SESAR 3 ER 1 Green-GEAR – D4.7 – ECO-EVAL – Separation Minima

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Abstract

Green-GEAR aims to enable and incentivise optimum green trajectories and airspace use through new ATM procedures; it develops three new SESAR Solutions to this end.

The "Separation Minima" Solution 0407 assesses the feasibility of reducing the vertical separation minima to 500 ft in upwards-extended Reduced Vertical Separation Minima (RVSM) airspace with the use of improved altitude keeping expected with GNSS altimetry, also named the RVSM 2 concept. This report contains the cost-benefit analysis of potential benefit and impact mechanisms for the RVSM 2 concept at TRL2, covering the period from 2026 to 2050.

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The beneficiaries/consortium confirm(s) the correct application of the Grant Agreement, which includes data protection provisions, and compliance with GDPR or the applicable legal framework with an equivalent level of protection, in the frame of the Action. In particular, beneficiaries/consortium confirm(s) to be up to date with their consent management system.

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Green-GEAR

GREEN OPERATIONS WITH GEOMETRIC ALTITUDE, ADVANCED SEPARATION & ROUTE CHARGING SOLUTIONS

Green-GEAR

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1 Executive summary

This document provides the economic evaluation (ECO-EVAL) related to the ECAC level deployment of SESAR Solution 0407 "Separation Minima" that has been matured through validation activities with a target of TRL 2. The ECO-EVAL covers the period from 2026 to 2050.

The "Separation Minima" activity generally aims at reducing CO_2 emissions and increasing capacity by further reducing separation minima in en-route airspace, enabled by the use of geometric altimetry, while keeping the level of safety of operations at least as it is today. The scope of the Solution has been limited to the investigation of the potential feasibility of a reduction of minimum separation to 500 ft in upper airspace between FL 290 and FL 600 (Reduced Vertical Separation Minima 2, "RVSM 2").

The introduction of the predecessor RVSM has taken 18 years. We expect a comparable timeframe for RVSM 2, allowing also for a kind of "shadow mode" period where classical rules are still applied but monitoring takes place to ensure that specifications for altitude keeping could be met in practice. For these reasons, the estimated start of deployment (SOD) is relatively late: the year 2040.

The safety studies, namely collision and wake turbulence risk, required parameters that are dependent on the operations and traffic mixes in the investigated airspace. For this development the ICAO EUR region was used as reference airspace.

The expected key benefits are capacity and environment, with safety not negatively affected, from providing more usable flight levels and consequently finer granularity of the usable altitudes, allowing aircraft to fly closer to their optimal cruise altitude. It was shown that the reduction of vertical separation could be feasible from a collision risk point of view when improving the specifications for several systems, while the wake vortex risk would need to be mitigated by a new safety net, airborne or ground-based, and/or procedural adaptations. Indications for capacity increase and improved operational and environmental efficiency are given. A robust quantification would require a fast-time traffic simulation at ECAC level with a sufficient degree of realism, which was beyond the scope of the present analysis.

Major cost drivers have been identified for all involved stakeholders, which are mainly ANSPs, airspace users in RVSM airspace and aircraft/equipment manufacturers. As the solution contains functions that are not yet attributed to systems or actors, such as a wake vortex warning tool, and procedures that are not yet developed, such as the fall-back to barometric altimetry for single or all aircraft, cost attributions are not final.

The cost assessment and parts of the benefit assessment could only be performed in a qualitative manner, partially due to the pending development of necessary functions and procedures, so that no recommendations can be made towards a deployment of the solution from the cost-benefit perspective. Further research is required to conclude whether the solution is viable not only from a technical perspective, but also from the cost benefit perspective.

2 Introduction

2.1 Purpose of the document

This document defines the economic evaluation (ECO-EVAL) related to the deployment of SESAR Solution 0407, "Separation Minima" that has been matured through validation activities in Green-GEAR with a target of TRL 2.

This Solution generally aims at reducing CO_2 emissions and increase capacity by further reducing separation minima in en-route airspace, enabled by the use of geometric altimetry, while keeping the level of safety of operations at least as it is today. The reduction of separation includes aircraft currently in service, zero emissions aircraft and other new entrants, such as Unmanned Aircraft Systems (UAS) and High-Altitude Operations (HAO) aircraft. In view of available resources, the scope of the Solution has been limited to the investigation of the potential feasibility of a reduction of minimum separation to 500 ft in upper airspace between FL 290 and FL 600 ("RVSM 2").

In accordance with the OSED [32], the ECO-EVAL considers deployment for all airspace users in a given RVSM 2 airspace, i.e. there is no concurrent use of barometric and geometric altitude references. This is ensured through appropriate access rules for the RVSM 2 airspace (as is the case analogously for RVSM airspace today).

The expected key benefits are capacity and environment, with safety not negatively affected, from providing more usable flight levels and consequently finer granularity of the usable altitudes, allowing aircraft to fly closer to their optimal cruise altitude. The use of geometrical altimetry is an enabler for the integration of unconventional air vehicle configurations as well as high-altitude operations (HAO) that have difficulties with precise barometric altimetry.

In accordance with the project plan, safety has been quantified [33] as a sine qua non for the concept while the other KPIs are only addressed quantitatively. These assessments are explained in the present document. At the current low TRL, the assessment of additional costs also could only be performed in a qualitative manner as no detailed quantitative numbers have been available for all involved stakeholders. However, his ECO-EVAL identifies the major cost drivers for all involved stakeholders, which are mainly ANSPs, airspace users in RVSM airspace and aircraft/equipment manufacturers.

The deployment of the Separation Minima solution not only concerns the en-route airspace design but is also connected to the development of surveillance and aircraft capabilities. Also the use of geometric altimetry meets many open questions today concerning particularly integrity and availability of the signals. For this reason, the deployment time horizon is relatively long with a start of deployment date of 2040. The required development and certification effort for geometric altimetry as a prerequisite, the update of safety nets such as ACAS and STCA and in general the collection of supporting data for the pre-implementation safety case will probably take at least that time. This estimation is in line with the observation that the RVSM introduction into operations took 18 years from the first studies.

For future assessment of the solution towards higher TRLs, it is recommended to enhance the economic evaluation with a quantitative assessment of the costs of the related stakeholders. This would in the end be required to finally investigate whether the solution is not only technically feasible but also economically viable.

2.2 Scope

The ”Separation Minima” activity generally aims at reducing CO_2 emissions and increasing capacity by further reducing separation minima at various phases of flight, enabled by the use of geometric altimetry, while keeping the level of safety of operations at least as it is today. The scope of the Solution has been limited to the investigation of the potential feasibility of a reduction of minimum separation to 500 ft in upper airspace between FL 290 and FL 600 (“RVSM 2”).

The safety studies, namely collision and wake turbulence risk, required parameters that are dependent on the operations and traffic mixes in the investigated airspace. For this development the ICAO EUR region was used as test airspace, and hence the deployment of the Solution is assumed to take place in the EUR region upper airspace, in line with SESAR expectations. It is conceivable that, in order to ensure sufficient safety regarding wake vortex encounters, the application of the new rules may depend on conditions such as the weather situation or the aircraft pairing. Generally, however, they are intended to be deployed throughout the entire EUR region airspace.

The reduction of separation includes all airspace users in RVSM 2 airspace, i.e. aircraft currently in service, zero emissions aircraft and other new entrants, such as Unmanned Aircraft Systems (UAS) and High-Altitude Operations (HAO) aircraft. The vertical navigation according to geometric altimetry means that corresponding capabilities need to be developed by aircraft / equipment manufacturers, installed and maintained by the airspace users and finally employed by the airspace users for vertical navigation and the ANSPs as basis for air traffic control.

There are a number of assumptions based around future aircraft navigation system capabilities and both air and ground conformance monitoring tools. There is also an assumption that the operation can revert to barometric altitude as a fall-back mode, requiring appropriate training for controllers and pilots alike.

The cost drivers for the necessary implementation efforts are identified in this document. The reference time period for the analysis is 2026-2050, in line with the Common Assumptions document [5] that gives 2026 as start year of the ECO-EVAL and 2050 as end year of the ECO-EVAL.

2.3 Intended readership

This document is aimed at the following stakeholders:

- All Green GEAR consortium members who are contributing directly to the solution research or contributing to related Solutions or work packages in the project (Airbus, DLR, EUROCONTROL, NATS, NLR, UNITS, UoW)
- Relevant SESAR projects, especially those form the Green Deal flagship
- Members from PEARL
- SJU Program representatives, as the owner and final approver of this document.

2.4 Background

Direct precursors (previous ECO-EVALs/CBAs covering the SESAR solution or parts) are not available as this SESAR Solution is developed from scratch. However, the ECO-EVAL for Solution 0406, Vertical Navigation using Geometric Altimetry [27], has been consulted as far as the introduction of GNSS-based altimetry is considered.

Concerning activities that have an impact on past and future *technical* activities the following existing and planned research on the reduction of separation minima has been analysed, including work done and foreseen for SESAR, ICAO, EASA, European Commission and EUROCONTROL.

Worldwide aircraft separation standards are laid down in ICAO Doc 4444 (Procedures for Air Traffic Management) [40], ICAO Annex 2 (Rules of the Air) [41] and ICAO Annex 11 (Air Traffic Services) [42]. These standards ensure safe separation from the ground, from other aircraft and from protected airspace:

- Vertical separation is achieved by requiring aircraft to use a prescribed altimeter pressure setting within designated airspace, and to operate at different altitude or flight levels;
- Lateral separation is achieved by reference to different geographical locations (position reports) or by requiring aircraft to fly on specified tracks separated depending on type of navigation aid;
- Longitudinal separation for aircraft on the same track is applied through speed control/ instructions so that the spacing between aircraft is never less than a specified minimum when passing over a specific point in the airspace.

Wake turbulence separation standards are applied in various flight phases to ensure that following aircraft are not endangered by effects of wake vortex turbulence generated by a preceding aircraft. Aircraft are categorised according to their Maximum Take-Off Mass (MTOM) and minimum separation times or distances so that aircraft following a higher MTOM aircraft are given a greater minimum spacing.

EUROCONTROL and NLR are responsible for pre-implementation [43][44] and post-implementation safety studies of RVSM in ICAO's European and Africa Indian Ocean Regions respectively. These studies analyse data on the height keeping performance of aircraft to ensure that the risk of collision between aircraft is sufficiently low and properly mitigated. Collision risk models and tools endorsed by the ICAO Separation and Airspace Safety Panel (SASP) [37][38][39] are used by EUROCONTROL and NLR.

Reduction of wake turbulence separation standards has been studied extensively by consortium partners (EUROCONTROL, Airbus, NATS, DLR, NLR) in European Commission research for the last 20 years (e.g. S-Wake, ATC-Wake, I-Wake, FAR-Wake, C-Wake, CREDOS) and by SESAR/EUROCONTROL (Time Based Separation, RECAT-EU, WIDAO, R-Wake). Under contract to EASA, NLR has reviewed the safety cases that were brought forward to the ICAO Wake Turbulence Study Group for approval.

While many opportunities exist for further reduced separation minima, Green-GEAR has focussed on Reduced Vertical Separation Minima to 500 ft (RVSM 2) in a geometric altimetry environment. The aim has been to assess whether operations would be still acceptably safe with this change only, or possible advanced modes of separation (e.g. dynamic and/or geometry-dependent horizontal separation) and/or additional safety nets would be needed to ensure the safety of operation. More detailed specification of these modifications beyond the possible identification of their necessity is outside of the scope of the project.

Table 1 below lists past projects on which the consortium built the R&I work.

Project name	Expertise
ICAO AFI RVSM	Implementation of 1000 ft Reduced Vertical Separation Minimum (RVSM) in the Africa - India Ocean (AFI) Region, using collision risk models (NLR)
Time Based Separation (TBS)	New operation for reducing separation between aircraft by time during strong headwind conditions, instead of distance, developed by EUROCONTROL and NATS, and deployed at Heathrow.
RECAT	Wake Turbulence Recategorisation (RECAT) is a decrease in wake turbulence separation standards between certain aircraft pairs to improve airport capacity. EUROCONTROL, NATS, NLR involved.
USEPE (SESAR)	Exploring potential separation methods to ensure the safety of UAS operations in urban environments (enabled by U-Space), DLR.
S-Wake, ATC-Wake, CREDOS	EC research projects at TRL1 to TRL4 dedicated to the safety analysis and development of concepts for reduced separation in the airport environment. NLR and EUROCONTROL coordinated the projects, with participation by DLR.

Table 1. Green-GEAR partners' expertise in relevant past international projects.

2.5 Structure of the document

This ECO-EVAL Document is structured as follows:

- Chapter 1 gives an executive summary of the ECO-EVAL and provides a summary of the key information and elements contained in the document.
- Chapter 2 describes the purpose, scope, intended readership, background and structure of the document. It also contains a glossary of terms and a list of acronyms used in the ECO-EVAL.
- Chapter 3 describes the objectives and scope of the ECO-EVAL.
- Chapter 4 summarises the benefits as outlined in the ERR.
- Chapter 5 describes the results of the cost assessment in terms of high level (qualitative) costs for the different stakeholders stemming from implementing the SESAR solution.

The following chapters are present but empty in the current document at TRL2; they will be filled as required in further studies of the Solution aiming at TRL4:

- Chapter 6 will describe the model used for the cost-benefit analysis (CBA).
- Chapter 7 will detail the CBA results.
- Chapter 8 will contain the sensitivity and risk analysis.

Finally, the concluding material is already present in this initial version of the document:

- Chapter 9 gives recommendations next steps in the context of the ECO-EVAL.
- Chapter 10 lists the references.

2.6 Glossary of terms

Term	Definition	Source of the definition
ECO-EVAL reference scenario	The scenario against which the solution is compared, i.e. the situation without the proposed SESAR solution (but including other improvements which have been implemented in the meantime).	DES transversal CBA team
ECO-EVAL solution scenario	The scenario with the proposed SESAR solution and other improvements which have been implemented in the meantime.	DES transversal CBA team
Economic evaluation (ECO-EVAL)	The economic evaluation assesses the potential benefits that an innovative idea or application under analysis by an exploratory research project could provide against an initial high-level estimation of the costs that it may imply.	SESAR 3 JU Project Handbook – Programme Execution Framework, edition 01.00, 11 April 2022
Implementation cost	All costs related to the acquisition and implementation of the SESAR solution.	SESAR 16.06.06_D26_03 Methods to Assess Cost and Benefits for CBAs, ed. 00.02.02
Investment cost	The investment cost covers the pre-implementation costs (e.g., feasibility studies) and the implementation costs (e.g., system integration). Note that the pre-implementation costs shall not consider the SESAR R&I costs.	DES transversal CBA team
Operating cost	All costs related to the change in daily operations that is brought about by the SESAR solution.	SESAR 16.06.06_D26_03 Methods to Assess Cost and Benefits for CBAs, ed. 00.02.02
Pre-implementation cost	All costs that need to be used up to define the needs, to develop solutions, and to decide which solution best serves the needs. Note that the SESAR R&I costs shall not be included as costs in any DES CBA/ECO-EVAL.	SESAR 16.06.06_D26_03 Methods to Assess Cost and Benefits for CBAs, ed. 00.02.02
Geometric Altitude / Geo Alt	Mode of altimetry where altitude is determined relative to a fixed reference system such as WGS 84.	Project definition (WP3 / Solution 0406)

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Term	Definition	Source of the definition
RVSM 2	The concept studied in WP4, where vertical separation minima are set to 500 ft in en-route airspace (FL290 – FL600 inclusive), where altitude is determined through geometric altimetry, and separation is managed through geometric altitudes.	Project definition
Target level of Safety	The level of risk considered to be the maximum tolerable value for a safe system.	ICAO
Climate Hotspot	A volume of airspace where the atmospheric conditions are such that flying through it creates much higher climate impact than in the other areas.	Project Definition (WP5 / Solution 0408)

Table 2: glossary of terms

2.7 List of acronyms

Term	Definition
AAD	Assigned Altitude Deviation
ACAS	Airborne Collision Avoidance System
AFI	Africa / India Ocean (ICAO Region)
AIM	Aeronautical Information Management
AIS	Aeronautical Information Services
ANSP	Air Navigation Service Provider
ASAP	Aircraft Separation Assurance Programme
ASE	Altimetry System Error
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer, Air Traffic Controller
AUS	Airspace Utilisation Service
BIM	Benefit impact mechanism
CAP	Capacity
CBA	Cost benefit analysis
CISP	Common information service provider

Term	Definition
CWP	Controller Working Position
DES	Digital European Sky
DIAL	Der individuelle und automatisierte Luftverkehr (The individual and automated air traffic) [name of DLR internal project]
DLR	Deutsches Institut für Luft- und Raumfahrt, German Aerospace Center
DSD	Digital Sky Demonstrator
EASA	European Union Aviation Safety Agency
ECAC	European Civil Aviation Conference
ECO-EVAL	Economic evaluation
EFB	Electronic Flight Bag
ENV	CO2 emissions per flight
ERR	Exploratory Research Report
EUR	Europe
FEFF	Fuel efficiency
FL	Flight Level
FOC	Final operating capability
FRD	Functional requirements document
FTE	Flight Technical Error
GNSS	Global Navigation Satellite System
HAOHigh Altitude Operations Aircraft	
ICAO	International Civil Aviation Organization
IFR	Instrumental flight rules
IOC	Initial operating capability
KPI	Key performance indicator
MTMO	Maximum Take-Off Mass
NATS	National Air Traffic Services (UK)

Term	Definition
NLR	Royal Nationaal Lucht- en Ruimtevaartlaboratorium (National aerospace laboratory (Netherlands))
NWP	Numeric Weather Prediction
OCD	Operation Concept Document
OSED	Operational service and environment description
PEARL	Performance Estimation, Assessment, Reporting and Simulation
PI	Performance indicator
RAIM	Receiver Autonomous Integrity Monitoring
RECAT	Re-categorisation of Wake Turbulence Separation Minima
RECAT-EU	European separation standard for aircraft wake turbulence
RMA	Regional Monitoring Agency
RSVM	Reduced Vertical Separation Minimum
SAF	Sustainable Aviation Fuels
SASP	Separation and Airspace Safety Panel
SESAR	Single European sky ATM research
SJU	SESAR Joint Undertaking
SM	Separation Minima
SOD	Start of deployment date
STCA	Short-Term Conflict Alert
TBO	Trajectory-based Operations
TBS	Time-Based Separation
TLS	Target Level of Safety
TMA	Terminal manoeuvring area
TRA	Required Time for Arrival
TRL	Technology readiness level
TVE	Total Vertical Error
UNITS	Università degli studi di Trieste

Term	Definition
UoW	University of Westminster
UAS	Unmanned aerial system
USSP	U-space service provider
VFR	Visual flight rules
WIDAO	Wake Independent Departure & Arrival Operations
WTRA	Wake Turbulence Risk Analysis

Table 3: list of acronyms

3 Objectives and scope of the ECO-EVAL

3.1 Problem addressed by the SESAR solution

Aviation is a fast-growing industry, while impacting the environment. This rises significant challenges for the future. First, the growth of the industry should result in a smaller impact on the environment, meaning an efficient operation is key. Research into efficient operations and fuel savings are of major importance to reduce the environmental footprint of aviation.

Second, more aircraft make use of the same blocks of airspace. Therefore, the airspace capacity could become too small since aircraft have to be vertically separated appropriately for a safe operation.

Third, aircraft determine their altitude using barometric altimetry. This means that altitude estimates are made using air pressure. Due to the decreasing pressure with altitude, the accuracy of the altitude estimates reduces with altitude. This makes it challenging to reduce the vertical separation minima at high altitudes.

3.2 SESAR solution description

Traditionally vertical separation minima have been set to 1000 ft up to FL290. Because of the decreasing accuracy of barometric altimeters with increasing height, the separation minima from FL290 to FL410 were set at 2000 ft. In order to increase capacity above FL290 the Reduced Vertical Separation Minima (RVSM) programme was introduced, resulting in the reduction to 1000 ft minimal vertical separation between FL290 and FL410. [35]

In the current operation commercial, military and general aviation mainly rely on barometric measurements for determining the altitude of the aircraft. Even though aircraft are equipped with GNSS receivers and broadcast both geometric and barometric altitudes for surveillance purposes, navigation is usually done using barometric altimetry. [35]

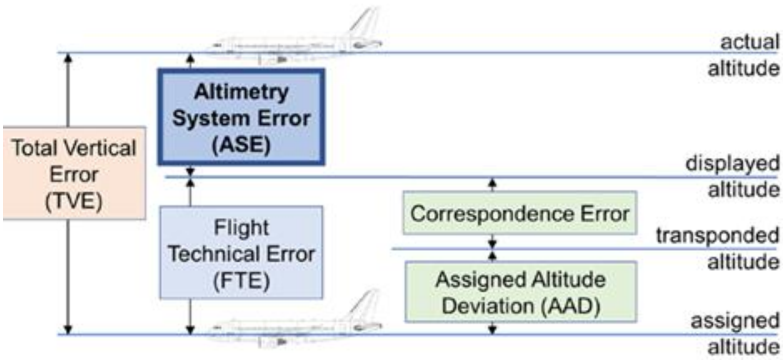

Figure 1: vertical errors definition (drawn after ICAO Doc 9574).

Geometric altimetry can achieve greater accuracy (i.e. lower Altimetry System Error (ASE), see Figure 1) at high altitudes than barometric altimetry, as it is nearly insensitive to local weather and is not impacted by the low atmospheric pressure. Green-GEAR's Separation Minima solution therefore investigates whether the use of geometric altimetry would allow a reduction of the SM from the

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current 1000 ft in RVSM airspace (FL290 – FL410), or 2000 ft (FL410 – FL600) to 500 ft. As the added altimetry system errors of two passing aircraft are assumed to be less than 500 ft in the current standard, a reduction by this margin is not straightforward even in the hypothetical case of perfect altimetry. [35]

The main goals of the Green GEAR project (Green Geometric altitude, Advanced separation and Route charging) are to enable optimum green trajectories, accelerate decarbonisation and decrease the climate impact on flights. The present investigates Separation Minima (SM) aiming to reduce CO_2 emissions and increase capacity by further reducing separation minima at various phases of flight, while keeping the level of safety of operations at least as it is today. The reduction of separation includes aircraft currently in service, zero emissions aircraft and other new entrants, such as Unmanned Aircraft Systems (UAS) and High-Altitude Operations (HAO) aircraft [20][35]. This RVSM 2 concept results in an airspace as shown in Figure 2.

A prerequisite is flight with geometric altimetry (i.e. the determination of altitude by GNSS measurements), instead of barometric altimetry as used in current operations.

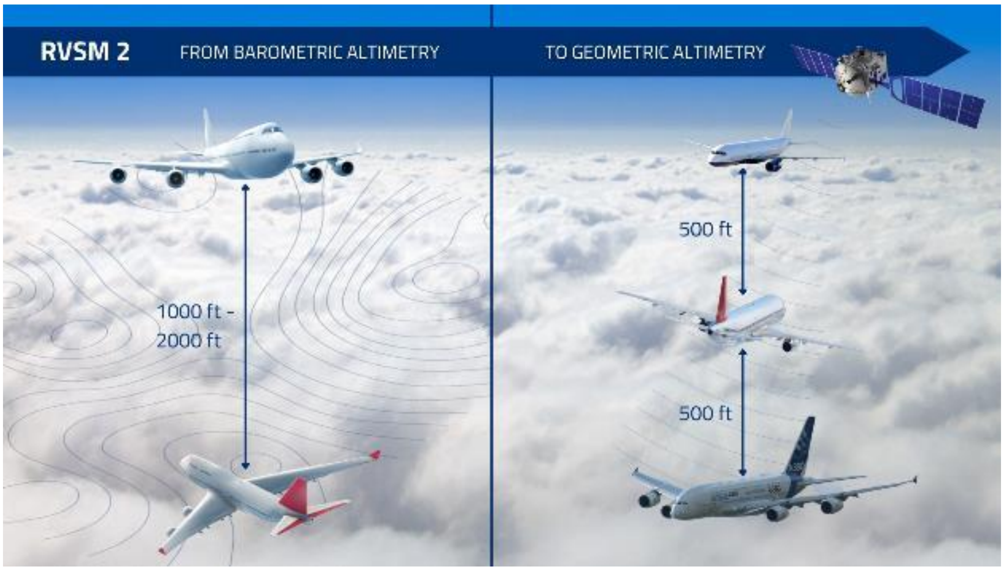

Figure 2: artist's impression of current operations and the RVSM 2 concept.

The present Solution addresses upper airspace only, but the use of geometric- instead of barometric altimetry is also relevant for air vehicles whose configuration complicates the measurement of static air pressure, such as many types of drones. Furthermore, HAO aircraft could benefit due to the decreasing pressure gradient with increasing height: the same absolute error in measuring the static air pressure translates into a larger vertical error with increasing height. It is therefore investigated whether geometric altimetry could allow extending RVSM airspace upwards up to FL600. [35]

As the technical risk of loss of separation is dependent on the characteristics of the traffic, which varies by airspace, results of an investigation would not be universally applicable but dependent on the region chosen (see RVSM manual). Green-GEAR therefore addresses European (EUR) region en-route airspace (FL290 – FL600). [35]

3.2.1 SESAR solution interdependencies

There are some interdependencies between the developed “Separation Minima” solution 0407 and other SESAR solutions. Mainly, these interdependencies concern the “Geometric Altimetry” solution 0406 and the “Green Route Charging” solution 0408 from Green-GEAR.

Interdependency towards the Vertical Guidance using Geometric Altimetry solution (SESAR Solution 0406)

Shared Objectives: Both solutions aim to minimise the environmental impact of flights by enabling more efficient flight trajectories through the use of geometric altimetry, which thus is an enabler for both. The Separation Minima solution allows aircraft to fly closer to their optimal altitude through provision of additional usable flight levels. Those stem from the reduction of the vertical separation minima which in turn require a highly accurate measurement of the altitude, which does not appear feasible to the necessary degree with barometric altimetry. Geometric altimetry is considered a possible means to provide the required measurement accuracy. The Geometric Altimetry solution draws its environmental benefits from the higher predictability of a flight path in the TMA that is defined with geometric constraints.

Complementary Approaches: The use of geometric altimetry in cruise, which would be a prerequisite for the reduction of vertical separation in this stage of flight, is not part of the Geometric Altimetry solution itself because of the evaluated drawbacks in aircraft operations and performance when using Geometric Altimetry in cruise *without further changes*. In a holistic view, however, a reduction of vertical separation minima enabled through use of geometric altimetry, as investigated in the present solution, might bring the necessary benefits. Besides finer granularity of available flight levels, higher capacity would mitigate the negative effects of detours / flight level changes to avoid climate hotspots, convective weather or congestions.

Joint requirements: Both solutions use GNSS as altimetry source and have the requirement that sufficient integrity and availability of the signals is achieved. The accuracy requirements are more stringent for the present Separation Minima solution though, whereas the Geometric Altimetry solution can operate with the status quo. Both solutions require a high reliability for the detection of jamming and spoofing and would initiate fall-back procedures using barometric altimetry in that case. As the present Separation Minima solution not only uses geometric altimetry but employs reduced vertical separation based on it, however, these procedures should be necessary much less often; consequently, it has higher requirements on GNSS availability and continuity. Jamming and spoofing must be suppressed here through system design as far as possible (multi-frequency and multi-constellation receivers, message authentication, improved RAIM algorithms) and reliably detected if not, where the timely detection as such might suffice for the Geometric Altimetry solution. Both solutions acknowledge the existence of (external) technological threads working on improved robustness of onboard systems to jamming and spoofing.

SESAR Programme: Both solutions are part of the same program and contribute to the "Aviation Green Deal" flagship initiative, which aims to promote sustainability and efficiency within European aviation.

Collaboration: Both solutions, Separation Minima and Geometric Altimetry, are connected in the framework of the Green-GEAR project, and have collaborated especially as the mutual enabler GNSS and its problems (mainly jamming and spoofing) as well as flight performance in cruise are concerned.

Interdependency towards the Green Route Charging solution (SESAR Solution 0408)

Shared Objectives: Both solutions aim to minimise the environmental impact of flights while enhancing airspace efficiency. Reduced separation minima allow aircraft to fly closer together safely, enabling more direct and efficient flight paths. This not only increases airspace capacity and reduces congestion but also leads to lower fuel consumption and emissions. These environmental benefits align closely with the objectives of green route charges, which provide economic incentives for airlines to choose fuel-efficient, environmentally friendly flight paths.

Complementary Approaches: Reduced separation minima and green route charges complement each other: the former creates operational possibilities for more efficient flight paths, while the latter motivates airlines to take advantage of these possibilities, thereby reinforcing a shift towards lower CO_2 emissions and improved airspace usage. In addition, besides finer granularity of available flight levels, higher capacity would mitigate the negative effects of detours / flight level changes to avoid climate hotspots, convective weather or congestions.

Joint requirements: Accurate and real-time emissions data (e.g., fuel burn, CO_2 impact per route) is critical for determining green route charges and evaluating the environmental benefits of reduced separation minima. In addition, close coordination among ANSPs, airlines, and regulators is necessary to align operational decisions with environmental incentives and to manage increased airspace complexity due to tighter separations and flexible routing. Finally, both solutions may necessitate redesigning routes, sectors, and procedures to safely accommodate closer separations and incentivise environmentally friendly routing.

SESAR Programme: Both solutions are part of the same program and contribute to the "Aviation Green Deal" flagship initiative, which aims to promote sustainability and efficiency within European aviation.

Collaboration: Both solutions — Separation Minima and Green Route Charging — are connected within the framework of the Green-GEAR project. Their collaboration has particularly focused on exploiting the positive effects of increased capacity to inform the design of route charging schemes that incentivise airlines to adopt environmentally and economically efficient routes.

3.3 Objectives of the ECO-EVAL

The objective of this TRL2 ECO-EVAL is to help build an assessment of whether SESAR Solution 0407 is worth deploying, across ECAC, from an economic perspective for the involved stakeholders. This ECO-EVAL provides a consolidated assessment of the costs and benefits of deploying SESAR Solution 0407 in en-route airspace included in the ECO-EVAL solution scenario (see section 3.5.2).

This ECO-EVAL includes the evidence gathered to estimate the benefits and costs of the solution. At the current low TRL this is necessarily qualitative. The document contains an overview of the high-level impact of costs and benefits per stakeholder group, recommendations and next steps.

When the Solution is further developed, this document will be upgraded into a cost-benefit analysis (CBA).

3.4 Stakeholder identification

Stakeholder	Deployment locations (or sub-operating environments)	Cost drivers	Benefits in operations	Involvement in the ECO-EVAL analysis
ANSP	en-route ANS	invest in new functionality, upgrade of surveillance systems / safety nets, controller training	increased airspace capacity	provided inputs
Airport operators	not applicable			not involved
Network manager	en-route flow prediction	invest in tools / software upgrade		not involved
Scheduled airlines (mainline and regional)	aircraft equipage; pilot training facilities; flight operations centres (FOC)	equipment installation and maintenance; initial and recurrent pilot training of flight procedures; updates of flight planning software	reduced operating costs	provided inputs through Advisory Board
Business aviation	aircraft equipage; pilot training facilities; flight operations centres (FOC)	equipment installation and maintenance; initial and recurrent pilot training of flight procedures; updates of flight planning software	reduced operating costs	not involved

Stakeholder	Deployment locations (or sub-operating environments)	Cost drivers	Benefits in operations	Involvement in the ECO-EVAL analysis
General aviation IFR	(aircraft equipage; pilot training facilities; flight operations centres (FOC))	(equipment installation and maintenance; initial and recurrent pilot training of flight procedures; updates of flight planning software)	reduced operating costs	not involved
General aviation VFR	not applicable			not involved
Rotorcraft	not applicable			not involved
UAS operators	(depending on operating location: if in RVSM 2 airspace) GNSS capabilities are usually already available	(depending on operating location: if in RVSM 2 airspace) GNSS capabilities are usually already available	easier access to airspace	not involved
Military	(in general same as civil users, only that GNSS capabilities are usually already available)	(in general same as civil users, only that GNSS capabilities are usually already available)	partially reduced operating costs	not involved
Common information service provider (CISP)	not applicable			not involved
U-space service provider (USSP)	not applicable			not involved
other impacted stakeholders: weather forecast service provider	meteorological services: provision of gridded weather prediction data	software development cost for defining format / interface	income from service provision	not involved

Stakeholder	Deployment locations (or sub-operating environments)	Cost drivers	Benefits in operations	Involvement in the ECO-EVAL analysis
other impacted stakeholders: GNSS service provider	*space segment, ground segment*	*upgrade of signal specifications, safety studies*		*not involved*

Table 4: SESAR Solution 0407 ECO-EVAL stakeholders and impacts

3.5 ECO-EVAL scenarios and assumptions

This section describes the scenarios that are compared in the ECO-EVAL. The aim is to reflect the delta (difference) between the ECO-EVAL reference scenario (where the SESAR solution is not deployed, bottom box in Figure 3) and the ECO-EVAL solution scenario (reflecting the proposed deployment of the SESAR solution across ECAC, box in Figure 3). The comparison between the ECO-EVAL scenarios considers the point in time when the solution is available to be deployed and hence differs for each solution.

The delta approach means that the focus is on identifying the impact of the changes between the ECO-EVAL reference and ECO-EVAL solution scenarios. For example, new systems to be deployed, training requirements or changes in operating costs.

Defining the ECO-EVAL reference scenario has proven to be challenging because of the assumptions that need to be made regarding the 'ongoing deployments' that are relevant for the solution and their impacts.

To avoid being blocked by this issue, some elements of this TRL 2 ECO-EVAL focus on the difference between the current situation and the ECO-EVAL solution scenario. This is reflected in the following scenario descriptions.

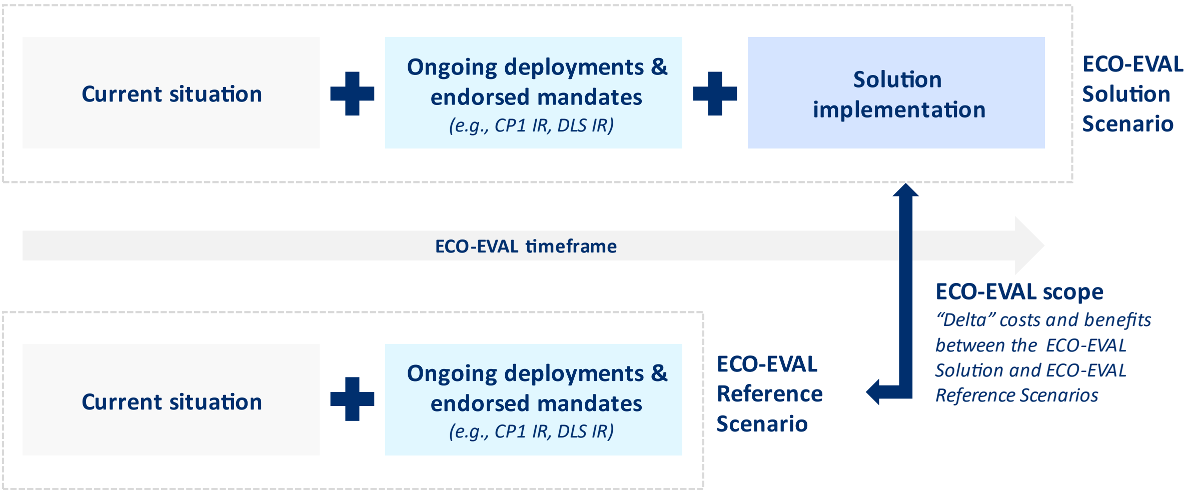

Figure 3: ECO-EVAL scenario overview

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3.5.1 ECO-EVAL reference scenario

The reference scenario that is used is the current operation in RVSM airspace in the EUR RMA region. Altimetry is done using barometric measurements and the minimal vertical separation is 1000 ft. The corresponding passing frequencies, traffic mix and TLS apply. As to the writers' knowledge, no deployments are currently foreseen that will significantly change altimetry modes or vertical separation in the en-route part of the flight.

Even though much regarding jamming and spoofing issues is still unclear, the reference scenario assumes that critical issues regarding these topics will have been resolved, especially as these issues are not specific to the solution.

3.5.2 ECO-EVAL solution scenario

In the solution scenario, the vertical separation minima are reduced to 500 ft in upwards-extended RVSM airspace (i.e. FL290 to FL600 inclusive), from previously 1000 ft and 2000 ft below and above FL410 respectively, with the use of geometric altimetry. Here geometric altimetry is defined as geometric altitude reference with altimetry based on GNSSs, provided by some yet-to-be-determined system (e.g. GPS, Galileo, multi-constellation, dual frequency, etc.). It is assumed that all airspace users have sufficient capabilities, routes could be free or fixed and the fleet is comparable to today. The European airspace is taken as a reference, even though the concept would likely be introduced on a global scale.

ECO-EVAL timeline

The ECO-EVAL covers the period from 2026 to 2050 as defined in the common assumptions [5]. This means that the net present value would be calculated by discounting the cash-flows back to 2026 (the end of DES wave 1) if we were quantifying costs.

Table 5 lists the key dates used in the ECO-EVAL and Figure 4 shows them over a timeline. Please note that the timeline relates to the full deployment capabilities of all stakeholders. The redesign of en-route airspace using geometric altitudes and different flight level definitions as such is a relative simple task but the prerequisites for that are complex and time-consuming. New capabilities would need to be developed – just to mention the most important ones –

- aircraft capabilities (development and certification on new aircraft navigation capability; update of ACAS; possible development of wake vortex encounter warning tool)
- ANSP capabilities (update of surveillance functions; modification of STCA tool; possible development of wake vortex encounter warning tool)
- a solution to current GNSS integrity and availability problems, not only related to jamming and spoofing suppression but also concerning regulatory problems (specifications do not meet the requirements even if observed signal-in-space performance could be satisfactory)
- fall-back procedures to solve GNSS unavailability at single aircraft level ("Procedure Single Unable Altimetry") and traffic level, locally or even globally ("Procedure Multiple Unable Altimetry") as per the FRD [34]

and those are not easily done. In fact, the introduction of RVSM has taken 18 years. We expect a comparable timeframe for RVSM 2, allowing also for a kind of "shadow mode" period where classical rules are still applied but monitoring takes place to ensure that specifications for altitude keeping could be met in practice. For these reasons, the estimated SOD is relatively late.

Dates	SESAR Solution 0407
Start of deployment date (SOD): the start of investments for the first deployment location	2040
End of deployment date: the end of the investments for the final deployment location, same as FOC	2050
Initial operating capability (IOC): the time when the first benefits occur following the *minimum deployment* necessary to provide them. Costs continue after this date as further deployment occurs at other locations.	2045
Final operating capability (FOC): maximum benefits from the *full deployment*[2] of the SESAR solution at applicable locations. Investment costs are considered to end[3] here although any operating cost impacts would continue.	2050

Table 5: ECO-EVAL investment and benefit dates

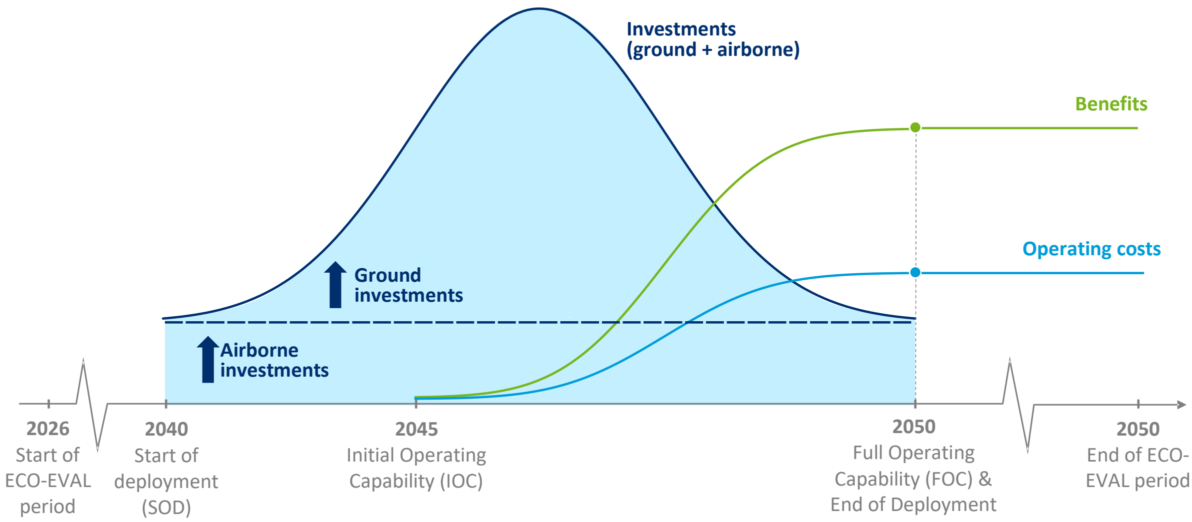

Figure 4: overview of ECO-EVAL dates

Figure 4 shows that:

- Investment costs are the addition of the (i) ground investment costs (spread following a bell curve[4] between the start and end of deployment dates), and (ii) airborne investment costs (spread linearly between the start and end of deployment dates). The latter assumes a more

[2] Where ***full deployment*** means deploying the SESAR solution in all the locations where it makes sense to deploy it (i.e. it does not mean it has to be deployed everywhere)

[3] The basic assumption is that infrastructure does not need to be replaced during the ECO-EVAL period.

[4] The bell curve is based on the diffusion of innovation theory (see Investopedia for further reference).

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or less continuous introduction of the airborne capabilities, which may or may not be the case depending on the design of the transition between RVSM and RVSM 2;

- Benefits ramp-up following an ‘S’ adoption curve[4] between IOC and FOC and then continue up to the end of the ECO-EVAL period;
- Operating cost impacts (increases or decreases) would also start at IOC and ramp-up following an ‘S’ adoption curve to FOC before continuing for the rest of the ECO-EVAL duration.

3.5.3 Assumptions

For the ECO-EVAL the following assumptions have been made on top of the DES common assumptions:

- It is assumed that the equipage rate of aircraft in RVSM 2 airspace is 100 % for the solution scenario. This is in accordance with the benefit analysis, where also an equipage rate of 100 % is assumed. This will be necessary to reduce complexity and manage safety in the en-route airspace, which would be very difficult to ensure with concurrent barometric and geometric operations and which would require safety buffers that are in contradiction with the very idea to provide more usable flight levels. Indeed already RVSM has applied access rules to the corresponding airspace;
- It is assumed that costs for the mitigation of jamming/spoofing are not part of the developed solution. It is assumed that any development that might possibly be required regarding jamming/spoofing is already available before the deployment of the geometric altimetry. Hence jamming/spoofing would have no impact on costs for the deployment of the solution.

4 Benefits

4.1 Benefits overview

The RVSM 2 airspace has a few major advantages. Aircraft's climate impact will be reduced due to route optimisation. Aircraft will be able to fly closer to their optimal altitude due to the additional flight levels that are introduced. These additional flight levels increase the airspace capacity, preventing congestion and limiting the length of detours (e.g. due to climate hotspots or adverse weather). Lastly, RVSM 2 with the use of geometric altimetry enables the RVSM airspace to increase to FL 600, thus further increasing the airspace capacity and benefitting operation of HAO aircraft.

The exercises described in the ERR [33] have determined that RVSM 2 could be safely introduced under conditions, including regulatory and standardisation advances and update/introduction of safety tools. These are crucial conditions to achieve the described performance contributions. The expected performance areas that the Separation minima Solution aims to contribute to are summarised in the table in the next section and described individually in the following ones. Due to limited resources and scope of the activity, it has not been possible to perform all assessments though beyond a coarse qualitative estimation, with the exception of the collision risk and operational safety which have been quantified. Note, however, that it is not the aim of the project to increase safety of operations but to enable more environmentally efficient operations without a negative impact on safety.

4.2 Benefit summary

Table 6 summarises the solution benefits showing the benefit impact mechanisms (BIMs) impact (positive, negative or neutral). It explains how the solution provides estimates. The BIMs themselves are visualised in the Final OSED [35].

KPI / PI	BIM impact	How the solution provides the benefit and evaluation (low, medium, high impact)
CAP2 En-route throughput in challenging airspace per unit time	+ (ECAC level)	The addition of flight levels will obviously increase capacity; it is quite expectable though that the protection of climbing and descending traffic will limit practical capacity increase to far below a hypothetical doubling of capacity in (current) RVSM airspace. The safety case has shown that from a collision risk point of view there is no limit on the capacity increase but the wake turbulence risk needs to be mitigated by either means to predict and avoid potentially hazardous encounters or introduction of new separation modes. A further question is the ability of ATC to handle the possible additional throughput, which is to a greater extent determined by the complexity of the traffic and airspace rather than the sheer number of aircraft. This question requires substantial analysis and modelling and is beyond the scope of the project. However, all in all it is expected to find a high impact on capacity.

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KPI / PI	BIM impact	How the solution provides the benefit and evaluation (low, medium, high impact)
FEFF1 Average fuel burn per flight	– (ECAC level)	The influence of added capacity is twofold: traffic through currently congested airspaces may need to fly less detours (FEFF9), and more traffic is able to fly at the individual optimum cruise altitude (FEFF10). A secondary, smaller effect is expected from the fact that the finer granularity of permissible altitudes by itself will support the latter effect. Additional capacity is in support of the full Solution of Green-GEAR's Solution #408, Green Route Charging, where the efficiency of detours around so-called climate hotspots is greatly increased by providing higher capacity in adjacent airspace, including a higher number of flight levels available for vertical hotspot avoidance (due to aircraft performance reasons, this would typically imply flying below the hotspot). The effects have not been assessed quantitatively except for a coarse estimation of the flight efficiency improvement through finer granularity of the flight levels in otherwise unchanged operations, resulting in a low effect (the fuel saving from finer granularity overcompensates the flight efficiency disadvantage from flying according to geometric rather than barometric altitude). **TEFF6:** En-route time. As a secondary effect, higher capacity in en-route airspace means less necessity for time-consuming detours, especially in conjunction with the above-mentioned Green Route Charging Solution.
ENV1 Average CO_2 emissions per flight	– (ECAC level)	There is an expectation to reduce CO_2 emission as a direct effect of the expected reduction in fuel burn (FEFF1, see above). As per assumption in [19], CO_2 emission is directly linked to fuel burn, with 3.15 kg of CO_2 produced per 1 kg of fuel burnt.

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KPI / PI	BIM impact	How the solution provides the benefit and evaluation (low, medium, high impact)
SAF1 ATM safety outcome	+ / – (ECAC level)	Specifically: SAF1.1, Mid-air collision – En-Route The investigation has quantified the mid-air collision risk in the en-route flight segment. A hypothetical reduction of minimum vertical separation under barometric altimetry in itself would obviously increase the collision risk; this is counteracted by the increased accuracy of geometric altimetry. The latter is a mixed blessing though: while collision risk of aircraft properly separated, the so-called technical risk, decreases with higher accuracy altimetry, the collision risk of aircraft that are erroneously on the same flight level, the so-called operational risk, increases. The investigation has quantified the collision risk according to an adaptation of the ICAO RVSM methodology and shown that it can be fulfil the target level of safety, which would mean a neutral impact. The changes in separation will also have an influence of the risk of encountering wake vortices in cruise. These generally cause accelerations, attitude changes, flight state and flight path excursions of the encountering aircraft (mainly SAF1.10.2, SAF1.10.3). The investigation has quantified the relative change in wake vortex encounter risk, without being able to absolutely quantify the cited indicators. It has been shown that there would be an increase of the encounter risk by a factor of approximately 3 to 4, which is not acceptable. Therefore the concept foresees encounter detection/prevention tools and/or procedural mitigation, both to be developed in subsequent activities. These items could also have a beneficial effect on current operations, as the wake encounter risk in cruise has never been formally analysed according to modern safety standards. Note: wake-related incidents / accidents in the en-route phase are not part of the list of PIs.

Table 6: solution performance benefits

4.3 En-route throughput in challenging airspace per unit time (CAP2)

The increase of the number of available flight levels can significantly enhance en-route throughput capacity (CAP2), particularly in congested or complex airspace regions. A precedent for this is the implementation of Reduced Vertical Separation Minima (RVSM), which effectively doubled the number of usable flight levels between FL290 and FL410. This change led to capacity increases ranging from 10% to 40%, depending on regional airspace complexity and traffic density.

The main mechanisms that drove these capacity improvements include:

- Enhanced Vertical Separation: Reducing vertical separation minima from 2,000 to 1,000 feet above FL290 allows more aircraft to occupy the same airspace volume safely, effectively increasing capacity.
- Optimised Airspace Utilisation: With more flight levels available, air traffic controllers can distribute aircraft more evenly across cruising altitudes, reducing congestion at popular levels, and improving overall traffic flow.
- Improved Conflict Resolution: Additional flight levels provide more flexibility in resolving potential conflicts, thereby decreasing the likelihood of delays and rerouting. Although not a factor when the original RVSM concept was developed, this effect is especially beneficial with free routings in trajectory-based operations (TBO) which are being introduced in increasing parts of the European airspace.

Similarly, proposals to reduce vertical separation minima to 500 feet aim to further increase en-route airspace capacity. However, such reductions introduce significant technical, operational, and safety challenges that must be carefully addressed prior to implementation. These include:

- Altimetry Accuracy: Current barometric altimeters have inherent errors that become critical when separation is reduced to 500 feet. Achieving the necessary accuracy will require advances in altimetry, such as the adoption of geometric altimetry. Indeed the latter has been assumed in the safety study.
- Wake Turbulence: Reduced vertical spacing increases the risk of wake turbulence encounters, potentially affecting the safety of following aircraft. The study identifies the need for mitigation through a safety net and/or procedural means.
- Operational Complexity: Air traffic controllers would face increased workload and complexity when managing traffic with narrower vertical separation, necessitating advanced training and more sophisticated decision-support tools. On the other hand, assuming an unchanged amount of traffic, fewer flights share the same flight level, reducing significantly the probability of conflicts
- Aircraft Performance Variability: Variations in aircraft climb and descent performance could make it more difficult to maintain precise vertical separation, particularly during transitions between flight levels.

While increasing the number of available flight levels will undoubtedly enhance theoretical capacity, the introduction of new separation standards to mitigate the wake encounter risk and the need to

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protect climbing and descending aircraft will likely limit practical gains. The actual capacity increase in modified RVSM airspace is expected to fall well short of a theoretical doubling. The development of a comprehensive safety case will be essential in establishing an upper bound for achievable capacity enhancements.

A further consideration is the ability of ATC systems and personnel to manage increased throughput. Evaluating this aspect requires detailed modelling and analysis of human and system performance, airspace structures especially regarding temporary restricted areas (TRAs) and the avoidance of adverse, namely convective, weather; this is beyond the scope of the current project. However, conceptual studies have shown that even under current separation rules the theoretical capacity for conflict-free trajectories is far larger than the current ATM system's ability to handle it.

The DLR internal project DIAL investigated the en-route airspace limits under the assumption of an approximately 150% traffic growth between 2019 and 2050, i.e. nearly 2.5 times the number of flights as 2019, or almost 310,000 daily flights worldwide. Free routing between origin and destination airports and a hypothetical appropriate extension of their runway capacities to handle the traffic was assumed. Furthermore a fully automated air traffic management at least for en-route traffic was envisaged, i.e. it was assumed that controller workload as one capacity limiting factor would no longer be relevant; instead the number of flights would be constrained by the required horizontal and vertical separations between them (i.e minima of 5 NM laterally, 3 to 8 NM in trail as per current wake vortex separation [40] and 1000 ft vertically). It was shown that current deconfliction methods (strategic conflict resolution using time shifts of a few minutes and tactical lateral detours or climb-above/descend-below manoeuvres) are generally able to provide a conflict-free scenario even for this high demand with very low average penalty on flight efficiency [45].

Today en-route airspace capacity limits stem from sector capacities that are in turn determined by controller workload, and thus also dependent on airspace complexity, locally substantial volumes of airspace reserved for military (training) activities, and regionally complete closure of airspaces due to military conflicts, terrorist threats and/or political reasons. At the time of writing this especially concerns the routings from Europe to Asia which nearly all need to pass over Turkey. This means that even if the capacity of the globe's airspace could deal easily with much more traffic than today, so many limits exist in practically usable airspace that added capacity there could still make a difference.

4.4 Fuel efficiency (FEFF1) and CO_2 (ENV1)

Aircraft's climate impact will be reduced due to route optimisation. Aircraft will be able to fly closer to their optimal altitude due to the additional flight levels that are introduced. These additional flight levels increase the airspace capacity, preventing congestion.

FEFF1: Average fuel burn per flight

The EUROCONTROL Performance Review Report 2023 highlights that vertical en-route flight (in)efficiency significantly impacts fuel consumption, with aircraft generally burning less fuel at higher altitudes. Additionally, the European Aviation Overview 2024 reports an average excess fuel burn of 9–11.8% during 2024, influenced by factors such as weather-related flow measures, capacity and staffing constraints, and military activity.

In this context, the introduction of new flight levels—designed to increase en-route capacity—is expected to reduce fuel burn through two primary mechanisms:

- Reduced Need for Detours (FEFF9): By alleviating congestion in busy airspaces, additional capacity allows traffic to follow more direct routes, avoiding inefficient detours.
- Improved Access to Optimum Cruise Altitude (FEFF10): More available flight levels increase the likelihood that aircraft can operate at or near their optimal cruise altitude, where fuel consumption is minimised.

On the other hand, it was concluded in the Geometric Altimetry Solution 0406 that the use of geometric altimetry instead of barometric in cruise flight without further changes leads in average to a slight increase of the fuel consumption. For an example aircraft type this increase was quantified to about 0.2% of the trip fuel. The flight time is only affected in a negligible way [26]. The reason for this is that aircraft performance is correlated with atmospheric properties, and those are related to barometric / pressure altitude rather than the geometric one.

This disbenefit in turn would be mitigated in this Separation Minima solution by a benefit stemming from the finer granularity of permissible flight levels, which can slightly improve the match between aircraft performance profiles and available altitudes. An initial, coarse estimation has been made for the aircraft type that was also exemplarily used in the above-mentioned study of geometric altimetry in cruise, a very common medium-range single aisle airliner. Figure 5 shows its fuel flow over distance (through the air) as a function of pressure altitude (flight level) and aircraft mass at a typical cruise Mach number. In Figure 6 and Figure 7 the fuel benefits are plotted that one would achieve by not having to fly 1000 ft (10 flight levels) and 500 ft (5 flight levels), respectively, lower than the current flight level.

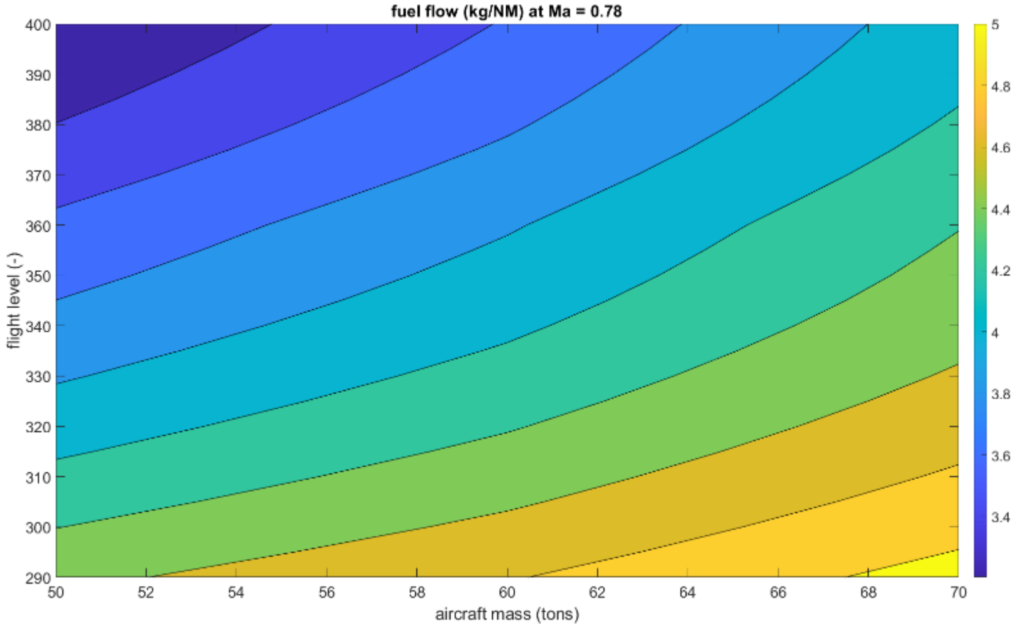

Figure 5: fuel flow for medium-range single aisle aircraft at typical cruise Mach no.

With the semi-circular flight rule, the usable flight altitudes are dependent on the aircraft's heading [35] so only every other flight level that is available in principle can actually be used, leading to a 2000 ft granularity of available altitudes under RVSM (up to FL 410, with 4000 ft granularity above that) and 1000 ft granularity under RVSM 2, the solution scenario. This improves the FEFF10 KPI.

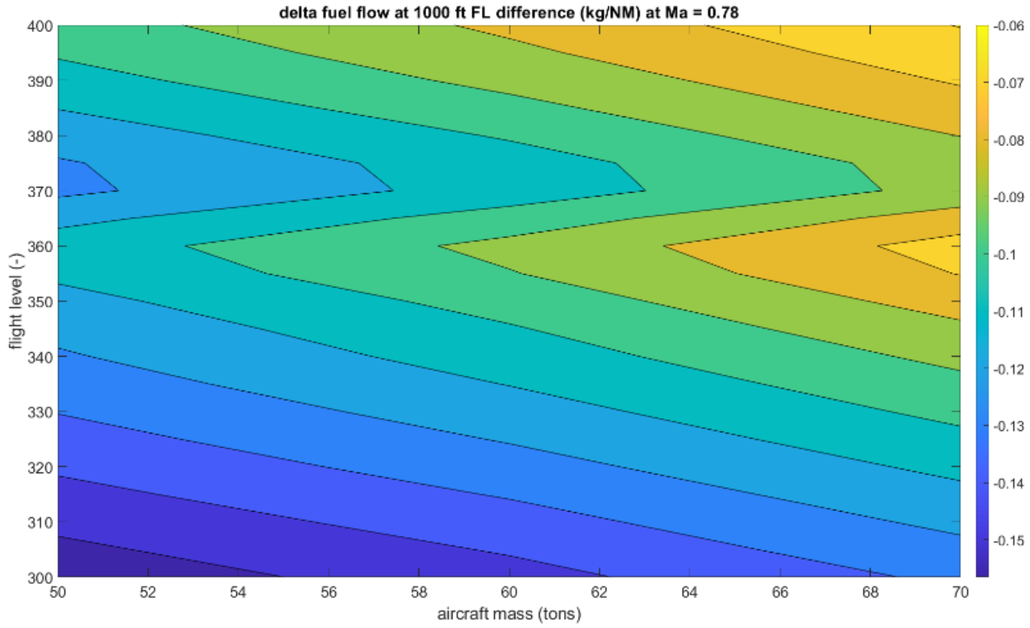

Figure 6: difference in fuel flow at given flight level against flight at 1000 ft (10 FLs) lower

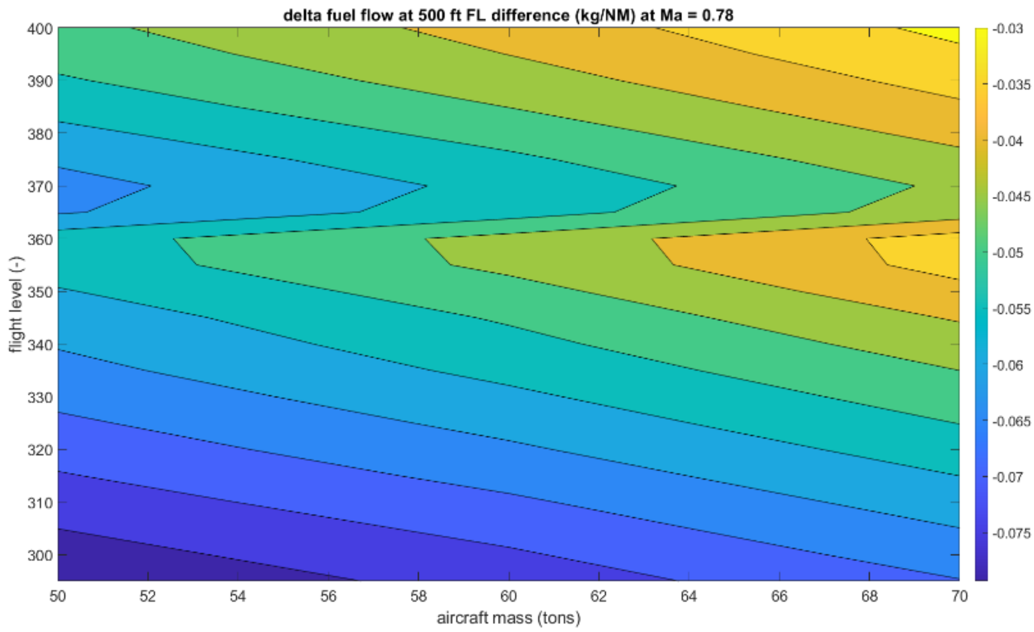

Figure 7: difference in fuel flow at given flight level against flight at 500 ft (5 FLs) lower

The optimum altitude slowly but constantly increases with the weight loss due to fuel use, so that aircraft perform step climbs on longer flights as far as operationally possible, typically once every one to three hours. Estimating the difference between the optimal altitude and the actually flown one to be roughly half of the granularity on average, we can conclude from the comparison of Figure 6 and Figure 7 that the fuel penalty from having to fly at one of the available flight levels is halved in the RVSM 2 scenario. Relating this difference to the absolute fuel flow depicted in Figure 5, the fuel flow benefit would be around 0.9%. This is only a coarse estimation and the cruise phase is only part of the whole flight, but for typical leg lengths it can be concluded that the fuel savings due to finer flight level granularity (FEFF10) would typically overcompensate the penalties for flying with a geometric altitude reference, i.e. there would be an overall improvement in fuel efficiency (FEFF1).

Increased en-route capacity also supports the implementation of Green-GEAR's Solution #408, Green Route Charging, by improving the efficiency of detours around climate-sensitive areas ("climate hotspots"). With more capacity available in adjacent airspace, aircraft can reroute more efficiently, preserving environmental and operational performance.

However, the realisation of these benefits depends on several factors, including:

- Operational Constraints: The structure of the airspace, prevailing traffic density, and the extent to which the new flight levels can be effectively utilised without introducing additional complexity or bottlenecks.
- Technological Advancements: The adoption of advanced air traffic management (ATM) systems and trajectory-based operations is essential to fully exploit the flexibility and efficiency gains offered by additional flight levels.

Given these dependencies, a quantitative assessment of the potential fuel efficiency improvements requires detailed modelling and data analysis, and is therefore beyond the scope of this report.

ENV1: Actual Average CO2 Emission per flight

There is an expectation to reduce CO_2 as a direct effect of the expected reduction in fuel burn (FEFF1, see above).

An increased number of available flight levels can reduce CO_2 emissions primarily by improving the efficiency of aircraft trajectories, especially during the en-route cruise phase, which is where aircraft spend most of their flight time and consume the most fuel. The main reasons are:

Improved Access to Optimal Cruise Altitude

- Aircraft are most fuel-efficient at high altitudes, typically near their optimum cruise level (which depends on weight, engine type, and weather).
- When congestion limits available flight levels, aircraft may have to fly lower than optimal, leading to higher fuel burn.
- More flight levels allow more aircraft to fly closer to their optimal cruise altitude, reducing fuel consumption and thus CO_2 emissions.

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Fewer Detours and More Direct Routing

- In congested airspace, aircraft are often rerouted away from ideal trajectories to avoid conflicts.
- Increased vertical capacity (i.e., more flight levels) allows better traffic distribution, enabling shorter and more direct routes, which normally means less fuel, and therefore less CO_2.

Support for Environmentally Optimised Trajectories

- Initiatives like trajectory-based operations and climate-sensitive routing (e.g., avoiding climate hotspots, see “Green route Charging” Solution #0408) benefit from flexibility in vertical space.
- With more levels to choose from, it is easier to find routes that both avoid high-emission areas and maintain fuel efficiency.

Reduced Congestion-Related Flow Measures

- When airspace is saturated, regulations like spacing or metering are applied, causing suboptimal fuel use.
- An increased number of flight levels reduces congestion, minimising the need for such flow constraints.

4.5 Safety (SAF)

The KPA that was studied most extensively in this solution was Safety (SAF). The validation exercises described in the ERR [33] have determined whether RVSM 2 can be safely introduced, which is a crucial condition to achieve the above-described performance contributions. Detailed information on the safety study and its three parts (Collision Risk Analysis, CRA; Wake Turbulence Risk Analysis, WTRA; Safety Case) can be found in this document.

In the former and latter activities the safety was assessed using an evaluation against a threshold. The nominal risk (risk under nominal operations, i.e. in the absence of failures and operational errors) and the non-nominal risk were evaluated. A maximally allowable level of risk was defined, and requirements were deduced, using a ‘top down’ approach. As such it is guaranteed that the safety remains within acceptable limits. Even though the overall level of risk is likely to increase within the system, it is within acceptable bounds, and therefore the outcome for this KPA for the CRA and Safety Case can be regarded as neutral.

The WTRA used a comparative approach, using current 1000 ft minimal vertical separation with barometric altimetry as the reference. It was shown that wake vortex safety would be negatively affected, with an increase of encounter probability by a factor of 3 to 4 across all encounter severities, when the vertical separation minima are reduced to 500 ft with geometric altimetry and no further changes are made to the separation standards.

Considering the results of all validation exercises combined, it can be stated that within the RVSM 2 concept as initially defined, the safety would be negatively affected overall. As this is not acceptable, the concept has been extended to foresee mitigation of the wake encounter risk. This mitigation could consist of

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- prerequisites for the application of reduced vertical separation, typically the existence of certain weather conditions, especially for aircraft on the same or parallel tracks;
- advances in separation modes, meaning that longitudinal / lateral separation minima on one hand and vertical separation minima on the other would no longer be completely independent from each other and/or dependent on the affected aircraft pairing (as envisaged in the R-WAKE project [46];
- the introduction of a safety net: analogous to ACAS and ATC's short-term conflict alert (STCA), a ground-based or airborne predictive tool to identify and prevent potentially hazardous wake encounters could be employed. Despite the relatively high effort for development and operation of such a tool, the potential benefit is large as operational limits, and thus capacities, would no longer need to be dictated by the worst-case assumption.

The evaluation and development of these mitigation means is a recommendation for further work, also regarding the cost-benefit trade-off.

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5 Cost assessment

Stakeholder	Cost category	Yes/No	Cost driver	Deployment locations (or sub-operating environments)
ANSPs	Investment cost	Yes	see sections below	en-route airspace
	Operating cost	Yes	see sections below	
Airport operators	Investment cost	No	-	n.a.
	Operating cost	No	-	
Network manager	Investment cost	Yes	see sections below	NMOC
	Operating cost	No	-	
Airspace users in RVSM 2 airspace (scheduled airlines, business aviation, general aviation IFR, UAS operators (partially))	Investment cost	Yes	see sections below	SA, BA, GA (aircraft fleet)
	Operating cost	Yes	see sections below	
Airspace users outside of RVSM 2 airspace (rotorcraft, UAS operators (partially), general aviation VFR)	Investment cost	No	-	n.a.
	Operating cost	No	-	
Military	Investment cost	Yes	see sections below	aircraft equipage
	Operating cost	Yes	see sections below	
Common information service provider (CISP)	Investment cost	No	-	n.a.
	Operating cost	No	-	
U-space Stakeholder	Investment cost	No	-	n.a.
	Operating cost	No	-	
other impacted stakeholders: weather forecast service provider	Investment cost	Yes	see sections below	meteorological services
	Operating cost	Yes	see sections below	
other impacted stakeholders: GNSS service provider	Investment cost	Yes	see sections below	space segment, ground segment
	Operating cost	Yes	see sections below	

Table 7: identification of solution's cost drivers and deployment locations

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Because of the relatively low TRL of 2, the identified costs per stakeholder can only be expressed in a qualitative way. In the following sections operational and investment costs for the related stakeholders are identified and outlined. A quantitative assessment of each cost category cannot be performed here.

5.1 ANSPs costs

Investment Costs:

- AIS / AIM changes
- ATCO Training based on geometric altitude and new separation minima
- ground system altimetry conformance monitoring system development
- Short-term Conflict Detection Tool further development
- Wake Vortex Safety Net system development (unless airborne)
- flight data processing based on geometric altimetry
- CWP update to manage and display geometric altimetry
- update of procedures, safety cases, etc.
- project delivery of RVSM 2: including Safety and HF assessment, regulatory oversight

Operating Costs:

- ATCO fall-back training for baro fall-back procedures

5.2 Airport operators costs

The solution concerns the RVSM 2 part of en-route airspace only, there is no need for airport operators to implement any changes.

5.3 Network manager costs

The network manager will need to update airspace structures and capacities as used in the flow management and the tools to predict performance of the flight plans under use of geometric altimetry.

Investment Costs:

- flight planning tools to show geometric altimetry capability (prerequisite from RVSM 2 airspace access)
- flight planning tools update to predict performance of the flight plans under use of geometric altimetry
- update of separation and capacity model

5.4 Airspace user costs

The assessment of SESAR solution 0407 has been performed taking into account all civil airspace users that fly in RVSM 2 airspace (scheduled or chartered airlines, business aviation, general aviation (IFR), partially UAS operators) by either a generic approach, or by using real-world traffic demand. The following costs related to the introduction of the solution apply to them:

Investment costs:

- aircraft equipment costs (retrofit and linefit) for GNSS receivers and possibly safety nets (ACAS; Wake Vortex Safety Net system (unless ground-based)
- EFB software update
- initial pilot training
- FOC flight planning software update
- initial flight dispatcher training

Further civil airspace users (rotorcraft, general aviation (VFR), partially UAS operators) do not fly in RVSM 2 airspace and hence would not be affected by the introduction of the solution.

Operating Costs:

- recurrent pilot training
- maintenance of new equipment and systems and/or (additional) maintenance items on new hardware / software functions
- recurrent flight dispatcher training

5.5 Military costs

Green-GEAR deals with the civil application of geometric altimetry in RVSM 2 airspace; there are no specific conditions or requirements for military users of this airspace. Thus military airspace users could be treated in the same way as civil airspace users in terms of their costs; indeed they are often already equipped with GNSS altimetry. However, it may be necessary that they use civil GNSS services and frequencies to ensure consistency of altimetry with civil users, possibly necessitating equipage updates.

5.6 CISP and U-space stakeholder costs

The solution concerns the RVSM 2 part of en-route airspace only, i.e. altitudes not lower than FL290. The is no overlap with U-Space, and therefore neither U-space stakeholders nor Common Information Service Providers (CISPs) would be affected by the solution.

5.7 Other relevant stakeholders

5.7.1 Weather forecast service providers

Meteorological services would need to provide gridded weather prediction data to the network manager, ANSPs and airspace users so that ground and onboard performance predictions could be

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calculated based on geometric altimetry. This would possibly include pressure altitude in addition to wind, temperature, etc.

Investment costs

- software development costs for defining format / interface (unless existing formats can be used)

Operating Costs:

- possibly provision of existing numerical weather prediction (NWP) data in the new format

5.7.2 GNSS service providers

Current GNSS specifications are not sufficient for the implementation of geometric altimetry in cruise in a way that it enables reduced vertical separation minima. Especially the integrity problem (jamming and spoofing disturbances) is not constrained to this solution, and the measures to overcome it **are not part of the solution's scope**. Nevertheless we note that the following, by definition solution-external, costs would be incurred:

Investment costs

- studies on the design of more robust signal structures including measures such as signal shapes, encoding and/or message authentication
- development of the necessary specifications
- software and hardware development costs for implementation
- possibly costs for construction of (further) ground monitoring stations

Operating Costs:

- operating costs for signal monitoring infrastructure to ensure signal integrity
- operating costs for signal monitoring infrastructure to ensure performance monitoring

6 CBA model

This chapter shall be completed in the CBA deliverable that is expected for solutions aiming at a higher maturity level than TRL2.

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7 CBA results

This chapter shall be completed in the CBA deliverable that is expected for solutions aiming at a higher maturity level than TRL2.

8 Sensitivity and risk analysis

This chapter shall be completed in the CBA deliverable that is expected for solutions aiming at a higher maturity level than TRL2.

9 Recommendations and next steps

The ”Separation Minima” activity generally aims at reducing CO_2 emissions and increasing capacity by further reducing separation minima at various phases of flight, enabled by the use of geometric altimetry, while keeping the level of safety of operations at least as it is today. The scope of the Solution has been limited to the investigation of the potential feasibility of a reduction of minimum separation to 500 ft in upper airspace between FL 290 and FL 600 (“RVSM 2”).

The safety studies, namely collision and wake turbulence risk, required parameters that are dependent on the operations and traffic mixes in the investigated airspace. For this development the ICAO EUR region was used as test airspace.

It was shown that the reduction of vertical separation could be feasible from a collision risk point of view when improving the specifications for several systems, while the wake vortex risk would need to be mitigated by a new safety net, airborne or ground-based, and/or procedural adaptations.

At the current TRL of 2 a quantitative assessment of costs and benefits cannot be performed. The evaluation of benefits has been performed quantitatively for the safety outcome (which is a prerequisite but not a target as such), while the operational benefits and costs could only be assessed in a qualitative way. It is therefore highly recommended to perform a quantitative cost and benefits assessment to improve the economic evaluation, if the solution is to be further developed for higher TRL. In order to do so, quantitative input is required from the involved stakeholders regarding their respective cost drivers. Even if the qualitative cost assessment is more or less generic for the involved stakeholders, the benefit assessment could be influenced by the deployment region (e.g. airspace congestion). This should be further investigated in the future.

The assessment of the benefits particularly concerns airspace capacity and operational efficiency (flight closer to optimum flight level, more direct routings and the savings in fuel and CO_2 stemming from those), which would need to be done on the level of a fast-time simulation of the whole of the European airspace. This simulation should realistically model airspace configuration and capacities, weather influence on operations and flight performance, and especially the latter with sufficient accuracy to properly quantify the changes in fuel flow. A requirement would also be the ability to generate realistic flight plans and from those deconflicted traffic flows using the new separation rules

The solution contains functions that are not yet attributed to systems or actors, such as a wake vortex warning tool, and procedures that are not yet developed, such as the fall-back to barometric altimetry for single or all aircraft. These need to be developed and the cost of possible contingencies estimated. Also some technical developments in the field of mitigation of jamming/spoofing are considered as necessary prerequisites. These necessary developments are not considered as part of the Separation Minima solution as such. However, the future development of those means for jamming/spoofing mitigation is likely to result in additional costs. This should also be considered for future development of the solution.

As the cost assessment and parts of the benefit assessment could only be performed in a qualitative manner, no recommendations can be made towards a deployment of the solution from the cost-benefit perspective. Here, further research is required to conclude whether the solution is viable not only from a technical perspective, but also from the cost benefit perspective.

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10 References

10.1 Applicable documents

This ECO-EVAL complies with the requirements set out in the following documents:

SESAR solution pack

[1] SESAR DES Solution Definitions Green-GEAR V1.0, 3rd June 2024.

[2] SESAR Operation Concept Document OCD 2023, 02.00.00, 14th July 2023.

[3] SESAR DES & DSD Solutions slides 2023 (1_0).pptx

Content integration

[4] Content Integration – Executive Overview, Edition 00.01, 16th February 2023.

[5] DES Common Assumptions, Edition 00.02.01, 29th June 2023.

[6] DES Performance Framework, Edition 00.01.04, 29th June 2023.

[7] DES Performance Framework – U-space Companion Document, Edition 00.01.02, 3rd April 2023.

Content development

[8] SESAR 3 Joint Undertaking – Communication Guidelines 2022-2027, Edition 0.03, 23rd November 2022.

System and service development

Performance management

[9] Performance Assessment and Gap Analysis Report (PAGAR) 2019 – updated version, Edition 00.01.00, 20th May 2021.

[10] SESAR Solution Cost Benefit Analysis (CBA) Quick Start Guide (1_0).docx

[11] SESAR ECO-EVAL Quick Start Guide (1_0).docx

[12] Performance Assessment and Gap Analysis Report (2019), Edition 00.01.02, 13th December 2019.

[13] SESAR Guidelines for Producing benefit and Impact Mechanisms, PJ16.06.06, ed. 03.00.01, 23rd June 2016.

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Validation

[14] DES HE requirements and validation / demonstration guidelines, Edition 3.00, 15th September 2023.

[15] DES SESAR Maturity Criteria and sub-Criteria_01_01 (1_1).xls

System engineering

Safety

[16] DES expanded safety reference material (E-SRM), Edition 1.2, 17th November 2023.

[17] Guideline to Applying the Extended Safety Reference Material (E-SRM), Edition 1.1, 17th November 2023.

Human performance

[18] SESAR DES Human Performance Assessment Process TRL0-TRL8, Edition 00.03.01, November 2022.

Environment assessment

[19] SESAR Environment Assessment Process, Edition 05.00.00, 23rd July 2024.

Security

Programme management

[20] Green-GEAR Grant Agreement No. 101114789, version 1, signed 11th May 2023.

[21] SESAR 3 JU Project Handbook – Programme Execution Framework, Ed. 01.00, 11th April 2022.

[22] Common Taxonomy Description (1_0).pdf, Edition 1.0, 7th February 2023.

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[24] Project Reviews 2024_guidance for IR1 & ER1 (1_0).pptx

10.2 Reference documents

Green-GEAR Project Documents

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[27] Vechtel, D.; Zapata Arenas, D.; Godsell, J.; Bauer, T.: "SESAR 3 ER 1 Green-GEAR – D3.6 – ECO-EVAL – Geometric Altimetry". Version 01.00, submitted 28th May 2025.

[28] Jonk, P.; Boshuizen, I.; Koloschin, A.; Klein Obbink, B.; Smeltink, J.: "SESAR 3 ER 1 Green-GEAR – D4.1 – Initial OSED – Separation Minima". Version 01.00, 28th June 2024.

[29] Bauer, T.; Koloschin, A.; Jonk, P.; Boshuizen, I.; Smeltink, J. and Klein Obbink, B: "SESAR 3 ER 1 Green-GEAR – D4.2 – ERP – Separation Minima v1". Version 01.00, 31st July 2024.

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[31] Bauer, T. and Koloschin, A.: "Green-GEAR – iD 4.2 – Separation Minima – Wake Turbulence Risk Analysis". Project internal report, v2.0, 30th May 2025.

[32] Jonk, P.; Klein Obbink, B.; Smeltink, J. and Boshuizen, I.: "SESAR 3 ER 1 Green-GEAR – D4.3 – RVSM 2 Safety Case". Version 01.00, 28th February 2025.

[33] Bauer, T.; Koloschin, A.; Jonk, P.; Boshuizen, I.; Klein Obbink, B; Smeltink, J.: "SESAR 3 ER 1 Green-GEAR – D4.4 – ERR – Separation Minima". Version 01.00, submitted 30th May 2025.

[34] Jonk, P.; Boshuizen, I: "SESAR 3 ER 1 Green-GEAR – D4.5 – FRD – Separation Minima", Version 01.00, submitted 30th April 2025.

[35] Jonk, P.; Boshuizen, I.; Koloschin, A.; Klein Obbink, B.; Smeltink, J., Bauer, T.: "SESAR 3 ER 1 Green-GEAR – D4.6 – Final OSED – Separation Minima". Version 02.00, submitted 30th April 2025.

External references

[36] EUROCONTROL's Standard Inputs for Economic Analyses, release 10.0.3

[37] ICAO, "Manual on Implementation of a 300 m (1000 ft) Vertical Separation Minimum Between FL 290 and FL 410 Inclusive," International Civil Aviation Organization, 2002.

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[39] ICAO: AIR TRAFFIC CONTROL OPERATIONS MANUAL FOR IMPLEMENTATION OF REDUCED VERTICAL SEPARATION MINIMUM IN THE AFI REGION. 2008.

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[42] ICAO: Annex 11 to the Convention on International Civil Aviation. *Air Traffic Services*. 15th Edition, 2018.

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[44] Smeltink, J., & Moek, G.: Pre Implementation Collision Risk Assessment for RVSM in the Africa Indian Ocean Region. 2005.

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[46] Busto J.; Ruiz, S.: Final Project Report. SESAR 2020 R-WAKE Deliverable D2.1, ed.01.00.00, 2018.

Appendix A Maturity criteria (self-assessment)

The only maturity criterion identified as relevant for the ECO-EVAL at TRL 2 is PER.TRL2.3:

Does the TRL2 ECO-EVAL contain a qualitative (order of magnitude) description of the costs and benefits of the solution that allows the different impacted stakeholders to have confidence on the continuation of further research for the proposed ATM solution?

Overall costs as well as benefits have been outlined qualitatively. Only the safety criterion regarding mid-air collisions under nominal and non-nominal operations has been able to be quantified; the other benefits and, given the low TRL of 2, costs could not be evaluated quantitatively other than exemplarily. Qualitative assessments, however, are available so in accordance with the TRL 2 requirements, the maturity criterion is preliminarily assessed as "achieved".

The sub-criteria are assessed as follows:

Are the following elements clearly described in the TRL2 ECO-EVAL:

(1) scope of the solution (in particular considering the cost-drivers).

Yes, the scope of the solution is described in section 2.2, and cost-drivers are described in chapter 5, with an overview in Table 7. It needs to be noted that some solution components described in the FRD [34], such as the wake vortex warning tool, are only loosely defined at this point and their cost attribution (airborne or ground) is not clear yet.

(2) interdependencies with other solutions.

Yes, interdependencies with other solutions are described in section 3.2.1.

(3) implementation/deployment options.

Yes, implementation and deployment are described in section 3.5. There are no *options* for the deployment as per the nature of the solution (it will either apply to all airspace users in the affected airspace, or it will not be applied).

(4) identification of the impacted stakeholders.

Yes, the impacted stakeholder have been identified; a commented list is available in Table 4 in section 3.4.

(5) qualitative description of the benefits, in line with the BIMs in the OSED TRL2, including the most impacted KPAs and KPIs.

Yes, the benefits have been described in accordance with the BIM contained in the Final OSED [35]and related to the investigated KPIs (see chapter 4). The safety criterion regarding mid-air collisions under nominal and non-nominal operations has been quantified; for the other KPIs qualitative assessments are available (see the overview in Table 6 and individual information per KPI in sections 4.3, 4.4 and 4.5).

(6) identification of cost drivers.

Yes, the major cost drivers have been identified and are described in chapter 5, with an overview in Table 7.

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