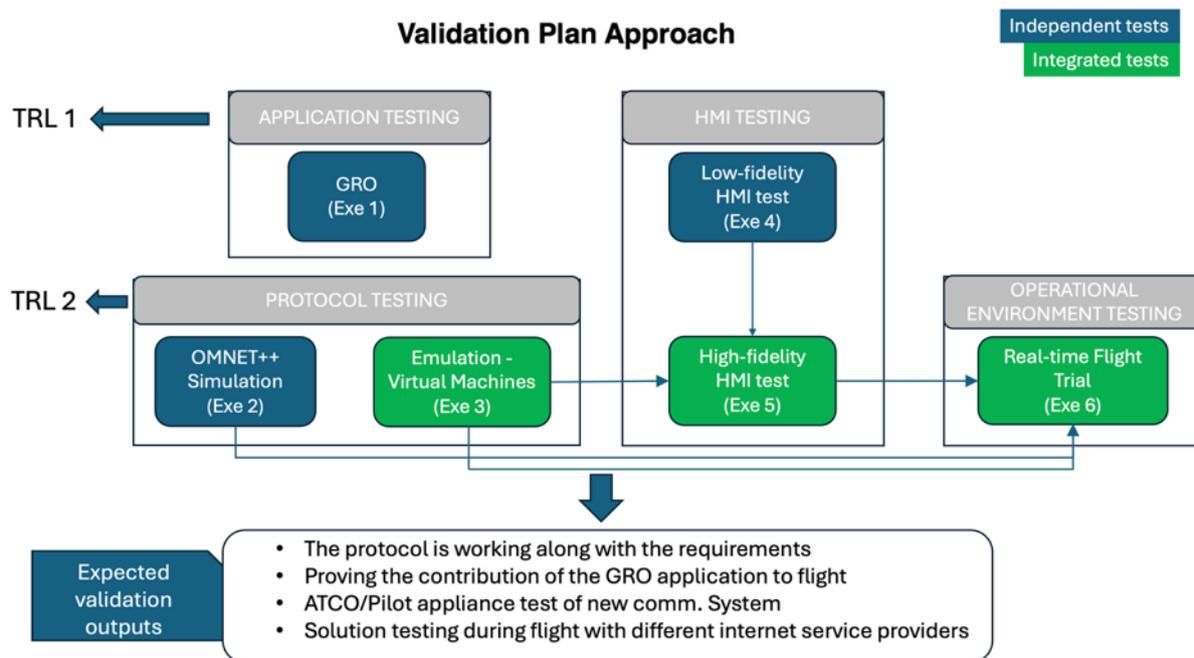


Figure 4-1: reference architecture

The six exercises are interdependent and logically sequenced (See Figure 4-1):

- Protocol and applications validation progresses from simulation (Exe #2) to emulation (Exe #3) to flight trial (Exe #6).
- HMI design evolves from concept evaluation (Exe #4) to operational simulation (Exe #5).
- GRO validation (Exe #1) complements protocol and HMI validation by quantifying efficiency and environmental contributions.

Feedback from intermediate results, prior SESAR research (e.g., ATN/IPS and FCI studies), and stakeholder involvement will be incorporated throughout the plan. Iterative refinement will ensure the solution evolves consistently with operational needs, SESAR guidelines, and performance requirements.

The ERP directly targets SESAR KPAs (See Section 3.4). They, together, ensure comprehensive coverage of all functional, non-functional, and human-centred requirements needed to reach TRL2 maturity level. By the completion of the ERP, the ATMACA solution will demonstrate:

- Feasibility of its protocol and operational applications under representative conditions.
- Human-centred HMIs tailored for pilots and controllers.
- Quantified performance contributions across all KPAs.
- Proof of concept supported by both analytical and experimental validation, ready for transition to higher TRLs.

In summary, this ERP provides a structured pathway to bring ATMACA from TRL1 to TRL2. The combination of analytical, experimental, human-centred, and flight validation activities is sufficient to demonstrate the feasibility of the proposed ATN/IPS datalink solution, while ensuring traceability to SESAR’s performance ambitions.

4.2 Stakeholders’ expectations and involvement

The ATMACA project addresses critical challenges in air-ground datalink communication, referring not only to text-based exchanges but also to text-based services, and extends the traditional concept of mobility management (which generally focuses on terminal mobility) to include session, user, and service mobility, together with advanced human-machine interaction, all of which directly impact a broad spectrum of aviation stakeholders.

Each stakeholder group has specific expectations of the validation activities, linked to their operational roles and performance objectives, and contributes actively to the planned exercises. The table below (Table 4-1) describes the identified stakeholders and their expectations related to the ATMACA solution under research.

Stakeholder	Involvement	Why it matters to the stakeholder
ATCos	Exe #4 (low-fidelity HMI evaluation), Exe #5 (human-in-the-loop simulation), partial involvement in Exe #6 (flight trial).	Need reduced workload, seamless handovers, improved situational awareness, and reliable datalink communication for safe and efficient ATC operations.
Pilots	Exe #4 (HMI evaluation), Exe #6 (flight trial).	Expect intuitive HMIs, uninterrupted datalink sessions, and predictable communication to support flight efficiency and safety across all airspace domains.
ANSPs	Exe #2 (protocol simulation), Exe #3 (protocol emulation), Exe #5 (ATC HMI simulation), Exe #6 (flight trial).	Require seamless mobility across intra-/inter-domain boundaries, reliable communication services, and interoperability to ensure operational continuity and cost-efficiency.
Airlines	Exe #1 (GRO validation), Exe #6 (flight trial with THY aircraft).	Aim for reduced fuel burn and CO ₂ emissions, predictable operations, and cost savings through optimised trajectories and efficient communication.
Airports	Exe #1 (trajectory data analysis for GRO), Exe #6 (support for gate-to-gate operations).	Benefit from improved predictability of arrivals/departures, smoother gate-to-gate operations, and integration into broader ATM processes.

SESAR / Regulatory Bodies (EASA, ICAO)	Oversight across all exercises, especially Exe #6 (flight trial).	Ensure alignment with SESAR objectives, regulatory compliance, and evidence that ATMACA contributes to the Digital European Sky vision with measurable KPA/KPI improvements.
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Table 4-1: stakeholders' expectations and involvement

4.3 Validation objectives

The Validation Objectives (VOs) of the ATMACA Exploratory Research Plan (ERP) are designed to address the key research and innovation (R&I) needs identified in Section 3.3. They decompose the high-level challenges into specific, measurable targets aligned with SESAR’s KPAs and KPIs.

The objectives cover technical feasibility, operational integration, environmental impact, and human performance. They will be validated progressively across the six planned exercises, from analytical simulations to a flight trial, supporting the solution’s progression from TRL1 to TRL2.

- **Validation Objective 1 (VO1): Seamless Mobility Management**

<p>OBJ-ATMACA-TRL2-ERP-001 (VO1):</p> <p>Validate that the ATMACA protocol ensures continuous connectivity and seamless handovers across multilink environments (satellite, terrestrial, and cellular), maintaining datalink service continuity throughout intra-domain, inter-domain, horizontal, and vertical mobility events.</p> <p>KPAs: SAF, CEF, DIGI.</p> <p>KPIs / Metrics: Handover delay, message loss rate, session continuity rate.</p>	
Success criterion ID	Success criterion description
CRT-ATMACA-TRL1-ERP-001-001	All mobility scenarios, across domains and link types, are executed with minimal service disruption, demonstrating compliance with safety-critical QoS thresholds and ensuring sustained CPDLC/DLCM session continuity.

Table 4-2: success criterion for VO1

- **Validation Objective 2 (VO2): Integrated Session, Connection, and Context Management**

<p>OBJ-ATMACA-TRL2-ERP-002 (VO2):</p> <p>Demonstrate that ATMACA supports session continuity and context-aware communication across operational phases and interconnected systems, ensuring consistent data availability for CPDLC and related services.</p> <p>KPAs: HP, SAF, CEF, DIGI.</p> <p>KPIs / Metrics: Session continuity rate, reconnection time, context synchronisation accuracy, system resource utilisation.</p>

Success criterion ID	Success criterion description
CRT-ATMACA-TRL1-ERP-002-001	Active sessions remain uninterrupted during mobility or system transitions, and context information (flight intent, trajectory, weather, and operational state) remains synchronised and accessible across all ATC and flight operator nodes.

Table 4-3: success criterion for VO2

- **Validation Objective 3 (VO3): Robust QoS and Security**

<p>OBJ-ATMACA-TRL2-ERP-003 (VO3):</p> <p>Assess ATMACA’s ability to sustain service quality and datalink performance under dynamic operational and network conditions, ensuring reliable delivery of safety-critical communications. Assess ATMACA’s ability to integrate security mechanisms under dynamic operational conditions.</p> <p>KPAs: SAF, SEC, EFF, DIGI.</p> <p>KPIs / Metrics: End-to-end latency, throughput, loss rate.</p>	
Success criterion ID	Success criterion description
CRT-ATMACA-TRL1-ERP-003-001	The protocol maintains QoS within aviation-grade performance thresholds during varying traffic loads and link transitions, ensuring consistent and prioritised delivery of datalink messages without degradation or interruption.
CRT-ATMACA-TRL1-ERP-003-002	A security risk assessment has been carried out.
CRT-ATMACA-TRL1-ERP-003-003	Security requirements have been derived
CRT-ATMACA-TRL1-ERP-003-004	Risk level per security assessment is lowered after risk treatment

Table 4-4: success criterion for VO3

- **Validation Objective 4 (VO4): Environmental Efficiency through GRO**

<p>OBJ-ATMACA-TRL2-ERP-004 (VO4):</p> <p>Demonstrate ATMACA’s contribution to sustainable operations through trajectory optimisation and integration of weather data.</p> <p>KPAs: ENV, OPS</p> <p>KPIs / Metrics: Reduction in CO₂ emissions, fuel burn (kg/flight), flight time predictability.</p>	
Success criterion ID	Success criterion description
CRT-ATMACA-TRL1-ERP-004-001	Optimised trajectories (validated with historical French airspace data) demonstrate measurable reductions in emissions and fuel use compared to baseline dataset.

Table 4-5: success criterion for VO4

- **Validation Objective 5 (VO5): HMI Effectiveness**

<p>OBJ-ATMACA-TRL2-ERP-005 (VO5): Assess the impact of the ATMACA operational concept on the performance of pilots and ATCos. KPA: SAF, HP KPIs / Metrics: ATCO/pilot workload, situational awareness, usability, communication error rate.</p>	
Success criterion ID	Success criterion description
CRT-ATMACA-TRL1-ERP-005-001	Majority of pilots and ATCos confirm that ATMACA air-to-ground, ground-to-ground, and handover procedures are clear, complete, and internally consistent.
CRT-ATMACA-TRL1-ERP-005-002	Majority of pilots and ATCos confirm that ATMACA procedures can be executed accurately and in a timely manner.
CRT-ATMACA-TRL1-ERP-005-003	Majority of pilots and ATCos confirm that the shift to predominantly text-based communications is acceptable and operationally efficient.
CRT-ATMACA-TRL1-ERP-005-004	Majority of pilots and ATCos confirm that ATMACA does not increase their workload compared with current practice.
CRT-ATMACA-TRL1-ERP-005-005	Majority of pilots and ATCos confirm that the ATMACA operational concept and procedures are at least as trustworthy as today's procedures.
CRT-ATMACA-TRL1-ERP-005-006	Majority of pilots and ATCos confirm that ATMACA enables clearer and faster communication across diverse operational actors and organisational units than current practice.
CRT-ATMACA-TRL1-ERP-005-007	Procedures that should remain voice first or primarily voice supported are captured and documented based on end-user feedback
CRT-ATMACA-TRL1-ERP-005-008	Majority of pilots and ATCos confirm they can allocate attention effectively across tasks with the additional ATMACA display, without impairing other monitoring duties.
CRT-ATMACA-TRL1-ERP-005-009	Majority of pilots and ATCos confirm that the training required to adopt ATMACA procedures and tools is acceptable.

Table 4-6: success criterion for VO5

- **Validation Objective 6 (VO6): HMI Impact**

<p>OBJ-ATMACA-TRL2-ERP-006 (VO6): Assess the impact of the ATMACA HMI on the performance of pilots and ATCos KPA: SAF, HP KPIs / Metrics: ATCO/pilot workload, situational awareness, usability, communication error rate.</p>	
Success criterion ID	Success criterion description

CRT-ATMACA-TRL1-ERP-006-001	Majority of pilots and ATCos confirm that information in the ATMACA HMI is sufficient, well placed, and easy to find.
CRT-ATMACA-TRL1-ERP-006-002	Majority of pilots and ATCos confirm that the workload induced by the ATMACA HMI is acceptable
CRT-ATMACA-TRL1-ERP-006-003	Majority of pilots and ATCos confirm that the HMI supports error prevention and recovery (e.g., confirm, correct, or recall) without adding undue steps.
CRT-ATMACA-TRL1-ERP-006-004	Majority of pilots and ATCos confirm that the ATMACA HMI supports situation awareness and meets stated situation awareness requirements.
CRT-ATMACA-TRL1-ERP-006-005	Majority of pilots and ATCos confirm that alerts and notifications are salient, prioritised appropriately, and do not cause overload
CRT-ATMACA-TRL1-ERP-006-006	Majority of pilots and ATCos confirm that the ATMACA HMI is easy to navigate and ergonomically appropriate, with suitable interaction methods.
CRT-ATMACA-TRL1-ERP-006-007	Majority of pilots and ATCos confirm that the ATMACA HMI colour use and colour coding are acceptable
CRT-ATMACA-TRL1-ERP-006-008	Majority of pilots and ATCos confirm that the ATMACA HMI requires reasonable levels of familiarisation to use effectively.
CRT-ATMACA-TRL1-ERP-006-009	Majority of pilots confirm that text-based interaction and use of a touch-screen are acceptable for cockpit use.
CRT-ATMACA-TRL1-ERP-006-010	Majority of ATCos confirm that the ATMACA HMI is appropriate for use across different ATC positions (ground, approach, en-route).

Table 4-7: success criterion for VO6

Variables

- Independent Variables (manipulated): Type of mobility event (intra-/inter-domain, horizontal/vertical), network type (satellite, terrestrial, cellular), traffic density, HMI design variant, trajectory optimisation algorithm.
- Dependent Variables (measured): Handover delay, packet loss, session continuity, latency, workload, situational awareness, CO₂ emissions, trajectory adherence.
- Control Variables (constant): Flight scenario data set, simulation environment, baseline CPDLC/VDL2 system for comparison, regulatory constraints (EASA standards).

Table 4-8 is a cross-mapping table that links Research Questions (RQ1–RQ8) to the Validation Objectives (VO1–VO5) and the six validation exercises (Exe #1–Exe #6):

Research Question (RQ)	Linked Validation Objective	Covered in Validation Exercises
RQ1: Mobility Performance	VO1 (Mobility)	Exe #2 (Simulation), Exe #3 (Emulation), Exe #6 (Flight Trial)
RQ2: Seamless Handover	VO1 (Mobility)	Exe #2, Exe #3, Exe #6
RQ3: Unified Mobility Framework	VO1 (Mobility)	Exe #3, Exe #6

RQ4: Integrated Management Functions	VO2 (Session/Context/Connection)	Exe #2, Exe #3, Exe #6
RQ5: GRO	VO4 (GRO)	Exe #1
RQ6: Security & Trust	VO3 (Security)	Exe #3, Exe #6
RQ7: Human–Machine Interaction	VO5 (HMI Effectiveness) VO6(HMI Impacts)	Exe #4 (Low-Fidelity HMI), Exe #5 (Human-in-the-Loop), Ex.6
RQ8: Interoperability & Scalability	VO3(QoS)	Exe #1 (GRO Validation), Exe #6

Table 4-8: research questions & validation objectives & validation exercises

4.4 Validation assumptions

The following assumptions apply at the ERP level and underpin all planned validation activities. They reflect operational, safety, performance, and technical considerations consistent with SESAR’s DES common assumptions framework. Exercise-specific assumptions will be further detailed in Section 5.

The validation assumptions are recorded in Table 4-9:

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
VA-01	Compatibility with Existing Infrastructure	ATMACA is assumed to interoperate with existing avionics, ATC ground systems, and CPDLC/DLIC (Data Link Initiation Capability) interfaces without requiring disruptive reconfiguration.	Based on OSED analysis and design principle of backward compatibility.	If interoperability is weaker than assumed, integration challenges may delay or limit validation outcomes.
VA-02	Availability of Hosting Systems	Aircraft EFB Class 3 or equivalent onboard units, and ATC-side hosting platforms, are assumed to be available and configured to run the ATMACA protocol.	Availability of standard hosting platforms is common in SESAR validations.	Lack of suitable hosting platforms may restrict scope of experiments, especially flight trials.
VA-03	End User Acceptance (Pilots & Controllers)	It is assumed that pilots and controllers will find ATMACA HMIs intuitive and operationally beneficial.	Supported by human-centred design approach and early usability studies.	If acceptance is lower than expected, additional HMI iterations may be required, delaying progress.
VA-04	Network Coverage & Multilink Reliability	Continuous network coverage across terrestrial, satellite, and cellular links is assumed for validation of mobility management.	SESAR performance framework assumes availability of operational	Connectivity gaps could distort results on mobility and continuity KPIs.

			links for research environments.	
VA-05	Safety & Security Standards Compliance	ATMACA protocol will comply with EASA safety requirements and aviation cybersecurity standards (encryption, authentication, redundancy).	Compliance is mandatory for aviation-grade systems and consistent with DES assumptions.	If security or safety mechanisms are not fully integrated, the results may not wholly reflect the true operational feasibility. However, at TRL2 it is neither expected nor feasible to implement the complete set of security and safety mechanisms.
VA-06	Representative Traffic & Operational Scenarios	Validation will use simulated, emulated, and live scenarios that are representative of European ATM operational contexts (airports, TMAs, en-route, oceanic).	Ensures external validity of results in SESAR framework.	If traffic/scenario realism is insufficient, performance contributions may be over- or underestimated.
VA-07	Scalability of Protocol	ATMACA is assumed to scale with increasing aircraft and service demands.	Derived from architectural design and SESAR scalability requirements.	If scalability cannot be demonstrated, impact on CEF and long-term adoption may be reduced.
VA-08	Gate-to-Gate Applicability	ATMACA is assumed to provide continuous support from departure to arrival across all operational domains.	Gate-to-gate continuity is a core SESAR objective.	Partial coverage may weaken conclusions on service continuity and safety.

Table 4-9: validation assumptions overview

4.5 Validation exercises list (Validation Exercise)

To answer the eight high level research questions (section 3.3 Key R&I Needs), 6 validation exercises have been envisioned. The following tables list all the relevant experiments/validation exercises foreseen by ATMACA Exploratory Research Plan.

Identifier	TVAL.01.1-ATMACA-0153-TRL1
Title	GRO Concept Validation
Description	This exercise evaluates the operational performance and environmental efficiency of the GRO application within the ATMACA framework. A set of direct trajectories simulated from historical flight

	plans will serve as the baseline, while wind-optimised trajectories will be generated using GRO's WINTEM networking and optimisation algorithms. The optimised trajectories will be compared with the baseline to quantify efficiency and environmental performance benefits.
KPA/TA addressed	ENV, OPS
Addressed expected performance contribution(s)	Reduced fuel consumption and CO ₂ emissions through optimised trajectories. Improved flight efficiency via more predictable and accurate routing.
Maturity level	TRL1
Use cases	UC4 in D2.3 OSED: Gate-to-gate trajectory optimisation. Cross-border trajectory planning across ANSP boundaries.
Validation technique	Analytical modelling and simulation (trajectory comparison using historical data)
Validation platform	Algorithmic testbed and data analytics tools (offline analysis)
Validation location	Remote/desk-based, using historical French airspace datasets.
Start date	01/05/2025
End date	30/09/2025
Validation coordinator	DELAHAYE, Daniel/ENAC
Status	Finished
Dependencies	Availability of historical flight and weather data. Dependency on definition of operational scenarios and KPIs from D2.3 OSED.
Linked Element Type	N/A
<SESAR Solution>	ATMACA
<Project>	ATMACA
<Sub-Operating Environment>	En-route and TMA (French ANSP domain)
<Validation Objective>	VO4 – Environmental Efficiency (GRO contribution)

Table 4-10: validation exercise #1 layout

Identifier	TVAL.02.1-ATMACA-0153-TRL2
Title	Simulation of Datalink Communication Protocol
Description	Protocol-level simulation in OMNeT++ to validate ATMACA's core features: session, connection, and mobility management. Benchmarked against baseline standards to assess KPIs such as latency, packet loss, and handover delay.
KPA/TA addressed	DIGI, SAF
Addressed expected performance contribution(s)	Reduced handover delays, lower signalling overhead, improved communication continuity and packet loss.
Maturity level	TRL1 -> TRL2
Use cases	UC1, UC2 in D2.3 OSED

Validation technique	Protocol-level simulation
Validation platform	OMNeT++ simulation environment
Validation location	Laboratory environment
Start date	01/06/2025
End date	28/02/2026
Validation coordinator	HAMZAOUI, Raouf/DMU
Status	in progress
Dependencies	Protocol design specifications, mobility models.
Linked Element Type	N/A
<SESAR Solution>	ATMACA
<Project>	ATMACA
<Sub-Operating Environment>	Intra-domain mobility scenarios
<Validation Objective>	VO1, VO3

Table 4-11: validation exercise #2 layout

Identifier	TVAL.03.1-ATMACA-0153-TRL2
Title	Emulation of Datalink Communication Protocol, DLCM and CPDLC message exchange
Description	Near-operational validation through real-time emulation with virtualised nodes. Integration of CPDLC and DLCM to assess ATMACA protocol stack performance under representative air-ground communication conditions.
KPA/TA addressed	SEC, SAF
Addressed expected performance contribution(s)	Session continuity during the four types of mobility (session, service, user, and terminal). DLCM and CPDLC message exchange on ATMACA protocol.
Maturity level	TRL1 -> TRL2
Use cases	UC1, UC2 in D2.3 OSED
Validation technique	Real-time emulation.
Validation platform	Virtualised testbed with protocol stack integration (ATMACA base protocol, DLCM, CPDLC, and HMI).
Validation location	Laboratory/testbed facility.
Start date	01/12/2025
End date	31/03/2026
Validation coordinator	HAMZAOUI, Raouf/DMU
Status	Planned
Dependencies	Output from Ex.2, CPDLC/DLCM modules, virtualised environment setup.
Linked Element Type	N/A
<SESAR Solution>	ATMACA
<Project>	ATMACA
<Sub-Operating Environment>	Multilink en-route/TMA mobility
<Validation Objective>	VO1, VO2, VO3

Table 4-12: validation exercise #3 layout

Identifier	TVAL.04.1-ATMACA-0153-TRL1
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Title	Early-Stage Evaluation of Low-Fidelity HMI
Description	Iterative usability evaluation of ATMACA HMIs using low-fidelity wireframes. End-user feedback from pilots and controllers will refine layout, interaction flows, and operational alignment.
KPA/TA addressed	HP, SAF
Addressed expected performance contribution(s)	Usability, positive user feedback based on expert evaluations.
Maturity level	TRL1
Use cases	UC3 in D2.3 OSED Pilot/ATCo interactions in ATC towers, radar stations, and flight decks.
Validation technique	Human-centred design evaluation with end-user workshops.
Validation platform	Wireframe prototypes and mock-ups.
Validation location	Remote workshops and on-site sessions.
Start date	01/10/2025
End date	31/01/2026
Validation coordinator	VENDRUSCOLO, Tommaso/ DBL
Status	In progress
Dependencies	HMI design readiness, availability of pilot/controller participants.
Linked Element Type	N/A
<SESAR Solution>	ATMACA
<Project>	ATMACA
<Sub-Operating Environment>	ATC Tower, Radar, Flight Deck
<Validation Objective>	VO4

Table 4-13: validation exercise #4 layout

Identifier	TVAL.05.1-ATMACA-0153-TRL2
Title	Role-Based Human-in-the-Loop HMI Simulation
Description	Human-in-the-loop simulation using SAERCO's ATC simulator. ATCos interact with simulated flights via ATMACA HMI to assess workload, communication efficiency, and situational awareness in realistic scenarios.
KPA/TA addressed	HP, SAF
Addressed expected performance contribution(s)	Reduced ATCo workload, fewer communication errors, enhanced role-specific usability.
Maturity level	TRL1 -> TRL2
Use cases	UC3 in D2.3 OSED Controller-Pilot interaction via CPDLC in en-route and TMA operations.
Validation technique	Human-in-the-loop simulation
Validation platform	SAERCO ATC simulator
Validation location	SAERCO simulation centre, Spain
Start date	01/02/2026
End date	31/03/2026

Validation coordinator	CARMONA FERNÁNDEZ, Ángel Ernesto/ SAERCO
Status	Planned
Dependencies	Refined HMI prototypes from Ex.4, simulator availability.
Linked Element Type	N/A
<SESAR Solution>	ATMACA
<Project>	ATMACA
<Sub-Operating Environment>	ATC operational simulation
<Validation Objective>	V04

Table 4-14: validation exercise #5 layout

Identifier	TVAL.06.1-ATMACA-0153-TRL2
Title	End-to-End ATMACA Datalink Validation Flight Trial
Description	Live, end-to-end proof-of-concept of the ATMACA solution (protocol, DLCM, CPDLC, and role-based HMIs) in representative gate-to-gate segments, demonstrating mobility continuity, session/context persistence, and secure datalink operations across multiple ATC nodes and access networks.
KPA/TA addressed	CEF, SAF, HP, DIGI
Addressed performance contribution(s)	<p>Enhanced Safety and Continuity: Continuous datalink connectivity across multiple ATC nodes and network transitions, reducing the risk of message loss and communication breakdown during handovers</p> <p>Improved Efficiency and Predictability: Shorter end-to-end CPDLC transaction times and faster DATs, supporting more predictable controller–pilot exchanges and streamlined traffic coordination.</p> <p>Reduced Pilot and ATCo Workload: Automated session and context management reduce manual coordination and voice interventions, enhancing focus on situational awareness.</p> <p>CEF and DIGI: Consolidated use of IP-based mobility management over existing communication links lowers infrastructure overhead while improving scalability for multi-service operations.</p>
Maturity level	TRL1 -> TRL2 (exit maturity gate)
Use cases	UC1, UC2, UC3 in D2.3 OSED
Validation technique	Quantitative flight-based validation combining live measurements of datalink continuity, latency, and session persistence with qualitative assessment of pilot and controller workload. Performance data are collected through synchronised airborne and ground recordings during real-time CPDLC, DLIC, and DAT operations, ensuring full traceability to D2.3 OSED use cases and TRL2 exit criteria
Validation platform	Live air–ground validation environment integrating an Airbus A330/350 equipped with the ATMACA EFB client, ATC ground servers, and hybrid Wi-Fi/SATCOM connectivity. The platform includes pilot and controller HMIs and enables real-time validation of datalink continuity, handover performance, session and context management, and human-performance aspects under operational flight conditions.
Validation location	Turkey + European air space + Spain

5 Validation exercises

5.1 Validation exercise #1 plan: GRO Concept Validation

5.1.1 Validation exercise description and scope

This validation exercise assesses the operational and environmental benefits of developing the GRO application within the ATMACA framework. By leveraging the context information made available through ATMACA such as traffic demand, airspace constraints, meteorological data, and other operational parameters, the GRO module can optimise trajectories and enhance wind-prediction performance in simulated real-world traffic scenarios to support more efficient and sustainable flight operations.

This exercise primarily addresses VO4: assess environmental and operational efficiency of GRO trajectories (fuel burn, CO₂/NO_x emissions, distance/time savings). The secondary coverage of VO3 is to assess trajectory predictability and stability under GRO.

There are two scenarios:

- Reference scenario – Historical flight plan and associated baseline trajectories (no GRO).
- Solution scenario – same flights optimised with ATMACA GRO algorithms and constraints.

An offline analytical and simulation approach will be employed. Historical flight plan and baseline trajectories will be processed through the GRO module to generate optimised trajectories; metrics will then be compared with baseline trajectories to quantify efficiency gains.

A dedicated ATMACA GRO simulation testbed will be used to incorporate:

- Historical French and cross-border en-route/TMA traffic data.
- Wind prediction and trajectory optimisation algorithms.
- Data analytics modules to calculate fuel/emission savings and predictability metrics.

This exercise supports the progression of ATMACA at TRL 1 by demonstrating the potential performance contribution of the GRO module using real operational data under representative conditions.

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

This validation exercise directly addresses SESAR KPAs and benefit mechanisms:

- KPAs addressed: ENV, OPS
- Benefit mechanisms: quantifiable emission savings, predictability improvements.

Stakeholders expect that this exercise will:

- Provide quantitative evidence of potential fuel and emission reductions when using GRO trajectories.

- Show improved trajectory predictability, enabling more stable sector planning and reduced controller workload.
- Demonstrate how GRO can be integrated into existing planning and tactical control processes with minimal disruption.
- Identify constraints, usability issues, and integration needs early, ensuring the module’s suitability for future higher-TRL validation.

The table below summarises stakeholder roles, involvement and expected benefits:

Stakeholder	Involvement	Why it matters to the stakeholder
ANSPs (e.g. DSN/A/Eurocontrol)	Provide historical flight data, wind data and operational constraints; review GRO outputs and metrics.	Expect improved capacity and predictability within sectors; evidence to support SESAR environmental objectives and sector planning improvements.
Airlines / AOCs (e.g. THY, Air France Ops)	Supply operational constraints and preferences; validate trajectory optimisation outputs.	Expect measurable reductions in fuel burn, CO ₂ /NO _x emissions and operating cost; ability to plan more efficient flights and align with green policies.
Pilots / Flight Crews	Participate in focus groups to review optimised routes and evaluate operational feasibility.	Expect optimised clearances and improve situational awareness; anticipate smoother handovers with fewer trajectory changes.
ATCos	Contribute to the definition of operational constraints and assess controller impacts in workshops.	Expect fewer last-minute trajectory conflicts, reduced tactical interventions, and potential workload reduction.
SESAR Joint Undertaking / Programme Management	Oversight of validation design, ensuring alignment with DES KPAs and performance framework.	Expect robust evidence of environmental and operational benefits to justify further SESAR-level integration and future TRL progression.
Technical Partners / Research Organisations	Configure and run the simulation testbed, process results, draft reports.	Gain validation of the ATMACA GRO algorithms against real data; identify refinements needed before live trials.

Table 5-1: stakeholders' expectations

5.1.3 Validation objectives

This exercise primarily supports Validation Objective VO4 (Environmental and Operational Efficiency) and partially covers VO3 (Trajectory Predictability).

Success criteria for each validation objective are aligned with the latest SESAR DES Performance Framework KPAs and KPIs, in particular:

- ENV1: Reduction of CO₂ emissions per flight.
- FEEF1: Reduction of fuel burn per flight.
- TEFF1: Reduction of flight time.
- PRD1, PRD2: Improved predictability.

The table below links ERP-level validation objectives to exercise-level objectives and success criteria:

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #1	Exercise validation objective	Exercise success criteria
VO4 – Validate environmental and operational efficiency of GRO	≥5% reduction in CO ₂ and ≥5% reduction in fuel burn vs. reference trajectories	Fully covered: historical data baseline allows direct quantification	Quantify potential environmental and operational gains from GRO-optimised trajectories	Simulation shows reduction in fuel burn and CO ₂ emissions across sample flights compared to historical baseline.
VO3 – Improve trajectory predictability and stability	Reduction in lateral/vertical deviations between planned and executed paths.	Partially covered: predictability assessed only in simulated environment (no ATC intervention yet)	Assess predictability improvements of GRO-optimised trajectories vs. actual tracks	Model outputs show improvement in predictability metrics (variance of trajectory vs. plan) compared to reference scenario.

Table 5-2: validation objectives addressed in validation exercise #1

5.1.4 Validation scenarios

This validation exercise compares a baseline scenario reflecting current operations with a solution scenario implementing the ATMACA GRO module. The scenarios are designed to be representative of realistic European en-route and TMA operations, using historical traffic and meteorological data.

5.1.4.1 Reference scenario(s)

The reference scenario represents the status-quo flight planning and execution without the application of ATMACA's GRO optimisation. Historical flight plans with their corresponding simulated trajectories will be used as the baseline.

Scope:

- Typical medium-haul and long-haul traffic crossing French airspace during high-density periods.
- Realistic wind and weather conditions corresponding to the actual operational day(s).

Purpose:

- Establish a baseline for fuel burn, CO₂ emissions, route length, and predictability metrics for direct comparison with the solution scenario.

Assumptions:

- No additional ATC clearances beyond what were historically issued.
- Same aircraft performance assumptions and constraints as in the solution scenario.

5.1.4.2 Solution scenario(s)

The solution scenario applies ATMACA's GRO trajectory optimisation to the same set of flights, incorporating predicted winds, airspace structure, and operational constraints.

Scope:

- Same traffic sample, airspace, and weather as the reference scenario.
- GRO generates optimised lateral and vertical profiles to minimise fuel burn and emissions while respecting ATC constraints.

Purpose:

- Quantify potential environmental and operational efficiency gains (fuel, emissions, predictability) achieved by ATMACA's GRO module.

Assumptions:

- Optimised trajectories are accepted by controllers without tactical interventions (controller feasibility to be addressed in later exercises).
- The same performance and meteorological inputs are used as in the reference scenario to isolate the effect of GRO.

5.1.5 Exercise validation assumptions

This sub-section lists the additional assumptions specific to the GRO concept validation exercise that may influence the interpretation of results. These assumptions will be reviewed with stakeholders before the start of the exercise. Deviations or limitations will be explicitly reported in the exercise report together with sensitivity analysis where feasible. All ERP-level assumptions (section 4.4) apply; the table below records only the additional or exercise-specific assumptions.

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
EX1-A1	Representativeness of data set	Historical flight plans and radar tracks from French en-route and TMA sectors accurately represent typical traffic flows and constraints.	Essential to ensure baseline scenario reflects realistic operations.	Medium – If data is not representative, calculated benefits may not generalise to other ANSPs or periods.
EX1-A2	Wind prediction fidelity	External wind model used for optimisation has comparable accuracy to operational forecasts.	Needed to simulate realistic conditions and compute fuel/emission savings.	Medium – Under/overestimation of winds affects predicted vs. actual trajectory gains.
EX1-A3	Acceptance of optimised trajectories	Optimised trajectories generated by GRO are assumed to be accepted without tactical interventions or reroutes by controllers.	Tactical controller actions are not modelled	High – Actual operational benefit may be lower if many clearances are denied.
EX1-A4	Aircraft performance consistency	Aircraft performance parameters (weight, cost index, climb/descent profiles) are assumed to be consistent between baseline and solution scenarios.	Required to isolate the effect of GRO optimisation on results.	Low – Minor impact if small variations occur.
EX1-A5	Availability of complete data	All required inputs (flight plan, track data, weather) are available and accessible to the simulation platform.	Ensures no data gaps in the analysis.	Medium – Missing data may reduce sample size and statistical power.

Table 5-3: validation exercise #1 assumptions

5.1.6 Limitations and impact on the level of significance

Although the GRO concept validation will be performed with high-fidelity data and an operationally representative simulation platform, several limitations may affect the strength and generalisability of the results:

- **Absence of live controller interaction:** The exercise assumes full acceptance of optimised trajectories without tactical interventions. As no human-in-the-loop ATC is modelled at this stage, the impact of controller workload, traffic complexity, or sector capacity constraints on GRO benefits cannot yet be quantified.
- **Reliance on historical data:** Using past flight plans limits the ability to capture future demand patterns, traffic mix, or new operational constraints. Results should therefore be interpreted as indicative of potential rather than actual benefits in future environments.
- **Model assumptions on aircraft performance and winds:** Simplified or averaged performance parameters and forecast winds may over- or under-estimate the achievable fuel and emission savings. Sensitivity analyses will be applied where possible.
- **Sample size and representativeness:** The number of flights and airspace segments analysed may limit statistical power. While the sample will cover typical flows in French en-route and TMA sectors, caution should be taken when extrapolating to other ANSPs or global operations.
- **Environmental benefit estimates:** Fuel burn and emissions will be modelled rather than measured; uncertainties in input data or algorithms may affect absolute values of savings, although relative comparisons between scenarios remain robust.

Impact on significance:

Because of these limitations, the results will primarily demonstrate proof-of-concept potential and identify trends (e.g. percentage improvement ranges) rather than provide definitive, deployable performance figures. The outputs will still be suitable to guide refinement of the GRO module and inform the design of higher-TRL in the future.

5.1.7 Validation exercise platform / tool and validation technique

5.1.7.1 Validation exercise platform / tool characteristics

The validation will be carried out on a dedicated ATMACA GRO simulation testbed, developed for early-stage concept validation. The platform integrates:

- Data ingestion modules to import and pre-process historical flight plans, baseline trajectories, and meteorological data (winds, temperatures) from ANSP and airline sources.
- Trajectory optimisation engine implementing ATMACA's GRO algorithms for lateral/vertical route planning under operational constraints.
- Environmental performance calculator for fuel burn, CO₂/NO_x emissions, and time/distance savings per flight.
- Graphical outputs will be generated to illustrate and compare key metrics between the baseline and optimised scenarios.

The testbed will run on secure servers at the technical partner's facilities, enabling large batch simulations of representative traffic samples. It will be configured to model both en-route and TMA phases, allowing assessment of gate-to-gate environmental performance.

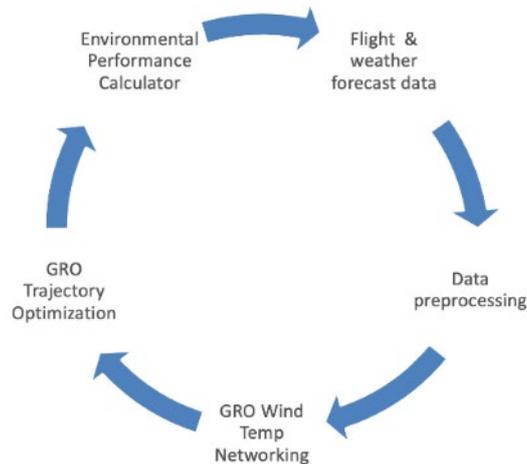


Figure 5-1: exercise #1 prototypes and validation infrastructure

5.1.7.2 Validation exercise technique

The chosen validation technique is offline analytical modelling and simulation:

- Baseline scenario: actual historical flight plan and baseline trajectories without GRO optimisation.
- Solution scenario: same flights re-routed with ATMACA GRO algorithms.
- Comparison method: compute KPIs (fuel burn, emissions, predictability metrics) for each flight and apply statistical tests to quantify improvements.
- Iteration: several optimisation/simulation cycles may be performed to test sensitivity to different wind forecasts or constraint sets.

5.1.8 Data collection and analysis

This data collection and analysis plan will provide quantitative, statistically supported evidence of the potential environmental and operational efficiency gains of ATMACA's GRO module. The results will be used to refine the concept, inform later human-in-the-loop, and provide KPIs aligned with SESAR DES performance indicators.

5.1.8.1 Data and data collection methods

Type of data to be collected:

- Flight plan and radar track data: historical routes, altitudes, speeds, sector entries/exits.
- Meteorological data: wind, temperature, pressure for the same periods (for trajectory optimisation).

- Operational constraints: airspace structure, route availability, sector capacity limits.
- Performance indicators: fuel burn, CO₂/NO_x emissions, lateral/vertical deviation from plan, arrival time predictability.

Sources and collection method:

- Data will be sourced from ANSP databases (e.g. DSN/AEurocontrol), AOCs, and public meteorological archives.
- All datasets will be imported into the ATMACA GRO simulation testbed, pre-processed and normalised to ensure consistent formats and units.
- A secure data-sharing agreement will be established with stakeholders to ensure confidentiality.

Data recording format:

- Raw data: CSV/GRIB for flight and weather inputs.
- Simulation outputs: tabular KPIs (per flight) and aggregated metrics (per scenario) plus Graphical outputs.
- Optional: graphical representations of trajectories for selected flights.

5.1.8.2 Analysis methods

Approach:

- Baseline and solution scenarios will be run on identical flight samples and weather conditions.
- For each flight, differences in fuel burn, CO₂ emissions, route length and predictability metrics will be computed.
- Statistical tests will be applied to determine significance of improvements.
- Sensitivity analyses will be performed on wind forecast errors and aircraft performance parameters.

Iteration and refinement:

- Several simulation cycles may be performed to test robustness of results under different operational assumptions.
- Outputs will feed back into refinement of GRO algorithms and identification of conditions for greatest benefit.

Software tools:

- The testbed's built-in analytics modules.
- Statistical packages (R or Python) for post-processing and visualisation.
- All results and intermediate datasets will be documented and stored in a version-controlled repository for traceability.

5.1.9 Exercise planning and management

5.1.9.1 Activities

The exercise is organised in three main phases: preparation, execution, and post-execution.

Preparation

- Establish data-sharing agreements with ANSPs, airlines and meteorological providers.
- Collect and clean historical flight, airspace, and weather data.
- Configure and test the GRO simulation platform.
- Define baseline and optimised scenarios, including constraints.

Execution

- Run initial baseline scenario to reproduce actual trajectories.
- Execute GRO-optimised trajectories.
- Conduct at least two further iterations to test sensitivity (wind forecast, route constraints).

Post-Execution

- Analyse outputs against KPIs (fuel burn, emissions, distance, predictability).
- Prepare performance-comparison tables and graphs.
- Conduct stakeholder review workshop to validate results and collect qualitative feedback.

5.1.9.2 Roles and responsibilities in the exercise

- Validation Coordinator (Lead Partner): Overall planning, execution oversight, data coordination, KPI reporting.
- Technical Lead (Simulation Tool Owner): Configuration and operation of the GRO simulation platform; technical support during execution.
- Data Providers (ANSPs/Airlines): Supply historical flight, airspace, and meteorological data sets; validate their accuracy.
- Performance Analyst: Process, clean, and normalise data; run statistical tests; generate performance dashboards.
- Stakeholder Liaison: Organise workshops with controllers/airlines to review results and collect feedback.

5.1.9.3 Time planning

In the table below, month 9 is May 2025 and month 13 is September 2025.

Activity	Month						
	9	10	11	12	...	13	
<i>Preparatory phase</i>							
<i>Execution phase</i>							
<i>Post-execution phase</i>							

Table 5-4: detailed exercise #1 time planning

5.1.9.4 Identified risks and mitigation actions

Risks	Impact (1-low, 2-medium, 3-high)	Likelihood (1-low, 2-medium, 3-high)	Criticality (calculated based on likelihood and impact)	Mitigation actions
Delayed access to historical flight data	3	2	High	Negotiate early data-sharing agreements; prepare synthetic or open data as fallback.
Simulation platform underperforms with large data sets	2	2	Medium	Conduct early stress-testing; optimise pre-processing and sampling.
Stakeholder availability for workshops	2	2	Medium	Schedule workshops well in advance; offer virtual participation.
Inconsistent or incomplete weather data	2	1	Low	Use multiple meteorological sources; interpolate missing values.

Table 5-5: exercise #1 risks and mitigation actions

5.2 Validation exercise #2 plan: Simulation of Datalink Communication Protocol

5.2.1 Validation exercise description and scope

This exercise focuses on validating the core functional capabilities of the ATMACA datalink communication protocol under simulated conditions. Exercise 2 is limited to validate terminal mobility

scenarios, excluding user, session, and service mobility, which will be validated in Exercise 3 using emulations. It covers three scenarios: single-continent, single-continent multi-region, and multi-continent. The evaluation includes CPDLC delay, throughput, and success rate. The analysis includes a baseline comparison with MIPv6 and a consistency check against RTCA DO-290 and EUROCAE ED-120 operational expectations.

The experiment reflects the gate-to-gate operational envelope described in the OSED (airports, TMAs, en-route and oceanic segments) and models both intra-area and inter-area handovers of data authority before progressing to emulation or live trials.

The simulated actors and roles are consistent with the FRD/OSED:

- Mobile clients: aircraft/pilots operating under Instrumental Flight Rules (IFR) or Visual Flight Rules (VFR) equipped with IP connectivity, moving across control areas, Flight Information Region (FIR) boundaries and communication domains.
- Stationary clients: ATCos on ATC workstations (tower, radar, ATM management) for issuing clearances, monitoring sessions and performing DATs.
- Area agents / intermediate nodes: logical context managers that maintain and synchronise session state during controller changes.

The processes covered include mainly CPDLC message exchange, handover of flight sessions and associated datalink hand-offs between ATCos, as described in Use Cases 1 and 2 of the OSED.

- Establishment of ATMACA sessions between simulated aircraft and multiple ATCos.
- Horizontal and vertical handovers across simulated multilink networks (SATCOM and WiFi).
- Transmission of CPDLC messages and context information to test protocol resilience and service continuity.
- Monitoring of CPDLC delay, throughput, and success rate.

The exercises will be performed with progressive validation steps:

- Single-Continent Scenario – baseline protocol operation.
- Single-Continent Multi-Region Scenario – inter-area handover performance.
- Multi-Continent Scenario – scalability and intercontinental transitions.

Exercise #2 supports the transition from TRL1 to TRL2 for the ATMACA protocol's mobility and context-management features. By benchmarking ATMACA against the OMNeT++ MIPv6 baseline (xMIPv6) under consistent traffic and topology assumptions, the exercise will show the expected performance improvements before moving to emulation (Exercise #3) and flight trial (Exercise #6).

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

The table below identifies the main stakeholders, their involvement in this simulation and why the exercise matters to them.

Stakeholder	Involvement	Why it matters to the stakeholder
ANSPs / ATC centres	Provide operational expertise for defining realistic mobility and handover scenarios; review simulation results against operational KPIs.	Need evidence that ATMACA maintains seamless CPDLC across sector boundaries and reduces handover-related disruptions to improve safety and controller workload.
Airlines / Aircraft Operators	Supply representative flight and traffic data; review outcomes for ATM.	Expect reliable, low-latency datalink connectivity.
Regulators / SESAR programme bodies	Oversee alignment with SESAR KPAs and DES performance framework; evaluate compliance evidence.	Require proof that ATMACA meets regulatory and performance standards before live testing and eventual certification.
Technology providers / Integrators	Adapt simulation models for protocol testing; analyse performance logs for implementation feedback.	Need to understand scalability, interface, and interoperability requirements to integrate ATMACA into future avionics/ground systems.
Pilots & Controllers (end-user reps)	Provide input on operational workflow assumptions.	Expect datalink continuity.

Table 5-6: stakeholders' expectations

5.2.3 Validation objectives

This simulation exercise targets the first quantitative validation of the ATMACA datalink protocol at TRL 2. It tests the protocol's core functions under controllable but realistic conditions before moving to emulation and flight trials. The exercise directly supports the R&I needs identified in Section 3.3 by demonstrating that ATMACA meets the SESAR KPAs and KPIs on mobility, session/context continuity, QoS and security at concept level.

It refines and apportions the ERP-level validation objectives (VO1 and VO3) to the simulation scope and specifies success criteria consistent with the DES performance framework.

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #2	Exercise validation objective	Exercise success criteria
VO1 – Seamless Mobility Management Validate continuous connectivity and seamless handovers across multilink environments.	KPAs: SAF, DIGI.	Partially covered: mainly on terminal mobility by simulated multiple intra-/inter-domain, horizontal and vertical handovers.	1. To quantitatively evaluate ATMACA's performance in maintaining CPDLC communication quality under mobility stress using RTCA/EUROCAE DO-290/ED-120-aligned metrics. 2. To compare ATMACA with MIPv6 using delay and packet loss measurements to assess terminal mobility efficiency during handovers across different access technologies and infrastructure domains.	ATMACA is ability to sustain low-latency, loss-free CPDLC sessions across intercontinental mobility paths. ATMACA outperforms MIPv6 on latency, packet loss, and handover delay under identical conditions. The simulation results are compliance with the RTCA DO-290 / EUROCAE ED-120 standards.
VO3 – Robust QoS & Security Assess ATMACA's ability to guarantee service quality and integrate security mechanisms under dynamic conditions.	KPAs: SEC	Partially covered – Some QoS performance tested; DATs modelled with security features.	To evaluate the Data Authority Transfer (DAT) process functions as the handover completion mechanism at the application layer.	Simulation can demonstrate the robustness of DAT.

Table 5-7: validation objectives addressed in validation exercise #2

5.2.4 Validation scenarios

This section defines the reference and solution scenarios for the simulation-based validation of the ATMACA datalink protocol. The scenarios are designed to replicate realistic air-ground datalink operations across multilink environments, enabling controlled measurement of mobility, session continuity, and QoS performance. They align with the operational environments described in the OSED (airports, TMAs, en-route, and oceanic/remote sectors).

5.2.4.1 Reference scenario(s)

The reference scenario represents current baseline datalink operations. For benchmarking purposes, MIPv6 was integrated into the ATMACA framework as a baseline IP mobility module to replicate ATMACA’s terminal mobility function while maintaining the same CPDLC application layer.

5.2.4.2 Solution scenario(s)

The solution scenario introduces the ATMACA protocol’s core capabilities into the same simulated environment to measure improvements in mobility, session continuity, and QoS.

5.2.5 Exercise validation assumptions

This simulation exercise inherits all ERP-level validation assumptions described in Section 4.4. The following additional assumptions are specific to Exercise #2 and may influence the validity and generalisability of the results:

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
EX2-A1	Accurate Simulation of Mobility Events	The OMNeT++ simulation accurately models intra-/inter-domain horizontal and vertical handovers across satellite, terrestrial, and cellular links.	Essential to measure handover delay, packet loss, and continuity under realistic conditions without deploying live systems.	If mobility modelling is oversimplified, results may over- or underestimate ATMACA’s real-world performance. Moderate impact on KPIs.
EX2-A2	Representative Traffic Density	The traffic load scenarios (number of aircraft sessions) reflect real en-route and inter-ANSP conditions in European upper airspace.	Needed to validate scalability and QoS under realistic stress conditions.	If traffic load is not representative, scalability metrics may not be transferable to operational environments. Medium impact on capacity KPIs.
EX2-A3	Stable Network Parameters	Link performance parameters for each network type (satellite, terrestrial, cellular) are based on	Enables consistent comparison between reference and	Deviations from real-world variability could affect latency and jitter results. Low-to-moderate impact on QoS KPIs.

		current operational averages.	IP solutions terminal	solution scenarios.	
EX2-A4	Baseline Protocol Behavior	Conventional mobility maintain mobility.		Establishes a valid baseline for comparison.	If baseline performance is unrealistic, relative ATMACA benefits may be misinterpreted. Medium impact on all KPAs.

Table 5-8: validation exercise #2 assumptions

5.2.6 Limitations and impact on the level of significance

Although Exercise #2 will provide the first quantitative evidence of ATMACA’s performance, several limitations could influence the significance and generalisability of the results:

- **Simulation vs. Operational Reality:** The experiment uses OMNeT++ simulations rather than live networks. While the model parameters are based on current operational averages, they cannot fully replicate the variability of real-world conditions. This may slightly under- or overestimate ATMACA’s performance.
- **Traffic Density Scaling:** The maximum number of concurrent aircraft sessions simulated is constrained by computing resources.
- **Sample Size for Scenarios:** The number of simulation runs per scenario is limited by project timelines.
- **Baseline Assumptions:** If baseline parameters deviate from actual operations, the measured relative improvements may not reflect true operational benefits.

Impact on Significance:

- Mobility and QoS KPIs will be highly representative at TRL2 but still indicative until confirmed by emulation (Exe #3) and flight trial (Exe #6).

Despite these limitations, the exercise is expected to produce statistically robust, reproducible performance data for ATMACA’s mobility management capabilities. These data will inform the configuration of subsequent emulation and flight-trial exercises.

5.2.7 Validation exercise platform / tool and validation technique

This section describes the simulation platform, associated tools, and validation technique selected for Exercise #2. It explains how these elements support the exercise’s objectives and provide evidence to meet the success criteria defined in Section 5.2.3.

5.2.7.1 Validation exercise platform / tool characteristics

- **Core Platform:** The exercise will use OMNeT++ (academic version 6.x) as the primary discrete-event simulation environment. OMNeT++ provides a modular network simulation framework that supports modelling of complex communication architectures, including multilink handovers and mobility events across heterogeneous networks.

- Traffic and Scenario Generation: Several testing scenarios will be generated to simulate realistic en-route and inter-ANSP conditions. Configurable parameters (e.g., number of aircraft sessions, network types, mobility events) will allow testing under different conditions.
- Output and Data Logging: All relevant KPIs (will be logged automatically during simulation runs and exported for statistical analysis.
- Availability & Resources: The simulation environment will be hosted on a dedicated workstation with sufficient CPU and memory to run multiple concurrent scenarios. Version control (Git) will be used to share the source code.

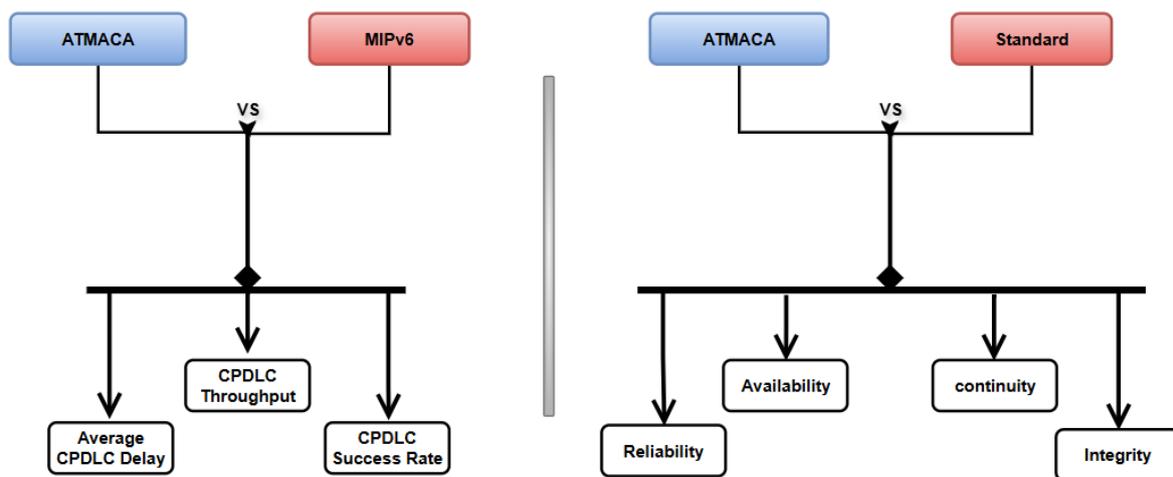


Figure 5-2: exercise #2 prototypes and validation infrastructure

5.2.7.2 Validation exercise technique

An OMNeT++/INET simulation is conducted to evaluate ATMACA’s terminal mobility performance during gate-to-gate operations. The simulated architecture includes area agents responsible for data authority and context management, dual-link aircraft equipped with Wi-Fi and SATCOM interfaces, and a SATCOM backbone network. CPDLC services are transported using the Transmission Control Protocol (TCP).

Delays and throughput metrics are derived from simulator timestamps collected over request/response message pairs, distinguishing between application-level delay (CPDLC message latency) and end-to-end transport delay. For comparative assessment, MIPv6 is run under the same network topologies and mobility scenarios.

Simulation allows controlled manipulation of independent variables and precise measurement of dependent variables. This technique is appropriate for TRL2 because it provides a low-cost, high-control environment to test ATMACA’s core protocol functionalities before investing in higher-fidelity emulations and flight trials. It also enables repeatable experiments under identical conditions for statistical significance.

Each scenario (reference and solution) is executed multiple times to obtain average values and confidence intervals for each KPI. Results are compared against success criteria defined in Section

5.2.3. The outcome of this technique is a quantitative performance benchmark of ATMACA versus baseline protocol, demonstrating the feasibility of its mobility management capabilities at TRL2.

5.2.8 Data collection and analysis

5.2.8.1 Data and data collection methods

During the simulation runs, both quantitative and limited qualitative data will be collected. Data sets will be structured to allow comparison between reference scenarios (MIPv6 baseline) and solution scenarios (ATMACA protocol).

5.2.8.2 Analysis methods

The analysis methods will fall into three main categories:

- Simulation-based performance analysis
- Comparative benchmarking (ATMACA vs MIPv6)
- Compliance assessment (RTCA DO-290 / EUROCAE ED-120 standards)

5.2.9 Exercise planning and management

5.2.9.1 Activities

Preparation

- Finalise simulation scenarios and parameter sets based on OSED and simulation design file.
- Configure OMNeT++ simulation environment and protocol modules.
- Import baseline and ATMACA solution models.
- Set up automated logging, data storage.

Execution

- Run each reference and solution scenario at least 20 iterations per condition.
- Monitor simulation runs for errors or instability.
- Collect real-time metrics.
- Document qualitative observations during runs.

Post-Execution

- Clean and pre-process data logs.
- Conduct statistical analysis and benchmarking against DES thresholds.
- Draft preliminary findings for consortium review.
- Iterate scenario parameters if required for additional runs.
- Consolidate results into the Exploratory Research Report (ERR).

5.2.9.2 Roles and responsibilities in the exercise

The roles and responsibilities of the participants involved in preparing, conducting and analysing the exercise:

- Validation Coordinator (Lead Partner): Oversees planning, ensures alignment with ERP objectives, approves scenario designs and success criteria.
- Simulation Development Team: Integrates ATMACA protocol into the simulation environment. Implement MIPV6 into the simulation environment.

5.2.9.3 Time planning

In the table below, month 10 is June 2025 and month 18 is February 2026.

Activity	Month									
	10	11	„	14	15	16	17	18		
<i>Preparatory phase</i>	■	■	■	■						
<i>Execution phase</i>				■	■	■				
<i>Post-execution phase</i>							■	■		

Table 5-9: detailed exercise #2 time planning

5.2.9.4 Identified risks and mitigation actions

Risks	Impact (1-low, 2-medium, 3-high)	Likelihood (1-low, 2-medium, 3-high)	Criticality (calculated based on likelihood and impact)	Mitigation actions
Simulation model instability or incompatibility with OMNeT++	2	2	Medium	Conduct pilot runs and debugging before full-scale simulation; maintain technical support from model developers.
Insufficient realism of input scenarios	3	1	Medium	validate parameters against real-world data.
Data loss or corruption during runs	2	2	Medium	Automated backup of logs after each run; replicate runs if needed.
Delays in analysis due to large data volumes	2	2	Medium	Allocate sufficient computing resources; pre-define scripts for automated processing.

Personnel turnover or unavailability	2	1	Low	Backup staff; maintain documentation for handover.
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Table 5-10: exercise #2 risks and mitigation actions

5.3 Validation exercise #3 plan: Emulation of Datalink Applications

5.3.1 Validation exercise description and scope

This exercise represents the first near-operational validation of the ATMACA datalink communication protocol, bridging the gap between analytical simulation (Exercise #2) and live flight trial (Exercise #6). It emulates the base framework, with the protocol stack under real-time conditions, with virtual machines in a Lab environment, network nodes and end-systems, allowing the integration of CPDLC and DLCM framework applications. This setup allows to emulate and evaluate how the ATMACA protocol and applications perform when integrated together and operate under dynamic controlled network conditions. The results will allow to check key application framework functionalities related to DLCM (session, service, user, and mobility capabilities) and CPDLC (flight and session handover in various environments as well as message interchange between nodes).

The system will be validated by emulating the following actors:

- Virtual En-route and Tower ATCos interacting with emulated ATC systems and the protocol communication framework.
- Pilots represented via virtual flight deck terminals interacting with virtual ATCos and other nodes.
- ATMACA protocol nodes (hosting session, connection, context, and mobility management modules from DLCM and datalink messaging service modules from CPDLC).
- Network nodes and ANSP Sector gateways emulated to reflect inter- and intra-domain mobility.

To emulate the following Processes / Use Cases:

- Gate-to-gate air-ground datalink sessions. Use Case 1: Streamlined advanced ATC and communication handover.
- Use Case 2: Fully flexible and customisable Flight Sessions Management.
- Use Case 3: Consistent and seamless datalink operations management featuring advanced HMI for pilots and controllers.
- Gate-to-gate air-ground datalink sessions.
- Handovers across multiple ATN/IPS links (WiFi, cellular).
- Exchange of CPDLC request and response messages between ATCos and pilots, including clearances and operational information using different services and scenarios.
- Mobility aspects including terminal, user, service and session mobility.

Exercise #3 directly addresses VO1 (Seamless Mobility Management) and VO2 (Integrated Session, Connection & Context Management) as defined in Section 4.3. Its objective is to validate protocol

behaviour under near-real-time conditions by evaluating the session continuity during CPDLC handover and message exchange in different emulated scenarios. The emulation environment is that the ATMACA protocol operates over multilink ATN/IPS with DLCM and CPDLC active, including both intra- and inter-domain handovers. No reference scenario is required for this exercise as several general functional conditions will be addressed as part of this exercise. The emulation runs the protocol stack and applications (DLCM and CPDLC) on interconnected (virtualised) ATMACA nodes. This setup provides deterministic control over session and mobility events while evaluating both DLCM mobility capabilities and CPDLC message exchange and handover with focus on session continuity. This approach:

- Validates session continuity during handovers and other events under conditions more representative of real operations than offline simulations.
- Enables testing of integrated applications and interaction with the emulated system.
- Ensures repeatability and fine-grained parameter control for experimental design.

Virtualised Emulation Testbed:

- Interconnected virtual ATMACA nodes hosting the ATMACA protocol stack and applications.
- Virtual ATC and flight-deck HMI interfaces running on emulated workstations for controller/pilot interaction through CPDLC messages.
- Scalable network configurations to emulate multiple ANSP domains and mobility events.

This exercise represents the transition from TRL1 to TRL2 by providing experimental evidence under emulated operational conditions. Results from Exercise #3 will be used to refine the protocol design and stack, confirm feasibility, and de-risk the subsequent flight trial (Exercise #6).

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

This exercise will provide stakeholders with evidence that the solution can operate reliably, with its key functionalities and applications, under realistic conditions, before committing to live flight trials. The results will directly inform decisions on scalability, regulatory acceptance, and further development. The table below summarises stakeholder involvement and benefits for Exercise #3:

Stakeholder	Involvement	Why it matters to the stakeholder
ANSPs / ATC Centres	Provide operational input on mobility scenarios, observe emulation sessions, review KPI reports.	Evidence of reduced handover delays and improved continuity across ANSP boundaries, supporting future deployment decisions and cost–benefit assessments.
Airlines / Aircraft Operators	Supply operational flight data for context synchronisation; review session continuity.	Assurance of minimal disruption to datalink services during handovers, leading to increased efficiency and reduced operational risk.
ATCos and Pilots	Provide mobility and handover and CPDLC message exchange assessments	Verify robust session continuity during emulated CPDLC exchanges.

System Integrators & Industry Partners	Configure emulation platform and integrate protocol components.	Confirm technical feasibility and identify gaps before industrial-scale deployment.
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Table 5-11: stakeholders' expectations

This stakeholder engagement ensures that the exercise not only validates technical KPIs but also captures end-user acceptance, operational feasibility, and regulatory readiness, critical aspects for the successful progression from TRL1 to TRL2.

5.3.3 Validation objectives

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #3	Exercise validation objective	Exercise success criteria
VO1 – Seamless Mobility Management	session continuity;	Fully covered under emulated intra-/inter-domain horizontal & vertical handovers.	Demonstrate ATMACA's ability to maintain seamless connectivity across different networks used in real-time emulation.	Session continuity during emulated mobility scenarios is working.
VO2 – Integrated Session, Connection & Context Management	Active sessions persist;	Fully covered through CPDLC message exchange using DLCM capabilities.	Validate session persistence and context-aware communication across operational phases and virtual ATN nodes.	Session remains persistent during several emulation scenarios. It remains active during CPDLC handovers and used in interchanges.

Table 5-12: validation objectives addressed in validation exercise #3

5.3.4 Validation scenarios

Exercise #3 is designed as a feasibility and functional performance evaluation of the ATMACA datalink communication protocol and its applications in a real-time emulation environment. The primary objective is to verify that the protocol stack along with DLCM and CPDLC operate correctly and provide the four mobility capabilities reliably in the emulated environment before moving to live trials.

5.3.4.1 Reference scenario(s)

Because this exercise focuses on technical feasibility rather than comparative performance improvements, it does not include separate reference scenarios. Instead, the emulation itself represents the “solution scenario,” configured to mimic representative air–ground conditions with multilink connectivity to test session continuity and mobility with handover and message interchange. This approach is justified because:

- The exercise is at TRL 2 and aims to confirm that the integrated protocol functions correctly under realistic but controlled conditions.
- Introducing full reference scenarios at this stage would add complexity without directly contributing to the main feasibility objective.
- Performance benchmarks can be derived analytically (from standards and literature) rather than by running a separate “reference” emulation.

5.3.4.2 Solution scenario(s)

This solution scenario design ensures that Exercise #3 validates the feasibility of the ATMACA solution in a near-operational environment while keeping the focus on proving technical functionality and baseline performance prior to live flight trials.

- Scenario Configuration: Virtualised ATN/IPS nodes emulate multiple ANSP domains with both horizontal and vertical handovers. The setup includes terrestrial, and cellular links configured to represent typical multilink conditions.
- Actors: Virtual controllers and pseudo pilots interacting through HMIs running on emulated ATMACA client nodes; system integrators configuring network nodes; observers from ANSPs and airlines.
- Operational Processes: Session initiation, handover procedures, message exchange, context synchronisation, CPDLC message reliability, and failover mechanisms tested during simulated scenarios.
- Network Conditions: limited terminal mobility and session persistence under network change.
- KPIs Measured: session continuity during all mobility events. Successful and reliable CPDLC message exchanges.

5.3.5 Exercise validation assumptions

This subsection lists the specific assumptions applicable to Exercise #3. All ERP-level assumptions from Section 4.4 remain valid (e.g. interoperability, scalability, safety, and security). The additional assumptions below apply specifically to the emulation environment used in this exercise. The assumptions in Table 5-13 provide a controlled and repeatable test environment for Exercise #3, enabling the project to focus on proving the technical feasibility of the ATMACA protocol stack and integrated applications before progressing to live or human-in-the-loop testing.

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
EX3-A1	Virtualised Network Fidelity	The emulation environment accurately replicates ATN/IPS multilink conditions representative of operational settings.	Emulation is used to stress-test the ATMACA protocol prior to live trials. Full physical replication of network conditions would be impractical at this stage.	If fidelity is lower than expected, some functions might not work properly.
EX3-A2	Stable Integration of DLCM & CPDLC	DLCM and CPDLC applications integrate seamlessly into the emulated ATMACA protocol stack without major re-engineering.	Ensures focus on validating protocol behaviour, not debugging application integration.	Integration issues could delay exercise execution or require reduced scope.
EX3-A3	Synthetic User Interaction	Pilot/controller interactions will be tested using scripted actions or test operators rather than live operational staff.	At TRL2, synthetic interaction is sufficient to test functional feasibility before human-in-the-loop studies.	Human factors will only be indicative; full assessment deferred to Exercises #4 & #5.
EX3-A4	Controlled Network Load Patterns	Network load scenarios (light, medium, heavy) will be pre-defined and repeatable for each run.	Ensures comparability between test iterations and reproducibility of results.	Unexpected traffic conditions may be under-represented, limiting extrapolation to real-world variability.

Table 5-13: validation exercise #3 assumptions

5.3.6 Limitations and impact on the level of significance

The following limitations may affect the level of significance and the generalisation of results:

Emulation vs. Operational Fidelity:

- The emulation platform replicates key multilink network characteristics (latency, bandwidth, packet loss, handover events) but cannot fully reproduce the variability and unpredictability

of real-world conditions (e.g. atmospheric interference, non-standard ATC procedures, or unexpected traffic surges).

- Impact: Performance metrics such as CPDLC message delivery rate and reliability may differ under live operational conditions, requiring further validation in Exercise 6.

Synthetic User Interaction

- Pilot and controller inputs will be simulated or performed by test operators following scripted procedures rather than by operational staff in real-time settings.
- Impact: Human factors indicators (e.g. situational awareness, workload) will be indicative only and must be validated in later human-in-the-loop and flight trial exercise.

Baseline Metrics Derived from Standards

- Without a live “reference scenario,” performance benchmarks are based on ICAO/SESAR standards and literature rather than direct baseline system measurements.
- Impact: Discrepancies between actual and benchmarked performance may emerge during later validation phases.

Limited Traffic Scenarios

- Predefined load levels ensure reproducibility but do not cover all potential operational extremes.
- Impact: Results may understate protocol performance limits under unusual or extreme conditions.

Sample Size and Iterations

- Due to resource constraints, the number of test runs and scenario variations may be limited at this stage.
- Impact: Reduced statistical power may limit the ability to detect marginal performance differences.

Despite these limitations, the controlled emulation environment is sufficient for TRL2 feasibility testing. The exercise is not intended to deliver fully generalisable operational performance evidence but to de-risk later validation stages by proving the integrated protocol’s functional viability. Results will provide a baseline for refining scenarios and success criteria in human-in-the-loop and flight trial exercises (Exercises #4–6).

5.3.7 Validation exercise platform / tool and validation technique

5.3.7.1 Validation exercise platform / tool characteristics

The real-time emulation environment will be configured to replicate ATN/IPS multilink conditions across multiple ANSP domains. The platform integrates:

- Virtualised ATN/IPS nodes representing ground stations, ATC centres, and airline networks.
- Emulated aircraft virtual endpoints hosting the ATMACA protocol stack, including DLCM and CPDLC applications.

- Multilink connectivity modules (WiFi, cellular) configurable to emulate terminal mobility.
- Monitoring and logging tools for capturing KPIs such as CPDLC delivery rate and reliability, and session continuity during mobility events (user, session, service and terminal mobility).

This setup enables a gate-to-gate emulation of air-ground communications, allowing for reproducible tests under multiple mobility scenarios. The exercise will integrate the latest ATMACA protocol prototype into the emulation platform, adding real-time components and network modules to stress-test mobility, session, and CPDLC message exchange under near-operational conditions.

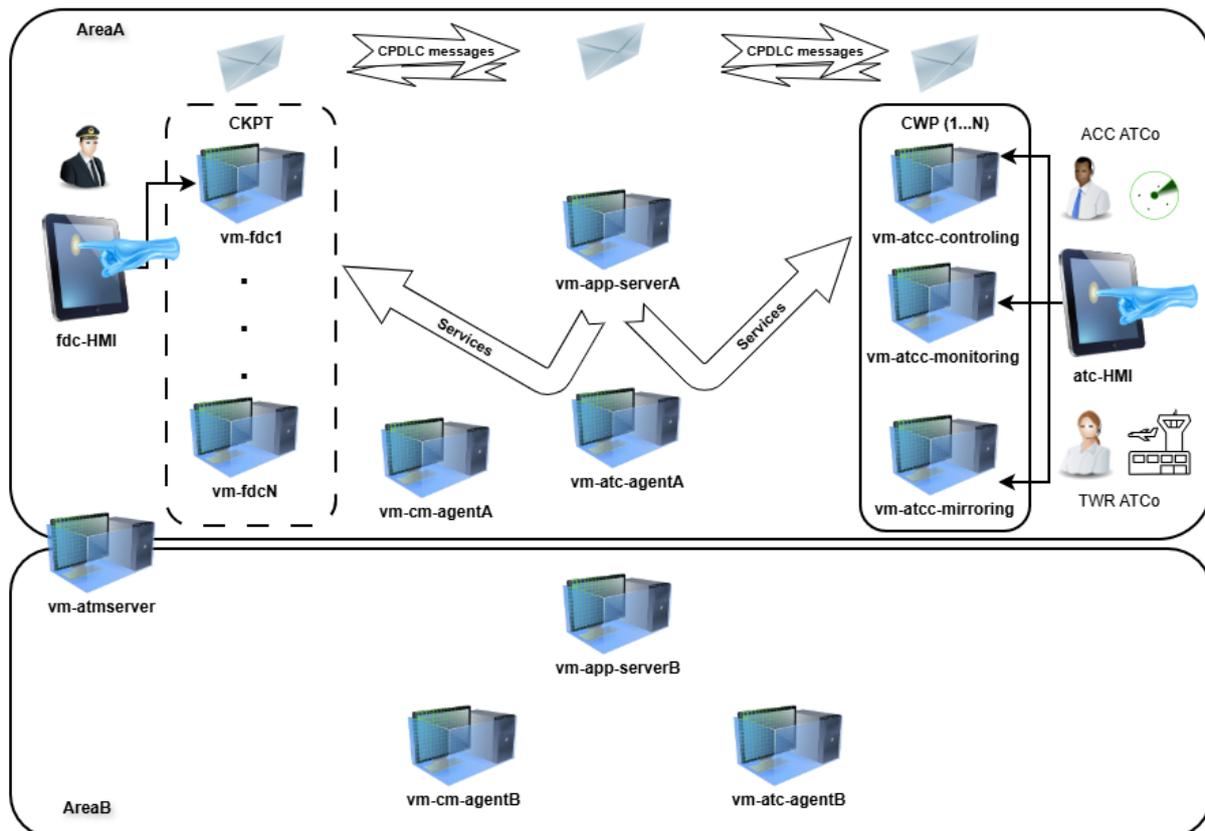


Figure 5-3: exercise #3 prototypes and validation infrastructure

5.3.7.2 Validation exercise technique

The real-time emulation-based validation technique combines:

- Protocol-level emulation to execute handover, session persistence, message exchange and context synchronisation events under dynamic conditions.
- Stress testing under predefined network conditions to evaluate performance thresholds and resilience.

This technique is chosen because it provides a way to use the ATMACA Protocol along with DLCM, CPDLC, and HMI to test CPDLC message exchange and DLCM implemented mobility capabilities.

5.3.8 Data collection and analysis

5.3.8.1 Data and data collection methods

This subsection outlines the types of data to be collected, the collection methods, and the analysis approach for Exercise #3. As this exercise is primarily a feasibility and functional validation step, data collection is focused on verifying protocol performance, reliability, and under emulated multilink conditions.

Types of Data Collected

- Network Performance Metrics: session continuity CPDLC message delivery rate and reliability.
- Protocol Functionality Logs: session related parameters, context synchronisation events, mobility events, CPDLC message exchange metrics.

Data Collection Methods

- Automated Logging: All emulated nodes (airborne and ground) will run scripts to capture all relevant performance metrics in real-time and store them in structured log files (CSV/JSON).

5.3.8.2 Analysis methods

The framework will be tested, and the results will be compared against ICAO/SESAR performance thresholds for safety-critical services (e.g. CPDLC session continuity, message delivery, and reliability).

Output Format: Structured data sets (CSV/JSON) for KPIs.

5.3.9 Exercise planning and management

Exercise #3 focuses mainly on software testing tasks to validate the feasibility and correct functioning of the ATMACA datalink communication protocol and its applications under emulated multilink conditions. The planning and management of this exercise are designed to ensure repeatability, traceability, and timely delivery of results.

5.3.9.1 Activities

The activities are divided into preparatory, execution, and post-execution phases:

Preparatory Phase

- Integrate the ATMACA protocol stack and applications (DLCM + CPDLC) into the emulation platform.
- Configure virtual ATMACA nodes and multilink network modules.
- Use synthetic pilot/controller interactions to test both CPDLC and DLCM capabilities including message exchange, service, user, session, and terminal mobilities.
- Define scenario parameters (link types, mobility events, traffic load levels).

Execution Phase

- Run iterative emulation sessions with predefined scenarios.
- Apply controlled link degradation and handover events to stress-test the protocol.

Post-Execution Phase

- Prepare interim technical reports highlighting compliance with success criteria.
- Refine configuration or scenarios as needed for repeat runs.

5.3.9.2 Roles and responsibilities in the exercise

The roles and responsibilities of the participants involved in preparing, conducting and analysing the exercise:

- Validation Coordinator (Lead Partner): Oversees planning, ensures alignment with ERP objectives, approves scenario designs and success criteria.
- Software Development Team: Integrates ATMACA protocol into the emulation environment, maintains test scripts and fault injection tools.
- Network Simulation Specialists: Configure multilink conditions, ensure fidelity of latency, packet loss, and bandwidth parameters.
- Observer Stakeholders (ANSP/Airline Reps): Review test scenarios and interim results to ensure operational relevance.

5.3.9.3 Time planning

In the table below, month 16 is December 2025 and month 19 is March 2026.

Activity	Month			
	16	17	18	19
<i>Preparatory phase</i>				
<i>Execution phase</i>				
<i>Post-execution phase</i>				

Table 5-14: detailed exercise #3 time planning

5.3.9.4 Identified risks and mitigation actions

Risks	Impact (1-low, 2- medium, 3- high)	Likelihood (1-low, 2- medium, 3- high)	Criticality (calculated based on likelihood and impact)	Mitigation actions
Integration delays of ATMACA protocol stack	3	2	6 High	Begin integration early; allocate additional

					developer resources.
Emulation fidelity insufficient for stress-testing	2	2	4	Medium	Validate network parameters against real-world benchmarks; adjust configuration iteratively.

Table 5-15: exercise #3 risks and mitigation actions

5.4 Validation exercise #4 Plan: Low-fidelity HMI Simulation

5.4.1 Validation exercise description and scope

The fourth validation exercise is characterised by a low fidelity HMI simulation. The goal of the exercise is to evaluate the Concept of Operations (CONOPS) and its HMI in an interactive and hands-on simulation activity. The validation will be carried out with the participation of end users and their contribution will be crucial to evaluate whether the functionalities satisfy their needs and expectations.

The exercise supports the early validation of usability, interaction flows, and role-specific functionalities, helping to ensure that HMI design decisions align with operational requirements and SESAR human performance guidelines.

The actors involved are:

- ATCos: tower, en-route, supervisors
- Pilots

The simulation will be held online, asynchronously. The end users, namely the ones mentioned above, will have to perform some tasks based on low-fidelity scenarios that are related to the use cases described in the D2.3 OSED. The entire experiment will be run on a user testing platform called Useberry, accessible via a dedicated link, one for each HMI.

Every link will open a user testing session, that will be characterised by the following materials:

- A presentation of the project
- Demographic and openness to technology questionnaires
- An HMI walkthrough
- Scenario-based tasks alternated with questionnaires to evaluate human performance, HMI usability
- Debriefing questionnaire

All the activities will be recorded and saved on the Useberry platforms, allowing to access all the results and advanced analytics. These results will be elaborated and combined into a validation report.

5.4.2 Stakeholder’s expectations and benefit mechanisms addressed by the exercise

This exercise is the first opportunity for end users and stakeholders to directly influence the design of the ATMACA HMIs. It provides early feedback to ensure that the system meets operational needs and SESAR human-performance guidelines before integration into higher-fidelity simulations and flight trials. The table below shows how each stakeholder contributes to and benefits from the early-stage HMI evaluation, ensuring a user-centred design process.

Stakeholder	Involvement	Why it matters to the stakeholder
ATCos	ATCos will be first-hand involved in the exercise.; they will provide structured feedback on prototype usability and human performance metrics. They will be asked to perform scenario-based tasks that mainly involve assuming a flight, communicating with a pilot, and handing off the flight.	ATCos require an HMI that supports clear, efficient datalink communication and trajectory management without increasing workload. Early involvement ensures the interface fits real operational workflows.
Pilots (Flight Deck Users)	Pilots will be first-hand involved in the exercise; they will provide structured feedback on prototype usability and human performance metrics. They will be asked to perform scenario-based tasks that mainly involve communicating with an ATCo.	They need an intuitive, role-specific interface that integrates with cockpit operations and reduces seamlessly communication errors.
Airlines (e.g., THY)	Provide pilot participants and operational feedback; review interface alignment with airline procedures.	Ensures the HMI integrates smoothly with airline Standard Operating Procedures (SOPs) and minimises training and transition costs.
Human Factors Specialists	Collect usability and workload data and advise on design improvements.	They ensure that usability testing follows best practices and generates valid, actionable data.

Table 5-16: stakeholders' expectations

5.4.3 Validation objectives

Two pillars, reflected in the validation objectives that follow in Table 5-17:

- the impact of the new communication procedures and modalities on ATCo and pilot performance.
- the assessment of the ATMACA HMI as an appropriate operator tool to execute said procedures and ensure safe, efficient communication across all actors.

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #4	Exercise validation objective	Exercise success criteria
<p>OBJ-ATMACA-TRL2-ERP-005:</p> <p>Assess the impact of the ATMACA operational concept on the performance of pilots and air traffic controllers.</p>	<p>CRT-ATMACA-TRL1-ERP-005-001:</p> <p>Majority of pilots and ATCOs confirm that ATMACA air-to-ground, ground-to-ground, and handover procedures are clear, complete, and internally consistent.</p>	<p>Partial coverage. To be re-evaluated during the Real Time Simulation exercise.</p>	<p>Same as solution objective.</p>	<p>Same as solution success criteria.</p>
	<p>CRT-ATMACA-TRL1-ERP-005-002:</p> <p>Majority of pilots and ATCOs confirm that ATMACA procedures can be executed accurately and in a timely manner</p>			
	<p>CRT-ATMACA-TRL1-ERP-005-003:</p> <p>Majority of pilots and ATCOs confirm that the shift to predominantly text-based communications is acceptable and operationally efficient.</p>			
	<p>CRT-ATMACA-TRL1-ERP-005-004:</p> <p>Majority of pilots and ATCOs confirm that ATMACA does not increase or reduces their workload compared with current practice</p>			
	<p>CRT-ATMACA-TRL1-ERP-005-005:</p> <p>Majority of pilots and ATCOs confirm that the ATMACA operational concept and procedures are at least</p>			

	as trustworthy as today's procedures.			
	<p>CRT-ATMACA-TRL1-ERP-005-006:</p> <p>Majority of pilots and ATCOs confirm that ATMACA enables clearer and faster communication across diverse operational actors and organisational units than current practice.</p>			
	<p>CRT-ATMACA-TRL1-ERP-005-007:</p> <p>Procedures that should remain voice first or primarily voice supported are captured and documented based on end-user feedback</p>			
	<p>CRT-ATMACA-TRL1-ERP-005-008:</p> <p>Majority of pilots and ATCOs confirm they can allocate attention effectively across tasks with the additional ATMACA display, without impairing other monitoring duties.</p>			
	<p>CRT-ATMACA-TRL1-ERP-005-009:</p> <p>Majority of pilots and ATCOs confirm that the training required to adopt ATMACA procedures and tools is acceptable.</p>			
<p>OBJ-ATMACA-TRL2-ERP-006:</p> <p>Assess the impact of the ATMACA Human Machine Interface (HMI) on the performance of pilots and air</p>	<p>CRT-ATMACA-TRL1-ERP-006-001:</p> <p>Majority of pilots and ATCOs confirm that information in the ATMACA HMI is sufficient, well placed, and easy to find.</p>	<p>Partial coverage. To be re-evaluated during the Real Time Simulation exercise.</p>	<p>Same as solution objective.</p>	<p>Same as solution success criteria.</p>

traffic controllers				
	CRT-ATMACA-TRL1-ERP-006-002: Majority of pilots and ATCOs confirm that the workload induced by the ATMACA HMI is acceptable			
	CRT-ATMACA-TRL1-ERP-006-003: Majority of pilots and ATCOs confirm that the HMI supports error prevention and recovery (e.g., confirm, correct, or recall) without adding undue steps.			
	CRT-ATMACA-TRL1-ERP-006-004: Majority of pilots and ATCOs confirm that the ATMACA HMI supports situation awareness and meets stated situation awareness requirements.			
	CRT-ATMACA-TRL1-ERP-006-005: Majority of pilots and ATCOs confirm that alerts and notifications are salient, prioritised appropriately, and do not cause overload			
	CRT-ATMACA-TRL1-ERP-006-006: Majority of pilots and ATCOs confirm that the ATMACA HMI is easy to navigate and ergonomically appropriate, with suitable interaction methods.			
	CRT-ATMACA-TRL1-ERP-006-007: Majority of pilots and ATCOs confirm that the ATMACA HMI colour use and colour coding are acceptable			
	CRT-ATMACA-TRL1-ERP-006-008: Majority of pilots and ATCOs confirm that the ATMACA HMI requires			

	reasonable levels of familiarisation to use effectively.			
	CRT-ATMACA-TRL1-ERP-006-009: Majority of pilots confirm that text-based interaction and use of a touch-screen are acceptable for cockpit use.			
	CRT-ATMACA-TRL1-ERP-006-010: Majority of ATCOs confirm that the ATMACA HMI is appropriate for use across different ATC positions (ground, approach, en-route).			

Table 5-17: validation objectives addressed in validation exercise #4

5.4.4 Validation scenarios

The ATMACA operational concept departs significantly from current practice in both day-to-day procedures and communication modalities. Accordingly, this exercise bases its assessment in a comparison between a reference (current) scenario and a solution scenario with ATMACA integrated.

A standalone HMI assessment, detached from its operational context, would be insufficient: communications are already central to ATCO and pilot work, and the focus must be on the impact of the proposed changes rather than on interface usability in isolation.

The sections that follow briefly describe the reference scenario reflecting current practice and the solution scenario reflecting future practice with ATMACA services integrated into the operational environment

5.4.4.1 Reference scenario(s)

The reference scenario stems from the conduct of communication tasks in the work domain today (See D2.1).

Air-ground

Voice remains the primary modality for air-to-ground communication in contemporary aviation. Terminal and most continental en-route airspace utilises Very High Frequency (VHF) channels for the issuance of clearances, frequency changes, and tactical instructions, with pilot readbacks serving as confirmation. In oceanic and remote regions, HF (High Frequency) voice is the standard, though its audio fidelity can suffer from degradation due to variable ionospheric propagation. As a result, SATCOM is often employed as a more reliable alternative in these environments.

In addition to voice, datalinks for text-based communication are integral to modern air-to-ground operations, although their implementation is not globally uniform. Automatic Dependent Surveillance - Broadcast (ADS-B), Automatic Dependent Surveillance - Contract (ADS-C), CPDLC and Aircraft

Communications Addressing and Reporting System (ACARS) serves as datalink applications for transmitting text-based messages.

Ground-ground

Voice channels are still widely used for inter-position and inter Area Control Centre (ACC) communication, with Voice over IP (VoIP) based on EUROCAE ED-137 replacing traditional analogue lines and legacy protocols. Datalinks are also widely used for standardised information exchange such as coordination, transfer, flight-plan updates and acknowledgements. In Europe this is provided via On-Line Data Interchange (OLDI), with the ICAO-specified ATS Inter-Facility Data Communication (AIDC) as the global analogue. Finally, fixed messaging between organisations - such as flight-plan filing/amendment, NOTAM and MET - uses the ATS Message Handling System (AMHS); in Europe, the Integrated Initial Flight Plan Processing System (IFPS) validates and distributes IFR flight plans within the IFPS Zone.

5.4.4.2 Solution scenario(s)

It is thus evident that day-to-day communications and information exchange today operate over a fragmented set of systems with different protocols, processes and capabilities. ATMACA departs from this reference by introducing a session-based framework in which each flight has a single flight session that consolidates air-ground communications, flight data and context, with automatic logon/continuity across links and sectors. Based on D2.3 and for the purpose of the present exercise, the operational side of the solution scenario is described as follows:

- **ATCOs:** For each flight, a persistent flight session with all air-ground communications is shown in the HMI together with relevant flight data, operational context and communication history. In day-to-day operations, ATCOs use the ATMACA HMI to access the flight sessions under their responsibility; sessions can be shared and transferred across sectors/ACCs to support handovers and flexible workload reallocation. Clearances and instructions can be issued via datalink within the session, and instant messaging reduces the need for voice in non-critical phases. Past clearances, communications and flight/trajectory data are available through the session history; coordination/transfer information is part of the session context. When a handover is performed, the session is duplicated for the receiving sector before transfer; the receiving ATCO is granted full access without manual data exchange, and normal, pre-scheduled handovers do not require ATCO-ATCO voice.
- **Pilots:** At this stage of concept maturity, pilots are expected to use a unified ATMACA display for all ordinary communications, accessed through a tablet or electronic flight bag carried in the cockpit. Once the pilot initiates a flight session, all exchanges are visible in the interface via datalink and instant messaging (including clearances, information and requests). The session remains active and persistent across sectors, airspaces and geographical areas; should connectivity drop, session data is preserved, queued and resynchronised automatically on reconnection, without repeated manual authentication. Handovers and transfers of control are performed automatically by the system without pilot input.

Operational scenario for the exercise

To allow participants to assess the solution environment, the exercise will use a prototype-based HMI journey that will replicate, step by step, two ordinary communication scenarios with ATMACA: one aircraft departure and one aircraft arrival. The scenarios will be based on recorded operations from a medium-to-high traffic day at Fuerteventura Airport, Spain. They will be pre-scripted with

operational experts to include realistic communication steps between airport ATC (Clearance Delivery, Ground, and Tower) and the departing/arriving aircraft.

The same pre-scripted scenarios will be used for pilots and ATCos to ensure a uniform, consistent assessment. In both cases, the prototype will advance clearance by clearance. Participants will view the active flight session, consult prior exchanges in the session history, and use the HMI’s templates and controls to issue acknowledgements, instructions, or requests appropriate to their role and position. After completing the scenarios, participants will answer structured and open-ended questions on the concept, the designed processes, the HMI, and the perceived impact of ATMACA on human performance. Sector handovers will be handled by ATMACA session management so the flight session will remain continuous across ATC positions; for this exercise, Delivery, Ground, and Tower may be operated by a single controller within the aerodrome control unit.

A brief, high-level description of the two scenarios follows:

Case 1 — Departure (Delivery, Ground, Tower, then handover to Approach)

- Initial contact with Clearance Delivery and issuance/acceptance of the departure clearance (route or SID, initial level, squawk), with readback and acknowledgement in the HMI.
- Transfer to Ground; request and approval for push-back/start as applicable.
- Taxi clearance to the runway holding point, including any intermediate holds or crossings; step-by-step taxi instructions and readbacks through the flight session.
- Transfer to Tower; line-up instruction (or hold short), followed by take-off clearance.
- Post-lift-off confirmation of the initial climb in accordance with the SID; handover to Approach completes the case.

Case 2 — Arrival (handover from Approach, then Tower, Ground, stand)

- Handover from Approach to Tower on final; confirmation of runway in use and sequence.
- Landing clearance and runway occupancy management; instruction to vacate and any required runway/taxiway crossings.
- Handover to Ground; taxi routing to stand with intermediate holds as applicable.

Blocks-on confirmation and end of communications for the case.

5.4.5 Exercise validation assumptions

The table below lists the additional validation assumptions specific to Exercise #4. All ERP-level assumptions described in Section 4.4 (e.g. compatibility, safety, network coverage) are also applicable. Because this exercise focuses on low-fidelity HMI prototypes, some assumptions differ from later high-fidelity or operational exercises.

Assumpti on ID	Assumpti on title	Assumption description	Justification	Impact Assessment
ASM-ATMACA-TRL2-ERP-	Delivery, Ground, and Tower positions combined	In all exercise scenarios, one controller will operate Clearance	To streamline execution, ensure continuity of the single flight session, and expose participants to	Medium — common at smaller airports; removes inter-position coordination effects but remains

EXE04-001		Delivery, Ground, and Tower.	the full set of aerodrome communications; participants may work across these positions in practice.	acceptable for scripted single-aircraft cases.
ASM-ATMACA-TRL2-ERP-EXE04-002	Pre-scripted traffic scenarios	Two predefined, guided single-aircraft scenarios will be used for the validation. Participants will perform only the instructed actions within the prototype	The exercise is mock-up/prototype-based; time and scope constraints and the LFS objectives do not permit responsive mock-ups. Pre-scripted runs ensure consistency across roles and reduce confounding factors.	Medium — limits free exploration and may reduce task realism, but is acceptable at low TRL given the focus on concept and HMI.
ASM-ATMACA-TRL2-ERP-EXE04-003	Only text communications	All ATC–pilot communications will be text-based and conducted via the ATMACA HMI; voice instructions will not be used.	Aligns with the core ATMACA operational concept and focuses the LFS on evaluating the text-centric modality and associated procedures.	High — this departs from today’s bi-modal practice by design. The assumption focuses the validation on the text-only concept; voice fallback or mixed-mode procedures will not be evaluated in this exercise and, if needed, will be captured separately as requirements.
ASM-ATMACA-TRL2-ERP-EXE04-004	Only basic/critical HMI functionalities available	The prototype HMI will implement only the functions required for the scripted steps (e.g., message templates, compose/send/acknowledge, session history, delivery/status/alerting). Non-critical features may be stubbed or omitted.	Low-TRL (TRL2) prototype with time and scope constraints; the exercise focuses on validating the concept and core communication workflows rather than full functional coverage.	Medium — limits breadth of usability testing but does not compromise the objectives. Wider functionality will be evaluated in the Real-Time Simulation exercise #5.
ASM-ATMACA-TRL2-	Prototype-paced, step-by-	Scenario timing will be controlled by the prototype; real-time	The new procedures must be presented step by step so participants	High — execution time, workload under time pressure, and

ERP-EXE04-005	step execution (no live traffic dynamics)	traffic dynamics beyond the scripted steps will not be simulated.	can understand the operational concept and its implications	situation awareness driven by live traffic will not be assessed here. These aspects will be covered by the Real-Time Simulation exercise #5.
ASM-ATMACA-TRL2-ERP-EXE04-006	Scope limited to aerodrome operations	Handover to/from the terminal radar controller will be treated as a boundary condition (end/start of cases). TMA/ en-route control logic is out of scope except where needed to provide handover context.	Assessing en-route/terminal radar operations would require a mock-up integrated with a Plan View Display at the controller working position and a different experimental design with APP/ACC controllers, which is beyond the current low-TRL exercise.	Medium — narrows coverage to aerodrome operations while still yielding valuable feedback; qualitative notes on APP/ACC implications may be collected for the follow-on Real-Time Simulation and more mature iterations of the project.
ASM-ATMACA-TRL2-ERP-EXE04-007	Nominal network performance and session continuity	Network performance and system latency will be nominal unless a step explicitly introduces a degraded condition. Scenario scripts will not include session connection losses.	Connectivity and session persistency are covered by technical validation activities; this LFS focuses on human performance with stable links.	Medium — assessment under degraded network conditions is deferred to technical exercises and, where appropriate, the Real-Time Simulation.
ASM-ATMACA-TRL2-ERP-EXE04-008	Baseline derived from participant experience	The baseline for comparison (“today’s practice”) will rely on participant judgement and experience rather than concurrent live trials.	Consistent with the mock-up-based HMI demonstration used to introduce the new concept and procedures; running parallel live baselines is outside the scope of this LFS.	Low — participants are qualified pilots and ATCos familiar with current operations.
ASM-ATMACA-TRL2-ERP-EXE04-009	Success criteria assessed via end-user feedback,	Success criteria will be assessed primarily through structured end-user feedback (majority agreement), complemented by	Appropriate for a low-TRL, mock-up-based exercise focused on concept/HMI suitability; simplifies setup and maximises session time	Medium — limits quantitative granularity but is sufficient to meet the LFS objectives.

	observation & logs	observer notes and prototype logs. No eye-tracking or physiological measures will be used.	for task exposure and discussion.	
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Table 5-18: validation exercise #4 assumptions

5.4.6 Limitations and impact on the level of significance

This simulation is characterised by the limitations that are typical of a LFS. First of all, there is a lack of realism, both in terms of visual representation and interactivity. The functionalities are limited, and complex interactions are avoided. Variance in operational scenarios is limited, however ensuring the assessment of all the HMI functionalities, and no real operational data is used. In fact, the final software to simulate real responses will be available for Validation Exercise #5. Therefore, the engagement as well as the user experience is limited.

Despite these limitations, the exercise is not focused on the functionality but on the clarity and usability of the HMI. For this reason, the limitations do not affect the scope of the simulation.

The results of the simulation can be considered valid for non-urgent operational situations and are limited to the scenarios tested. The participant sample will include between 10 and 30 individuals, depending on availability, including ATCos, pilots, and ATC students, recruited through convenience sampling. Only one trial per participant is foreseen, thus avoiding potential sequence effects such as fatigue or learning. Data will be collected using validated questionnaires to ensure the reliability and validity of the results.

5.4.7 Validation exercise platform / tool and validation technique

5.4.7.1 Validation exercise platform / tool characteristics

The simulation exercise will be held online on a computer. The HMI screens will be provided on a user testing tool, Useberry, where ad-hoc HMI walkthroughs will be conducted. Useberry is an online, browser-based system. This choice is made to enable remote participation, thereby overcoming the accessibility barriers typically associated with ACCs and increasing the potential pool of participants (i.e., asynchronous data collection). Additionally, the platform has minimal hardware requirements, functioning effectively on standard personal computers, which further mitigated accessibility issues. This system also allowed for the recording of user interactions, including clicks, hovers, and timestamps, facilitating comprehensive data collection and analysis.

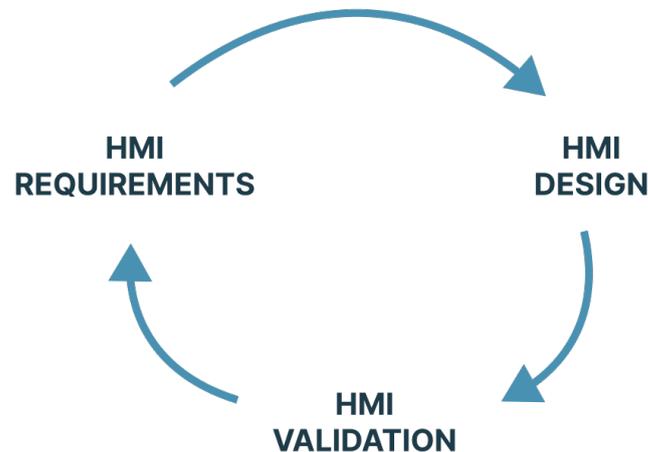


Figure 5-4: exercise #4 prototypes and validation infrastructure

5.4.7.2 Validation exercise technique

In this exercise, a Low-fidelity simulation (LFS) is utilised. LFS allows researchers to test/evaluate concepts, also in complex systems, at a lower level of maturity of the system development. This approach is characterised by a lower level of similarity between certain aspects of the simulated system and the real system, tailored to the specific context in which the simulation is conducted. The reduced fidelity allows for planning, designing, and executing the simulation with less effort compared to high-fidelity simulations, such as HITL simulations.

Our primary focus is on validating the HMI and its suitability for operations, including information flow, structures, interactions, software ergonomics, phraseology, procedures and clarity of tasks for the end users. This therefore made the LFS an HMI assessment with lower similarity to actual operations

5.4.8 Data collection and analysis

5.4.8.1 Data and data collection methods

During the exercise qualitative data will be collected. The exercise is characterised by:

- A **pre-questionnaire** about the sociodemographic aspects of the participants, as well as preliminary question items such as openness to technology, attitudes towards automation, and acceptability of the ATMACA solution.
- **Two questionnaires** about the usability of the interface and Human Performance were administered after the simulation.
- A **post-questionnaire** to investigate the participants' perception on relevant KPAs.

Descriptive statistics will be applied to summarise the questionnaire results and to provide an overview of trends and participant responses. While processing the data invalid responses will be removed and the full anonymisation of participants to ensure data quality and confidentiality. As the analysis is entirely based on information collected during the simulation, no external or open data sources will be used. All data will be securely stored in .csv format for subsequent processing and analysis.

Further testing and quantitative validation are planned in Validation Exercise #5, where a more comprehensive dataset will be analysed.

5.4.8.2 Analysis methods

The results of the exercise will be analysed primarily using qualitative methods, complemented by descriptive statistical analysis to summarise the questionnaire responses. No inferential statistical tests are planned at this stage.

Post-processing of the data will include aggregation of responses and the removal of outliers to ensure the quality and consistency of the dataset. Data collected from the Useberry platform will be transferred to appropriate analysis software such as Excel, Matlab, or R to facilitate this process.

The analysis aims to assess the usability of the HMI and the impact of the ATMACA solution on user performance. The results will be presented using graphs and tables to provide a clear and structured overview of trends and participant feedback, supporting the evaluation of relevant KPAs.

5.4.9 Exercise planning and management

5.4.9.1 Activities

Preparatory phase

This phase is characterised by the preparation of the following materials:

- **Briefing pack:** users received a PowerPoint (ppt) briefing pack for presenting the activities.
- **Consent form:** read and signed by the participant.
- **User testing tool:** this is an online testing platform (Useberry) allowing participants to assess the HMI.
- **Prototypes:** interactive mockups of the HMIs are prepared on Figma.
- **The word script:** this is a word file containing information about what each actor should do during the exercise.
- **The questionnaires:** these are the pre-questionnaire (socio-demographic), during questionnaires (HMI/usability and HP categories) and post-questionnaire (all KPAs relevant to validation exercise #4).

Execution phase

The activity is spread to the end users through a Useberry link. On the platform, the users will go through the following activities:

- **Briefing phase:** Explanation of the activities, presentation of the ATMACA scenarios and HMI functionalities.
Execution of the simulation: the users perform the tasks assigned to them and answer to questionnaires.

Post-execution phase

This phase is characterised by the analysis of the results of the simulation. It comprehended

- **Qualitative analysis:** analysis of the results, performed in excel
- **Documenting** the results of the analysis and guidelines for HMI design and refinement.

5.4.9.2 Roles and responsibilities in the exercise

This subsection describes the roles and responsibilities of the ATMACA consortium in preparing, conducting and analysing the validation exercise.

- ESTU, THY and SAERCO manage the involvement of the end users.
- DBL prepares the validation material (interactive mockups, scenarios, set up the online platform etc,) and executes the analysis of the results.

5.4.9.3 Time planning

In the table below, month 14 is October 2025 and month 17 is January 2026.

Activity	Month			
	14	15	16	17
<i>Preparatory phase</i>				
<i>Execution phase</i>				
<i>Post-execution phase</i>				

Table 5-19: detailed exercise #4 time planning

5.4.9.4 Identified risks and mitigation actions

Risks	Impact (1-low, medium, high)	Likelihood (1-low, medium, high)	Criticality (calculated based on likelihood and impact)	Mitigation actions
The proposed HMI concepts get negative reviews from the end users.	3	1	3	(1) Adopt a HCD approach; (2) Perform a dry run of the HMI concepts and low fidelity prototypes with SMEs internal to the project (SAERCO, THY) prior to validation exercise; (3) Validate low-fidelity prototypes of the HMI concepts with end users early in the development phase.

Low participant availability (ATCos/pilots)	3	2	6	Early recruitment, flexible scheduling, use of remote usability tools
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Table 5-20: exercise #4 risks and mitigation actions

5.5 Validation exercise #5 plan: Role-Based Human-in-the-Loop HMI Simulation

5.5.1 Validation exercise description and scope

Exercise #5 evaluates the ATMACA HMIs in a high-fidelity, role-based, human-in-the-loop (HITL) environment to verify usability, workload, and situational awareness under realistic ATC conditions. It directly involves ATCos using SAERCO’s ATC simulator and pilot participants (or pseudo-pilots) interacting via the integrated CPDLC/DLCM applications.

Actors and Processes

- ATCos at tower/radar positions issuing clearances and trajectory changes via ATMACA HMI.
- Pilots/pseudo-pilots (simulated or live) responding to CPDLC messages.
- ATMACA HMI integrated with SAERCO simulator (scripts) to mirror operational workflows.

Key Validation Objectives

- Validate VO4 (HMI Effectiveness): usability, workload, situational awareness, and communication error rate.
- Partially validate VO1 (Mobility) and VO2 (Session/Context Management) by demonstrating session continuity and context sharing during HMI use.

Scenario: low to high-density traffic, mixed clearances (trajectory modifications, emergencies) to test HMI under stress.

Validation Technique: Human-in-the-loop simulation with quantitative workload and situational awareness metrics plus qualitative user feedback.

Validation Platform: SAERCO ATC simulator with ATMACA prototype HMIs (controller working position + simulated cockpit interface).

Applicable TRL 2: human factors feasibility and concept refinement prior to flight trials.

5.5.2 Stakeholder’s expectations and benefit mechanisms addressed by the exercise

Stakeholder	Involvement	Why it matters to the stakeholder
ATCos	Active participation in HITL simulation,	Directly impacts controller workload, safety and communication efficiency

	provide feedback on workload/usability	
Pilots (or pseudo-pilots)	Respond to CPDLC messages during simulation, give feedback on clarity and timeliness	Ensures cockpit usability and manages cognitive workload, reduces communication errors
ANSPs / ATC Training Centres	Provide simulator facilities and subject-matter expertise	Validate that ATMACA HMI fits operational training and deployment contexts
ATMACA Human Factors Team	Design experiments, collect/analyse data	Needs evidence to refine HMI and support SESAR KPAs for HUM and SAF

Table 5-21: stakeholders' expectations

5.5.3 Validation objectives

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #5	Exercise validation objective	Exercise success criteria
VO4 – HMI Effectiveness	HMIs rated intuitive & effective; reduced workload, reduced errors, increased situation awareness.	Fully covered	Demonstrate usability, situational awareness and workload performance of ATMACA HMI in role-based HITL	≥80% of ATCos rate usability ≥4/5; ≥15% reduction in NASA-TLX workload vs baseline; ≥20% reduction in comm errors
VO2 – Integrated Session/Context Management	Context synchronised between actors using HMI	Partially covered	Demonstrate that flight intent/trajectory data visible in controller and cockpit HMIs remain synchronised	100% context update propagation within 1s.

Table 5-22: validation objectives addressed in validation exercise #5

5.5.4 Validation scenarios

In accordance with the SIM's capabilities, the requirements specified in the OSED will be fulfilled; however, the validation of the remaining functions must be conducted through other means. To this

end, three validation scenarios will be planned for each airspace type, featuring variable workloads and incorporating a combined gate-to-gate exercise.

5.5.4.1 Reference scenario(s)

Since the baseline for workload and usability is established through predefined benchmark tasks and NASA-TLX baseline scores, this exercise does not include a separate full reference scenario. This approach is justified because the emphasis is on relative usability and workload metrics rather than on direct operational KPIs.

5.5.4.2 Solution scenario(s)

- Low to high-density TMA traffic with mixed trajectory clearances, weather deviations, and emergency message tests.
- Controller issues CPDLC messages; pilot responds via simulated cockpit HMI.
- Inject simulated network transitions to test session continuity.

5.5.5 Exercise validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
EX5-A1	Representative participants	ATCos and pilots in the study are representative of operational users	Ensures findings generalisable to future end-users	High impact
EX5-A2	Simulator fidelity	SAERCO simulator replicates realistic ATC workload and message flow	Needed to approximate real operational context	Medium impact
EX5-A3	Stable prototype	ATMACA HMI stable during sessions	Minimises confounding effects of software glitches	Medium impact

Table 5-23: validation exercise #5 assumptions

5.5.6 Limitations and impact on the level of significance

- Small participant sample (limited ATCos and pilots availability) may reduce statistical power; mitigated by repeated measures and effect size estimation.
- Simulator environment cannot replicate all field conditions (e.g. full avionics integration).
- Results are indicative of usability/workload trends rather than definitive operational performance metrics.

5.5.7 Validation exercise platform / tool and validation technique

5.5.7.1 Validation exercise platform / tool characteristics

Platform: SAERCO ATC simulator with integrated ATMACA HMI prototypes for controller and cockpit roles.

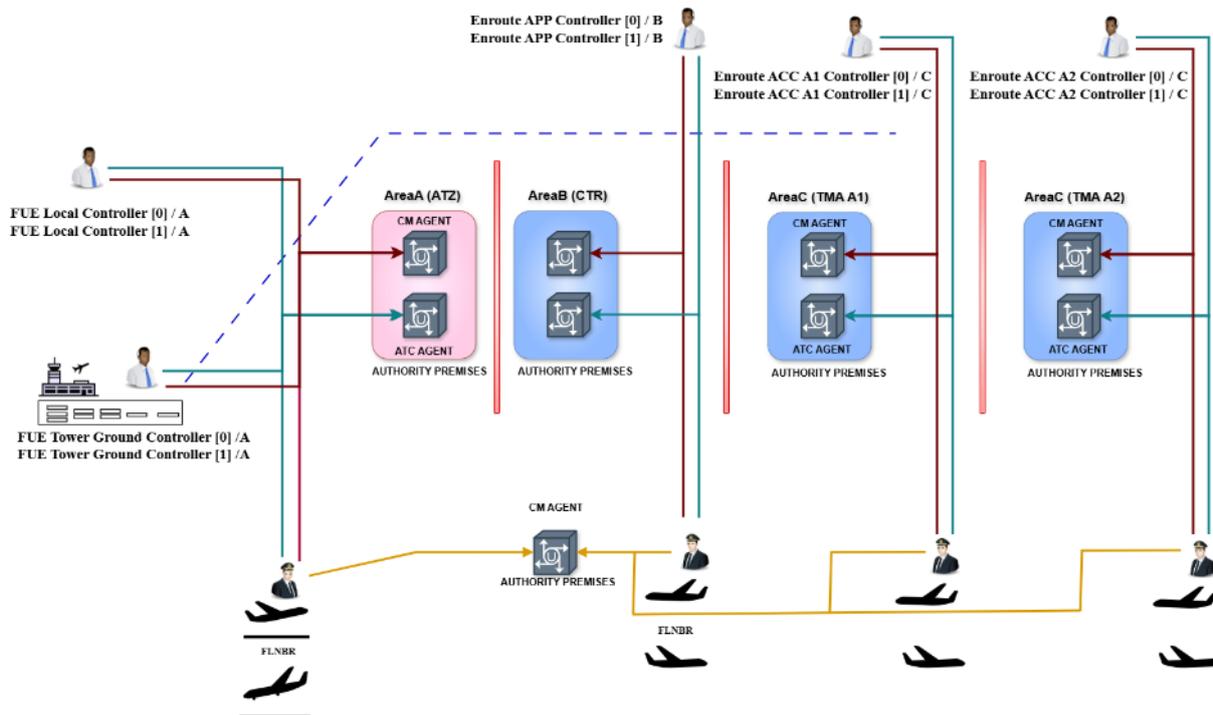


Figure 5-5: exercise #5 prototypes and validation infrastructure

5.5.7.2 Validation exercise technique

Technique: Moderated human-in-the-loop simulation, repeated measures across tasks; quantitative workload and error metrics plus qualitative debriefs.

5.5.8 Data collection and analysis

5.5.8.1 Data and data collection methods

Data types: NASA-TLX workload scores, situational awareness ratings (SAGAT), task completion time, communication error logs, user satisfaction (SUS).

Collection methods: Direct observation, automated logs, post-task questionnaires, debrief interviews.

Analysis methods

5.5.9 Exercise planning and management

5.5.9.1 Activities

This exercise will be structured into three different phases: preparation, execution and post-execution.

PREPARATORY PHASE: scenarios development, actors recruitment, scripts preparation, setting-up simulators

- Define the operational context, variables, and metrics for each scenario.
- Design the sequence of events and triggers for each scenario.
- Recruit actors.
- Translate the approved scenario designs into detailed technical scripts for the simulation platform.

EXECUTION PHASE: execution and validation of exercises, record data

- Load and technically verify all prepared scenario scripts and data sets within the simulation environment.
- Conduct pre-exercise briefings with participants before each validation session to review objectives and procedures.
- Supervise the exercise flow, providing guidance to participants and pseudo-pilots as required.
- Securely store and back up all collected raw data at the end of each validation session.

POST EXECUTION PHASE: data analysis

- Synthesise all findings to assess the fulfilment of the OSED requirements and validation objectives.

5.5.9.2 Roles and responsibilities in the exercise

- ATCos & Pilots (or pseudo-pilots): Participate in HITL simulation performing the assigned test tasks and providing feedback.
- Human Factors Team: Design test protocols, collect and analyse usability/workload and situational awareness data.
- WP Leader: Oversee all scheduling, ensures alignment with ERP and validation objectives.

5.5.9.3 Time planning

In the table below, month 18 is February 2026.

Activity	Week 1-8 of Month 18-19							
	1	2	3	4	5	6	7	8
<i>Preparatory phase</i>								
<i>Execution phase</i>								

<i>Post-execution phase</i>									
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Table 5-24: detailed exercise #5 time planning

5.5.9.4 Identified risks and mitigation actions

Risks	Impact (1-low, 2-medium, 3-high)	Likelihood (1-low, 2-medium, 3-high)	Criticality (calculated based on likelihood and impact)	Mitigation actions
Participant unavailability	3	2	High	Early scheduling, substitute pseudo-pilots
Prototype instability	2	2	Medium	Internal dry-runs before sessions
Data privacy issues	2	1	Low	Informed consent, anonymisation

Table 5-25: exercise #5 risks and mitigation actions

5.6 Validation exercise #6 plan: End-to-End ATMACA Datalink Validation Flight Trial

This section demonstrates how the final integrated ATMACA solution will be validated in an operational environment.

5.6.1 Validation exercise description and scope

Exercise #6 is the culminating step of the ATMACA ERP, aiming to validate the integrated ATMACA solution under real-world flight conditions on board a THY aircraft. It will demonstrate end-to-end datalink communication, seamless multilink mobility, and session continuity across multiple ATC nodes in an operational-like environment.

Actors and Processes

- Aircraft crew (pilots) operating a THY aircraft equipped with ATMACA protocol terminals.
- Ground-based ATC stations simulating operational ANSP environments (including cross-border handovers).
- ATMACA datalink applications (CPDLC, DLDM) running on on-board and ground systems.
- ATMACA HMIs for role-specific interactions (controller workstation, flight deck terminal).

Key Validation Objectives and Scenarios

- Validate VO2 (Session, Connection, Context Management) under real flight conditions.
- Validate aspects of VO3 (QoS and Security) by measuring latency, packet loss, authentication success.

- Provide supporting evidence for VO4 (HMI usability) under flight conditions (limited evaluation due to partial HMI integration).

Validation Platform

- A THY aircraft outfitted with ATMACA onboard terminal/EFB or dedicated unit.
- Ground-based testbeds simulating multiple ATC centres.
- Network monitoring equipment for multilink performance measurements.

Validation Technique

- Live flight trial with controlled data collection and scenario-based injection of mobility events (e.g. handover between ATC nodes).

Applicable TRL 2: proof-of-concept demonstrated in operational environment.

5.6.2 Stakeholder’s expectations and benefit mechanisms addressed by the exercise

Stakeholder	Involvement	Why it matters to the stakeholder
THY	Provide aircraft, flight crew, and operational support for live trial	Demonstrates feasibility and safety of ATMACA under actual flight conditions; potential operational and cost benefits
Pilots	Operate ATMACA terminal during flight, provide feedback on usability and reliability	Ensures cockpit usability and minimal workload increase
ATC Centres / ANSPs	Operate ground-based ATMACA nodes simulating multiple ATC sectors	Validates seamless handovers and data exchange across ANSP boundaries
ATMACA Consortium Partners	Integrate protocol, run monitoring, collect and analyse data	Provide evidence of TRL2 exit criteria and SESAR KPAs

Table 5-26: stakeholders' expectations

Expected Benefits / KPAs:

- Safety: continuous connectivity and secure communications.
- Efficiency: reduced delays in ATC clearances and handovers.
- HUM: early feedback on HMI usability under flight conditions.

5.6.3 Validation objectives

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective in exercise #6	Exercise validation objective	Exercise success criteria
VO1 – Seamless Mobility Management	Handover delay, packet loss and session continuity within aviation QoS thresholds	Fully covered	Demonstrate end-to-end seamless mobility across satellite/terrestrial/cellular links during live flight	Same as SESAR solution success criteria
VO2 – Session/Context Management	Active sessions continue uninterrupted; context synchronised	Fully covered	Validate persistence of CPDLC sessions and context updates across ATC nodes during flight	Same as SESAR solution success criteria
VO3 – Robust QoS & Security	Maintain latency/jitter/throughput thresholds; successful authentication	Partially covered (security tests limited to benign conditions)	Measure real-world latency, jitter, throughput, and authentication success during flight	Same as SESAR solution success criteria
VO4 – HMI Effectiveness HMIs rated intuitive and effective	HMIs rated intuitive and effective	Partially covered (reduced scope – no full HMI integration)	Gather preliminary feedback from pilots on ATMACA cockpit terminal usability	Same as SESAR solution success criteria

Table 5-27: validation objectives addressed in validation exercise #6

5.6.4 Validation scenarios

5.6.4.1 Reference scenario(s)

Not applicable: this is a proof-of-concept flight trial where the baseline is collected from current CPDLC/VDL2 performance metrics; the main aim is to demonstrate feasibility rather than compare to an active reference flight.

5.6.4.2 Solution scenario(s)

- Live THY flight across multiple ATC sectors, simulating handover between ground nodes (with different network types).
- Inject controlled events (e.g. network switchovers, weather deviations) to test resilience.

5.6.5 Exercise validation assumptions

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
EX6-A1	Aircraft availability	THY aircraft equipped with ATMACA terminal available for trial flight	Essential for live validation	High
EX6-A2	Regulatory clearance	Necessary permissions and safety approvals obtained for test flight	Ensures compliance and safety	High
EX6-A3	Network coverage	Sufficient satellite/terrestrial/cellular coverage along flight path	Required for testing multilink mobility	Medium
EX6-A4	Prototype stability	ATMACA software stable during flight	Prevents confounding results	Medium

Table 5-28: validation exercise #6 assumptions

5.6.6 Limitations and impact on the level of significance

- Single flight trial limits statistical significance: results will be indicative but not generalisable to all traffic or weather conditions.
- HMI evaluation limited (no full integration in cockpit); focus on datalink protocol performance.
- Regulatory and logistical constraints may restrict flight path or scenario complexity.

5.6.7 Validation exercise platform / tool and validation technique

5.6.7.1 Validation exercise platform / tool characteristics

Platform: THY aircraft equipped with ATMACA terminal/EFB; ground-based multi-node ATC testbeds; network performance monitoring tools.

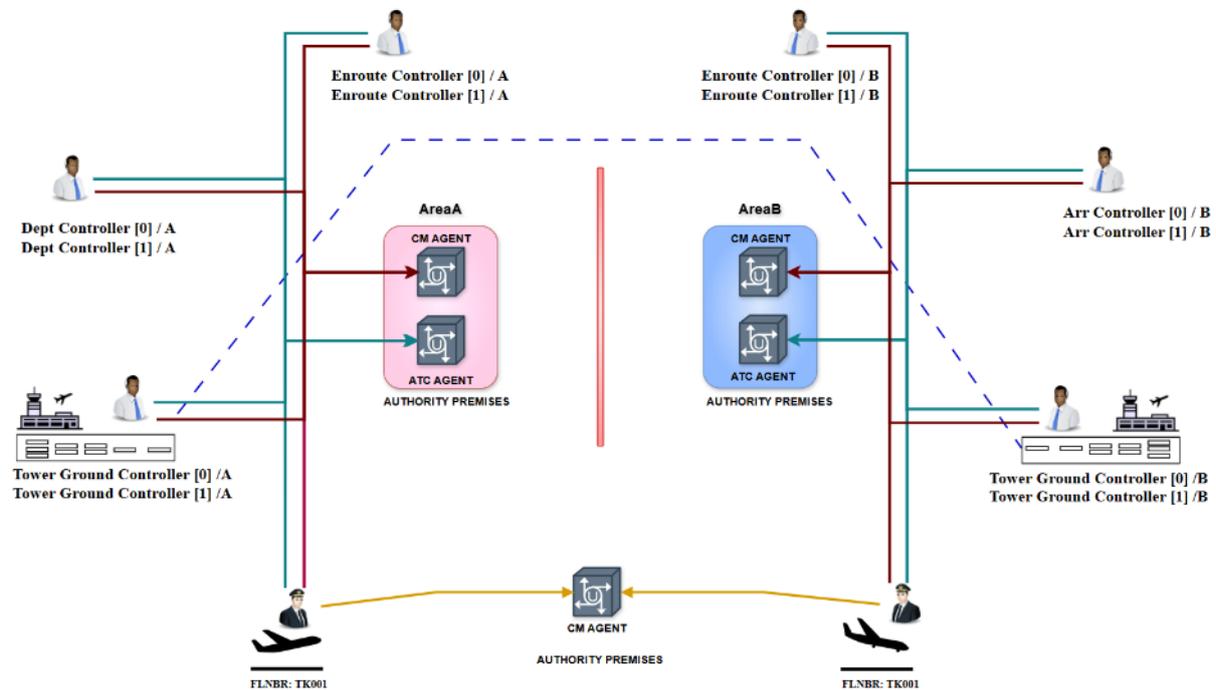


Figure 5-6: exercise #6 prototypes and validation

5.6.7.2 Validation exercise technique

Technique: Live flight trial with pre-defined test script and network events; quantitative measurements of protocol performance plus qualitative pilot feedback.

5.6.8 Data collection and analysis

5.6.8.1 Data and data collection methods

Data Types: Handover delay logs, packet loss, latency, jitter, throughput, session continuity, authentication success; pilot and ATCos usability questionnaire.

Collection Methods: Automated logging on onboard and ground systems; network sniffers; post-flight debrief forms.

5.6.8.2 Analysis methods

Analysis: Compare measured KPIs to aviation QoS thresholds; descriptive stats and time-series plots; thematic analysis of pilot feedback.

Iterations: At least one full flight trial with potential follow-up ground-based emulation to reproduce anomalies.

5.6.9 Exercise planning and management

5.6.9.1 Activities

- Preparatory (Months 15–18): Finalise ATMACA integration on THY aircraft; obtain regulatory clearances; plan flight path; set up ground nodes and monitoring Test plan, safety case, regulatory approvals
- Execution (Month 19): Conduct flight trial, inject scenarios, collect data Raw logs, pilot questionnaire, ground observer notes
- Post-Execution (Months 20–21): Analyse data, produce validation report, identify refinements Flight trial report, KPI analysis, recommendations

5.6.9.2 Roles and responsibilities in the exercise

- THY Flight Operations: provide aircraft and crew.
- ATMACA Technical Team: integrate and monitor ATMACA systems onboard and on ground.
- Validation Coordinator: oversee safety, scheduling, and data compliance.
- ANSP/ATC Nodes: simulate multi-ANSP environment on ground.

5.6.9.3 Time planning

In the table below, month 20 is April 2026. Multiple trials might be arranged based on the results.

Activity		Week 1-4 in Month 20			
		1	2	3	4
<i>Preparatory phase</i>					
<i>Execution phase</i>					
<i>Post-execution phase</i>					

Table 5-29: detailed exercise #6 time planning

5.6.9.4 Identified risks and mitigation actions

Risks	Impact (1-low, 2- medium, 3- high)	Likelihood (1-low, 2- medium, 3- high)	Criticality (calculated based on likelihood and impact)	Mitigation actions
Regulatory delays	3	2	High	Begin approval process early, coordinate with aviation authorities
Network coverage gaps	2	2	Medium	Select route with robust coverage, supplement with satellite fallback
Prototype malfunction in flight	3	1	Medium	Conduct extensive ground tests and emulations before flight

Table 5-30: exercise #6 risks and mitigation actions

6 References

6.1 Applicable documents

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

Content integration

- [1] Common Taxonomy, ed. 01.00, 07/02/2023
- [2] Content Integration – Executive Overview, ed. 00.01, 16/02/2023

Content development

- [3] SESAR operational concept document 2023, 09/11/2023

Validation

- [4] DES HE requirements and validation / demonstration guidelines (3.0).

System engineering

- [5] SESAR 2020 Requirements and V&V guidelines.

Safety

- [6] SESAR Expanded Safety Reference Material (E-SRM) Core Document, Edition 1.0 20221020 (1.0)

Human performance

- [7] SESAR Human Performance Assessment Process TRLO-TRL8

Environment assessment

- [8] SESAR, Environment Reference Material, alias: “Environmental impact assessment as part of the global SESAR validation”, 2014.
- [9] ICAO Doc. 10031, “Guidance on Environmental Assessment of Proposed Air Traffic Management Operational Changes.” 2014.

Security

- [10] 16.06.02 D103 SESAR Security Ref Material Level.

Project and programme management

- [11] 101167070 ATMACA Grant Agreement, 25/06/2024
- [12] SESAR 3 JU Project Handbook – Programme Execution Framework

[13] SESAR 3 JU, European ATM Master Plan, 2025 edition

6.2 Reference documents

- [14] ATMACA-SESAR, Deliverable D1.1, Project Management Plan, 2024
- [15] ATMACA-SESAR, Deliverable D1.5, TRL Monitoring Report, 2025
- [16] ATMACA-SESAR, Deliverable D2.1, Review of Current and Future ATM Communication Network, 2024
- [17] ATMACA-SESAR, Deliverable D2.2, Functional Requirements Document (FRD), 2025
- [18] ATMACA-SESAR, Deliverable D2.3, Operational Service and Environment Definition (OSD), 2025
- [19] ATMACA-SESAR, Deliverable D3.1, Protocol Design Plan, 2025.
- [20] ATMACA-SESAR, Deliverable D3.2, Protocol Development Technical Diagram, 2025.
- [21] ATMACA-SESAR, Deliverable D3.3, Protocol Testing Report, 2025.
- [22] ATMACA-SESAR, Deliverable D4.1, GRO Application Report, 2025.
- [23] ATMACA-SESAR, Deliverable D4.2, CPDLC Application Design Document, 2025.
- [24] ATMACA-SESAR, Deliverable D4.3, DLIC Application Design Document, 2025.
- [25] ATMACA-SESAR, Deliverable D5.1, Determination of HMI Requirement, 2025.
- [26] S. A. Baset, V. K. Gurbani, A.B. Johnston, H. Kaplan, B. Rosen, J. D. Rosenberg, "The Session Initiation Protocol (SIP): an evolutionary study," in *Journal of Communications*, 7(2), pp. 89-105, 2012. <https://doi.org/10.4304/jcm.7.2.89-105>
- [27] Commission Regulation (EU) 2015/340, 20.02.2015
- [28] EUROCONTROL, SESAR DOD Lexicon - Glossary of Terms and Definitions, EUROCONTROL, D2.2-049, 2014 [Online]. Available: <https://www.eurocontrol.int/sites/default/files/2022-10/E3-WP2-D2.2-049-TEC-V2.00-lexicon.pdf>
- [29] EUROCAE, *ED-120: Safety and performance requirements standard for air traffic data link services in continental airspace (Continental SPR Standard)*, EUROCAE, 2004.
- [30] V. Fajardo, J. Arkko, J. Loughney, and G. Zorn, "Diameter Base Protocol," RFC 6733, Oct. 2012
- [31] ICAO Annex 11, Air Traffic Services, 15th edition.
- [32] ICAO Doc 4444, Air Traffic Management, 6th edition.

- [33] ICAO Doc 9880, Manual on Detailed Technical Specifications for the Aeronautical Telecommunication Network (ATN) using ISO/OSI Standards and Protocols, First Edition – 2010.
- [34] ICAO Doc 9896, Manual for the ATN using IPS Standards and Protocols, 1st edition.
- [35] ICAO 10037 - Global Operational Data Link (GOLD) Manual - First Edition
- [36] ICAO Doc 10039 (Manual on System Wide Information Management (SWIM) Concept)
- [37] ICAO PANS ATM (Procedures for Air Navigation Services Air Traffic Management).
- [38] RTCA, DO-290: *Safety and performance requirements standard for air traffic data link services in continental airspace (Continental SPR Standard)*, RTCA, 2004.
- [39] SESAR Solution, SESAR 2020 PJ.14-W2-77 “FCI Services”
- [40] SESAR Solution, #46 “Initial system-wide information management (SWIM) technology solution”
- [41] J. Rosenberg, H. Schulzrinne, G. Camarillo, A. Johnston, J. Peterson, R. Sparks, M. Handley, and E. Schooler, "SIP: Session Initiation Protocol," RFC 3261, Jun. 2002
- [42] H. Schulzrinne and E. Wedlund, Application-layer mobility using SIP. *Mobile Computing and Communications Review*, 4(3), pp. 47–57, (2000)
- [43] J. Wozniak, Mobility management solutions for current IP and future networks. *Telecommun Syst*, 61, pp. 257–275, (2016). <https://doi.org/10.1007/s11235-015-9999-3>