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Abstract

Green-GEAR aims to enable and incentivise optimum green trajectories and airspace use through new ATM procedures, developing three new SESAR Solutions towards TRL2: The “Vertical Guidance using Geometric Altimetry” Solution assessed possible efficiency benefits of GNSS altimetry for flight path definitions in the TMA, while the “Separation Minima” Solution investigated the feasibility of reducing the vertical separation minima to 500 ft in upwards-extended Reduced Vertical Separation Minima (RVSM) airspace under GNSS altimetry (RVSM 2). Last but not least, the “Green Route Charging” Solution studied the incentivisation of higher horizontal efficiency in flight planning, for initially CO_2 and later also non-CO_2 emissions reduction, through suitable modulation of en-route charges.

Authoring & approval

Author(s) of the document

Author	Organisation	Date
Tobias BAUER	**DLR**	08/09/2025, 07/01/2026
Tatjana BOLIĆ	**UoW**	08/09/2025, 22/01/2026
John GODSELL	**NATS**	08/09/2025, 23/01/2026
Patrick JONK	**Royal NLR**	08/09/2025
Lorenzo CASTELLI	**UNITS**	08/09/2025, 27/01/2026
Henrike SCHMIDT	**DLR**	08/09/2025, 28/01/2026
Daniel ZAPATA ARENAS	**Airbus**	08/09/2025, 27/01/2026
André KOLOSCHIN	**DLR**	08/09/2025
Fulvio VASCOTTO	**UNITS**	08/09/2025

Reviewed by

Reviewer	Organisation	Date
Andrew COOK	**UoW**	08/09/2025
Carsten SCHWARZ	**DLR**	08/09/2025
Bart KLEIN OBBINK	**Royal NLR**	08/09/2025

Approved for submission to the SESAR 3 JU by[1]

Name, function, organisation	Date
Daniel ZAPATA ARENAS, Airbus	09/09/2025, 30/01/2026
EUROCONTROL	09/09/2025, 30/01/2026
John GODSELL, Solution Lead 0406 / Lead WP3, NATS	09/09/2025, 30/01/2026
Bart KLEIN OBBINK, Solution Lead 0407 / Lead WP4, Royal NLR	08/09/2025, 30/01/2026
Lorenzo CASTELLI, Solution Lead 0408 / Lead WP5, Università di Trieste	08/09/2025, 30/01/2026
Tatjanja BOLIĆ, Lead WP2, University of Westminster	08/09/2025, 30/01/2026
Henrike SCHMIDT, CDE Lead / Lead WP6, DLR	08/09/2025, 30/01/2026
Tobias BAUER, Project Manager / Lead WP1, DLR	09/09/2025, 30/01/2026

[1] Representatives of the participants to the project

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Rejected by[2]

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Green-GEAR

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

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1 Executive Summary

1.1 Abstract

Since the early days of aviation, barometric pressure measurements have been a simple and robust method for altimetry. Two drawbacks exist though: there is no direct reference to terrain, and the constant variations in pressure caused by the weather lead to increased vertical profile variability restricting capacity and flight efficiency in today's high traffic density. One goal of Green-GEAR thus has been to investigate the environmental potential of geometric altimetry enabled by satellite navigation, increasing safety and eliminating waste of airspace by removal of the transition layer and supporting more environmentally friendly climb and descent operations.

Using the example of the Northern London TMA, it was shown that airspace designers can use geometrically-defined vertical paths to create optimised procedure allowing greater flight efficiencies in the TMA, netting a benefit overall for fuel and emissions at 2035 traffic levels. No safety or human performance showstoppers were identified for the removal of the transition layer, improving environment and safety by removing variation due to atmospheric conditions and potential for human error. Aircraft design considerations found no technical showstopper for descent and approach using geometric altimetry for required navigation performance (RNP) arrivals down to the intersection with the final precision approach segment, where the vertical guidance is by geometrical reference already today, allowing simplification of the charting and cockpit procedures. On the other hand, the use of a prescribed vertical path for departures was found to have significant impacts on airborne systems and operations.

With the change of the vertical reference, not only integration of manned aviation with drones (that are already using geometric altimetry in current operations) is facilitated, but Green-GEAR has also looked at the potential for reduced vertical separations enabled by geometric altimetry. Exemplarily, the so-called RVSM 2 concept envisages reducing the minimum vertical separation from 1,000 ft to 500 ft in upwards extended reduced vertical separation minimum (RVSM) airspace, enabled by improved altitude-keeping performance with geometric altimetry (RVSM 2 concept).

The project work has focused on the assessment of safety, showing that the collision risk could possibly be met by a small margin, based on *observed* performance of GNSS altimetry system error and flight technical error. However, the *nominal* values are not sufficient so that the implementation of RVSM 2 would require adaptations to existing regulations and standards. A substantial increase is predicted for the wake vortex encounter risk, which would need operational or functional mitigations, and the Functional Hazard Analysis has identified further requirements. In sum, the operational safety is a substantial challenge but not obviously infeasible, provided the significant regulatory and legislative challenges of tightening performance specifications are overcome. On the plus side, initial capacity analysis shows no restrictions on using the additional flight levels from the collision risk point of view, and it was exemplarily indicated that their finer granularity might increase flight efficiency by allowing aircraft to fly closer to their preferred flight levels.

Last but not least the project has investigated the potential of environmentally driven route charging, with new mechanisms for charging airspace users for en-route air navigation services in a manner to

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incentivise minimum climate impact. The modulation of route charges is designed to reward those who avoid volumes of airspace with a high climate impact and disincentivise flight planning through high-demand sectors or flight altitudes except where it optimises environmental benefit overall, while being cost neutral to airspace users and passengers on average and keeping air navigation service providers' revenues per service unit stable.

Given the complexity of the task, the Solution has been developed in two stages. The Initial Solution focuses on reducing horizontal inefficiencies caused by differences in unit rates and the mitigation of demand-capacity imbalances at the strategic level, i.e. without impact on processes at the tactical level. A reduction of CO_2 emissions by 0.25–1.36% was demonstrated for the ECAC airspace, and demand-capacity imbalances were significantly alleviated. The Full Solution targets the reduction of the total climate impact of aviation (both CO_2 and non-CO_2), through the incentivisation of avoidance of climate hotspots, at the (pre-)tactical level. Initial results tested the mechanism on a limited sample, where a 12.3% reduction of full emissions impact (measured in increase of temperature at the 20 years horizon) was demonstrated.

1.2 Technical Summary

The Green-GEAR project developed and matured three Solutions with the aim of reducing the climate impact of aviation in two ways: For once, enabling optimum green trajectories and reducing vertical separation (with higher capacities at optimum flight levels) through the use of geometric altimetry leads to increased efficiency and lower CO_2 emissions of the *individual flight*. Further reduction of climate impact at the *network level* is achieved through business and operational incentivisation of climate-friendly flight planning in the form of route charging. A second step includes addressing the equally important non-CO_2 effects by stimulating the avoidance of areas with high climate impact contributions.

Vertical Guidance using Geometric Altimetry (GeoAlt, Solution 0406, target TRL 2) considering geometric operations relevant to all flight phases within the TMA (climb, descent and approach), with the key difference being that aircraft are now required to use geometric altimetry as the primary reference for altitude reporting and vertical navigation, with GNSS as the primary navigation source. Two options for this end state were explored: Method 1 envisages a replacement of barometric altitude constraints on flight profiles with geometric ones (i.e. the only change against current flight path definitions would be the altitude reference), improving operational efficiency and safety by allowing continuous climb or descent through the current transition layer. The aim of Method 2 is to additionally enable route separation based on vertical path performance limits, i.e. there is a published 3-D geometric path with vertical containment assumptions. This is a paradigm change against current operations, where only the lateral flight path has a full nominal definition.

The Solution was assessed under both nominal and non-nominal conditions. The impacts on fuel burn, CO_2 emissions and airspace capacity were assessed quantitatively through fast-time simulations, whereas the impacts on aircraft systems and operations, ATC operations, safety and human performance were assessed qualitatively through expert judgement. The quantitative study covered the idealised end state (fully geometric operations); the transition state (mix of geometric and barometric operations) is addressed in the operational concept. As a result of the validation activities, a composite Solution of the two methods was found to be the optimal final end state of the concept.

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In accordance with the objectives, it was shown on the example of the Northern London TMA that

- airspace designers can use geometrically-defined vertical paths to create greater flight efficiencies in the TMA than can be achieved using current day (barometric) principles. The cumulative results provided a net benefit overall for fuel and emissions at 2035 traffic levels; there was an average fuel disbenefit of 2 kg per flight in the climb phase, offset by a larger average benefit of 24 kg per flight in the descent and approach phases. The overall decrease in fuel consumption is mostly a result of the optimised procedure-designed vertical profiles enabled by geometric altimetry;
- GeoAlt can enable the safe removal of the transition layer with no safety or human performance showstoppers at this stage of project exploration, improving environment and safety by removing variation due to atmospheric conditions and potential for human error;
- aircraft design considerations identified with no technical showstopper for descent and approach using geometric instead of barometric altimetry for required navigation performance (RNP) arrivals down to the intersection with the final precision approach segment. In this last flight phase before landing, the vertical guidance is by geometrical reference already today (e.g. through the Instrument Landing System), which allows for a simplification of the charting and cockpit procedures. On the other hand, the use of a prescribed vertical path for departures was found to have significant impacts on airborne systems and operations.

For completeness, use cases for geometric altimetry in the cruise phase were also assessed; these showed a small fuel disbenefit on average in the given short and medium length flight scenarios and also operational drawbacks, as both optimum cruise and recommended maximum operating altitudes for aircraft are determined by atmospheric conditions and thus necessarily defined barometrically. Conversely, geometric cruise could potentially be considered as part of a broader rollout alongside a geometric TMA if there is a demonstrable benefit at the system level, as indicated by Green-GEAR’s other Solutions.

GNSS jamming and spoofing threats as seen today challenge the concept. Barometric fallback should only need to be operated very infrequently. The deployment of Geometric Altimetry solutions in all phases of flight should thus await the (ongoing) implementation of the necessary mitigations, but this does not preclude follow-up research. Recommendations include to consider a transition between GeoAlt in the TMA and standard barometric altimetry in cruise. Also, the high-capacity TMA that has been used as an example in Green-GEAR has particular problems with required level-offs in climb for traffic separation, which may not be relevant in other high-capacity TMAs. Nevertheless, the safety and efficiency benefit of removing the transition layer and the ease of integration with emerging airspace users such as drones should be studied, while it is noted that the concept could be deployed locally, i.e. there is no need to implement it in every TMA. Therefore, higher-fidelity assessment of the target concept of operation is recommended, a quantitative analysis of Method 1 to trade off costs and benefits, and further development of ground and airborne technical functions, notably the latter’s implementation through the flight Management system (FMS).

Separation minima (SM, Solution 0407, target TRL 2) aims to reduce CO_2 emissions and increase capacity by further reducing separation minima in the en-route phase of flight and for current and future aircraft types alike, enabled by the higher accuracy of geometric vs. barometric altimetry, while keeping the level of safety of operations within an acceptable level. The reduction of separation

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includes aircraft currently in service, zero emissions aircraft and other new entrants, such as unmanned aircraft systems (UAS) and high-altitude operations (HAO) aircraft. 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 (thus extending current **r**educed **v**ertical **s**eparation **m**inima (RVSM) airspace beyond FL 410, as geometric altimetry does not suffer the same degradation with altitude as its barometric counterpart). This new concept is termed RVSM 2 and intentionally does not foresee further modifications of separation provision beyond the reduction of the vertical separation minimum initially, i.e. without proof of necessity.

The Solution work has focused on the assessment of safety under the assumed full application of the concept, as safety is not the only but arguably the most relevant potential showstopper. As this assessment is dependent on assumptions about traffic mixes, levels and patterns, the European airspace (more precisely the European (EUR) Regional Monitoring Agency (RMA) region) is taken as a reference, even though the concept would likely be introduced on a global scale. The safety assessment has been executed in three validation exercises: a collision risk analysis (CRA) addressing the technical (nominal) risk of aircraft collision through analytical modelling; a wake turbulence risk analysis (WTRA) executed through fast-time simulations of several full-day scenarios for the European airspace; a functional hazard assessment (FHA) considering the operational (non-nominal) risk analytically. These assessments have been compiled in a preliminary safety case providing an over-arching perspective on the risk.

In accordance with the objectives,

- the tools for the risk evaluation in terms of simulation software to quantify collision risk and wake turbulence were (further) developed and validated for the purpose, and the initial RVSM 2 concept taking into account UAS and HAO aircraft was developed as described above;
- the above safety assessment has been produced addressing risks under nominal operations (collision and wake encounter risks) and under non-nominal operations (operational and failure risks) thus deriving safety requirements for the altimetry system; also an initial, qualitative capacity analysis has been performed.

  The results show that the collision risk could possibly be met by a small margin, based on observed rather than specified performance of GNSS altimetry system error (ASE) and flight technical error (FTE). However, regulatory and legislative aspects in terms of tightening the flight control specifications and obtaining guarantees of GNSS performance from the respective system providers will likely pose a significant, possibly insurmountable challenge. For the wake vortex risk the simulations predict a substantial increase (by a factor of three to four on average for occurrence with small changes in severity) against the current concept of operations. This would mean a degradation of safety, so possible operational / functional mitigations (by a new safety net, airborne or ground-based, and/or procedural adaptations) are suggested. The FHA has identified the need for a controlled airspace and an update of airborne and ground-based safety nets, including but not limited to the airborne collision avoidance system (ACAS). In sum, the operational safety is a substantial challenge but not obviously infeasible.

  The initial capacity analysis shows that there are no restrictions on using the additional flight levels from the collision risk point of view, while the implications of the mitigation of the wake vortex risk would need to be further investigated. Even if today they are (sector) capacity restrictions due to controller workload, these may be relieved with increased automation, and

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there are many bottlenecks due to unusable parts of airspace that would benefit from added capacity in usable ones.

In an exemplary comparison for a very common aircraft type it was further indicated that flight efficiency might be increased by allowing aircraft to fly closer to their preferred flight levels through the finer granularity, outweighing the penalties identified in the GeoAlt Solution's cruise study for cruise flight with geometric reference as such. A robust quantification would require a fast-time traffic simulation for the whole of the EUR region and with a sufficient degree of realism, which was beyond the scope of the present analysis. Indeed, further research is required to conclude whether the Solution is viable not only from a technical, but also from the cost-benefit perspective.

Green route charging (Green RC, Solution 0408, target TRL 2) intended to develop 'Green route charging' mechanisms that incentivise airspace users to reduce the environmental impact of aircraft operations, limited to the en-route charges. These are collected from airspace users (AUs) and are proportional to the costs of provision of en-route air navigation services (ANS). The route charging mechanism principally allows the so-called modulation of costs/charges to incentivise desired behaviours, although this is not yet implemented. The focus here has been to develop mechanisms and modulations that would result in the best trade-off between the reduction of overall environmental impact, and keeping the economic and capacity impacts stable.

Given the complexity of the task, the GRC Solution is being developed in two stages: the Initial and Full Solutions. The Initial Solution focuses on reducing horizontal inefficiencies caused by differences in unit rates and the mitigation of demand-capacity imbalances at the strategic level, i.e. without impact on processes at the tactical level, thus promoting flight paths reducing CO_2 emissions. The Full GRC Solution investigates the possibility of reduction of the total climate impact of aviation (both CO_2 and non-CO_2), through the incentivisation of avoidance of so-called climate hotspots[3] at the (pre-)tactical level.

In accordance with the objectives,

- green route charging mechanisms were developed through use cases in collaboration with stakeholders. The proposed mechanisms were discussed and fine-tuned with the stakeholders (e.g. AUs, air navigation service providers (ANSPs), the Network Manager (NM)), reviewing the current practice and additionally collecting desired characteristics of the newly proposed ones through the stated-preference (SP) method (for AUs). The SP served to quantify their acceptance of the proposed green route charging mechanisms in terms of willingness to pay (WTP) or 'utility' (i.e. total satisfaction, including but not limited to direct costs);
- existing network models were extended and adapted to simulate the implementation of the GRC mechanisms and used to assess their effectiveness and impact on stakeholders and network, through comprehensive assessment across different indicators and the trade-offs achieved by different options. The validation scenarios used in the fast-time simulation exercises were based on a set of representative days of European air traffic, carefully selected

[3] A climate hotspot is a volume of airspace where the atmospheric conditions are such that flying through it creates much higher climate impact (e.g. 95th percentile). They have been assessed as defined by algorithmic climate change functions (aCCFs) evaluating meterolological forecasts.

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to reflect the dynamics of the air traffic network throughout the year. Feasibility was addressed by ensuring that the Solutions are compliant with stakeholder needs by verifying the underlying model assumptions. Feasibility ensured, the evaluation focused on the environmental impact of the solutions:

The **Initial Solution** demonstrates a reduction of CO_2 emissions (ENV1) by 0.25–1.36%, with the most pronounced improvements observed for flights entirely within ECAC airspace. Demand-capacity imbalances in strategic planning were significantly alleviated, with capacity violations decreasing by 91.2–94.1% across the traffic periods assessed.

Due to the complexity of non-CO_2 emissions, the project first assessed whether the climate hotspot-based approach foreseen by the **Full Solution** was viable, requiring a simplified new model. Initial results tested the mechanism on a larger (but limited) sample, where it was demonstrated that most of the KPIs were affected in a slightly negative or neutral manner, except the PI on full emissions, which showed a 12.3% reduction of full emissions impact (measured by ATR20. i.e. the total emissions, CO_2 and non-CO_2, produced by a flight, or a set of flights, measured in general in nanoKelvin of increase of temperature at the 20 years horizon).

The validation results demonstrate promising trends in environmental efficiency, demand-capacity imbalance reduction, and cost savings. The limited sample size and reliance on historical data from 2019 temper the statistical certainty, while operational realism is constrained by the absence of edge cases. On the other hand, the consistent performance across different scenarios strengthens confidence in the applicability of the environmental modulation for CO_2.

Promising research avenues that warrant further investigation include expanded operational scenarios, i.e. more diverse traffic conditions (e.g., extreme weather, major disruptions) to assess robustness under atypical operational environments. The modulation could also be tailored to specific aircraft types or engines, especially as regards (future) zero-emissions aircraft (which would still need to avoid contributions to congestion). Dynamic pricing could also be the scope of further studies, to investigate the impact of varying charge modulation strategies at the tactical level, which might need the deployment of machine learning enhancements. Finally, uncertainty is a big issue, especially for the non-CO_2 emissions. A significant research effort is needed to enhance the accuracy of the models of climate hotspot prediction in view of the dynamicity of the atmosphere, to take into account the heterogeneity of the aircraft and engines flying in Europe and then to manage the remaining uncertainty more rationally.

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2 Project Overview

2.1 Operational/Technical Context

The European Green Deal[4] set the objective of reaching net-zero greenhouse gas emissions by 2050, which requires a shift in the mobility towards smarter and environmentally sustainable operations. As such, aviation also needs to develop solutions for emissions reduction. Measures like changes in aircraft propulsion (electric or hydrogen powered aircraft, wide-spread use of Sustainable Aviation Fuel (SAF)) will have a significant bearing on the environmental footprint of aviation but will it be decades before they produce full effect, and hence shorter-term solutions are needed. So Green-GEAR focused on options with highest impact and feasibility for the air traffic management (ATM) operations, directly linked to air navigation services (ANS), and optimising flight trajectories of current and future aircraft types and traffic mixes alike.

The Green-GEAR project developed and matured three Solutions that will reduce the climate impact of aviation in two ways: enabling optimum green trajectories and reduced vertical separation (with higher capacities in optimum flight levels) through the use of geometric altimetry directly reduces noise and greenhouse gas emissions through increased efficiency of the *individual flight*. Further reduction of climate impact, including the equally important non-CO_2 effects, is obtained through business and operational incentivisation of climate-friendly flight planning in the form of route charging, stimulating the avoidance of areas with high climate impact contribution.

As there is the need for accelerating the aviation emissions reduction, the Solutions developed need to be understood and accepted by all aviation stakeholders. To this end, the consortium involved stakeholders in different phases of the project through consultations and workshops.

Vertical guidance using geometric altimetry (GeoAlt)

Outside of the Final Approach, commercial aircraft, military aircraft and general aviation currently rely on a barometric pressure model to determine the altitude which they use to navigate their vertical path. A fixed relation between measured static pressure and indicated altitude is used (ICAO Standard Atmosphere barometric formula), with the assumed pressure at sea level being the only configurable parameter irrespective of the actual state of the atmosphere. In cruise, a standard setting for this value is used (STD setting, 1013 hPa), and the resulting vertical position indication is denoted as flight level (FL). As a consequence of the STD setting, the absolute accuracy of the indicated altitude can be several thousands of feet off, but the relative accuracy is sufficient for vertical separation of traffic. Closer to the ground, obviously a large deviation of displayed altitude cannot be tolerated: here the reference value is determined such that the MSL altitude at the runway threshold is displayed correctly (QNH setting, for commercial traffic) or the runway altitude is displayed as zero (QFE setting, typically for sports aviation). It is important to note that the altitude obtained through this process and the actual altitude generally will only coincide at the reference altitude itself, i.e. the runway threshold, due to deviations between the theoretical and actual state of the atmosphere.

This model requires that there be a **Transition Layer** between where local and standard pressure datums are used, see Figure 1. The nominal altitude of the Transition Layer varies from state to state

[4] Communication on The European Green Deal | European Commission (europa.eu)

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and sometimes within a Flight Informastion Region (FIR), while its actual vertical position and thickness is dependent on the weather. Setting and changing the pressure datum is reliant on manual action by the pilot, and airline Standard Operating Procedures (SOPs) vary in terms of when the change is actioned. Typically, SOPs dictate either:

(a) The pressure datum is changed at the altitude the aircraft reaches the Transition Layer, or

(b) The pressure datum is changed at the time the flight is cleared to an altitude on the other side of the Transition Layer.

which results in flight inefficiencies in a number of ways:

- There is a safety risk that incorrect transmission or entry of QNH will lead to an incorrect indication of onboard altitude, which could lead to insufficient terrain clearance or a level bust, potentially putting the aircraft in conflict with other traffic.
- There is a capacity limitation due to pressure variations compared to STD pressure leading to loss of highest useable Altitude (below the Transition Layer) and lowest usable Flight Level (above the Transition Layer) [5].
- There is an inefficiency in fuel burn and related emissions, including noise, for any standard instrument departure (SID) or standard instrument arrival (STAR) procedures transiting the Transition Layer, as their design needs to take into account the considerable vertical uncertainties.

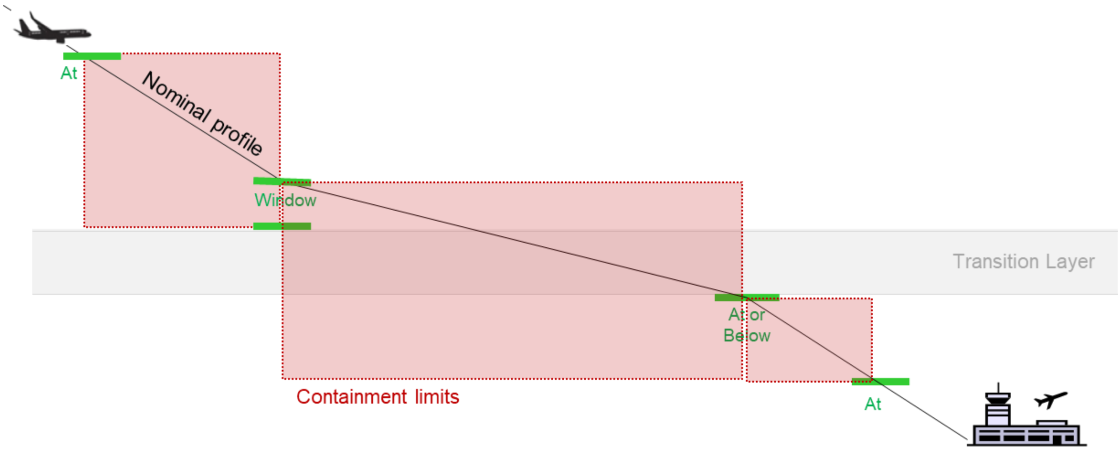

Figure 1: Airspace inefficiencies due to the reliance on barometric vertical navigation in descent and approach. Flight profile efficiency is limited by the Transition Layer, whose vertical position and thickness change with the weather, requiring large containment areas.

Large containment limits are necessary to accommodate for the changes in displayed barometric altitude when flying through the Transition layer where the manual pressure setting is changed (local

[5] The Transition Altitude (TA) typically relates to the climb and denotes the highest useable altitude prior to transition to Flight Level (FL). When transitioning through the TA, the pilot needs to switch from local pressure (QNH) to standard pressure (STD). The Transition Level (TL) typically relates to the descent and denotes the lowest useable FL prior to transition to altitude. When transitioning through the TL, the pilot needs to switch from standard pressure (STD) to local pressure (QNH).

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pressure - QNH/QFE to standard pressure - STD in climb and vice versa in descent), see Figure 1. Besides, altitude compensation in temperature, in particular when temperature is extremely cold, can limit the use of lower altitudes.

Furthermore, geometric altimetry for vertical navigation is used for specific operations on Final Approach, introducing another altitude reference datum. These procedures include Approach with Vertical Guidance LPV, SBAS or GBAS or RNP APCH using LNAV/VNAV and are reliant on single constellation GNSS. Technically, the ground-based Instrument Landing System (ILS) or Microwave Landing System (MLS) also provide a geometric path. Thus the transition from a barometric Initial Approach to a geometric Final Approach creates another unpredictable transition.

An additional complexity is that the altitude of the Transition Layer can vary between 3,000 ft and 18,000 ft depending on the country, and even from region to region within a country. For example, in the UK the Transition Altitude is 3,000 ft outside of controlled airspace and generally 6,000 ft within controlled airspace, except for Manchester TMA which is at 5,000 ft. By contrast, the USA and Canada use a common 18,000 ft Transition Layer. There was a big push for a common European Transition Altitude but, after detailed project work, the idea was abandoned due to cost and practicality issues.

Outside of the Final Instrument Approach, which defines a vertical path, vertical containment is only assured at waypoints that have altitude constraints associated with them, as air traffic control (ATC) are currently unable to define Instrument Flight Procedures in three dimensions: there is no vertical equivalent to (lateral) Performance Based Navigation (PBN). On one hand, this enables aircraft to determine their own vertical profile in-between the waypoints so long as they comply with the waypoint constraints (see Figure 2), allowing for optimisation of the individual flight profile. From an ATC perspective on the other hand, this amounts to large uncertainties about where the aircraft could be in the vertical plane in-between waypoints, leading to sub-optimal airspace designs due to large allowances for deconfliction with other routes and flights. There is a continued need for tactical intervention even if, with experience, the controller will know what to expect, which reduces tactical uncertainty considerably.

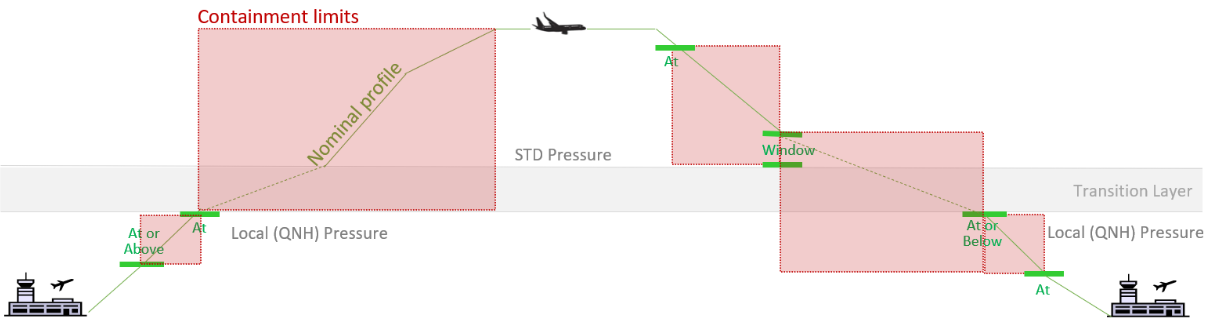

Figure 2: current operating method for vertical profile definition using barometric altimetry

Finally, in cruise, aircraft fly along the isobars meaning that the geometrical cruise level fluctuates according to pressure variations. This results in small geometric climbs and descents during cruise flight when the atmospheric pressure is changing, requiring small changes of the engine thrust. However, flying along the isobars ensures that the flight state with respect to the surrounding atmosphere is not changing and thus the aerodynamic drag of the aircraft remains constant. This reduces thrust fluctuations that would otherwise occur when using geometric altimetry. It needs to be assessed whether one of these counteracting effects would outweigh the other, and what would be the overall effect on fuel burn.

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Green-GEAR has thus assessed the use of GeoAlt for all flight phases, applying to both en-route and TMA environments; however, the main expected benefit, or impact, would be to TMA operations.

A prerequisite for geometric altimetry is obviously Global Navigation Satellite Systems (GNSS) equipage. This is commonplace and increasing, with more and more aircraft being equipped with augmented GNSS in the shape of Satellite-Based Augmentation Systems (SBAS) sensors, and particularly with emerging airspace users, such as delivery/inspection/survey drones and air taxis, that use geometric altimetry for vertical reporting and navigation in all phases of their flight. This currently puts them on a different altitude datum to crewed commercial aircraft, military aircraft and general aviation, which use geometric altimetry in the terrain avoidance function but not for navigation (with the exception of the final approach segment at multiple locations in Europe and the US). The GeoAlt application in the TMA will thus promote use of GNSS Landing Systems (GLS) and SBAS Landing System (SLS) employing the Ground-Based Augmentation System (GBAS) or respectively the Satellite Based Augmentation System (SBAS), which offer significant advantages in cost, airspace and procedures design against the conventional Instrument Landing System (ILS).

Conversely, GNSS in its current implementation is susceptible to intentional or accidental interference. The number of GNSS jamming occurrences are increasing around the world in particular near military theatre of operations, while the GNSS spoofing threat is being considered by airworthiness authorities for future GNSS airborne receiver standards.

Separation minima (SM)

The overall ambition of the Separation Minima Solution is to reduce CO_2 emissions and increase capacity by further reducing separation minima at various phases of flight, while keeping the safety of operations at least at the current levels.

Worldwide aircraft separation standards are laid down in ICAO Doc 4444 (Procedures for Air Traffic Management) [85], ICAO Annex 2 (Rules of the Air) [86] and ICAO Annex 11 (Air Traffic Services) [87]. 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 altitudes 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 are defined depending on the pairing of the categories. This means that aircraft following a higher MTOM (category) aircraft are given a greater minimum spacing.

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While many opportunities exist for further reduced separation minima, Green GEAR has focused on the possibilities of reducing vertical separation in a geometric altimetry environment, in line with the GeoAlt activity (see above).

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 pressure gradient becomes smaller, translating a given pressure measurement error into a larger altitude error), the separation minima from FL290 to FL410 were set at 2000 ft. In view of expected major benefits for the division of airspace and in order to increase capacity above FL290, the Reduced Vertical Separation Minima (RVSM) programme was introduced at ICAO level in 1980, aiming to reduce the minimal vertical separation to 1000 ft also between FL290 and FL410. This activity, which took 18 years until operational implementation, has studied the height-keeping performance above FL290 and tightened the requirements for barometric altimetry in terms of sensor calibration and constant performance monitoring [81][82].

The main driver for the determination of the value of 1000 ft for the vertical separation minimum has been to meet the Target Level of Safety (TLS) for the **collision risk** between two aircraft which are nominally vertically separated but actually operating on (nearly) the same altitude due to large, opposite-sign altitude-keeping errors. To implement RVSM in operations, airworthiness performance requirements for aircraft, new operational procedures and a comprehensive means of monitoring the safe operation of the system were established [81][82]. For the operational implementation, an evaluation of the collision risk dependent on the actual traffic mix is required, necessitating individual implementation per airspace (ICAO region, e.g. [83] or [84]). Monitoring activities are constantly performed, with a yearly evaluation of the observed vs. specified performance and also the continued applicability of the assumptions on traffic patterns, by RVSM Regional Monitoring Agencies (RMAs).

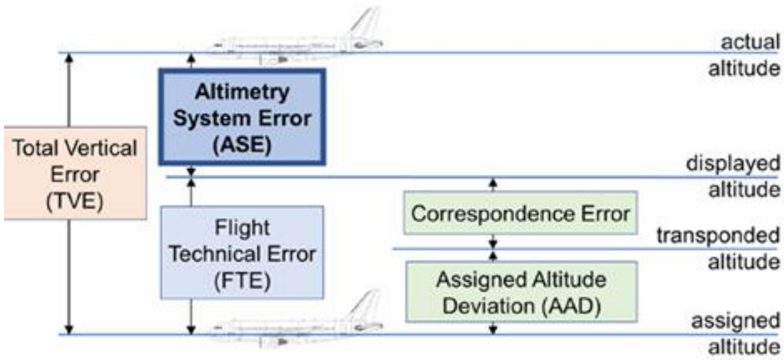

Figure 3: vertical errors definition (drawn after ICAO Doc 9574)

Even if in the current operation commercial, military and general aviation need to rely on barometric measurements for determining the altitude of the aircraft, most of them are equipped with GNSS receivers. Geometric altimetry can achieve greater accuracy (i.e. lower Altimetry System Error (ASE), see Figure 3) at high altitudes than barometric altimetry, as it is not sensitive to local weather and is not impacted by the low atmospheric pressure. Green-GEAR's Separation Minima solution has been defined to investigate whether the use of geometric altimetry would allow a reduction of the vertical separation minimum from the current 1000 ft in RVSM airspace (FL290 – FL410), or 2000 ft above it (FL410 – FL600), to 500 ft. It is conceivable that a combination with advanced modes of separation (e.g. dynamic and/or geometry-dependent horizontal separation) might be needed to ensure the safety of operation. The initial concept (termed the **RVSM 2** concept, see Figure 4) investigated here,

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however, only foresees changes to the vertical separation minimum, as all changes to the standards need to be justified not only postulated. Even though most commercial air traffic does not operate extensively above the current upper limit of RVSM airspace at FL410, the envisaged reduction of separation would benefit aircraft currently in service, zero emissions aircraft and new entrants expected to join the aviation system such as Unmanned Aircraft Systems (UAS) and High-Altitude Operations (HAO) aircraft [20][30].

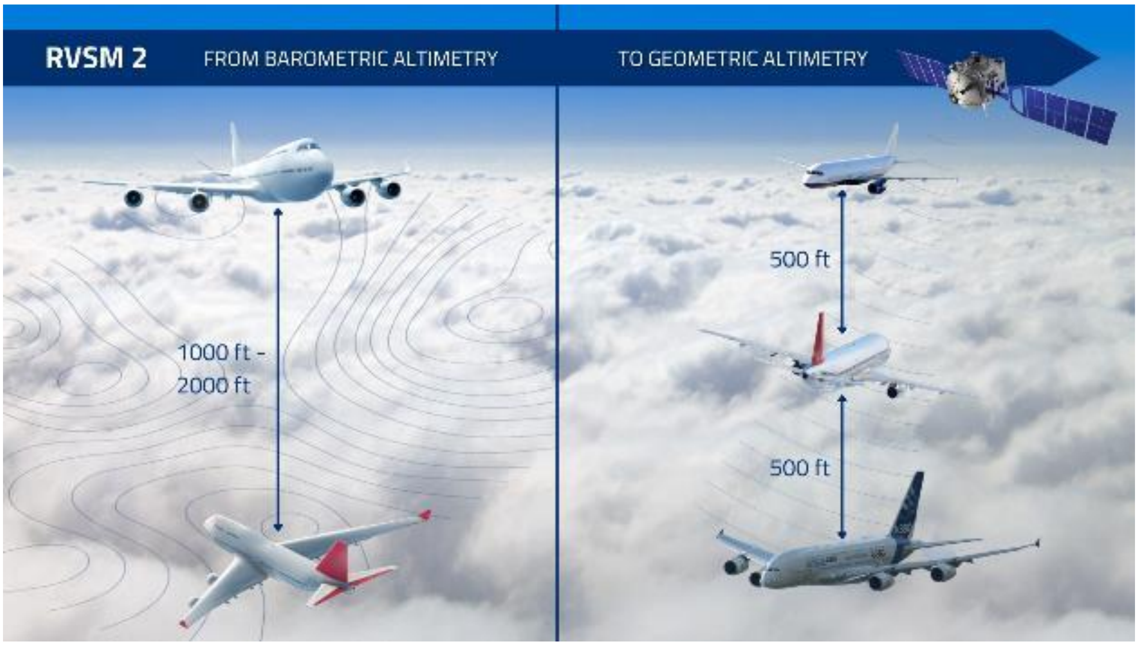

Figure 4: artist's impression of current operations and the RVSM 2 concept.

As the added ASEs 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. I.e., the Flight Technical Error (FTE, capability of the flight control system to keep the aircraft at the envisaged altitude assuming perfect measurement) needs to be reduced as well to achieve an acceptable Total Vertical Error (TVE), see again Figure 3 [52].

Besides the collision risk under reduced vertical separation, for which an established evaluation method endorsed by ICAO exists, the impact on the **wake vortex encounter risk** (both in frequency of occurrence and severity) needs to be assessed. This has not been of particular interest in the original RVSM programme [102], probably due to widespread belief that the vertical travel of wake vortices is quite limited, while accidents at 1000 ft vertical separation have happened in the meantime [76] and recent in-situ measurements have even shown significant remaining circulation (vortex strength) at 2000 ft below the generator's altitude [75]. A comparative study of en-route wake encounter risk could thus also lead to relevant insights into the current operations, complementing work in R-WAKE [77].

The potential capacity benefit associated with RVSM 2 has a strong environmental aspect as well. As far as possible with ATC's capability to handle additional traffic, extended capacity could help limiting the necessity of detours because of congestion or adverse weather. In addition, in crowded upper airspace many aircraft cannot fly at their most fuel-efficient altitude today – RVSM 2 has the potential to address this inefficiency by providing not only more capacity, but also a finer granularity of available flight levels.

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Green route charging (Green RC)

The third Solution under Green-GEAR is a set of “Green route charging” mechanisms that ***incentivise airspace users to reducing the environmental impact of aircraft operations***, limited to the en-route charges here (i.e. excluding terminal charges).

The current European charging system has limited influence on the environmental behaviour of aviation stakeholders. Although the EU States are mandated by the Single European Sky (SES) Performance and Charging Scheme[6] to set up Performance Plans that include a target on *average horizontal en-route flight efficiency of the actual trajectory,* they have no obligation to establish incentive schemes for ANSPs to achieve this target. Similarly, the SES Performance and Charging Scheme foresees the possibility for States to set up mechanisms modulating air navigation charges that incentivise AUs to *reduce the environmental impact of flying*, but none has been implemented so far.

The common system and policy for the establishment, calculation and collection of route charges in the European Union and beyond is laid down in the Multilateral Agreement relating to route charges[7] that is signed by 41 contracting states and is implemented by EUROCONTROL’s Central Route Charges Office (CRCO). This agreement, which applies the principles set in the International Civil Aviation Organisation’s (ICAO’s) Policies on Charges for Airports and Air Navigation Services [89] , is not binding and does not include any environmental provision per se. However, it is consistent with the EU rules set under the Single European Sky framework, in particular the Performance and Charging Scheme, meaning that any evolution taking place in this scheme will be implemented de facto via the CRCO route charging.

With the Green Deal ambitions, there is an urgent need to reinforce the environmental dimension of the route charging system, and address its limitations.

The Green route charging Solution is planned to be scalable with a two-step implementation corresponding to two levels of ambition/complexity, linked to the time horizon of the possible implementation:

1. ***Initial Solution,*** taking only CO_2 into account (i.e. minimising fuel burn), aiming at accelerating the maturity and Solution acceptance operationally. This level was be considered at pre-TRL1 at the beginning and has been brought to TRL2 in the project’s self-assessment.
2. ***Full Solution***, involving the reduction of climate impact of both CO_2 and non-CO_2 emissions. The TRL was at 0 at the beginning and is TRL1 at the end of the project.

The solution specifically explored the following issues:

- How to eliminate flight inefficiencies resulting from the route charging scheme itself (i.e. detours as a result of unit rate differences) and incentivise environmentally friendly trajectory planning?
- How to ensure revenue neutrality with appropriate recalibration of charges? Regardless of the approach, revenue neutrality is likely to require some form of ex-post reconciliation process, possibly involving some modification to the existing revenue risk sharing arrangements. Those will also be explored.

[6] Commission Implementing Regulation (EU) No 2019/317 of 11 February 2019

[7] https://www.eurocontrol.int/publication/multilateral-agreement-relating-route-charges

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- How to ensure that ICAO principles of Doc 9082 [86] are all satisfied, in particular gradual increases / decreases in charges as well as modulation related to new air services are applied on a temporary basis?

Expected synergies

The GeoAlt Solution determines the feasibility of using geometric altimetry instead of barometric altimetry in various phases of flight, including cruise. This concept is taken up in the Separation Minima Solution, which investigates the use of geometric altimetry to facilitate a reduction of vertical separation minima. Both approaches face common challenges (notably GNSS jamming and spoofing issues), but it is also conceivable that only the reduction of the vertical separation minima will make the use of geometric altitude reference in cruise viable, as it is not obviously beneficial a priori (by contrast to geometric altimetry in approach, where potential efficiency and safety benefits are more pronounced). Lastly, the Green RC Solution tries to incentivise the avoidance of certain climate-sensitive portions of the airspace, where the added capacity in adjacent regions and altitudes brought by reduced Separation Minima limits the necessity for detours.

2.2 Project Scope and Objectives

Green-GEAR has aimed to make significant contributions at two levels: (i) at the methodological level, by developing new concepts of operations while using geometric altimetry (GeoAlt and SM); (ii) at an applied level, by formulating and assessing test-case Instrument Flight Procedures (GeoAlt), reduced separation (SM) concept, and new route charging mechanisms.

In order to achieve these contributions, seven high-level objectives had been defined in the project proposal. One of them (Objective 2.2) has been amended during the project execution and is cited in its final form. In detail, the project's objectives have been the following:

Vertical guidance using geometric altimetry

Objective 1.1: Determination of whether Geo Alt can safely deliver a net fuel efficiency benefit for an ATM network. This objective targets the TMA environment.

Success criteria for measuring the objective achievement: The analysis of a TMA route structure based on the London TMA shows a net environmental benefit with a minimal, or zero, negative impact to capacity and no unaddressed safety issues.

Objective 1.2: Determination of whether GeoAlt can enable safe removal of Transition Layer. This objective targets the whole descent from cruise to landing, and the climb from take-off to initial cruise altitude.

Success criteria for measuring the objective achievement: There is a technical and/or procedural solution with a demonstrable environmental benefit with minimal, or zero, impact to capacity and no unaddressed safety issues.

Objective 1.3: Use of Geometric Altimetry instead of barometric altimetry for required navigation performance (RNP) arrivals down to the intersection with the final precision approach segment, where the vertical guidance is by geometrical reference already today. This objective addresses the (extended) TMA environment.

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Success criteria for measuring the objective achievement: simplification of the charting and cockpit procedures for the connection of the RNP and XLS vertical paths (both flown with same sensor and with same descent angle), with safety and environmental benefits owing to higher RNP trajectory.

Separation minima

Objective 2.1: Development of the tools for evaluation of a novel concept for reduced separation minima when geometric altimetry is used, while considering UAS & HAO aircraft. It is part of the work to define the most promising flight phases and scenarios.

Success criteria for measuring the objective achievement: availability of validated simulation software to quantify collision risk and wake turbulence risk for chosen scenarios.

Objective 2.2: Estimation of the capacity potential of RVSM 2 (reduced vertical separation of 500 ft in upper airspace). This objective targets RVSM airspace and includes HAO aircraft.

Success criteria for measuring the objective achievement: the safety assessment is produced addressing risks under nominal operations (collision and wake encounter risks) and under non-nominal operations (operational and failure risks) thus deriving safety requirements for the altimetry system, and an initial capacity analysis is performed.

Green route charging

Objective 3.1: Develop green route charging mechanisms (i.e. through use cases) in collaboration with stakeholders, quantifying the stakeholders' acceptance of the proposed green route charging mechanisms.

The goal was to develop green route charging mechanisms that consider the environmental impact, economic (for air navigation service providers (ANSPs), AUs, and the network overall) and capacity constraints. The proposed mechanisms were discussed and fine-tuned with the stakeholders (e.g. AUs, ANSPs, NM), reviewing the current practice and additionally collecting desired characteristics of the newly proposed ones through the stated-preference method for AUs. Through the implementation of stated-preference survey we tried to quantify the willingness to pay (WTP) or 'utility' (i.e. total satisfaction) of AUs, across various key performance indicators (KPIs). This method is much stronger in assessing the stakeholder acceptance than the more common practice of inferring preferences from post hoc (e.g. machine learning) models.

Success criteria for measuring the objective achievement:

- short list of use cases/mechanisms;
- stated-preference (SP) survey designed and administered;
- the use cases/mechanisms prioritised based on the user acceptance quantification (i.e. willingness to pay).

Objective 3.2: Network model/s extended and adapted to simulate the implementation of the green route charging mechanisms.

This objective aimed at implementation of the green route charging mechanisms (Objective 3.1) in the network models, to be able to assess their effectiveness and impact on stakeholders and network, through the comprehensive assessment across different indicators and the trade-offs achieved by different options.

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Success criteria for measuring the objective achievement: Among the analysed use cases, some demonstrate positive environmental impact when simulated at network level, while being assessed as acceptable by a majority or stakeholders from a cost efficiency or operational perspective. This will be achieved through:

- the model/s applied at regional level; the results used to inform stated-preference survey (see Objective 3.1);
- the model/s applied at network level, integrating the stakeholder acceptance quantification;
- results obtained and used in the Solution assessment.

2.3 Work Performed

Work in all three Solutions started with a refinement / definition of the respective concept, leading to tentative Solution descriptions. A dedicated activity coordinated a harmonisation of the assumptions and the evaluation concepts [35]. Owing to the low TRL, all validation activities were done by analytical modelling, fast-time simulations and/or expert judgment. The outcome hase been used to update the three Solution descriptions.

Vertical guidance using geometric altimetry

High level R&I objectives for this Solution were developed into seven Use Cases through the Green GEAR Initial OSED for Geometric Altimetry [29]. These use cases covered the application of geometric altimetry for vertical navigation within a TMA environment and were assessed under both nominal and non-nominal conditions.

Two methods for this end state were considered for climbing and descending traffic. Method 1 considered flight procedures continuing to constrain vertical flight profiles through the use of altitude constraints, but the constraints become geometric altitudes instead of barometric. Method 2 involved a paradigm change in flight procedures, now being vertically defined by published geometric paths with vertical containment assumptions.

The validation objectives covered both qualitative and quantitative assessment. The impacts to fuel burn, CO_2 emissions and airspace capacity were assessed quantitatively, while the impacts to aircraft systems and operations, ATC operations, safety and human performance were assessed qualitatively.

DesignAir, a NATS in-house airspace design tool, was used to construct the reference scenario as a fully barometric TMA (see Figure 5). This is an optimised TMA based around PBN procedures with altitude or Flight Level constraints applied where necessary for procedural separation. DesignAir was also used to construct a fully geometric TMA for the Solution scenario based on the design principles as described in the Exploratory Research Plan (ERP) [39] (see Figure 6).

AIXM files for both models were exported from DesignAir and imported into AirTOp, a fast-time simulation tool used to model and simulate both the reference and Solution scenarios with traffic samples.

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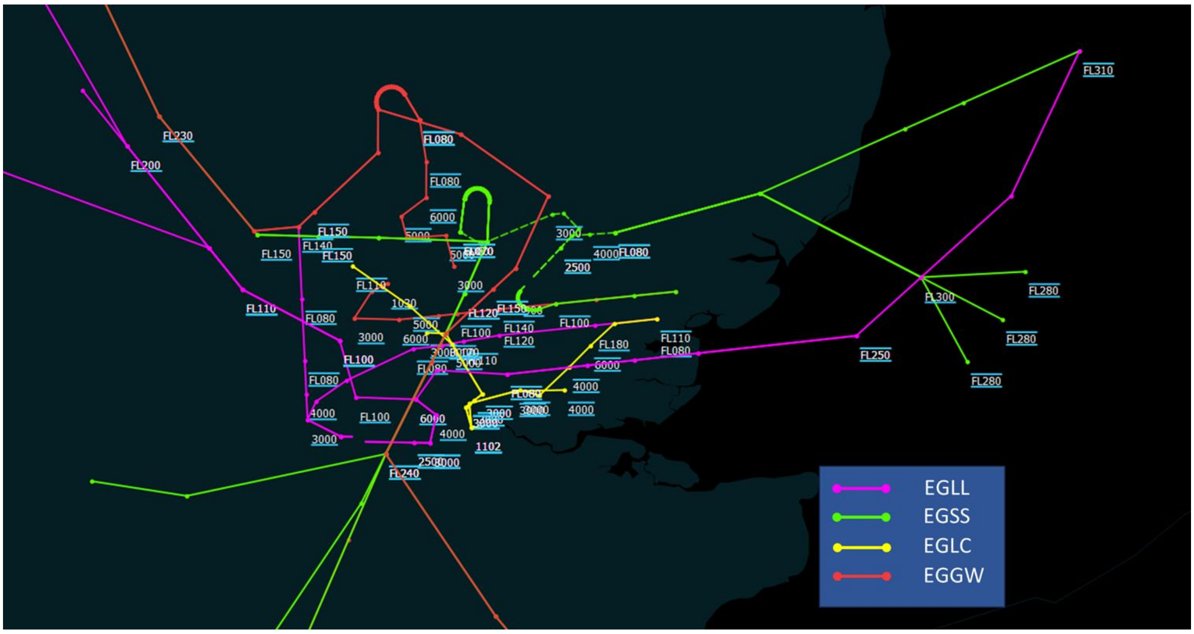

Figure 5: Reference Scenario - barometric altimetry with Altitude and Flight Level constraints at waypoints

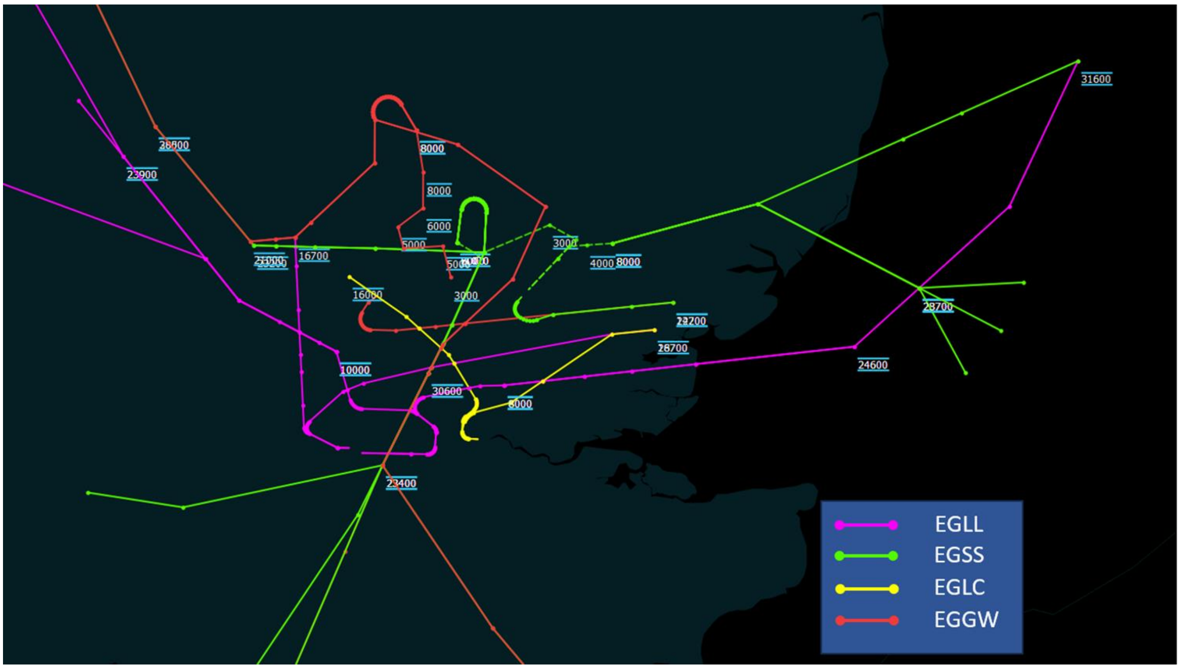

Figure 6: Solution Scenario - fixed climb/descent gradients based on geometric point-to-point vertical paths

A more detailed evaluation of approach and departure on aircraft level, taking account many effects that are beyond the accuracy of ATM simulations, has been exemplarily performed by using a desktop simulation of an Airbus A320 aircraft. For this purpose, the simulation model of DLR's research aircraft ATRA (Advanced Technology Research Aircraft) shown in Figure 7 has been used as described in more detail in the Exploratory Research Report (ERR, D3.3) [45]. Because the simulation model is based on data from extensive flight testing, the flight dynamics of the model are considered to be as accurate as possible without proprietary data from the airframe manufacturer. However, the Flight Control

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System (FCS) and Flight Management System (FMS) are of limited fidelity due to lack of detailed data and due to being implemented in-house with limited resources. Most of these limitations do not affect this evaluation, but a few of them remain relevant. All these limitations have been addressed, and a solution has been established to deal with these limitations so that these do not affect the evaluation negatively, see again the ERR [45].

Figure 7: DLR research aircraft A320 ATRA

In total, 14 different scenarios have been evaluated (4 approach procedures and 3 departure procedures, all of these in a baseline configuration and in a Solution configuration) with different types of altimetry and different values for the atmospheric pressure. This resulted in a total number of 294 simulation runs that required about 30 hours of computation time.

The difference between the baseline and the Solution scenario is illustrated in Figure 8 using the NUGRA1H STAR and BNN27L transition at London Heathrow Airport as an example. The lateral profile consists of the same waypoints or nearly the same waypoints but with modified altitude constraints. Generally, all solution scenarios only include “At altitude” constraints and no other altitude constraint types such as “At or Above”. Also, the solution scenarios do not include any level flight segments in the approach procedure but instead all constitute continuous descent approaches (CDAs). For the departure scenarios, the same principle is applied that the scenarios only include “At altitude” constraints and no other altitude constraint types such as “At or Below” and no level flight segments. In the example shown here, the main difference between the baseline scenario and the solution scenario is that the first altitude constraint after the top of descent is at FL239 in the solution scenario instead of FL200 in the baseline scenario. This allows the aircraft to stay at a higher altitude for longer and thus reduces the fuel consumption. Also, the solution scenario includes only two altitude constraints along the Standard Instrument Arrival Route (STAR) (one constraint at the beginning of the STAR at FL239 and one constraint at the end of the STAR at FL100) and then one altitude constraint at the end of the transition for the ILS intercept. The waypoints and altitude constraints are different for each scenario, but the same principle how the Solution versions have been optimised compared to the baseline versions applies to all scenarios in the same way. In principle, the baseline versions should be flown with barometric altimetry and the Solution versions should be flown with geometric altimetry, but to distinguish between the influence of the altimetry type on one hand and the influence of the procedure optimisation on the other, the baseline versions and the solution versions both have been simulated with barometric altimetry and with geometric altimetry.

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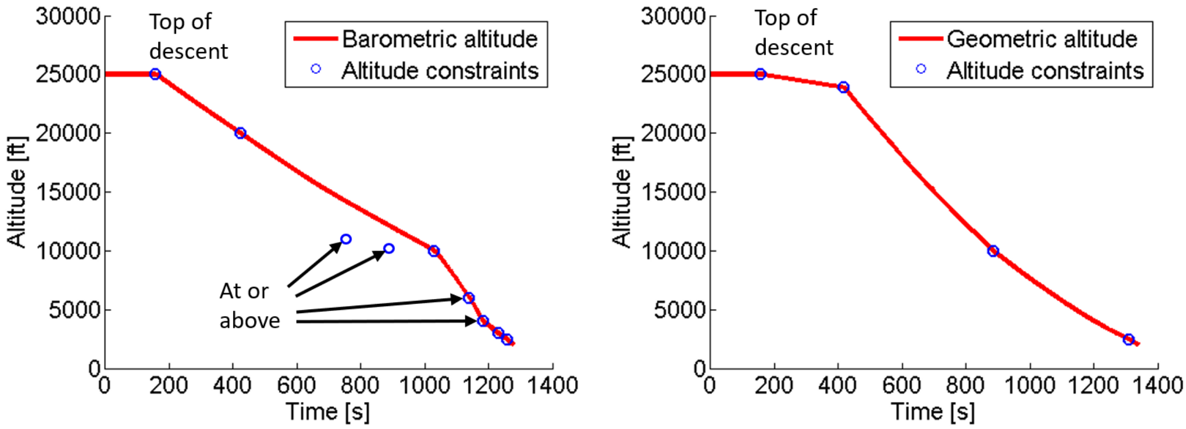

Figure 8: Example scenario to illustrate the difference between the baseline approach scenario (left hand side) and the solution scenario (right hand side)

For completeness, and also addressing a research question posed in the Call, use cases were also developed to assess geometric altimetry in the cruise phase. As rightly observed in the Call description, flying to barometric reference implies climbing and descending against Earth's gravitational field with the isobars. On the other hand, aircraft performance is determined by the atmospheric conditions i.e. primarily tied to barometric altitude. The differences between the two methods are small, however, so that again the validated high-fidelity aircraft simulation of DLR's research aircraft ATRA was utilised as for the above climb and descent analysis. An initial generic simulation study was conducted to investigate individual flight physical effects from the use of GeoAlt separately.

Figure 9: Overview of the tracks of all evaluated flights for the geometric cruise investigation

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Based on the knowledge thus gained, a dedicated fast-time simulation was developed and used to re-simulate and analyse the cruise sections of 617 consecutive actual flights of a single A320 aircraft of a major German airline between 25th June 2024 and 19th October 2024, see Figure 9. The differences in fuel consumption under barometric and under geometric altimetry as well as in flight times were quantified [41][45].

Human Factors and Safety were addressed in dedicated expert workshops. Safety and HP assessment was carried out through a workshop focus group paper exercise to identify the key features for ATC in a fully geometric environment. During the workshop, ATC experts were asked to consider the use of a geometric-only environment as well as a mixed mode of operation between geometric and barometric altitude references.

The impact on aircraft systems and architecture was addressed through a paper study based on expert judgement. This assessment was conducted with a team of airborne-industry experts in ATM, Cockpit Operations, Flight Management System (FMS) and Navigation systems (other than FMS), also supported by Flight Performance specialists. The assessment covered technical and operational feasibility considerations in the following areas:

- Flight Management System (FMS) and Flight Performance
- Navigation Systems (other than FMS)
- Management of Jamming & Spoofing Threats
- Compatibility with Surveillance Functions
- Cockpit Systems and Flight Crew Operation

The validation objectives covered both qualitative and quantitative assessment. The impact to fuel burn, CO_2 emissions and airspace capacity were assessed quantitatively. The impact to aircraft systems and operations, ATC operations, safety and human performance were assessed qualitatively.

Also, an Economic Evaluation of the Solution was performed. Preliminary quantitative figures on fuel benefits were available from validation activities, but only a qualitative costs assessment could be performed, in line with TRL2 expectations.

Separation minima

If aircraft use GNSS for vertical navigation and if such a geometric altimetry system is introduced, it might be feasible to reduce the currently applied vertical separation minima. A reduction of the vertical separation minima would increase capacity and would allow aircraft to fly closer to their preferred altitude, thereby possibly offering efficiency, cost and environmental benefits. The possibility to operate with reduced vertical separation minima is the main topic of the Separation minima Solution. There are basically two reasons why this might indeed be feasible. The main reason is that GNSS altimetry is supposed to be more accurate than barometric altimetry, and the related margins in spacing might therefore be reduced. The second reason is that the accuracy of GNSS altimetry is not as sensitive with respect to altitude as barometric altimetry is. The currently applied vertical separation minima of 2000 ft above FL410 could then be reduced, even if GNSS altimetry is only as accurate as barometric altimetry at lower altitudes. Starting from a low TRL, there has been no prior evidence that the reduction of vertical separation based on geometric altimetry might work, but it has rather been the project’s aim to study the viability. Due to this fact and due to limited resources, a simple future concept of operations is assumed for RVSM 2, where only vertical separation minima are changed (target state).

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The RVSM 2 concept aims to reduce vertical separation minima 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 a geometric altitude reference with altimetry based on GNSSs, provided by some yet-to-be-determined system (e.g. GPS, Galileo, multi-constellation, dual frequency, with or without augmentation by SBAS, etc.). It is assumed that all airspace users have sufficient capabilities, routes could be free or fixed and the fleet is comparable to today in physical dimensions and flight performance. Alternate types of propulsion (electrically or hydrogen-powered aircraft) are included in the concept, but not separately treated at the present low TRL. The European airspace is taken as a reference, even though the concept would likely be introduced on a global scale, to allow a quantification of the relevant performance indicators. The concept was further described in the Initial OSED (D4.1 [30]) and the Final OSED (D4.6 [52]).

In this first step we have investigated the safety of operations in the RVSM 2 target state, without regard to possible transition mechanisms in the adoption of the new concept, as these are undoubtedly possible showstoppers but moot points when the feasibility of the target scenario is not given. The safety work was structured by considering the technical (nominal) risk and the operational (non-nominal) risk separately, which add up to the total, or overall risk.

The three Validation activities have addressed both the ***nominal (technical) risk*** contributions:

- the technical collision risk under nominal conditions (**Collision Risk Analysis**, CRA). This study has followed the collision risk assessment process developed by ICAO for the original RVSM concept (EUROCONTROL, 2001) and included the development of the necessary extensions, tools and inputs (iD4.1 [43]). The approach was to adopt the Target Level of Safety (TLS) of 1000 ft RVSM, to adapt the ICAO Collision Risk Model (CRM) to RVSM 2, from that to derive the requirements on the altitude keeping performance and to translate this into conditions on the Altimetry System Error (ASE) and Flight Technical Error (FTE) distributions, as documented in the ERR (D4.4 [50]);
- the risk of encountering wake turbulence of a strength that cannot be shown to be dealt with safely under all circumstances, again under nominal conditions (**Wake Turbulence Risk Analysis**, WTRA). Note that a wake encounter is a highly dynamic process depending on many variables, including reaction of flight control system and / or pilot flying, and therefore difficult to quantify in absolute terms. Additionally, a TLS for the wake turbulence risk is not available. Therefore, a comparative study has been performed, as documented in the ERR (D4.4 [50]).

  The study was conducted through fast-time simulations of several full-day scenarios for European region traffic, comparing baseline (reference) and new concept of operations. The reference scenario was an original traffic sample for the complete EUR region that comprises flight plan trajectories based on flight levels with the current separation scheme (1000 ft vertical separation in RVSM airspace, 2000 ft above). The Solution scenario was a modified version of the same traffic samples based on flight levels with 500 ft vertical separation, adapted for this purpose as described in [51]. Different models for altitude keeping were developed for barometric and geometric altimetry, respectively, based on the figures from the collision risk assessment [43]. Low- and high-wind scenarios were investigated, as the wind directly influences wake transport and indirectly vortex decay (through usually higher turbulence levels associated with stronger winds, although this is not always the case at cruise altitudes). Due to a limitation of the weather data input driver, older data sets had to be used; namely, 3rd June 2014 was selected as a day with particularly low average wind speeds in the

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RVSM airspace and 14th February 2014 as a high-wind-speed day. This results in four full-day scenarios: the low-wind-speed scenario and the high-wind-speed scenario both with 1000 ft / 2000 ft vertical separation under barometric and with 500 ft vertical separation under geometric altimetry.

Existing fast-time simulation tools (see Figure 10) have been extended as part of the work with the above features (path definition under geometric altimetry, modelling of barometric and geometric altitude keeping); additionally a concept to model the distribution of the stochastic variability of wake vortex behaviours has been developed and implemented. The deduction of atmospheric turbulence from numerical weather prediction (NWP) data has been added, and a coarse quantification and classification of encounter severity has been performed through an evaluation of the so-called roll control ratio (RCR) that relates the rolling moment induced by the wake vortex in a (hypothetical) worst case to the aircraft's available control power to counteract it (see ERR, D4.4 [50], iD 4.2 [51] and also section 2.4 below). The so-called SHAPe method [96][98] was added to the wake conflict detection that, depending on the chosen RCR value, determines vertical and horizontal additions to the cross section of the actual wake corridor that need to be avoided (or nullifies the cross section if the given RCR value is not reached anywhere within it). This approach is dependent on the properties of the encounter aircraft and thus may need to be repeated for the same generator's wake, making it relatively time consuming. On the other hand, the question of how far an existing wake can be safely approached is obviously dependent on the encounter aircraft: a generic answer would need to assume the worst case and thus include too much conservatism for the purpose.

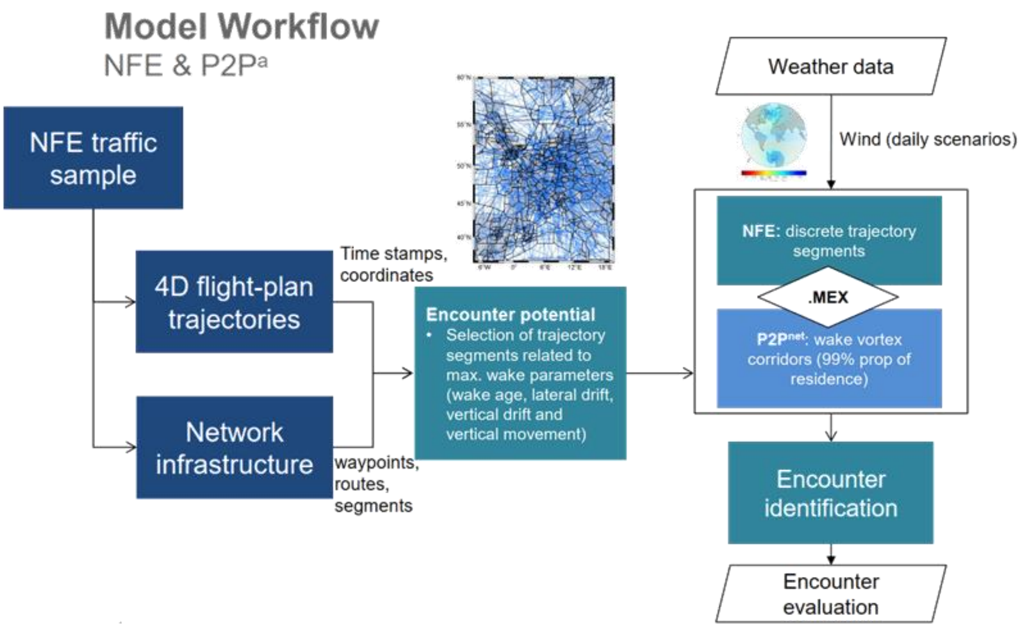

Figure 10: overview of the NFE-PINGUIN environment extended for use in Green-GEAR[90]

It must be noted that the assumptions and the detail level of the modelling (particularly as regards atmospheric properties) do influence the numerical results; indeed several improvements to the modelling have been identified and implemented during the analysis beyond the immediate necessities for geometric altimetry, as described above (see also iD 4.2 [51]). It seems reasonable to assume that the obtained simulation accuracy is sufficient for

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comparisons between reference and envisaged future operations to hold sufficient significance at the envisaged TRL 2 maturity (concept definition).

as well as the ***non-nominal (operational) risk***:

- a **preliminary safety case** in the shape of a Functional Hazard Assessment (FHA) addressing consequences and mitigations under non-nominal conditions, i.e. in the presence of system failures or of operational errors, in addition to the nominal risk was conducted (D4.3 [46]). The Safety Case also provides an over-arching perspective on the risk of the three parts as a whole. Like in the CRA, the TLS of 1000 ft RVSM for the non-nominal risk was adopted. The RVSM 2 concept was described functionally, by considering the altitude information-, airborne- and ground domains separately. Primary and secondary functions were defined, where the secondary functions ensure safety in case the primary functions are jeopardised. Hazards were defined by considering the failure of primary functions, and the hazards were analysed to provide estimates of the severity and maximally allowable likelihood, which serve as a safety specification. These results will serve as guidance on the further development of the concept.

Further KPIs beyond safety, namely the expectable performance improvements in terms of expectable en-route airspace ***capacity increase*** and ***fuel efficiency benefits*** of flying closer to the optimal altitude, as enabled by the finer granularity of the flight levels in the RVSM 2 concept, were addressed in a simple, qualitative estimation as part of the Solution's ECO-EVAL [49].

Green route charging

Route charge "is a levy that is designed and applied specifically to *recover the costs* of providing facilities and services for civil aviation." [89]. The Route per State Overflown route charging system is applied in Europe, which implies that a flight needs to pay a route charge to each State crossed. Each State needs to establish one or more 'en-route charging zones'. The charging zone is a volume of airspace that extends from the ground up to, and including, upper airspace, where en-route air navigation services are provided and for which a single cost base and a single *unit rate* are established. Unit rate is a unique tariff per service unit. The number of service units for a flight is determined by the product of the distance and weight factors. The *distance factor* is proportional to the great-circle distance (GCD) between entry and exit points to each of the charging zones, whereas *the weight factor* is introduced to relate the price to be paid for the air navigation services to the productive capacities of the aircraft. Therefore, heavier aircraft are expected to pay more for the air navigation services than lighter aircraft. The weight factor is less than proportional related to the maximum take-off weight of the aircraft.

Relying on this framework, the Green Route Charging (GRC) Solution was designed in two steps: the Initial and Full Solutions, which were developed and assessed through modelling and stakeholder consultations as is outlined in D5.2 (ERP) [33] and reported in D5.7 (Final ERR) [56]. The validation exercises have then tested the feasibility and effectiveness of the GRC mechanisms in realistic operational scenarios to ensure their robustness and scalability.

The ***Initial Solution*** introduces a novel route charging mechanism designed to improve horizontal flight efficiency and reduce associated CO_2 emissions. It addresses route charging from a strategic flight-planning perspective, providing AUs with a price signal that promotes more efficient planning in terms of environment, while also enhancing predictability and optimising capacity use. For example, it incentivises trajectories that avoid congested airspace during peak periods and removes the incentive to take detours to bypass costly airspaces.

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The flight distance was assumed to be a proxy for CO_2 emissions. Vertical flight efficiency was not modelled at this TRL level. Other ATFM phases was not covered, as the setting of the unit rates for route charging is a strategic process that needs to be stable for at least a year of operations.

Two options were explored in the Initial Solution:

- A **'Modulation of route charges' (MRC)** mechanism, applied to the current trajectory-based route charges. A modulation factor *M* is determined for each route of a given origin-destination traffic flow, with the objective to reduce the environmental impact of flying, while addressing the airspace congestion. In addition to the modulation factor, the mechanism also gives a 'delay signal'. This indicates that on some routes, a small strategic time shift of departure time could reduce additional delays and/or congestion occurring on the day of operations.

- An **'Origin-destination charging' (ODC) combined with the 'Modulation of route charges' (MRC)** mechanism. In the ODC mechanism, the distance factor is calculated on the great circle distance between the origin and destination airports, which is therefore identical for all routes of a given city pair, irrespective of the trajectory/distance flown. ODC establishes a simple reference for airspace users, with an identical baseline charge for all routes of a given city-pair. By construction, the ODC baseline aggregated at network level is a 'clean baseline' that does not include 'route charges optimised' trajectories and is therefore not biased by difference in trajectory lengths resulting from differences in unit rates. The modulation factors *M* and the proposed time shifts that the MRC model produces are then applied to the ODC baseline.

Both mechanisms were designed to be compliant with the revenue neutrality principle, i.e., each ANSP receives the same revenue for the same amount of workload (measured in terms of service units).

Figure 11 illustrates the main functions of the Initial Solution in the wider ATFM context, and the related information flows with stakeholders. This is valid for both options, MRC or ODC+ MRC.

The validation exercises performed on the solution covered three main objectives: feasibility, environmental impact and reduction of demand-capacity imbalances. The feasibility of each model – defined as the compliancy of the model with the stakeholders' requirements – was validated using a small-scale scenario (a statistically representative sample of the real traffic). The environmental impact was assessed over two AIRAC cycles: a high traffic and a low traffic period.

Demand-capacity imbalance was assessed by comparing the number of capacity violations between the reference, MRC and ODC+MRC scenarios. Although, as is well known, capacity is generally managed at the tactical level, this study has also investigated the effect that strategic-level actions may have on mitigating demand–capacity imbalances, since previous research has highlighted their potential benefits [95] [74]. Specifically, it has been observed that a distribution of traffic aligned with the declared nominal capacities of airports and sectors across the entire network can reduce the amount of ATFM delay imposed on the day of operations in two ways. First, by eliminating the need to impose ATFM delay to respect nominal capacities, as these are already balanced through the mechanism. Second, by reducing the amount of delay resulting from other types of regulations that impose stricter limitations than the declared nominal capacity. The causes of such regulations can typically only be identified on the day of operations (e.g., weather-related restrictions). Even in these cases, however, strategic traffic redistribution could lead to smaller delays, as the number of flights exceeding imposed capacity would be lower than under current conditions, given that nominal

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capacity is practically not enforced. Therefore, a strategic redistribution of air traffic has the potential to reduce the number of ATFM interventions on the day of operations, and the Initial solution has shown very promising results in this regard (see section 2.4).

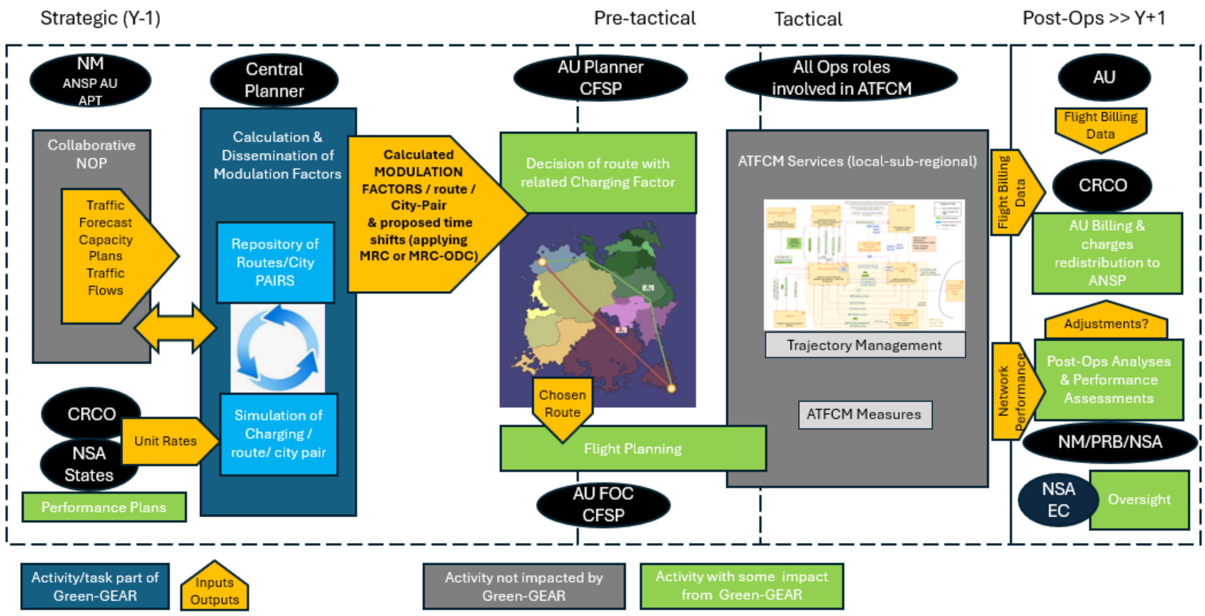

Figure 11: GRC Initial Solution - ATFM phases and stakeholders' view.

The ***Full Solution*** aimed to incentivise the use of climate friendly trajectories, when considering both CO_2 and non-CO_2 emissions. The mechanism rewards avoidance of climate sensitive areas (i.e. climate hotspots, determined by calculating the CO_2 and non-CO_2 combined effects), while still leaving the flexibility for aircraft operators to use the said areas, against a higher charge, and keeping revenue neutrality.

The SP survey and the climate hotspots analysis come together in the model that is tasked to implement the Full GRC Solution. The way airlines behave when hotspots appear will drive the efficiency of the policy that could lead to a reduction of CO_2 and non-CO_2 emissions. Here, we assume that airlines minimise a utility function when choosing their flight plans pre-tactically. This utility function is composed of the parameters that can be sorted out in two big categories, delay and cost, with added category for the environmental impact.

Hence, the core policy idea is to identify climate hotspots, either strategically or tactically and put a modulated charge on top of the standard route charges on the trajectories going through hotspots, to de-incentivise their choice. The extra revenues coming from the modulation may then be offset by a decrease of the route charges at a strategic level to ensure revenue neutrality for ANSPs.

Given a modulation scheme and an offset mechanism the task is then to forecast how much airlines will avoid the hotspots, keeping in mind constraints linked to capacity. The full GRC Solution is interested in setting strategically modulation levels that will be applied tactically, akin to how ANSPs compute their unit rates for the next reference period. Hence, the level of details at the tactical level may be enough in the analytical model to capture most of the impact that we want to see from the mechanism. This method was used in validation exercises.

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The model used is a simple one designed to show the main trends that can be expected when applying the Full Solution. The Full Solution consists in the following process:

- At the start of a reference period (e.g. every 5 years, or every year), the Central planner decides the 'environmental impact tax rate' (EI rate).
- X hours before a flight plan (e.g. 6 hours, typically on the same time scale than weather forecast), the Central planner defines environmental "hotspots", in the form of 3D volumes.
- Any flight going through a hotspot has to pay an extra charge in the form of the distance flown through the hotspot times the EI rate.

The model presented aims at answering the following questions:

- Given a traffic forecast at the beginning of the reference period and an environmental impact (EI) rate, what is the expected impact of the EI rate on the behaviour of airlines, without considering capacity issues, and what is the resulting impact on the KPIs? This prediction is called the 'free' prediction in the following, because it does not take into account capacity optimisation of EI impact.
- Similarly, what is the impact of the EI rate given capacity constraints? This prediction in the following is called the 'cap' prediction. It takes into account various capacity constraints.
- Finally, how much should the EI rate be to minimise the environmental impact? What is the impact of this rate? This prediction in the following is called 'full'.

KPIs: The impact of the EI rate has to be measured in several different dimensions. Given the scope of the model, we selected the performance indicators (PIs): Environmental impact (EI), ANSP revenues, airline costs, fuel consumption, and delays.

This model required various input data in order to compute the needed expected values:

- Typical trajectories for each OD (obtained via clustering),
- Airspace structure (simplified, we considered only a horizontal slice of sectors and one opening scheme),
- Average values for fuel consumption,
- Values of route charges,
- **Distributions of EI on each OD pair**,
- Distribution of external delays, fitted for each OD,
- **Behavioural parameters for airlines** (obtained from the stated preference (SP) survey).

The main work for input data for Full Solution focused on SP survey design, administration and analysis, climate hotspot determination (needed to determine EI), and trajectory determination.

An SP survey allows to directly collect respondents' preferences, as respondents articulate their choices, rather than researchers inferring preferences from actual behaviour, known as "revealed preference" (see section 5.1.1.3.1 of D5.2, ERP [33]). The survey aims to assess airlines' willingness to pay (WTP) for avoiding climate hotspots and their sensitivity to delays and costs. By focusing on four key attributes—cost sensitivity, short delay aversion, long delay tolerance, and environmental considerations—we gathered insights into what matters most to participants in their decision-making processes. Members of the Advisory Board, including representatives from airlines and IATA, assisted in recruiting participants. The survey was distributed via a survey link on September 25th, 2024 and

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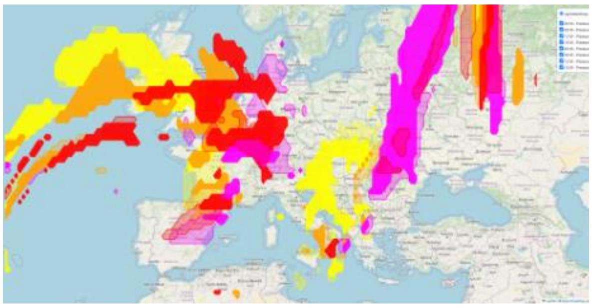
remained open until October 31st, 2024. We received 13 complete responses. Incomplete responses were removed from the analysis. Since an adaptive SP survey design was used, participants encountered varying numbers of choice tasks, resulting in a total of 128 observations across all responses.

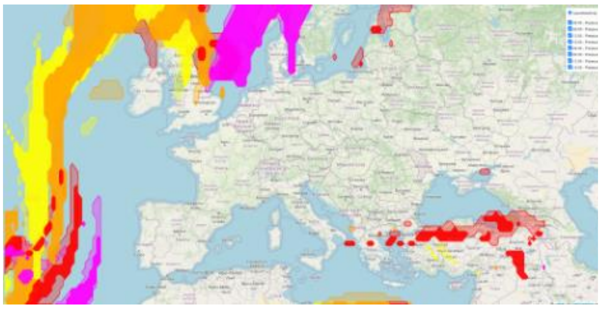
The analysis of SP survey responses reveals that cost sensitivity and long delay tolerance show statistical significance. Short delay aversion is significant for responses in the network carrier and low-cost carrier categories, while environmental consideration is less reliable, particularly within responses in the network carrier and regional carrier categories.

To determine the hotspots, we utilised the CLIMaCCF library on ERA5 data. First analysis used ERA5 data for four selected weeks (1st weeks of March, June, September, and December of 2019) to gain insights into the dynamics of climate hotspots. The hotspots are determined as a percentile of the value of aCCF merged (algorithmic climate change function), where the impact of different species is merged, and expressed in K/kg fuel. CO2 is excluded, as CO_2 effect does not depend on the state of the atmosphere.

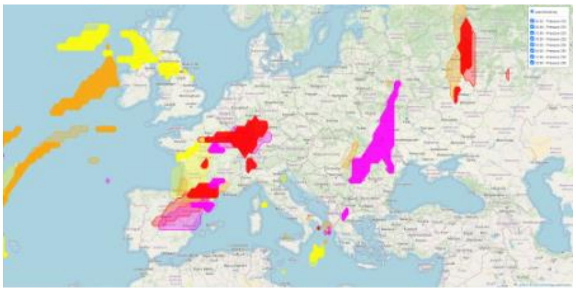
Figure 12 illustrates the progression of the hotspots over two days: one in September 2019 (left-hand side of the Figure 12), and another in December 2019 (right-hand side). The colours represent different times of day—yellow for midnight, orange for 06:00, red for 12:00, and magenta for 18:00—allowing us to observe how these hotspots shift with atmospheric movements. We examined two flight levels—FL340 at 250 hPa and FL360 at 225 hPa, with the hotspots at the latter level appearing more transparent in the depiction. Notably, the hotspot areas differ between levels, indicating that high-altitude avoidance patterns may vary.



Hotspots for 3rd September 2019, 95th percentile



Hotspots for 3rd December 2019, 95th percentile



Hotspots for 3rd September 2019, 99th percentile

Hotspots for 3rd December 2019, 99th percentile

Figure 12: Daily evolution of hotspots, for FLs 340 and 360, at 95th and 99th percentile.

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Additionally, it can be noted that the hotspot areas are significantly larger at the 95th percentile, highlighting the need to establish a suitable percentile for a route-charging scheme. Figure 12 depicts a possible seasonal difference in climate hotspots. The hotspots also depend on the **aircraft engine type**. Table 1 shows the percentile values for generic wide-body and single aisle aircraft, across the dataset that contains the month of September 2019 and first two weeks of December 2019.

Percentile	Wide body	Single aisle
0.90	1.584e-13	1.154e-13
0.95	1.955e-13	1.469e-13
0.99	3.677e-13	8.165e-13

Table 1: Percentile values of aCCF merged for generic wide-body and single aisle aircraft.

The identification of climate hotspots is influenced by weather forecast data (specifically, its resolution) and the selection of various parameters, as detailed in the related manual (Yin, Matthes, & Grewe, 2023).

Figure 13 illustrates the main functions of the GRC Full Solution in the wider ATFM context, and the related information flows with stakeholders.

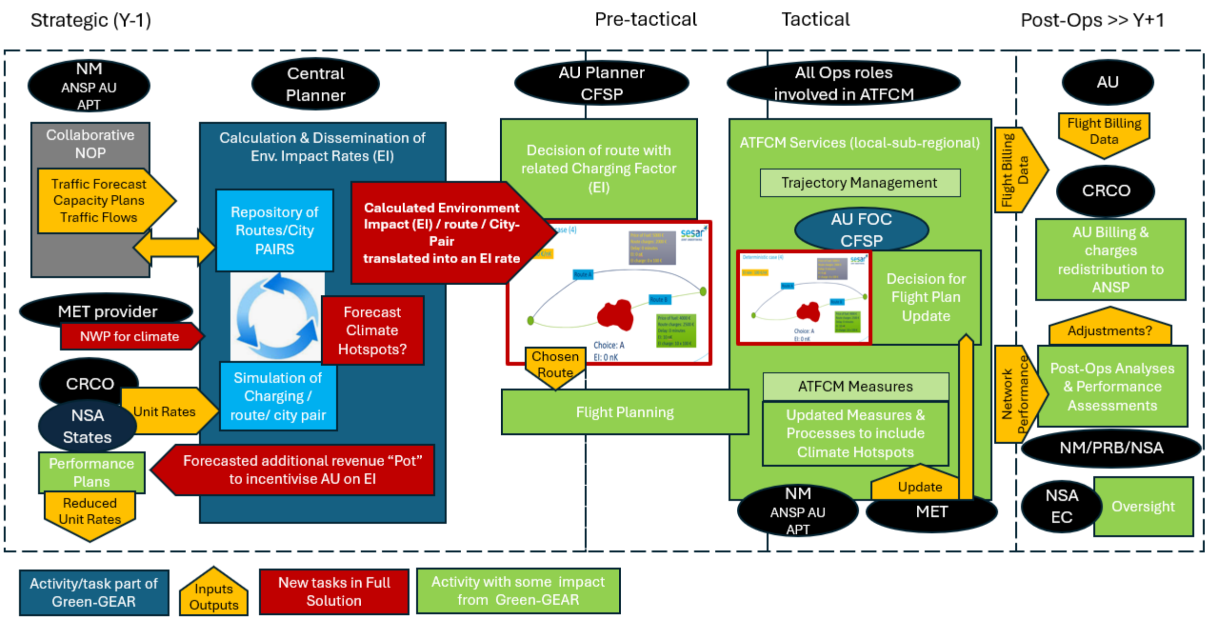

Figure 13: GRC Full Solution - an example of ATFM phases and stakeholders' view.

The results of the validation exercises for both Initial and Full solutions are presented in D5.7 (Final ERR) [56] and summarised in Section 2.4.

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Project level: common methods, data integration, stakeholder consultations

The planned Green-GEAR Solutions address different, but related topics. The planning and the requirements of specific experiments needed, having the same approach to definition of research hypotheses, definition of experimental/validation scenarios, reliability, sensitivity and validity of exercises, generalisation of the exercise results and their transfer to the operational environment, was secured through the application of common methods. As a part of this, the common baseline was envisioned across the Solutions, which was then adapted to individual validation exercise requirements. The common methods are described and published (online) in the "Green-GEAR – Common assessment methods" document [35].

Furthermore, two stakeholder workshops were organised with the Advisory Board members and other interested stakeholders. The workshops were split along the Solutions, to allow for more stakeholder involvement. The feedback obtained is included in Solutions' ERR and ECO-EVAL deliverables.

2.4 Key Project Results

As above, the results are grouped by Solution.

Vertical guidance using geometric altimetry

Results related to geometric altimetry in TMA (core Solution scope)

Two methods were addressed for the use of geometric altimetry for vertical guidance:

- **Method 1** - Waypoint/fix altitude constraints defined relative to geometric altitude instead of barometric.
- **Method 2 (Geo Path)** - Procedural vertical paths are defined as geometric paths with Instrument Flight Procedures (IFPs) defined in 3 dimensions; one sub-option with a vertical tolerance established in certification; the second sub-option as a Vertical-RNP type solution with onboard performance monitoring and alerting.

From an **airspace design** perspective, the use of Geo Path in TMA has been demonstrated to be practical and potentially beneficial.

In the fast-time simulation for the entire TMA, the **environmental results** were derived as a direct factor of the fuel results because the analysis only considered a measure of the CO_2 equivalent emissions (CO2e) directly generated from the fuel burn: fuel x 3.15.There were significant potential fuel benefits for Geometric Path in descent but minimal to negative fuel benefit for Geometric Path in climb, as indicated in Table 2.

	ARRIVALS			DEPARTURES		
	Fuel Burn (T)	CO2e (T)	% change	Fuel Burn (T)	CO2e (T)	% change
2023	-4,833	-15,224	-1.6%	-331	-1,042	-0.1%
2035	-5,949	-18,739	-1.8%	302	952	0.1%

Table 2: Combined summary of arrival and departure total fuel/CO2e in UK FIR.

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	ARRIVALS + DEPARTURES		
	Fuel Burn (T)	CO2e (T)	% change
2023	-5,164	-16,266	-0.8%
2035	-5,647	-17,787	-0.8%

Table 3: Overall Green Gear Total fuel benefit in UK FIR

Overall, there is a significant fuel benefit (Table 3).

No **capacity** increase was indicated through the proxy metrics analysed. However, there was no conclusive significant detriment to capacity either. Concerning sector entries per hour, the trend between the models is similar with no difference to traffic levels spread across the day. For the 2035 traffic sample, across all hours of the day there are on average roughly 10% more hourly sector entries in the reference scenario than in the solution scenario, and on average occupancy times increase marginally across all the sectors due to the less steep 7% climb profiles than statistically observed at 8% on the SIDs.

The analysis has also indicated that the overall number of interactions between aircraft in the Solution Scenario has increased by 27% compared to the Reference Scenario for the 2035 traffic sample. it was determined that these interactions were caused by shortcomings of the airspace design rather than the concept itself; these would be caught and resolved through standard iterative airspace design processes.

To address the primary objective on whether GeoAlt could enable the safe **removal of the transition layer,** controllers indicated that removing the transition layer in a fully geometric environment would be feasible and pose minimal hazards to the operation, in the context of the current day operation prior to airspace systemisation. This positive feedback suggests that removing the transition layer, from a controller point of view, would simplify altitude management without introducing significant operational challenges. Removing the transition layer associated with pressure datum changes between QNH and standard pressure eliminates the need for pilots to adjust altimetry mid-flight or the potential for the wrong QNH given. No major **safety** hazards were identified with the move to GeoAlt and the removal of the transition layer, additional consideration and analysis will be required for the transition to a systemised airspace on top of the transition to GeoAlt.

Regarding the **Human Performance** assessment (conducted for the ground side, i.e. ATCOs, but not for the airborne side, i.e. pilots), it was found that switching from barometric to geometric altimetry within the current airspace structure would likely have minimal impact on controllers' daily tasks, workload, and situational awareness. However, transitioning to a systemised airspace with geo-based prescribed lateral and vertical paths would shift the controller's role from active control to a primarily monitoring role, potentially decreasing situational awareness. In case of non-nominal conditions requiring fallback to traditional baro-based traffic management, this may lead controllers to experience a significant increase in workload.

Overall, while GeoAlt presents opportunities and benefits to the operation, a careful phased approach to its implementation will be essential to address any human performance issues as well as establishing the appropriate airspace design. Whilst no significant HP issues were identified, it should be noted that this was an early theoretical assessment that encompassed of several use cases and airspace environments. A switch from barometric to geometric constraints without changing the airspace was

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considered to be relatively simple and may result in managing less complex and easier interactions. However, with the development of an airspace change to a more optimised airspace, this in turn impacts the severity of the effect on roles, technology, communication and training for the controller.

In order to evaluate **flight performance** on aircraft level, an exemplary evaluation for a very common single-aisle airliner was conducted as described in the last section. The descent analysis shows several different effects: The change of the altimetry type influences the fuel savings by a very small amount and can be positive or negative depending on the barometric pressure (as expressed by QNH), while the change from baseline to solution descent profile results in average fuel savings of about 6.6% during this flight phase. These fuel savings are mostly not a direct consequence of the geometric altimetry but an indirect one as it enables an optimised descent. Also, the usage of geometric altimetry reduces the variance of the fuel consumption and therefore improves the predictability.

In climb, the influence of the altimetry type on the fuel savings similarly can be positive or negative depending on the QNH. For the example scenario, the change from the baseline to the solution climb profile results in marginal fuel savings of approximately 0.25%, due to two counteracting effects in the optimisation of the climb profile: the removal of the level-off segment in the solution scenario has a positive influence on the fuel savings, while forcing the aircraft to fly a fixed climb gradient has a negative one, as climb performance depends on weight and temperature, regarding the gradient also on wind. In contrast to the descent scenario, the usage of geometric altimetry in the climb scenario increases the variance of the fuel consumption and therefore decreases the predictability.

Generally, achieving a beneficial design for Climb is difficult as Climb performance varies significantly with aircraft type, weight, wind and temperature so any airspace design may require different SIDs for different aircraft categories to be effective or be limited to the lowest common denominator. From an airspace design perspective, Geo Path in climb offers the most predictable design in 3D. However, from an aircraft flight efficiency perspective, the more the vertical profile is constrained, the more challenging it would be for the individual flight to comply with the profile.

In addition, introducing prescribed vertical paths in Climb in the form of straight lines between altitude/FL constraints would have a significant impact on **aircraft systems**. A climb profile would have to be computed by the FMS, and a new type of guidance would have to be defined to ensure proper tracking of said profile (such capability only exists today for descent & approach). Technical feasibility assessment of such a major change would require further R&I work in collaboration with FMS suppliers.

Therefore, it has been concluded that the most suitable way forward for Climb phase is to use geometric altitude constraints at waypoints (Method 1) and only consider Geo Path in Climb in highly congested airspace when required for deconfliction as part of a composite solution together with Geo Path in Descent and Approach.

Regarding Descent and Approach phases, no technical showstopper has been found for the implementation of geometric altimetry with or without the Geo Path principle. However, an operational challenge has been identified for Geo Path: aircraft deceleration along a fixed vertical angle path is not the most operationally efficient, since in some cases the aircraft may need to start deceleration very soon and with a low deceleration rate, both of which may be operationally unpractical for flight crew and ATC for speed management purposes. Moreover, there is a significant diversity of aircraft deceleration performance, which means that some aircraft may have an adequate deceleration rate in clean configuration while others may not be able to decelerate without speed

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brakes or early flaps / landing gear extension, with the associated impact on noise and maintenance costs.

Based on the research outcomes, incremental steps have been identified for the deployment of Geometric Altimetry:

- Step 1 – Geo Approach procedures including not only final but also initial/intermediate approach segments.
- Step 2 – All altitude constraints within a defined airspace volume, e.g. TMA, switched from Baro to Geo Alt, with no airspace redesign.
- Step 3 (retained core Solution scope) – Composite geometric solution applied within a defined airspace volume, e.g. TMA, potentially divided into a set of sequential airspace changes, e.g. airport per airport. Geo Path applied to Descents where necessary for procedural deconfliction.
- Step 4 - Composite geometric solution applied within a larger airspace block, e.g. FIR. This solution may include geometric Cruise alongside geometric Approach, Descent & Climb, if beneficial as part of a holistic design. For, example if it enables RVSM 2.

Even when only targeting Step 3, the Geo Alt Solution introduces significant impacts on airborne and, to a lesser extent, ground systems. They cover the entire value chain involved in designing, managing and operating the new IFPs based on geometric reference, as well as related monitoring capabilities for timely switch to fallback operation based on barometric altimetry. The technical solution also addresses the transition between barometric and geometric airspace in nominal operations. A summary of airborne technical design considerations is provided in section 4.2.

The need to mitigate the increasingly present **jamming and spoofing** threats and become more resilient is confirmed, but this is a transversal challenge affecting whatever ATM Solution relying on GNSS for lateral and/or vertical positioning. So it is considered as a prerequisite for the GeoAlt Solution rather than part of its scope.

The way forward for airborne predictions computations is still to be consolidated since aircraft performance is always tied to barometric conditions and airborne systems do not currently have the capability to anticipate the pressure altitudes associated to the expected geometric altitudes. Whether the related technical solution can be standalone at airborne implementation level or would impose additional requirements on ground services such as AIM or MET, it is still to be assessed.

Regarding the **economic evaluation**, at the current TRL of 2, a preliminary benefits assessment could be performed quantitively, as described above, but the cost assessment could only be performed qualitatively.

Additional results related to geometric Cruise (not part of core Solution scope)

While the Solution definition is focused on Climb, Descent & Approach phases, the project has had the opportunity to conclude that the use of geometric altimetry is not operationally suitable for Cruise phase by itself, due to significant challenges inherent to the dependency of aircraft performance on barometric conditions, particularly regarding flight envelope (e.g. maximum operating altitude) and cruise altitude optimisation.

Indeed, aircraft performance is intrinsically based on barometric conditions, including the aircraft operating ceiling which is defined in pressure altitude.

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In today's **operations**, pilots can contribute to flight optimisation by requesting, when possible, a cruise flight level as close as possible to the optimum flight level computed by the FMS. The optimum altitude ("OPT ALT") is generally a few thousand feet below the maximum recommended altitude ("REC MAX"), which may be lower than the aircraft maximum certified altitude depending on performance-related flight and weather conditions.

In this context, a new paradigm defining in FMS a geometric cruise altitude and guiding accordingly may lead to locally exiting the aircraft flight envelope. Indeed, if the atmosphere's isobar is descending along the flight with regard to the geo altitude, this would be perceived by the aircraft as climbing in barometric conditions, potentially above the REC MAX.

In such event, the pilot would need to request to descent to a geo cruise altitude compliant with the maximum pressure altitude. Note that this occurrence would not be predictable as avionics systems cannot currently anticipate the isobar variations.

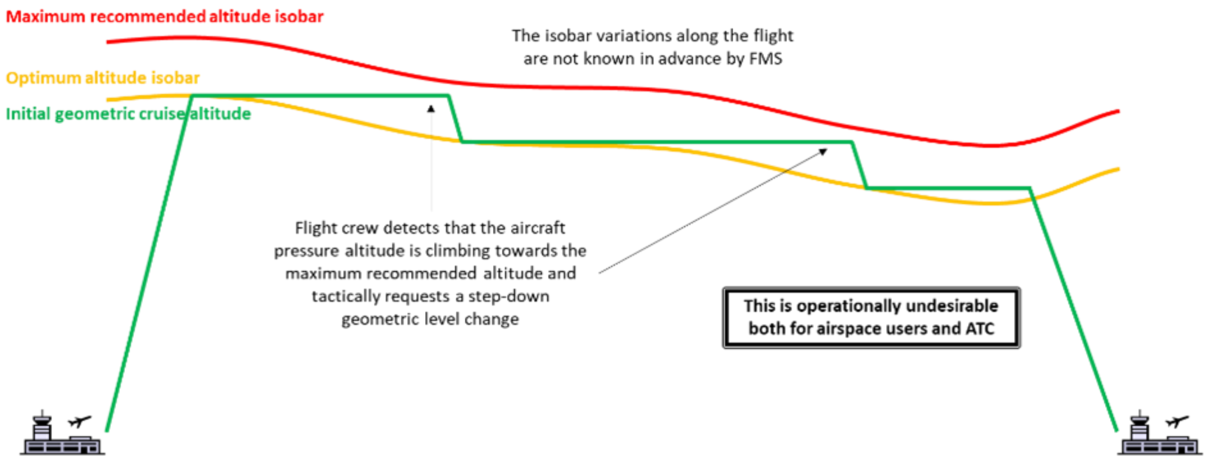

Figure 14: Geometric navigation in cruise – flight envelope and cruise altitude optimisation challenge (a)

The operational impact could be reduced by upgrading FMS and FOC flight planning tools to use meteorological data with pressure forecast grids at different geometric cruise levels (as currently done with wind and temperature at different barometric FLs) enabling anticipation and automation of the appropriate geometric level changes along the flight. However, the remaining operational complexity would still be undesirable.

An alternative mitigation would be to plan the flight geometric cruise at lower altitudes to create a buffer with respect to the maximum operating pressure altitude in order to minimise the need for safety-related step-down level changes, and briefing flight crews to limit optimisation-related level changes. However, this would bring a negative impact on environment, operational efficiency and potentially also capacity due to reduced use of the upper flight levels.

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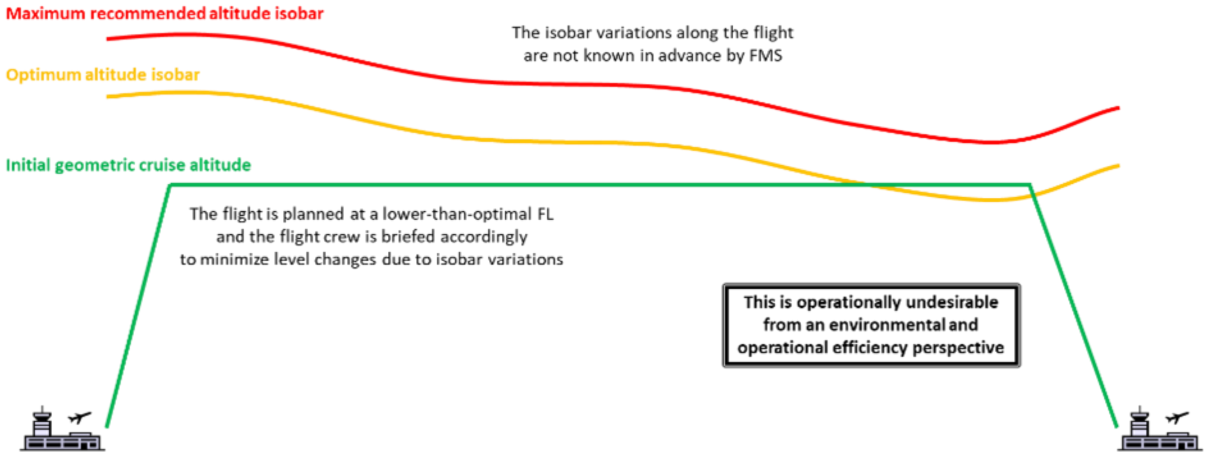

Figure 15: Geometric navigation in cruise – flight envelope and cruise altitude optimisation challenge (b)

From a **flight performance** point of view, the exemplary evaluation for a very common single-aisle airliner in short- and medium-range flights showed that the use of geometric altimetry instead of barometric for an equivalent flight level (i.e. not changing flight plan to a lower cruise level for the geometric flight) leads in average to a slight increase of the fuel consumption of about 0.2% of the trip fuel. The maximum observed increase in consumed fuel observed in the simulation is about 90 kg; higher values can be expected, however, under more extreme weather conditions. Increased fuel burn is proportionally transferred into increased CO_2 emissions. The flight time is only affected in a negligible way.

That said, if all flight phases were conducted using geometric altimetry, there would be no need for datum changes (i.e. between barometric and geometric), which would resolve the issues seen today due to the Transition Layer. However, the negative impacts on operational efficiency remain, i.e., geometric flights may need to be planned at lower altitudes to increase margin with respect to the Recommended Maximum Altitude (REC MAX), especially over longer distances. Therefore, another route is to develop technical solutions to interfacing between Baro in cruise and Geo in Climb or Descent, such as automatic altitude reference selection. Such a solution could be based on Flight Levels (1013 HPa) only, i.e. not subject to local pressure variations. However, such a solution would again require some kind of transition between Geo in the TMA and Baro (with STD pressure) in cruise. Such a transition would possibly be easier to be implemented, as the variable QNH would be omitted, and it could be performed at higher altitudes than the existing transition layer today, e.g. at about 20,000 ft.

In summary, the use of geometric altimetry in Cruise was only found worth considering in the future as part of a holistic geometric navigation solution, removing altitude datum transitions and potentially enabling other ATM Solutions relying on geometric altimetry in Cruise (e.g. Solution 0407 / RVSM 2 which intends to bring a capacity increase), if the associated benefits were demonstrated to outweigh the drawbacks identified so far.

More details on the results from the performed assessments, both for TMA and cruise, are outlined in the Exploratory Research Report (ERR, D3.3) [45] and the ECO-EVAL (D3.6) [48].

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Separation Minima

As explained in section2.3, the focus of the work was on safety, with three major areas of investigation: nominal (technical) risk in terms of collision risk and wake turbulence risk, and non-nominal (operational) risk.

The **Collision Risk Analysis** focused on the technical (or nominal) risk. When aircraft pass on adjacent flight levels, the Altimetry System Error (ASE) and Flight Technical Error (FTE) induce a small probability of lateral and vertical overlap (i.e., a collision). In order to determine requirements for the ASE and FTE such that the collision risk is acceptable, the Target Level of Safety of RVSM was adopted. A number of conservative estimates were made regarding typical traffic characteristics (for example, passing frequencies, lateral navigation performance, etc.) This led to a maximal allowable probability of vertical overlap of $2.5*10^{-8}$.

The requirements on the ASE and FTE were derived, and are shown in Figure 16. The TLS was shown to be met if the TVE ≤ 34 ft if it is Laplace distributed, or TVE ≤ 58 ft if it is normal distributed. The error budget available for either the ASE or the FTE directly depends on the budget that is reserved for the other. For example, under certain conditions, if either the ASE or the FTE distribution has a standard deviation $\sigma 1$ = 30 ft, this would allow the other distribution to have a standard deviation $\sigma 2$ ≤ 28 ft or $\sigma 2$ ≤ 50 ft respectively if both were Laplace or if both were normal distributions. The collision risk is highly dependent on the tails of the error distributions, which is reflected in the aforementioned requirements.

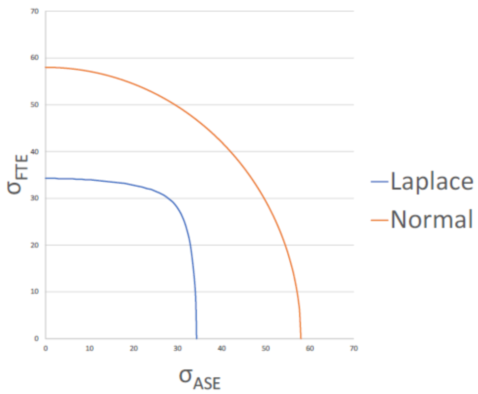

Figure 16: the maximal value of the standard deviation σ2 of the variable X2 to meet the TLS of 500 ft vertical separation, given the standard deviation σ1 of the variable X1 and given that the TVE is a sum of two independent variables X1 and X2 with X1 and X2 both Laplace (orange curve) or normal (blue curve), with zero mean.

According to the specifications of GPS and Galileo, the standard deviation of the Vertical Position Error (VPE), corresponding to the GNSS ASE, is above 20 ft, implying that the condition on the TVE distribution is not met. However, according to the quarterly reports on actual measurements, the standard deviation of the VPE is in the order of 7 ft or less (depending on GPS or Galileo and on single or dual frequency). It is noted however that these VPE values are collected under specific conditions that may not be fully representative for aviation en route.

The current MASPS for traditional RVSM prescribes a maximal standard deviation for the FTE of 43 ft. This would not be sufficient to meet the TLS. However, the real-word FTE that is estimated from height

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monitoring in the context of continuous RVSM Collision Risk Analysis is shown to be 33 ft, which could be sufficient to meet the TLS. A more detailed characterisation of these figures, perhaps through ADS-B data, is likely possible and required.

For the **Wake Turbulence Risk Analysis**, comparative fast-time simulations were performed for the complete EUR region as described in section 2.3. Based on flight plan data, scenarios for two full days were modelled, for a day with particularly low average wind speeds at the most common cruise altitudes and for a corresponding high-wind-speed day. For each day, traffic in RVSM 2 airspace was simulated with the current separation scheme (1000 ft vertical separation up to FL410, 2000 ft above) under barometric altimetry and the proposed new one (500 ft vertical separation through all altitudes) under vertical altimetry. This results in four full-day scenarios.

The occurrence of a (possible) wake encounter was determined through a geometrical detection of the crossing of an aircraft's flight path through the habitation corridor of another one's wake, while the (possible) wake encounter severity was rated by using the roll control ratio RCR that relates the rolling moment induced by the wake vortex in a (hypothetical) worst case to the aircraft's available control power to counteract it. Earlier research [96][97] had shown that for a value of RC ≤ 0.2 no unacceptable accelerations, attitude changes or flight path deviations were found independent of actual encounter geometry and axes (roll, pitch, yaw) disturbed, so this value was taken as limit for safe encounters. On the other hand, an RCR > 1 means that it cannot be excluded that aircraft control is temporarily lost, even if actually only for an irrelevant fraction of time or not at all. For the purpose of a safety analysis, however, a situation must be regarded as unsafe unless it can be proven to be safe. A third RCR value of 0.5 was arbitrarily set to distinguish between possible encounter severities. This results in twelve sub-scenarios in total: for each of the mentioned four full-day scenarios, three sub-scenarios with RCR limits of 0.2, 0.5, and 1.0. With a computation time of several days for a single sub-scenario, and the necessary repetition of simulation runs following improvements in the modelling, computational effort has been an important issue for the analysis.

With the caveat that the absolute numbers depend on the detail level of the modelling and are not necessarily fully representative of the real-world situation (which is why we look at the comparison between the two separation modes for conclusions), the simulation results are aggregated in Figure 17, Table 4 and Table 5; more information can be found in the ERR [50] and in ID4.2 [51].

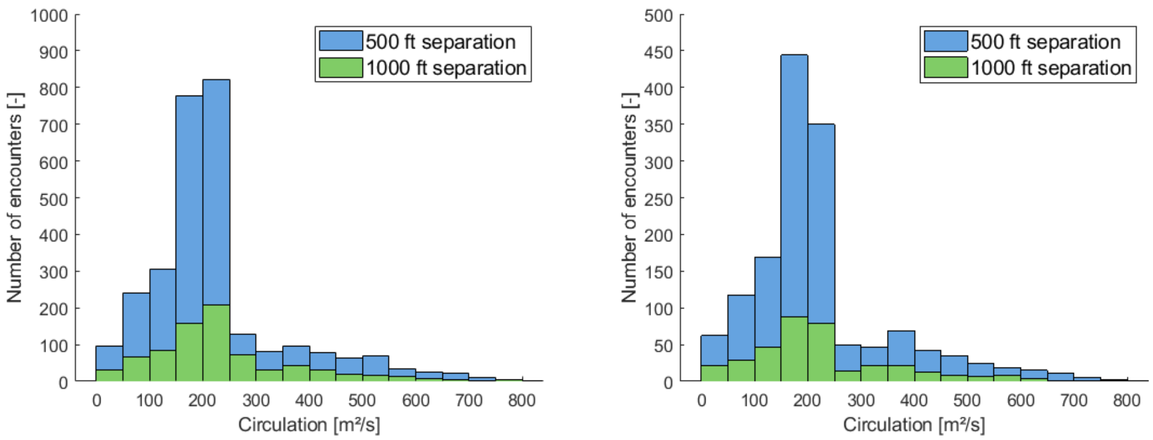

Figure 17: Distribution of the encountered circulation in the low-wind-speed (left) and high-wind-speed scenario (right); *note* the different vertical scaling.

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A comparison of the two scenarios with different wind speeds (Figure 17) reveals that the overall number of encounters is decreased (even when considering the slightly lower number of aircraft in the corresponding scenario) with higher wind speeds because more wake vortices are drifted away from aircraft on the same trajectory than reach other trajectories that would not be affected at a lower wind speed. With reduced vertical separation, the encounter frequency is increasing in both scenarios by approximately the same factor, which suggests that the relative increase of the encounter frequency when reducing the vertical separation is not dependent on the wind speed.

The increase as such can be considered as a realistic result because aircraft are allowed to fly in closer proximity to each other and therefore to the wake vortices. In some rare cases, a reduced vertical separation may prevent an encounter as the wake has already descended more than 500 ft below the wake creator, but in general the generation of new encounters due to the reduction of the vertical separation outweighs the elimination of some encounters and thus overall leads to an increase of the encounter frequency.

As described above, the SHAPe concept for a hazard assessment is already integrated in the modelling process, which results in encounters with a very low severity below the defined threshold not being present in the results, implying that encounters at lower circulation values concern smaller aircraft only. The encounters with an RCR above the threshold of 0.2 have been divided into three categories as shown in Table 4 and Table 5. A significant increase in encounters of all severity levels is clearly visible when reducing the vertical separation.

Low-wind speed scenario	RCR between 0.2 and 0.5	RCR between 0.5 and 1.0	RCR above 1.0
1000/2000 ft separation	378	158	255
500 ft separation	1200	690	964
Increase by a factor of	3.2	4.4	3.8

Table 4: categorisation of the encounters in the low-wind-speed scenario by their RCR value

High-wind speed scenario	RCR between 0.2 and 0.5	RCR between 0.5 and 1.0	RCR above 1.0
1000/2000 ft separation	171	96	95
500 ft separation	615	335	512
Increase by a factor of	3.6	3.5	5.4

Table 5: categorisation of the encounters in the high-wind-speed scenario by their RCR value

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It is important to note that these results do not mean that there are several hundreds of hazardous wake encounters in the European airspace every day. As described in [51], the SHAPe concept only claims that encounters with a severity below the threshold can be considered as non-hazardous, while those with a severity above the threshold may be but are not necessarily hazardous. An RCR above 1.0 need not result in a loss-of-control event even though, by definition of the RCR, the control capabilities of the aircraft *might* be exceeded. First of all, the hazard area is an *envelope* of all potentially hazardous points in space, and such a point need not be actually reached. The deformation of the vortices after a certain time (the so-called Crow instability, see [51]) increases the size of the envelope without increasing the actual vortex size, while tending to decrease the influence on the encountering aircraft [101]. Furthermore, most encounter durations are very short (a few seconds or even only a fraction of a second) and need not build up sizable disturbances. Still these encounters might be felt by the occupants of the aircraft as inconvenient situations. Keeping that in mind, a number of several hundred wake encounters discernible as such during a full day in the European airspace can be considered as a realistic result (see the ERR [50] for more information).

However, the simulation results suggest an increase of wake vortex encounters by a factor roughly 3 to 5, which indicates a relative decrease in safety against the status quo. In absence of a TLS this does not formally imply that absolute safety is unacceptable, but it is very probable that mitigation means would be required. These are discussed in chapter 4.

For the **Safety Case** a top-down approach was used where the system risk was evaluated against a threshold of $2.5 \cdot 10^{-9}$ collisions per flight hour, similar to traditional 1000 ft RVSM. The Safety Case was structured as an FHA. Considering the low maturity of the concept not all details are known yet, and a combination of qualitative and quantitative safety specifications were derived.

A total of four primary functions were derived, in short: altitude information is provided, aircraft's altitudes are estimated, altitudes are assigned to aircraft such that vertical separation is provided and that aircraft fly according to the assigned altitudes. The four hazards corresponding to the failure of primary functions were respectively defined as (H1) the altitude information is not provided properly in a part of the airspace, (H2) the estimate of the altitude of an aircraft is not provided properly, (H3) an aircraft has not an altitude assigned to it such that it is vertically separated and (H4) an aircraft does not fly according to its assigned altitude. These four primary functions are shown in Figure 18.

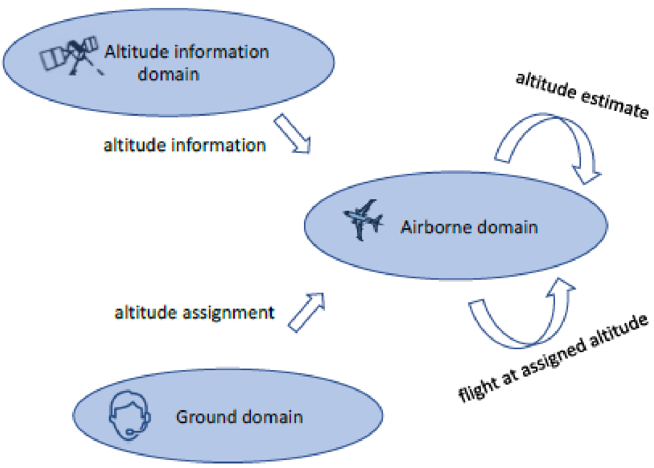

Figure 18: The three domains and the four primary functions.

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It was recognised that only the first hazard was significantly different from current RVSM operations. In GNSSs the altitude information provided through the electromagnetic systems can be disrupted, for example through intended or unintended interference, which would affect all airspace users in a given region. For this no analogue exists in barometric altimetry operations where air pressure is the medium that provides the altitude information. Solutions such as Dual Frequency GNSS receivers will likely be necessary to reduce the likelihood of H1, but it can still not be considered as negligible. If there is no ground domain that can take coordinative actions, a Procedure Single Unable Altimetry (PSUA) should be in place that multiple aircraft safely execute individually.

Having a ground domain that coordinates a contingency procedure, Procedure Multiple Unable Altimetry (PMUA), when multiple aircraft lose the ability to determine altitude, would likely be preferable. This would likely also require a function for the ground domain to detect inadequacy of the altitude domain, which could be provided through different means, such as *lack of altimetry integrity* messages from the altitude information domain, or *unable altimetry* messages from the airborne domain. Because such a procedure would constitute a serious disruption of the air traffic operations, it is rather loosely concluded that it should not be required to be enacted more than once every ten years.

The likelihood and severity of the latter three hazards may be different if not effectively mitigated with secondary functions, but the required functions and procedures are not very different from current operations. As such the frequency of occurrence of the latter three hazards were assumed to stay the same when transitioning to RVSM 2. Further effects from transitioning to RVSM 2 were studied by the use of the Mid-Air Collision En-Route Accident Incident Model (MAC ENR AIM) from the E-SRM. The AIM was first adapted to 1000 ft operations, showing that according to this model the current risk due to non-nominal deviations is a factor 10 below the maximally allowed TLS.

Due to the reduced separation, it was recognised that a number of barriers would become less effective when transitioning to 500 ft separation, and that ACAS would require a complete reconsideration due to incompatibility of the systems that are currently in use with 500 ft minimal separation. Assuming a recalculated effectiveness of the ATC collision prevention barrier and a maximally allowable risk of a mid-air collision of $2.5 \cdot 10^{-9}$ led to a minimal effectiveness requirement of the combined visual- and ACAS based avoidance of at least 93%, as opposed to the 97% effectiveness at 1000 ft in traditional RVSM.

The economic evaluation was conducted in a qualitive way and focussed on capacity and fuel efficiency [49]. 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 analysis.

Green route charging

The results in this section are presented separately for each component of the Green RC solution: the Initial Solution and the Full Solution. The validation activities focused on assessing both the feasibility and the performance of each component, measured through the appropriate KPIs.

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Initial solution

The initial solution, designed to reduce CO_2 emissions and congestion, consists of two models: Modulation of Route Charges (MRC) and Origin–Destination Charging with Modulation of Route Charges (ODC+MRC). The feasibility of each model—defined as their compliance with stakeholders' requirements—was validated using a small-scale scenario, based on a statistically representative sample of real traffic. A complete test was conducted, confirming full consistency with the underlying assumptions.

The environmental impact of the MRC model was assessed over two AIRAC cycles: a high-traffic period (1910) and a low-traffic period (1902). The analysis was performed at two different scales: a global scale, considering all flights to or from ECAC (and adjacent) states, and a local scale, focusing only on flights with both departure and arrival within ECAC (and adjacent) states.

The MRC model led to consistent reductions across all KPIs compared to the reference scenario. Tables 3 and 4 report the reductions in distance flown and fuel consumption for the different scenarios (1902 global, 1902 local, 1910 global, 1910 local). These results have been benchmarked against the 'Minimum distance' scenario, which, for each flight, corresponds to the distance of the shortest available route selected from the pool of available historical routes.

AIRAC cycle	Scenario	Origin or destination in ECAC			Origin and destination in ECAC		
		No. of flights	Distance flown	Diff	No. of flights	Distance flown	Diff
1902	Reference	725,431	1,325,262	/	571,746	571,876	/
1902	Minimum distance	725,431	1,318,792	-0.49%	571,746	565,406	-1.13%
1902	MRC	725,431	1,319,492	-0.44%	571,746	566,106	-1.01%
1910	Reference	929,640	1,726,552	/	739,305	824,530	/
1910	Minimum distance	929,640	1,713,831	-0.74%	739,305	811,809	-1.54%
1910	MRC	929,640	1,715,138	-0.66%	739,305	813,116	-1.39%

Table 6: Distance flown indicators of MRC model applied to two AIRAC cycles, one of high traffic and one of low traffic; comparison with reference and minimum distance scenario.

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AIRAC cycle	Scenario	Origin or destination in ECAC			Origin and destination in ECAC		
		No. of flights	Fuel consumption	Diff	No. of flights	Fuel consumption	Diff
1902	Reference	725,431	7,297,870	/	571,746	1,870,955	/
1902	Minimum distance	725,431	7,257,596	-0.55%	571,746	1,845,700	-1.35%
1902	MRC	725,431	7,279,678	-0.25%	571,746	1,852,762	-0.97%
1910	Reference	929,640	8,946,937	/	739,305	2,701,070	/
1910	Minimum distance	929,640	8,905,678	-0.46%	739,305	2,659,811	-1.53%
1910	MRC	929,640	8,910,106	-0.41%	739,305	2,664,238	-1.36%

Table 7: Fuel consumption indicators of MRC model applied to two AIRAC cycles, one of high traffic and one of low traffic; comparison with reference and minimum distance scenario.

The ENV1 indicator shows a similar pattern, with reductions of 0.41% (1910 global), 0.25% (1902 global), 1.36% (1910 local), and 0.97% (1902, local).

These results confirm that the MRC model is effective in reducing emissions and fuel consumption, with particularly significant benefits during high-traffic periods and for flights operating entirely within the ECAC region.

Similar results are obtained with the ODC+MRC model, although, as explained in Section 2.3, it introduces an additional layer of complexity. Unlike the simpler MRC, for each route the route charges to which the modulation is applied are calculated differently compared to the current approach. For the high-traffic AIRAC 1910 scenario, considering flights with either origin or destination in ECAC and adjacent states, the distance flown decreased by 0.67%, fuel consumption by 0.44%, and ENV1 by 0.44%. For flights entirely within ECAC, the distance flown decreased by 1.46%, fuel consumption by 1.44%, and ENV1 by 1.44%, respectively.

Demand-capacity imbalance was assessed by comparing the number of capacity violations across the reference, MRC, and ODC+MRC scenarios, where capacity was considered as the declared capacity for each resource (sectors and airports) in the network. Since all flights must be accounted for, only the global scenario—comprising departures and arrivals within ECAC and adjacent states—was considered. For the MRC scenario, the results show a significant reduction in violations for both traffic periods. For the high-traffic AIRAC 1910 period, violations decreased by 91.2%, while for the low-traffic AIRAC 1902 period, the reduction reached 94.1%. The ODC+MRC model also resulted in a reduction in violations, with capacity violations in the AIRAC 1910 period dropping by 90.9% compared to the reference case. This reduction, while substantial, is slightly lower than the one achieved by MRC alone.

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Full solution

The Full solution explored different ways in which full emissions reduction incentivisation could be applied. The design and formulation of the models to test the GRC solution was successfully completed, as well as their implementation, and all experiments have been conducted; the Stated-preference survey has been concluded, and a detailed analysis can be found in Appendix A and B of D5.7 [56].

Figure 19: Geographical coverage of the main Full Solution validation exercise.

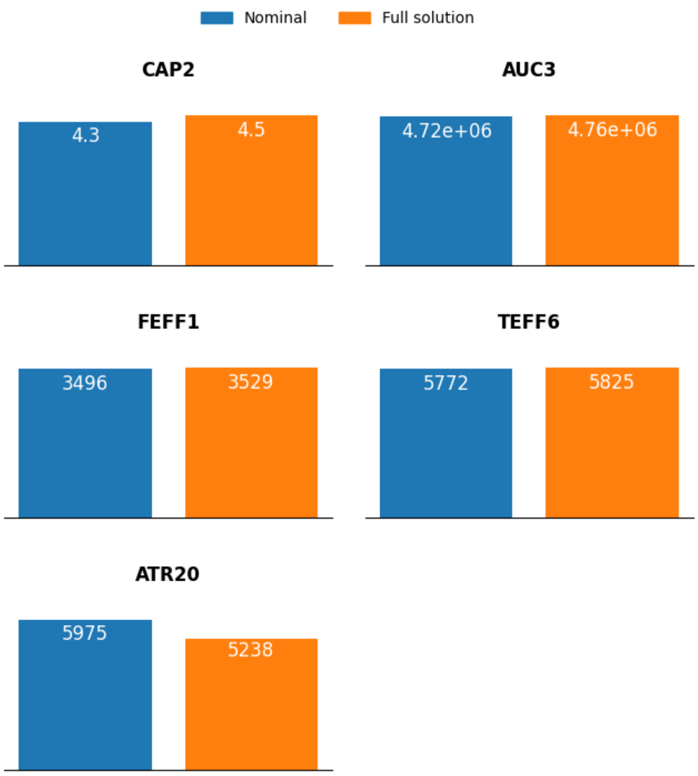

Figure 20: Estimation of SESAR KPIs and ATR20 in the reference/nominal (blue) and full solution (orange). CAP2 is in number of movements, AUC3 in euros, FEFF1 in kg of fuel, TEFF6 in minutes, ATR20 in nK

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The exercises demonstrated the initial feasibility of the route charging mechanism that takes into account all emissions. Regarding **capacity**, the Full Solution shows that traffic flows move, but the capacity with the Full Solution could become slightly more saturated. Furthermore, an important finding is that *when there is a lack of capacity*, it is much less possible to reduce the environmental impact of flights, as there is no space for manoeuvre left. For **efficiency**, FEFF1 and TEFF1 are slightly higher (less than 1%) in the solution scenario than in the reference one (see Figure 20 for details), which is a normal consequence of minimising emissions instead of fuel. The **environmental impac**t for all emissions, as measured by ATR20, is 12.3% lower in the solution scenario. The incentivisation to minimise the environmental impacts, slightly increases the costs **(cost-efficiency KPA)** to airlines (AUC3), less than 1%. This is due to higher fuel consumption, and EI modulation rate. The ANSP revenues are held constant, which is aligned with only slight increase in capacity saturation. Other KPAs are not impacted by this solution.

Solution interdependencies

Due to time and resources constraints, interdependencies between Green GEAR's Solution were only able to be addressed at a conceptual level, but at least Geometric Altimetry in the TMA and Green Route Charging appear beneficial already by themselves. The use of geometric altimetry in cruise, which would be a prerequisite for the reduction of vertical Separation Minima 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 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, in the former cases improving the effectiveness of the reduction of aviation's climate impact through Green Route Charging.

2.5 Project Deliverables

The following table lists and briefly describes Green-GEAR's Deliverables, ordered by issuing work package (as in the Description of Work). Both formal Deliverables (with official Deliverable number D<*x.y*>) and internal ones (following the numbering scheme iD<*x.y*>) as well as other deliverables (HE report, white paper) are itemised, i.e., all documents delivered to the SESAR 3 JU. The internal deliverables document the Validation activities in more detail than the respective ERRs, but have not undergone a review by the SESAR 3 JU.

Links to download (the respective latest version of) public documents can be found following the references next to the respective Deliverable number.

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<table>
<tr><th>Reference</th><th>Title</th><th>Delivery Date</th><th>Dissemination Level</th></tr>
<tr><th colspan="4">Description</th></tr>
<tr><td>D1.1 [25]</td><td>Initial Project Management Plan</td><td>30/11/2023</td><td>Sensitive</td></tr>
<tr><td colspan="4">D1.1 contains the Project Management Plan of the Project. It establishes the project management structure, detailing roles and responsibilities as well as the voting rules according to the Consortium Agreement. The data management and quality assurance procedures, including those to ensure adherence to the SJU rules such as in risk management and formal reporting, are described. D1.1 contains project planning information (e.g. timescales) and assembles information from Part A of the Grant Agreement such as the list of Deliverables and Milestones. It serves as reference for any formal decisions and clarification of details from the high-level description in Annex I.
D1.1 is superseded by D1.3 (updated Project Management Plan).</td></tr>
<tr><td>D1.2 [26]</td><td>Ethics Plan</td><td>30/11/2023</td><td>Public</td></tr>
<tr><td colspan="4">The Green-GEAR consortium is committed to respecting human autonomy and dignity, which includes the protection of personal data (personal information about identifiable human research subjects) as laid down in the EU Charter of Fundamental Rights as a crucial prerequisite. The research questions addressed in Green-GEAR project necessitate the processing – as far as possible in anonymised format – and exchange of personal data between the beneficiaries, some of which reside in the EU and some in the United Kingdom. D1.2, the Ethics Plan, describes the approach to safeguard the rights of humans participating in the project workshops and the measures undertaken for personal data protection throughout the project.</td></tr>
<tr><td>D1.3 [36]</td><td>Updated Project Management Plan</td><td>30/09/2024</td><td>Sensitive</td></tr>
<tr><td colspan="4">D1.3 is a formal update of D1.1 to the status at the end of first reporting period, and served as input to the Intermediate Project Review. D1.3 contains an update of the Project Management Plan of the Project, supplementing the Grant Agreement and providing detailed and up-to-date information about the project management and organisation, quality management and risk management plan procedures in accordance with the SESAR 3 Project Management Handbook. The PMP is the reference for any decision that is made on the project and for clarification of details from the high-level description in Annex I.</td></tr>
<tr><td>D1.1.10 [38]</td><td>Periodic Report #1</td><td>30/10/2024</td><td>Sensitive</td></tr>
<tr><td colspan="4">D1.1.10 reports overall progress and achievements within the reporting period September 2023 to August 2024 and gives an overview of the upcoming activities. All Deliverables scheduled in this period were submitted in time and all planned meetings took place, two Risks were activated. A self-maturity assessment of the three Solutions has resulted in an TRL 1 ongoing judgement for all three. Notably, Validations are ongoing so that generally the descriptive and planning activities including initial stakeholder consultations have been performed and possible performance contributions identified but obviously the results and conclusions to be drawn from them are not yet available.</td></tr>
<tr><td>D1.4 [61]</td><td>Project Summary Report</td><td>submitted 09/09/2025, 30/01/2026</td><td>Public</td></tr>
<tr><td colspan="4">D1.4, the present document, is the Project Summary Report that explains the background for the Solutions, describes the work and Validation activities performed and the results obtained. Conclusions are drawn and discussed concerning both suggestions for the next R&I phase of the three Solutions and other topics of interest that were identified during Green-GEAR work. The links to the SESAR Programme are described, including the three Solutions Definitions and Descriptions and the self-maturity assessments. D1.4 contains an annotated list of all Project Deliverables as well as an overview of CDE activities and publications until the end of the technical phase.</td></tr>
</table>

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Reference	Title	Delivery Date	Dissemination Level
	Description		
D2.1 [27]	Initial Data Management Plan	30/11/2023	Public
D2.1, the initial Data management Plan (DMP), compiles a list of necessary data to feed the activities in WP3, 4, and 5, and the means of results collection and dissemination. The input data/databases are described here, as is the eventual access to the data. Furthermore, the strategy for the management of the research outputs is described. The consortium fully supports the intentions of the Horizon Europe program to make publicly available, as soon as possible, all research data and take measures to enable third parties to access, mine, exploit, reproduce and disseminate these data, free of charge for any user. D2.1 is superseded by D2.2 (updated Data Management Plan).			
- [35]	White Paper: Green-GEAR - Common Assessment Methods	30/09/2024	Public
Green-GEAR's three Solutions address different flight phases and environments, but the planning and the requirements of specific experiments apply the same approach to definition of research hypotheses, definition of experimental/validation scenarios, reliability, sensitivity and validity of exercises, generalisation of the exercise results and their transfer to the operational environment. This paper details the approach taken in definition of scenario choices, performance assessment, validation methods and the steps to be taken in economic evaluation. Not all the Solutions will address the same KPAs, but the assessment plans are made jointly between those that do.			
D2.2 [34]	Updated Data Management Plan	30/08/2024	Public
D2.1 updates D1.1 to the status at the end of first reporting period and served as input to the Intermediate Project Review. It contains a list of necessary data to feed the activities in the three Solutions and the means of results collection and dissemination. The input data/databases are described here, as is the eventual access to the data and the strategy for the management of the research outputs. The consortium fully supports the intentions of the Horizon Europe program to make all research data publicly available, as soon as possible and as far as compatible with the input data owners' conditions.			
D2.3 [59]	Final Data Management Plan	submitted 28/01/2026	Public
D2.3 is a formal update of D2.2 to the status at the end of the technical phase of project and contains the Data management plan (DMP). It compiles a list of necessary data to feed the activities in the three Solution WPs 3, 4, and 5 and the means of results collection and dissemination. The input data/databases are described here, as is the access to the data and the strategy for the management of the research outputs. A list of the technical Deliverables serves as reference for the data that can only be made available in aggregated format due to proprietary resctrictions.			
D3.1 [29]	Initial OSED – Geometric Altimetry	28/06/2024	Public
D3.1 defines the operational service and environment description (OSED) for Geometric Altimetry. The operational concept is considered for both the idealised end state (fully geometric operations) as well as the transitory state (mix of geometric and barometric operations), limited to a number of key focus areas, and investigating two options for the end state. Geometric operations are considered relevant to all flight phases (Climb, Cruise, Descent and Approach), with the key difference being that aircraft are now required to use geometric altimetry at the primary reference for height reporting and vertical navigation, with GNSS as the primary navigation source. D3.1 is superseded by D3.4 (Final OSED).			

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Reference	Title	Delivery Date	Dissemination Level
Description			
D3.2 [39]	Exploratory Research Plan – Geometric Altimetry	30/08/2024, 22/11/2024	Sensitive
D3.2 is the exploratory research plan (ERP) for the Geometric Altimetry Solution that aims to define the vertical plane of Instrument Flight Paths geometrically, enabling route separation based on vertical path performance limits and continuous climb or descent through the Transition Layer. The document provides the description of the planned validation exercises, to be carried out through three tasks: Assessment of ATC considerations and TMA route design; Assessment of aircraft systems and architecture; Assessment of aircraft performance and procedures. The research approach consists of four exercises split across the three tasks in complement to one another.			
iD3.1 [40]	Geometric Altimetry – ATC and Route Design Impact Report	20/12/2024	Sensitive
iD3.1 is the internal project report on ATC and route design impact of using vertical guidance by geometric altimetry. It contains the analysis of the Fast-Time Simulation of the test case airspace designs developed and assessed: geometric procedures: SIDs, STARs and IAPs have been designed for a completely geometric TMA and compared against an equivalent reference scenario for a fully barometric TMA that was also designed and optimised using existing techniques. The Green GEAR design has an environmental benefit in terms of fuel and CO2 emissions reductions that increases more than proportionally when traffic is grown for 2035.			
iD3.2 [42]	Geometric Altimetry – Aircraft Systems and Architecture Impact Report	20/12/2024, 06/01/2025	Sensitive
iD3.2 is the internal project report on aircraft systems and architecture impact of using vertical guidance by geometric altimetry. It captures the outcomes of a validation exercise based on expert judgement addressing the technical and operational feasibility of the Solution's concept of operations as described in the Initial OSED from an airborne perspective: aircraft functions, architecture and cockpit systems, focused on large commercial aircraft (Airbus families). Its main conclusions is that Geometric Altimetry is not operationally suitable for cruise phase, while open points remain for its use in Climb and Descent phases.			
iD3.3 [41]	Geometric Altimetry – Flight Performance and Procedures Report	20/12/2024	Sensitive
iD3.3 is the internal project report on flight performance and procedures impact of using vertical guidance by geometric altimetry. Scenarios for the assessment are cruise flight and descent / operations in the TMA. Fast-time simulations with a high-fidelity aircraft model are performed to analyse flight aircraft performance and flying procedures, determining the impact to fuel use for individual flights. The evaluation in the TMA revealed possible benefits from the use of geometric altimetry (small fuel savings in climb, with potential for further improvement, and already significant fuel savings in descent), while cruise flight evaluations yielded a slightly increased fuel consumption.			
D3.3 [45]	Exploratory Research Report – Geometric Altimetry	28/02/2025	Public
As part of the Solution Data Pack for Geometric Altimetry, D3.3 is the exploratory research report (ERR), providing a description of the validation results. Fuel burn, CO_2 emissions and airspace capacity were assessed quantitatively and impacts to aircraft systems and operations, ATC operations, safety and human performance qualitatively. The results showed that geometrically-defined vertical paths can allow greater flight efficiencies in the TMA than with current day (barometric) principles, primarily in high-density airspace. Geometric Altimetry can enable the safe removal of the transition layer with no safety or human performance show-stoppers. The fuel and emissions impact of implementing geometric cruise showed a disbenefit.			

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Reference	Title	Delivery Date	Dissemination Level
	Description		
D3.4 [47]	Functional Requirements Document – Geometric Altimetry	30/04/2025	Public
As part of the Solution Data Pack for Geometric Altimetry, D3.4 is the Functional Requirements Document (FRD), describing the Solution functional architecture and requirements. Significant impacts are introduced on airborne and, to a lesser extent, ground systems, from designing, managing and operating the new Instrument Flight Procedures (IFPs) based on geometric reference, as well as related monitoring capabilities for possible fallback to barometric altimetry. The transition between barometric and geometric airspace in nominal operations is also addressed. The necessity for additional requirements on ground services such as aeronautical information management (AIM) or meteorological services (MET) is still to be assessed.			
D3.5 [53]	Final OSED – Geometric Altimetry	30/04/2025, 29/06/2025	Public
As part of the Solution Data Pack for Geometric Altimetry, D3.4 defines the operational service and environment description (OSED). A composite solution of the two methods (waypoint/fix definitions with geometric constraints in climb vs. 3-dimensional geometric path definition in approach) is considered to be the optimal final end state of the concept, with reversion to barometric altimetry as fallback. Assumptions relative to both methods based around future aircraft navigation system capabilities and both air and ground conformance monitoring tools are given. Key benefits are environment and safety, deriving primarily from removal of variation due to atmospheric conditions and improved vertical containment.			
D3.6 [48]	ECO-EVAL – Geometric Altimetry	29/05/2025	Public
As part of the Solution Data Pack for Geometric Altimetry, D3.6 provides the Solution's economic evaluation (ECO-EVAL), assessing its potential benefits and costs for various stakeholders. Benefits in fuel consumption during climb and descent operations in the TMA are outlined, transferring directly into benefits in fuel costs. Major cost drivers for all involved stakeholders, which are mainly ANSPs, airspace users and aircraft manufacturers, are identified, if only in a qualitative manner. Although the TMA design based on geometric altitudes would possibly be available earlier, the required development and certification effort on aircraft manufacturers' side would probably take until roughly 2040.			
D4.1 [30]	Initial OSED – Separation Minima	28/06/2024	Public
D4.1 defines the operational service and environment description (OSED) for Separation Minima. The RVSM 2 concept studies the reduction of vertical separation minima to 500 ft in Reduced Vertical Separation Minima (RVSM) airspace, the upper limit of which will be extended to FL 600. The enabler is geometric altimetry, benefitting many emergent airspace users already relying on it. It is assumed that there is some GNSS configuration (e.g. single- or dual-frequency, single- or multi-constellation, etc.) that provides sufficient accuracy, availability and integrity. The EUR RVSM region will serve as a testing ground and its extremities as transition airspace. D4.1 is superseded by D4.6 (Final OSED).			

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Reference	Title	Delivery Date	Dissemination Level
Description			
D4.2 [32]	Exploratory Research Plan – Separation Minima	31/07/2025	Sensitive
D4.2 is the exploratory research plan (ERP) for the Separation Minima Solution, studying the RVSM 2 concept, i.e. the reduction of vertical separation minima in upwards extended RVSM airspace to 500 ft. Objectives of the Validations are to (further) develop the necessary simulation environments and analytical models, to conduct a safety study and qualitatively determine the capacity potential of RVSM 2. Focus is on the safety study, comprising a Collision Risk Analysis (CRA) and a Wake Turbulence Risk Analysis (WTRA), both addressing the technical or nominal risk, and a preliminary Safety Case, addressing also the operational or non-nominal risk.			
iD4.1 [43]	Separation Minima – Collision Risk Analysis	31/01/2025	Sensitive
iD4.1 is an internal report and focuses on the nominal collision risk. The approach was to adopt the Target Level of Safety (TLS) of 1000 ft RVSM, to adapt the ICAO Collision Risk Model (CRM) to RVSM 2, from that to derive the requirements on the altitude keeping performance and to translate this into conditions on the Altimetry System Error (ASE) and Flight Technical Error (FTE) distributions. These seem to be just met when considering performance figures from the operational environment. Capturing them in system requirements will likely pose large challenges to the actual introduction of the concept.			
iD4.2 [51]	Separation Minima – Wake Turbulence Risk Analysis	31/01/2025, 30/05/2025	Sensitive
iD4.2 is an internal report focusing on the wake turbulence risk. An initial study has looked at the changes in expected en-route wake encounter frequency and severity with the introduction of RVSM 2. We find a substantial increase in wake encounter occurrences for all ranges of encounter severities as expressed by the magnitude of the circulation encountered. This is a reduction of safety in relation to the status quo but, due to the lack of absolute target figures, not a confirmation of the absence of an acceptable safety level. Possible remedies are suggested to maintain at least the current one.			
D4.3 [46]	RVSM 2 Safety Case	28/02/2025	Public
The work in D4.3 is part of a larger safety case (or safety assessment) for the RVSM 2 concept and focuses on the risk due to non-nominal causes. The Target Level of Safety (TLS) of 1000 ft RVSM was adopted and the RVSM 2 concept described on a functional level, allowing to derive safety specifications through a Functional Hazard Analysis (FHA). The most important insights are the need for a procedure in case GNSS altimetry is lost by all airspace users, which is only very rarely allowed to happen, and the need for a re-designed Airborne Collision Avoidance System (ACAS).			
D4.4 [50]	Exploratory Research Report – Separation Minima	31/05/2025	Public
As part of the Solution Data Pack for Separation Minima, D4.4 is the exploratory research report (ERR), providing a description of the validation results. The collision risk, determined using the suitably adjusted ICAO collision risk model, could possibly be met by a small margin albeit likely under challenging regulatory and legislative aspects. Simulations predict a substantial increase of the wake vortex risk against current operations; possible mitigations are suggested. The safety case identified the need for a controlled airspace and an update of airborne and ground-based safety nets. In sum, operational safety is a substantial challenge but not obviously infeasible.			

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<table>
<tr><th>Reference</th><th>Title</th><th>Delivery Date</th><th>Dissemination Level</th></tr>
<tr><th colspan="4">Description</th></tr>
<tr><td>D4.5 [54]</td><td>Functional Requirements Document – Separation Minima</td><td>30/04/2025, 09/07/2025</td><td>Public</td></tr>
<tr><td colspan="4">As part of the Solution Data Pack for Separation Minima, D4.5 is the Functional Requirements Document (FRD), describing the Solution functional architecture and requirements. ATM capabilities applicable to the RVSM 2 concept are identified in accordance with the SESAR architecture. Examples of capabilities are Positioning / Navigation / Timing of Mobiles (airspace) independent of Ground Navaids, Mid-Air Collision Avoidance and Navigation performance monitoring. The functional requirements are organised following the structure of the Safety Case, in three major domains: the airborne domain (i.e. aircraft), the ground domain (i.e. ANSPs) and the altitude information domain (i.e. GNSS constellation(s) and additional infrastructure).</td></tr>
<tr><td>D4.6 [52]</td><td>Final OSED – Separation Minima</td><td>30/04/2025, 25/06/2025</td><td>Public</td></tr>
<tr><td colspan="4">As part of the Solution Data Pack for Separation Minima, D3.4 defines the operational service and environment description (OSED). Observed performance of height keeping seems to be just sufficient to meet the Target Level of Safety (TLS) for the collision risk, but the current specifications are not. Matters regarding GNSS liability and responsibility will have to be clarified, and ACAS will need an update. Either a predictive function / warning system for prevention of hazardous wake vortex encounters is needed, or the applicability of 500 ft separation could be made operationally dependent on aircraft pairing and/or the weather situation.</td></tr>
<tr><td>D4.7 [49]</td><td>ECO-EVAL – Separation Minima</td><td>28/05/2025</td><td>Public</td></tr>
<tr><td colspan="4">As part of the Solution Data Pack for Separation Minima, D4.7 provides the Solution's economic evaluation (ECO-EVAL), assessing its potential benefits and costs for various stakeholders. Indications for environmental benefits (cruise flight closer to optimal altitudes enabled by finer granularity of usable flight levels) and capacity increase are given, although a robust quantification through fast-time traffic simulation was out of scope. Major cost drivers have been identified for the stakeholders (mainly ANSPs, airspace users in RVSM 2 airspace and aircraft/equipment manufacturers), some of them preliminary as some functions and procedures are not yet developed nor assigned to systems or actors.</td></tr>
<tr><td>D5.1 [31]</td><td>Initial OSED – Green Route Charging</td><td>29/04/2024</td><td>Public</td></tr>
<tr><td colspan="4">D5.1 defines the operational service and environment description (OSED) for Green Route charging. Initial Solution mechanisms are aimed at reducing CO2 emissions and improving horizontal flight efficiency, eliminating the incentive for airlines to detour to avoid higher charges. The Full GRC Solution investigates the possibility of reduction of total climate impact (CO2 and non-CO2) through the avoidance of climate hotspots as defined by algorithmic climate change functions. The GRC Solution operates within the 41 EUROCONTROL contracting States and adheres to the Multilateral Agreement on Route Charging. It specifically targets en-route airspace, influencing flight planning and route selection through economic incentives.
D5.1 is superseded by D5.4 (Final OSED).</td></tr>
</table>

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Reference	Title	Delivery Date	Dissemination Level
	Description		
D5.2 [33]	Exploratory Research Plan – Green Route Charging	31/07/2024	Sensitive
D5.2 is the exploratory research plan (ERP), providing the description of the planned validation exercises associated with the Green route charging Solution. It outlines the development of green route charging mechanisms and covers several key experiments, including the extension and adaptation of existing network models to simulate the implementation of these mechanisms. Objectives involve assessing their effectiveness in achieving the desired environmental benefits while maintaining economic and capacity feasibility. The validation scenarios will simulate real-world conditions to experiment with and validate the proposed mechanisms. Key inputs are the results of a stated-preference survey assessing airlines' sensitivity to delay and costs.			
D5.3 [44]	Intermediate Exploratory Research Report – Green Route Charging	30/10/2024, 12/02/2025	Public
D5.3 is the intermediate exploratory research report (ERR), providing an overview of the progress and key findings for the Green route charging Solution, which aims to develop environmentally friendly route charging mechanisms. The ERR highlights the status of validation exercises focused on en-route charges, addressing climate impact, economic effects on air navigation service providers (ANSPs) and airspace users (AUs), overall network efficiency, and capacity constraints. The intermediate ERR includes results from the initial validation exercise using representative samples of European air traffic, describes developments of the Full Solution, and presents insights from an ongoing stated-preference survey.			
D5.4 [57]	Final OSED – Green Route Charging	30/06/2025, 17/09/2025	Public
As part of the Solution Data Pack for Green Route Charging, D5.4 defines the operational service and environment description (OSED). Initial Solution mechanisms influence route selection by giving an early price signal to airlines to avoid congested airspaces at strategic level, thus promoting environmentally friendly flight paths, while the Full GRC Solution investigates incentivisation for avoidance of climate hotspots in (pre-tactical) operations. Implementation would be within the 41 EUROCONTROL contracting States and adheres to the Multilateral Agreement on Route Charging, impacting various stakeholders. It aims to balance capacity supply and demand, enhance airspace efficiency, and ensure revenue neutrality for ANSPs.			
D5.5 [58]	Functional Requirements Document – Green Route Charging	30/06/2025, 18/09/2025	Public
As part of the Solution Data Pack for Green Route Charging, D5.5 is the Functional Requirements Document (FRD), describing the Solution functional architecture and requirements. The former involves a Central Planner, which aggregates traffic forecasts, capacity forecasts and unit rate data. Based on these inputs, the Central Planner calculates modulation factors for route charges, which are then provided to airline flight planning systems to support optimised trajectory selection and to States for annual unit rate calculations. In the Full Solution, the Central Planner additionally integrates atmospheric data from meteorological providers. A key principle is the revenue neutrality for ANSPs.			

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Reference	Title	Delivery Date	Dissemination Level
	Description		
D5.6 [55]	ECO-EVAL – Green Route Charging	09/07/2025	Public
As part of the Solution Data Pack for Green Route Charging, D5.6 provides the Solution's economic evaluation (ECO-EVAL), assessing its potential benefits and costs for various stakeholders. The Initial Solution demonstrates a reduction of CO_2 emissions (ENV1) by 0.25–1.36% and a significant alleviation (by 91.2–94.1%) of congestion across the traffic periods assessed. Regarding non-CO_2 emissions, the project first assessed whether a climate hotspot-based approach was viable. Initial results tested the mechanism on a larger (but limited) sample, where most KPIs were affected in a slightly negative or neutral manner, except full emissions, showing 14% reduction (measured by ATR20).			
D5.7 [56]	Final Exploratory Research Report – Green Route Charging	30/06/2025, 16/09/2025	Public
As part of the Solution Data Pack for Green Route Charging, D5.7 is the final exploratory research report (ERR), providing a description of the validation results. Validation objectives addressed feasibility, ensuring that the solutions are compliant with stakeholder needs by verifying the underlying model assumptions, and the climate impact of the solutions, which is at the core of the project. The success criteria are a reduction in ENV1 for the Initial Solution and of total climate impact for the Full Solution. The issue of air traffic congestion was also addressed. These KPIs were compared between the reference and solution scenarios.			
D6.1 [28]	Initial Communication, Dissemination and Exploitation Plan	30/11/2023	Public
This document contains the Initial Communication, Dissemination and Exploitation Plan of the project assisting the partners in carrying out the right types of communication and dissemination activities, at the right time and towards the right target groups. D6.1 describes the Project's communication and dissemination strategy, criteria for determining its success, and presents a tentative planning of corresponding activities. Branding and templates for acknowledgements and disclaimers serve the Project partners in their communication and dissemination activities, whereas high-level messages and keywords provide SJU Communications with material for their communication activities at Programme level. D6.1 is superseded by D6.2 (Intermediate CDE Plan).			
D6.2 [37]	Intermediate Communication, Dissemination and Exploitation Plan	30/09/2024	Public
D6.2 updates D6.1 to the status at the end of first reporting period and served as input to the Intermediate Project Review. The document contains the Intermediate Communication, Dissemination and Exploitation Plan of the project, describing the Project's communication and dissemination strategy, criteria for determining its success. It is notably updated concerning achievements and planning of corresponding activities. Branding and templates for acknowledgements and disclaimers serve the Project partners in their communication and dissemination activities, whereas high-level messages and keywords provide SJU Communications with material for their communication activities at Programme level.			

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Reference	Title	Delivery Date	Dissemination Level
Description			
D6.3 [60]	Communication, Dissemination and Exploitation Report	submitted 30/01/2026	Public
Updating and extending D6.2 near the end of the final reporting period, D6.3 reports on the Dissemination and Communication activities of the Project. Events and activities performed during both technical and dissemination phases are summarised and evaluated against the goals of the Project's Communication and Dissemination strategy as laid down in the initial and final Dissemination and Communication Plans. This includes a review of targeted activities (conferences, scientific publications) as well as transversal ones (webpages, social media, workshops). Exploitation opportunities in view of the Project's Solutions' confirmed maturity (TRL1 / TRL2 with acceptable risks) are also described, and lessons learned are extracted.			

Table 8: accepted and submitted Project Deliverables. The second date, where given, refers to a resubmission of an updated version. All Deliverables accepted except where indicated as "submitted"

Reference	Title	Delivery Due Date	Dissemination Level
Description			
D1.1.20	Periodic Report #2	29/04/2026	Sensitive
formal technical and financial report on the project according to HE reporting rules			

Table 9: pending Project Deliverables

2.6 Communication, Dissemination and Exploitation Activities

This section summarises key activities in the areas of Communication, Dissemination and Exploitation activities. More information on early activities is available in D6.2 [37]; a complete description will eventually be available in D6.3.

All partners from Green-GEAR are encouraged to use the Communication materials produced by the project also for their respective in-house communication.

2.6.1 Website

In order to maximise visibility and facilitate finding information on the project, several web addresses are established:

- the SESAR 3 JU page for Green-GEAR (https://www.sesarju.eu/projects/GREEN-GEAR) containing the main facts about the project, objectives, consortium, and hosting news about the projects such as events, participations to conference and workshops.
- the European commission page for Green-GEAR (https://cordis.europa.eu/project/id/101114789) with more formal project information and a link to CORDIS which allows to download all public Deliverables;

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- the dedicated Green-GEAR domain (https://sesar-green-gear.eu/) hosted at DLR, providing up-to-date information on the project's objectives, status and (intermediate) outcomes. It promotes project related events such as project workshops or (third-party) conferences and allows downloading all public access materials. This includes project reports and scientific publications after their acceptance by the SESAR 3 JU or the editors, respectively, White Papers and further Communication materials. This website is used as the landing page for social media channels.

2.6.2 Press and media

The aim is to provide popularised messages on environmental performance evidence (CO_2 and non-CO_2 effects, fuel use reduction, etc.) from the analysis and fast-time simulation, showing especially the possible short- and medium-term benefits of Green-GEAR procedures, thus creating awareness and visibility of the project aims, and interest in the project activities. The ultimate objective is to inform / engage with society and show the impact and benefits of EU-funded R&I activities.

Media activity	Date	Link
	Past contributions	
Contribution to CORDIS Projects Info Pack on "Air Traffic Management and the Green Deal"	4th Dec 2023	https://www.sesarju.eu/node/4634
CORDIS project factsheet	Dec 2023	https://cordis.europa.eu/project/id/101114789
e-News Article #1 "Aircraft Efficiency starts with having the right altitude"-- Interview with Tobias Bauer	3rd May 2024	https://www.sesarju.eu/news/aircraft-efficiency-starts-having-right-altitude
Green-GEAR Teaser Video	15th May 2024	https://youtu.be/0-I_U6BLH1E?feature=shared
LinkedIn repost of Teaser Video	28th May 2024	https://www.linkedin.com/posts/sesar-green-gear_a-quick-introduction-to-the-green-gear-project-activity-7203297730926886913-w6VT?utm_source=share&utm_medium=membe _desktop
Twitter/X repost of Teaser Video	28th May 2024	https://x.com/SesarGreenGEAR/status/17954225 21753239594
LinkedIn Teaser post for eNews #1	15th June 2024	https://www.linkedin.com/posts/sesar-green-gear_sesar-ju-green-gear-activity-7209464701892644866-D8bG?utm_source=share&utm_medium=membe _desktop
Twitter/X Teaser post for eNews #1	27th June 2024	https://x.com/SesarGreenGEAR/status/18062929 82737629402

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Media activity	Date	Link
e-News Article #2 "Transforming altimetry for a safer, more efficient aviation future" – Interview with John Godsell	20th November 2024	https://www.sesarju.eu/news/transforming-altimetry-safer-more-efficient-aviation-future
DLR Flight Systems internal magazine "flugBLATT" - Project Profile	29th November 2024	(DLR internal document)
LinkedIn Post about new ATM Master plan and the way in which the Green-GEAR project fits in	12th December 2024	https://www.linkedin.com/feed/update/urn:li:activity:7273342792536326144
LinkedIn Holidays Post	20th December 2024	https://www.linkedin.com/feed/update/urn:li:activity:7275847690016423936
Green-GEAR profile page on DLR's Institute of Flight systems website	25th March 2025	https://www.dlr.de/en/ft/research-transfer/projects/green-gear
LinkedIn post announcing Green-GEAR participation in the SESAR Walking Tours at Airspace World	7th May 2025	https://www.linkedin.com/feed/update/urn:li:activity:7325797318715166720
LinkedIn post thanking participants of the Walking Tours for their interest and support	22nd May 2025	https://www.linkedin.com/feed/update/urn:li:activity:7330508451472740353
report on ASW in DLR Flight Systems internal magazine "flugBLATT	28th May 2025	(DLR internal document)
eNews Article #3 "Spotlight on the full Green Route Charging solution – Interview with Tatjana Bolic"	24th September 2025	SESAR Joint Undertaking | Spotlight on the full green route charging solution – Interview with Tatjana Bolic
eNews Article #4 "Exploring safer skies with reduced vertical separation" – Interview with Bart Klein Obbink	22nd October 2025	SESAR Joint Undertaking | Exploring safer skies with reduced vertical separation
eNews contribution – summary of project and invitation to Final Dissemination Workshop	28th January 2026	SESAR Joint Undertaking | Green-GEAR Final Dissemination Workshop
	Forecasted contributions	
Green-GEAR results video(s) addressing general public, highlighting project results and conclusion	February 2026	will be available on sesar-green-gear.eu, the SESAR hosted project page and the SESAR YouTube channel

Table 10: Contributions to external media.

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2.6.3 Social media

Throughout the duration of the Grant, Green-GEAR's activities are being promoted on LinkedIn. A brief trial run on Twitter/X was discontinued due to a high level of bot activity and concerns about effectively reaching the intended audiences. The chosen channels allow for accessible communication targeted at professional and policy actors, students, and the general public, supported by the strategic use of dedicated #hashtags.

Linkedin :

- https://www.linkedin.com/company/sesar-green-gear
- Green-GEAR SESAR3 Project - EXPLORATORY RESEARCH PROJECT Green-GEAR – Green operations with Geometric altitude, Advanced separation and Green Route charging solutions

X / Twitter :

- @sesargreengear
- Green-GEAR SESAR3 Project
- EXPLORATORY RESEARCH PROJECT Green-GEAR – Green operations with Geometric altitude, Advanced separation and Green Route charging solutions
- Discontinued

All social media communications tag or reference the SESAR 3 JU and EU in all related posts:

- Social media channels:
  - @SESAR_JU (X / Twitter), @SESAR Joint Undertaking (LinkedIn), SESARJU (Youtube)
  - @HorizonEU (X / Twitter) and @European Commission (LinkedIn)
  - @cinea_eu (X / Twitter), cinea - European climate, infrastructure and environment executive agency (LinkedIn)
- Social media hashtags
- #ATM #DigitalSky #innovation #SESAR3JU #HorizonEU
- #MobilityStrategy #Uspace
- #HorizonEurope #CEFTransport

2.6.4 Communication events

Due to the small size of the project, the Green-GEAR project team primarily participates in existing events but also organises specific events to promote the work throughout the duration of the project, with a focus on Dissemination for latter activity (see section 2.6.8). This is done in coordination with the SESAR 3 JU.

Event	Date	Place	Information to be shared	Importance for the project
SESAR Innovation Days	2023 2025	Seville, Spain Bled, Slovenia	Project approach final results(*)	promote the project and (ongoing) work, find collaboration partners for follow-up activities

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Event	Date	Place	Information to be shared	Importance for the project
66th meeting of the Study Group of Enlarged Committee for Route Charges	April 2024	Brussels, Belgium	GRC objectives and methodologies / research progress and intermediate results(*)	Ensure buy-in and collect feed-back on implementation issues at state level
Green-GEAR initial stakeholder workshop	May 2024	virtual	Project approach, explanation of each of the three solutions	ensure stakeholder buy-in and continued involvement, collect requirements
Green Deal Flagship	Jan 2024 June 2024 Oct 2024 May 2025	virtual Brussels, Belgium Brussels, Belgium Lisbon, Portugal	Project approach Project status Project progress Project results(*)	promote collaboration with and gather input from other projects
66th meeting of the Study Group of Enlarged Committee for Route Charges	April 2024	Brussels, Belgium	GRC objectives and methodologies / research progress and intermediate results(*)	Ensure buy-in and collect feed-back on implementation issues at state level
Green-GEAR Intermediate Review Meeting	November 2024	hybrid; Brussels, Belgium	review of all WPs' Progress	identify challenges and formulate solutions for better progress; identify areas for specific promotional activities
Presentation of Green Route Charging Solution to European Regional Aviation Association	December 2024	virtual	Project approach, initial and intermediate results(*)	Collect feedback on approach and eventual implementation issues
Green Route Charging Workshop	January 2025	Belgrade, Serbia	intermediate results of Green Route Charging Solution(*)	obtain feedback and coordinate remaining work (also with SJU)
Green-GEAR interim stakeholder workshop (2 days, WP3/4 and WP5 separately)	March 2025 April 2025	WP3/4 Workshop: virtual; WP5 Workshop: hybrid; Brussels, Belgium	Project interim Solutions / concepts of operation(*)	ensure stakeholder buy-in and continued involvement, collect quantitative and qualitative input
Airspace World	May 2025	Lisbon, Portugal	Project results(*)	promote the project and (ongoing) work
SESAR 3 JU Annual Conference	2025	Brussels, Belgium	Project progress and results	promote the project and ongoing work / results

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Event	Date	Place	Information to be shared	Importance for the project
International Conference on Optimization and Decision Science	September 2025	Milan, Italy	results of the Green Route Charging Initial Solution(*)	ensure visibility of project results beyond the consortium; collect feedback and foster engagement
Green-GEAR Maturity Gate Meeting	September 2025	hybrid; Brussels, Belgium	Exit Maturity Gate of all three solutions(*)	assess project results regarding objectives and Solutions' final TRL levels
10th CEAS Aerospace Europe Conference	December 2025	Turin, Italy	results of the wake vortex study from the Separation Minima Solution(*)	ensure visibility of project results within scientific community; collect feedback
Green-GEAR final stakeholder workshop	February 2026	virtual	Project final Solutions / concepts of operation(*)	ensure stakeholder involvement in activities beyond the project, collect feedback on project results
(*) also a Dissemination activity				

Table 11: Events

2.6.5 Publications and newsletters

Publications/newsletters/printed material	Description	Date	Link
Green-GEAR roll-up #1	physical poster (200 x 80 cms) explaining Project approach	27/11/2023	Currently available via SIDs virtual poster: https://whova.com/portal/webapp/sesar_202311/Artifact/96562
Contribution to CORDIS Projects Info Pack on "Air Traffic Management and the Green Deal"	(contribution to) brochure conveying project approach to general public	04/12/2023	https://www.sesarju.eu/node/4634
SESAR 3 JU publications (e.g. SESAR Solutions Catalogue, results brochures, annual highlights, e-news)	contribute by providing text and illustrative content, as needed.	various	e.g. SESAR Joint Undertaking | Vertical guidance using geometric altimetry SESAR Joint Undertaking | Separation minima SESAR Joint Undertaking | Green route charging

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Publications/newsletters/printed material	Description	Date	Link
SESAR 3 JU e-News Article #1	interview with Project Manager Tobias Bauer (DLR)	03/05/2024	https://www.sesarju.eu/news/aircraft-efficiency-starts-having-right-altitude
SESAR 3 JU e-News Article #2	interview with John Godsell (NATS) on GeoAlt Solution	20/11/2024	https://www.sesarju.eu/news/transforming-altimetry-safer-more-efficient-aviation-future
SESAR 3 JU e-News Article #3	interview with Tatjana Bolic (UoW) on Green Route Charging Solution	24/09/2025	https://www.sesarju.eu/news/spotlight-full-green-route-charging-solution-interview-tatjana-bolic
SESAR 3 JU e-News Article #4	interview with Bart Klein Obbink (Royal NLR) on Separation Minima Solution	22/10/2025	https://www.sesarju.eu/news/exploring-safer-skies-reduced-vertical-separation
Green-GEAR roll-up #2	physical poster (200 x 80 cms) explaining Project results	01/12/2025	https://sesar-green-gear.eu/images/Poster/posterSIDs25_GreenGEARv04.pdf
SESAR 3 JU e-News workshop announcement	announcement and invitation to final stakeholder workshop	28/01/2026	https://www.sesarju.eu/node/5293

Table 12: Printed material

2.6.6 Videos

A teaser video with an approximate duration of one minute has already been produced; it is shown as accompanying material at the SESAR Innovation Days (SIDs) 2023 and will be linked from website. A further, more comprehensive project teaser was produced in 2024. More material will follow explaining the project results.

Videos	Description	Planning	Link
Green-GEAR teaser	visualisation of project approach	for SIDs 2023 (available)	Currently available via SIDs virtual poster: https://whova.com/portal/webapp/sesar_202311/Artifact/96562
Green-GEAR Teaser Video	Project Problem Statement, Objectives and Approach in video form	15th May 2024	https://youtu.be/0-I_U6BLH1E?feature=shared

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Videos	Description	Planning	Link
Green-GEAR results video(s)	Interview medley with solution representatives; results overview for SIDs participants and general public	Q 1 / 2026	will be available on sesar-green-gear.eu, the SESAR hosted project page and the SESAR YouTube channel
Green-GEAR conclusions video	explaining technology or procedures developed, highlighting project results and conclusions	Q I / 2026	will be available on sesar-green-gear.eu, the SESAR hosted project page and the SESAR YouTube channel

Table 13: Videos

2.6.7 Scientific publications

All of Green-GEAR's scientific publication will be **open access,** i.e. provide online access to scientific information that is free of charge to the end-user and reusable. The preferable solution is **'gold' open access** where the publication's peer review and editing is funded by the publishing partner(s) to enable free on-line access to any interested party. Where not possible, peer reviewed papers of the projects' results will be made accessible the partners' public servers, e.g. DLR elib, and the project website at CORDIS (doi: 10.3030/101114789) (**'green' open access**).

The table below lists the current plans on scientific publications of Green-GEAR'S results. **Presentations** have been held at the following national and international scientific conferences: CEAS Air & Space Conference, International Conference on Optimization and Decision, Science SESAR Innovation Days. **Peer-reviewed Publications** are planned in the following relevant scientific journals allowing open access: Journal of Aircraft, CEAS Journal and others.

The detailed choice is a matter of deadlines of the respective medium vs. availability of results and availability of travel / publications budget, and will be updated in the next iterations of the present document.

Scientific papers/ presentations	Link	Information to be shared
poster from DLR, NATS, NLR, UoW for SIDs 2023, Nov 2023 [65]	https://sesarju.eu/SIDS2023 -> Posters	details on project approach for all three Solutions
conference paper from UoW for SIDs 2024, Nov 2024 Can route charging incentivise environmentally-friendly trajectories? (2024) Bolic, T.; Gurtner, G.; Cook, A.J.; Soolaki, M. [66]	https://doi.org/10.61009/SID.2024.1.38	intermediate results of route charging study (WP5)
presentation from UNITS at the International Conference on Optimization and Decision Science 2025, Milan, 1st - 4th September 2025 [67]	https://www.airoconference.it/ods2025/images/docs/ODS25_AbstractBook.pdf	final results from green route charging study (WP5) – Initial solution

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Scientific papers/ presentations	Link	Information to be shared
conference paper from DLR at 10th CEAS Aerospace Europe Conference, Turin, 1st - 4th December 2025 [69]	preprint: https://elib.dlr.de/221525/	results of wake vortex safety analysis for reduced vertical separation (WP4)
poster for SESAR Innovation Days, Bled, 1st - 4th December 2025 [71]	https://sesar-green-gear.eu/images/Poster/posterSIDs25_GreenGEAR v04.pdf	results of all three solutions (WPs 3, 4, 5)
conference paper from Royal NLR at SESAR Innovation Days, Bled, 1st - 4th December 2025 [70]	https://www.sesarju.eu/sites/default/files/documents/sid/2025/papers/SIDs_2025_paper_18-final.pdf	results of Collision Risk Analysis for RVSM 2 (WP4)
Journal paper from DLR for CEAS Aeronautical Journal (submitted) [68]	TBA	results of flight mechanical study of geometric altimetry in cruise (WP3)
journal paper from DLR (under preparation)	TBA	results of flight mechanical study of geometric altimetry in the TMA (WP3)
journal paper from DLR (under preparation)	TBA	results of wake vortex safety analysis for reduced vertical separation (WP4)
Journal paper from UNIT and UoW, Q I / 2026	TBA	consolidated results of Initial Solution from green route charging study (WP5)
Journal paper from UoW, Q II/Q III 2026	TBA	results of Full Solution from green route charging study (WP5)

Table 14: Scientific papers, publications and presentations

2.6.8 Dissemination events

Event	Date	Place	Information to be shared	Importance for the project
SG66 of Enlarged Committee for Route Charges	16th Aril 2024	Brussels, Belgium	Project approach, initial Results(*)	Ensure buy-in and collect feed-back on implementation issues at state level
Green-GEAR initial stakeholder workshop	14th, 15th May 2024	virtual	Project initial Solutions / concepts of operation(*)	ensure stakeholder buy-in and continued involvement, collect quantitative and qualitative input
Engage 2 Winter School	27th - 31st Jan 2025	Belgrade, Serbia	Green Route Charging initial concepts	ensure the education of new generation of aviation professionals on

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Event	Date	Place	Information to be shared	Importance for the project
				the climate impact of aviation
Green Route Charging Workshop	January 2025	Belgrade, Serbia	Intermediate results of Green Route Charging Solution(*)	Distribute intermediate results to ENGAGE network, obtain feedback for remaining work
Green-GEAR interim stakeholder workshop	March 2025 April 2025	WP3/4 Workshop: virtual; WP5 Workshop: hybrid; Brussels, Belgium	Project interim Solutions / concepts of operation(*)	ensure stakeholder buy-in and continued involvement, collect quantitative and qualitative input
GeoAlt Human Factors and Safety Workshop	April 2025	virtual	Results of the HF and Safety assessment of using GeoAlt in the TMA	ensure mutual understanding of achievements and possible further work
Airspace World / SESAR Walking Tour	14th May 2025	Lisbon, Portugal	Solutions objectives and results	ensure stakeholder buy-in, find collaboration partners for follow-up activities
Green Deal Flagship	May 2025	Lisbon, Portugal	Project results	Promote the project and (ongoing) works and results
International Conference on Optimization and Decision Science	September 2025	Milan, Italy	Dissemination of results of the Green-GEAR Green Route Charging Initial Solution(*)	ensure visibility of project results beyond the consortium, collect feedback and foster engagement
10th CEAS Aerospace Europe Conference	December 2025	Turin, Italy	Results of the wake vortex study from the Separation Minima Solution(*)	ensure visibility of project results within scientific community; collect feedback
15th SESAR Innovation Days	December 2025	Bled, Slovenia	Overall final results(*) Results of the collision risk study from the Separation Minima Solution(*)	promote the project and (ongoing) work, find collaboration partners for follow-up activities
Green-GEAR final Dissemination workshop	12th February 2026	vitual	Project outcomes (Solutions, concepts of operation)(*)	ensure stakeholder involvement in activities beyond the project, collect feedback on project results

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Event	Date	Place	Information to be shared	Importance for the project
AEROPLANE final Dissemination event	16th February 2016	Rome, Italy	Project outcomes, in particular the Green Route Charging solution	results sharing across SESAR 3 JU projects under the Green Deal Flagship
(*) also a Communication activity				

Table 15: Dissemination conferences and workshops

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3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

3.1.1 Solution Definitions

As an ER project, Green-GEAR has not worked on higher-TRL OI steps and enablers, but rather defined three new Solutions, see Table 16. Those have been matured from (pre-)TRL1 to TRL2 ongoing / TRL2 as indicated in the table, following assessment of the project during the Maturity Gate.

Said self-assessment of maturity can be found in section 3.2.1 for Geometric Altimetry, section 3.2.2 for Separation Minima and section 3.2.3 for Green Route Charging.

Code	Name	Project contribution: (Shortened) Solution Definition	Maturity at project start	Maturity at project end
#0406	Vertical Guidance using geometric altimetry	Airspace and procedures design based on geometric constraints and geometric vertical paths, increasing predictability and enabling continuous climb or descent ignoring atmospheric variation and the Transition Layer.	TRL0 (pre-TRL1)	TRL2
#0407	Separation Minima	Transition from 1000 ft to 500 ft minimum vertical separation in upwards extended RVSM airspace (FL 290 to FL 600), enabled by increased altitude measurement accuracy through geometric altimetry (RVSM 2 concept).	TRL1[8]	TRL2 ongoing
#0408	Green Route Charging	Charging mechanism that incentivises trajectories with minimum climate impact, while reducing airspace congestion.	Initial Solution: TRL1[8]	Initial Solution: TRL2
			Full Solution: pre-TRL1	Full Solution: TRL1
			Overall TRL1[8]:	Overall: TRL1

Table 16: Project Maturity

[8] Note that the maturity at project start had been given as a tentative TRL1 in the proposal for Separation Minima and Green Route Charging, but the assessment during the Intermediate Review revealed that many SESAR-specific criteria were not fulfilled even then. Consequently, a final TRL1 for Green Route Charging already implies progress during the project, as also evidenced by comparing the separate ratings for the Initial and Full Solutions.

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Table 16 lists shortened Solution Definitions due to layout constraints; the full versions read as follows:

Vertical Guidance using Geometric Altimetry

The Solution envisions a future where all airspace users utilise geometric altimetry for vertical navigation within and up to a common altitude beyond the TMA, mitigating inefficiencies in current flight operations and airspace use resulting from the limited accuracy of barometric altimetry. This unified altitude reference allows seamless integration of drones, eVTOLs, high-altitude operations, and traditional aviation.

There are two main methods:

(1) Defined lateral path with altitude constraints: Uses geometric altimetry for vertical paths with waypoints providing separation, with limited impact on current systems.

Benefits include improved safety, environmental gains, and increased capacity.

(2) Defined lateral and vertical path: Maintains vertical separation against a geometric path, akin to V-RNP, enabling better three-dimensional procedure design, requiring enhanced ATC tools.

Fast-time simulations based on London TMA showed significant fuel savings, especially for arrivals, with minor issues for departures. The approach improves efficiency overall.

Geometric cruise, however, slightly increases fuel use and presents operational limits, so it isn't standalone but may aid broader operational improvements.

Separation Minima

The solution aims to transition from 1000 ft / 2000 ft to 500 ft minimum vertical separation in extended RVSM airspace (FL 290 to FL 600), enabled by increased altitude measurement accuracy through satellite-based altimetry. Reduced vertical separation will increase capacity and allow more aircraft to fly closer to their optimal flight level, thus reducing CO_2 emissions.

The study has focused on the safety aspects. It is shown mathematically that the actual, nominal performance of satellite-based altimetry might be sufficient to reach the target level of safety for the collision risk. Fast-time simulations have shown a substantial increase in the number of critical wake encounter occurrences, highlighting the need for mitigation through systems or procedures. The risk analysis of non-nominal situations has identified GNSS jamming and spoofing, TCAS alerts and contingency procedures as critical points.

Green Route Charging

The Green Route Charging (Green RC) solution is designed to encourage airspace users to reduce the environmental impact of aircraft operations while maintaining economic and capacity effects.

En-route charges, proportional to the costs of providing en-route Air Navigation Services (ANS), are collected from airspace users. The current charging scheme allows for the modulation of charges to incentivise desired behaviours.

The Green RC solution is scalable, with a two-step implementation corresponding to different levels of ambition and complexity. Initially, the solution is designed to reduce CO_2 emissions and demand-capacity imbalances through the use of modulation of charges. Ultimately, it aims to mitigate the effects of non-CO_2 emissions as well.

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The Solution will eliminate flight inefficiencies resulting from the route charging scheme itself (e.g., detours due to unit rate differences) and incentivise environmentally friendly trajectory planning. Revenue neutrality will be maintained through the appropriate recalibration of charges. The principles set forth in the ICAO Document 9082 need to be maintained, particularly those pertaining to gradual changes in charges and the modulation of charges.

3.1.2 Solution Descriptions

In addition to the three Solution Definitions cited above, the following Solution Descriptions were produced to give a short overview of rationales and expected benefits, operational concepts and standardisation/regulation aspects.

Enhancing Airspace Integration with Vertical Guidance using Geometric Altimetry

Problem Statement/Rationale:

As airspace becomes increasingly congested with a diverse range of users, including drones, unmanned aircraft systems, vertical take-off and landing aircraft as well as high-altitude operations, the need for a unified vertical navigation reference has never been greater. Current reliance on barometric altimetry and manual pressure reference adjustments complicates operations, reduces efficiency, and carries a risk for human errors.

What is the Solution About?

The Green-GEAR Project aims to revolutionise vertical navigation by exploring the feasibility of adopting Geometric altimetry across all flight phases. This system uses a single common reference point for aircraft altitude, enabling a means for seamless integration between traditional and emerging airspace users, without the complication of local pressure settings and Transition Layers. The project examined two main methods for implementing Geometric altimetry:

Prescribed Lateral Path with Altitude Constraints**:** For this method, aircraft would construct and navigate vertical paths based on geometric altitude constraints at waypoints. This would enhance safety by eliminating the need for manual pressure setting changes when crossing the Transition Layer. Environmental benefits include more consistent altitudes, which at lower levels can improve performance and reduce noise. Additionally, airspace capacity would increase by removing the Transition Layer and avoiding the loss of flight levels associated with it. This method could be implemented with minimal changes to current airspace or instrument flight procedures. Geometric altitude would be reported alongside barometric altitude.

Prescribed Lateral and Vertical Path**:** For this approach, aircraft would construct geometric point-to-point vertical paths using Geometric altimetry, based on defined geometric path flight procedures, using as a form of Vertical Required Navigation Performance (V-RNP) to ensure procedural separation. It allows for more efficient 3D Instrument Flight Procedure (IFP) design and optimisation of airspace use but constrains the aircraft’s vertical profile. Implementation of this method would require updates to Air Traffic Management tools, including surveillance and safety nets like Mode-S cleared/selected flight level (CFL/SFL) checking and a Barometric Alerting Tool (BAT).

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This method greatly improves how flight paths are managed, allowing route planners to design more efficient routes using a fully three-dimensional airspace.

Regulation / Standardisation Aspects

To enable this concept, international standards would need to be updated to reflect vertical navigation by geometric altitude and barometric fallback procedures. It is highly likely that EU regulations would need to be created to mandate both ground system capability and airborne capability.

For the second of the two methods, V-RNP would need to be defined, with FMS capabilities standardised through EUROCAE and RTCA.

Geometric Altimetry is dependent on improved resilience to GNSS jamming and spoofing through technology improvements or mitigations and related new standards.

Benefits:

The adoption of Geometric altimetry promises numerous advantages:

- Safety: Eliminates the need for manual pressure datum changes, reducing pilot & controller workload and reduces human error. Reduces risk of high glideslope capture.
- Environmental Gains: Consistent altitudes allow better planning of the individual flight profile. The improved efficiency of airspace design enabled by Geometric altimetry may reduce fuel and emissions overall, depending on the impact to individual flight profiles.
- Capacity Increase: Enhanced containment and optimised route design in a truly three-dimensional airspace. No loss of Flight Levels due to Transition Layer, increasing the amount of airspace available.
- Cost Efficiency: Potential cost savings through engine wear reduction due to thrust consistency.

Enhancing Airspace Efficiency with Improved Vertical Separation

Problem Statement/Rationale

Current air traffic management in Reduced Vertical Separation Minimum (RVSM) airspace, which spans flight levels FL 290 to FL 410, relies on a 1000 ft minimum vertical separation between aircraft. As altitude increases, the accuracy of barometric altimetry decreases, necessitating a 2000 ft separation above FL 410. These vertical separation minima limit airspace capacity and thus contribute to increased emissions through longer routings or flight at unfavourable altitudes.

What is the Solution About?

The “Separation minima” Solution proposes transitioning to a 500 ft minimum vertical separation within RVSM airspace, enabled by geometric altimetry. Unlike barometric altimetry, geometric altimetry maintains high accuracy far above the altitudes that are relevant for conventional aviation, allowing the extension of RVSM airspace up to FL 600. The project has focused on the safety aspects, including the collision and wake turbulence risks, using the European RVSM region as a test case.

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Standardisation / Regulation aspects

The implementation of the reduction in minimum vertical separation would need a change of the Rules of the Air at ICAO level, specifically an amendment of the PANS-ATM (Doc 4444). However, during further maturation of the concept, the whole RVSM implementation process and requirements would need to be reworked. This will most probably also include an advancement of the MOPS and MASPS for GNSS receivers, an activity that is beyond this Solution and not specific to it.

Benefits

This enhanced separation will significantly boost airspace capacity, allowing more aircraft to fly at their optimal flight levels, reducing CO_2 emissions, and minimising detours to avoid climate-sensitive areas. It supports both civil and military aviation and facilitates the integration of advanced aircraft, such as Unmanned Aerial Systems (UAS) and High-Altitude Operations (HAO) aircraft, enhancing overall air traffic management efficiency and environmental sustainability.

Green Route Charging: A Sustainable Solution for Aviation

Problem Statement/Rationale:

The existing en-route charging scheme, which collects charges proportional to the costs of providing en-route Air Navigation Services (ANS) from airspace users (AU), does not take into account environmental considerations. Not only does it fail to incentivise environmentally friendly practices, but practical observations actually show flight inefficiencies resulting from the route charging scheme itself (e.g., detours due to unit rate differences).

What is the Solution About?

The "Green Route Charging" (Green RC) Solution makes use of the fact that the current charging scheme allows for the modulation of charges to incentivise desired behaviours; it introduces a scalable, two-step implementation process designed to modulate en-route charges. Initially, it focuses on reducing CO_2 emissions and alleviating congestion by adjusting charges to promote efficient and eco-friendly flight paths. Ultimately, it aims to address the impacts of non-CO_2 emissions as well.

Standardisation/Regulation Aspects:

The approach is in line with general ICAO principles (Doc 9082) which allow the modulation of charges, even if, in practice, no State has yet implemented this mechanism. It would be beneficial to consider regulatory changes concerning the Commission Implementing Regulations, with a view to specifying and harmonising the applicability conditions, in particular for non-CO_2 impacts.

Benefits:

Green RC has the potential to enhance flight environmental efficiency by encouraging sustainable trajectory planning, and by eliminating route inefficiencies due to current air navigation services (ANS) charging. It maintains revenue neutrality per service unit for ANSPs and overall cost neutrality for airspace users by recalibrating charges, and adheres to ICAO guidelines on gradual and modulated changes.

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3.2 Maturity Assessment

The Geometric Altimetry Solution has started at pre-TRL1, while Separation Minima and Green Route Charging Solutions were tentatively assessed as TRL1 before the project start. During the Intermediate Review it was revealed that many SESAR-specific criteria for TRL1 were not fulfilled even then. Consequently, a final TRL1 for Green Route Charging already implies progress during the project. As there is currently only one Solution with two "flavours", the lower maturity of the Full Solution determines the overall verdict, even if the Initial Solution has progressed to TRL2 (see Table 16.) Geometric Altimetry is assessed as having reached TRL2 with acceptable risks, while Separation Minima is rated as TRL2 ongoing.

3.2.1 Solution 0406, Vertical Guidance using Geometric Altimetry

The Geometric altimetry Solution is self-assessed against TRL1 and TRL2 criteria in Table 17 and Table 18, respectively. We find a fulfilment of TRL1 criteria now, which means progress against the initial state and that at the Intermediate Review, and an at least partial fulfilment of TRL2 criteria. The main deficiencies are the lack of a safety and human performance assessment for the airborne side, the omission of noise and local air quality from the environmental assessment and the limited consideration of possible interactions with other Solutions working on flight path definition in the TMA. Furthermore, only a specific type of high-density TMA has been investigated, meaning the results may not be transferable to high-density TMAs in general. As clear benefits have been demonstrated for the example TMA and it is not expected that the above-mentioned missing activities would identify major issues, the project self-assesses these issues as non-blocking, i.e. believes the maturity is sufficient to warrant initiation of the next maturity phase. The vedict at the maturity gate has been TRL2 with acceptable risks.

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.01	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? - Where does the problem lie? - Has the ATM problem/challenge/need(s) been quantified that justify the research done? Note: an initial estimation is sufficient	achieved	The OSED (D3.5) describes the risks, limitations and inefficiencies of using barometric altimetry. Primarily, these lie with the Transition Layer but also affects vertical predictability, which has knock-on impacts to airspace design and operational efficiency. This problem has not been quantified but it has a global impact.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.02	Have the solutions (concepts/capabilities/methodologies) under research been defined and described?	achieved	The initial operational concept was developed through project workshops and captured in the Initial OSED (D3.1). Then, following validation activities, the Solution scope has been readjusted and documented in the Final OSED (D3.5). **Note**: throughout this Maturity Assessment matrix, "OSED" with no qualifier refers to the Final OSED.
TRL-1.03	Have assumptions applicable for the innovative concept/technology been documented?	achieved	The operational concept description and related assumptions are documented in the OSED (D3.5). The preliminary technical solution description and related assumptions are documented in the FRD (D3.4).
TRL-1.04	Have the research hypothesis been formulated and documented?	achieved	The main assumptions for the research/validation phase were documented in the ERP (D3.2), and recalled in the ERR (D3.3), mainly related to: - Expected benefits to be assessed (i.e. using geometric altimetry for vertical guidance can reduce fuel/CO2, safety risks, and costs, can increase capacity and improve human performance). - Expected impact assessments to be conducted (e.g. safety, human performance and airborne systems). - Other expected constraints to be considered (i.e. GNSS environment and baro/geo mix during transition stages).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.05	Do the obtained results from the fundamental research activities suggest innovative solutions (e.g. concepts/methodologies/capabilities?) - What are these new concepts/methodologies/capabilities? - Can they be technically implemented?	achieved	Outcomes from validation activities have been captured in the ERR (D3.3). The retained operational concept, related ATM capabilities and preliminary technical requirements are documented in the OSED (D3.5) and the FRD (D3.4).
TRL-1.06	Have the potential strengths and benefits of the solution identified and assessed? If applicable, are the potential safety benefits identified and justified? - Qualitative assessment on potential benefits. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it should be used.	achieved	Benefit assessment and safety/HP assessment have been conducted as part of validation activities. Outcomes are captured in the ERR (D3.3).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.07	Have the potential limitations, weaknesses and constraints of the solution under research been identified and assessed? Do they include potential safety considerations (wrt. maintaining the current safety level)? Do they include potential security considerations? - The solution under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others. - Qualitative assessment on potential limitations. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it may be used.	achieved	Yes, limitations, weakness and constraints of the Solution are documented in the ERR (D3.3) and the OSED (D3.5). The retained Solution scope described in the OSED and the FRD (D3.4) has been adjusted according to validation outcomes. Safety considerations are included as part of validation outcomes documented in ERR and Solution design considerations documented in the OSED and the FRD. The main security threat for the Solution (GNSS jamming & spoofing) has been taken into account in the Solution's documentation.
TRL-1.08	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM Master Plan level, strategic research and innovation agenda (SRIA) and multiannual work programme (MAWP)?	achieved	The work is in line with the SESAR 3 ER1 call definition, more precisely the WA 2.7 ATM application-oriented Research for Aviation Green Deal. Validation results confirm the benefits of geometric altimetry for TMA, while shedding light on disbenefits of using it for Cruise. Outcomes are documented in the ERR (D3.3).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.09	Have stakeholders been identified, consulted and involved in the assessment of the results? Has their feedback been documented in project deliverables? Have stakeholders shown their interest on the proposed solution? Note: In the corresponding TRL1 ERP, this criterion should have been already covered and it might constitute quality acceptance criteria of the TRL1 ERP itself	achieved	The identified stakeholders are (i) Academic/Industrial research groups, (ii) Aircraft manufacturers, (iii) ANSPs, (iv) Airlines (v) Avionics Suppliers, and (vi) Communities neighbouring airports. Development of the concept has taken place through project workshops, covering i-iii. In addition, the advisory board has been consulted also covering iv. Their feedback have been taken into account in the Solution deliverables. v & vi have not yet been engaged but we believe this insignificant at TRL1.
TRL-1.10	Are recommendations for further scientific research documented?	achieved	ERR (D3.3) section 5.2 captures the main identified recommendations for next R&I phase, repeated in summarised shape in the present Project Summary Report (D1.4).

Table 17: Geometric altimetry Solution maturity assessment for TRL1

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
OPS.TRL2.1	Is the initial documented description of the ATM solution justified by the ATM Master Plan and/or Multi-Annual Work Programme (MAWP) e.g. reference to specific section or paragraph? Note: For U-space, the references are the latest applicable version of CORUS Concept (confirmed by the S3JU)	achieved	The work is in line with the SESAR 3 ER1 call definition, more precisely the WA 2.7 ATM application-oriented Research for Aviation Green Deal, as briefly mentioned in the ERP (D3.2) section 3.3.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
OPS.TRL2.2	Is there an initial identification and description of the ATM SESAR Solution?	achieved	The initial operational concept was developed through project workshops and captured in the Initial OSED (D3.1). Then, following validation activities, the Solution scope has been readjusted and documented in the Final OSED (D3.5). **Note**: throughout this Maturity Assessment matrix, "OSED" with no qualifier refers to the Final OSED.
OPS.TRL2.3	Have different options for the new operating method been described and assessed?	achieved	Different options for more efficient airspace design enabled by geometric altimetry have been considered (e.g. fixed lateral path + altitude constraints vs. fixed lateral & vertical path). Also, multiple options of target end state were considered and transition states in a sequence of steps (e.g. from introduction of geometric altimetry only in initial/intermediate approach, to end-to-end geometric flights) have been envisaged. Outcomes from validation activities have been documented in the ERR (D3.3), and Solution scope described in the OSED (D3.5) has been readjusted accordingly.
OPS.TRL2.4	Have potential operating environments been identified where, if deployed, the ATM SESAR Solution could bring performance benefits?	partial (non-blocking)	The Solution benefits are mainly foreseen in high-complexity high density TMAs. Validation environment has been focused on London TMA. Applicability of results to other high-complexity high-density TMAs still needs to be assessed, particularly due to potential influence of local airspace constraints in the achievable benefits.
OPS.TRL2.5	Have representative stakeholders been identified, are their needs and expectations for the ATM SESAR solution documented?	achieved	Stakeholders identification and expectations are provided in OSED (D3.5) appendix A.1.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
SYS.TRL2.1	Has the potential impact of the ATM solution on the target architecture been identified? e.g. what systems may be impacted? Note: For U-space, the references are the latest applicable version of CORUS Concept (confirmed by the S3JU)	achieved	The most significant impact of the Solution is on aircraft systems, but some ground systems upgrades are also required. Impact on the target architecture have been identified and documented in FRD (D3.4) section 3.
SYS.TRL2.2	Have several architectural options for the ATM solution been proposed / investigated?	achieved	Different options for the technical implementation are mentioned in the ERR (D3.3), particularly in the report of the validation exercise addressing aircraft impact assessment (Appendix C). The FRD (D3.4) is focused on the core Solution scope retained following validation outcomes, but also highlights in section 5.2 an open point regarding airborne predictions, which has potential architectural implications.
SYS.TRL2.3	Are there needs for supporting CNS infrastructure (if any) adequately identified and justified for the different operating environments relevant for the ATM SESAR Solution?	achieved	The most significant impact of the Solution is on aircraft systems, but some ground systems upgrades are also required. They are both documented in FRD section 3 (architecture) and section 4 (requirements). Note: as documented in the ERR (D3.3), the OSED (D3.5) and the FRD (D3.4), an increased robustness to GNSS jamming & spoofing is also deemed necessary for the deployment of this Solution, but it is considered as an ATM-wide objective rather than part of this Solution's scope. Solution features related to monitoring of the GeoAlt capability and fallback to barometric navigation have been kept generic, not specifically focused on jamming & spoofing or any other particular cause of GNSS loss.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.1	Has a TRL2 Human Performance assessment been performed and documented following SESAR HP Reference Material? Note: In the corresponding ERP TRL2, these criterion should have been already covered and it might constitute quality acceptance criteria of the ERP TRL2 itself	partial (non-blocking)	Consistently with the ERP (D3.2), Human Performance has been addressed as part of the Safety / Human Performance exercise with ATCOs. Some results of the aircraft impact assessment are related to flight crew operation, but no dedicated HP assessment has been conducted with pilots. Outcomes of both validation exercises are documented in the ERR sections 4.2.7, 4.2.9, 4.2.10 and related appendices, and have been taken into account in the OSED (D3.5) and the FRD (D3.4). A dedicated Human Performance Assessment Report (HPAR) is not expected in OSED template for Exploratory Research phase.
PER.TRL2.1.01	Have the most relevant HP arguments been identified (scoping and change assessment) and addressed at the level required in TRL2? Note: template for the scoping and change assessment is available in the HP reference material.	partial (non-blocking)	Human Performance considerations are included as part of validation outcomes documented in ERR (D3.3) sections 4.2.7, 4.2.9 and 4.2.10, and Solution design considerations documented in the OSED (D3.5) and the FRD (D3.4). A dedicated Human Performance Assessment Report (HPAR) is not expected in OSED template for Exploratory Research phase.
PER.TRL2.1.02	Are the ATM SESAR solution benefits and issues in terms of human performance identified and sufficiently assessed at the level required for TRL2 i.e. through subjective feedback from main involved actors or stakeholders?	partial (non-blocking)	Related considerations can be found in OSED (D3.5) section 3 and ERR (D3.3) sections 4.2.7, 4.2.9 and 4.2.10, based on workshops with ATCOs and workshops with airborne industry experts (without pilots' involvement).
PER.TRL2.1.03	Have potential interactions (if any) from HP point of view with other SESAR Solutions been considered?	achieved	No interaction from HP point of view has been identified at this stage.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.1.04	Is the level of human performance needed to achieve the desired system performance for the proposed ATM SESAR solution consistent with human capabilities?	achieved	HP issues identified during validation activities (e.g., related to the use of geometric altimetry in Cruise, to the use of fixed vertical paths in Climb and Descent, to the loss of GNSS, etc.) have been mitigated through recommendations and Solution scope readjustment, so no HP showstopper is identified at this stage.
PER.TRL2.1.05	Have the major factors been identified that influence the transition feasibility (e.g. changes in automation levels)?	partial (non-blocking)	Related considerations can be found in OSED (D3.5) section 3.2.2 and ERR (D3.3) sections 4.2.7, 4.2.9 and 4.2.10.
PER.TRL2.1.06	Has the next maturity phase been sufficiently prepared in terms of open issues/benefits and recommendations for further assessment?	achieved	ERR (D3.3) section 5.2 captures the main identified recommendations for next R&I phase.
PER.TRL2.2	Has a TRL2 Performance Assessment been performed and documented following SESAR Performance Reference Material? Note: In the corresponding ERP TRL2, these criteria and sub-criteria should have been already covered and they might constitute quality acceptance criteria of the ERP TRL2 itself	partial (non-blocking)	Consistently with the ERP (D3.2), the KPAs/KPIs from the SESAR Performance Framework most relevant to the Solution have been addressed through dedicated Validation Objectives. Associated results are documented in ERR (D3.3) section 4.2 and related appendices, and have been taken into account in the OSED (D3.5). A dedicated Performance Assessment Report (PAR) is not expected in OSED template for Exploratory Research phase.
PER.TRL2.2.01	Is there a documented analysis and description of the initial set of benefit Impact mechanisms (BIMs) and associated Influence Factors (and the rationale for their selection) for the different alternatives to the solution, aligned with SESAR guidelines e.g. Performance Framework KPAs and KPIs?	achieved	The BIM description is available in the OSED (D3.5) appendix A.2. The KPAs/KPIs from the SESAR Performance Framework most relevant to the Solution have been considered.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.2.02	Do validation results provide the qualitative and quantitative (at least estimated by expert judgement) evidences about impact on the most significant KPAs which are relevant (e.g. Capacity, Operational Efficiency, Cost-efficiency, Predictability, Flexibility etc.), using KPIs/PIs from SESAR Performance Framework (or a clear description of the mathematical translation mechanism when using other metric)? Note: In the corresponding ERP TRL2, the project should have planned per SESAR Solution the requires activities to initially estimate (qualitatively and quantitatively (if possible, or at least estimated)) the impact on those KPAs that are applicable to the SESAR Solution and confirmed through validations	achieved	Consistently with the ERP (D3.2), the KPAs/KPIs from the SESAR Performance Framework most relevant to the Solution have been addressed through dedicated Validation Objectives. Associated quantitative and/or qualitative results (as applicable) are documented in ERR (D3.3) section 4.2 and related appendices, and have been taken into account in the OSED (D3.5).
PER.TRL2.2.03	Are the validation results in line with what is estimated for the SESAR Solution? In case of deviation, has the project identified a concept/solution refinement to mitigate the gap?	achieved	Validation results confirm the benefits of geometric altimetry for TMA, but shed light on disbenefits of using it for Cruise. Moreover, for the use of geometric altimetry in TMA, validation results discourage the use of fixed vertical paths for Climb. Those outcomes have been documented in the ERR (D3.3) and taken into account in the OSED (D3.5) and the FRD (D3.4) to readjust the target Solution scope.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.2.04	Were the TRL2 Validation exercises executed in validation scenarios that are representative of the (sub) operating environments where the solution could be deployed?	partial (non-blocking)	The Solution benefits are mainly foreseen in high-complexity high density TMAs. Validation environment has been focused on London TMA. Applicability of results to other high-complexity high-density TMAs still needs to be assessed, particularly due to potential influence of local airspace constraints in the achievable benefits.
PER.TRL2.2.05	Are Baseline, Reference and Solution scenarios definition aligned with SESAR guidelines?	achieved	Scenarios in the validation exercises documented in the ERR (D3.3) are consistent with those described in the approved ERP (D3.2) and have been developed with regard to the respective SESAR guidelines.
PER.TRL2.2.06	Have potential interactions with related SESAR Solutions been considered? What are the solution relationship (e.g. cross effect, interdependent, mutually exclusive) and relative contribution to performance (e.g. weight per KPA) with the other solutions once the solutions will be deployed?	partial (non-blocking)	Solution 0406 may have interdependencies with other Solutions relying on the use of geometric altimetry or on the redesign of TMA instrument flight procedures. Some have been documented in ECO-EVAL (D3.6) section 3.2.1.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
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? Are the following elements clearly described in the TRL2 ECO-EVAL: (1) scope of the solution (in particular considering the cost-drivers) (2) interdependencies with other solutions (3) implementation/deployment options, (4) identification of the impacted stakeholders, (5) qualitative description of the benefits, in line with the BIMs in the OSED TRL2, including the most impacted KPAs and KPIs. (6) identification of cost drivers.	achieved	All those elements are properly documented in the ECO-EVAL (D3.6) with the information available at this R&I stage.
PER.TRL2.4	Has a TRL2 Scoping and change assessment been performed and documented in a Preliminary safety (support) assessment in the OSED in line with E-SRM Guidance A On scoping and change assessment? Note: In the Preliminary safety (support) assessment, these criteria and sub-criteria should be covered and they might constitute quality acceptance criteria of the OSED. The Preliminary Safety (Support) assessment shall justify the type of assessment (safety assessment or safety support assessment) expected to be conducted in later stages (beyond TRL2)	partial (non-blocking)	Consistently with the approved ERP, Safety has been addressed as part of the Safety / Human Performance exercise with ATCOs. Some results of the aircraft impact assessment are related to safety, but no dedicated Safety Assessment has been conducted for the airborne segment. Outcomes of both validation exercises are documented in the ERR sections 4.2.7, 4.2.9, 4.2.10 and related appendices, and have been taken into account in the OSED (D3.5) and the FRD (D3.4). A dedicated Safety Assessment Report (SAR) is not expected in OSED template for Exploratory Research phase.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.4.01	Does the Preliminary Safety (Support) assessment clearly identify the scope of the change and describe the key properties of the Operational Environment that are relevant to the preliminary safety (support) assessment?	partial (non-blocking)	The Solution scope and operational environment are described in the OSED (D3.5) section 3. A dedicated Safety Assessment Report (SAR) is not expected in OSED template for Exploratory Research phase.
PER.TRL2.4.02	For preliminary safety assessment only: Does the OSED document the identification of the hazards that are inherent in aviation within the scope of the Solution operations? For preliminary safety support assessment: Does the OSED perform a preliminary identification of the safety implications of the Solution based on the analysis of the new/impacted services delivered to the User(s) with due consideration of their safety needs?	partial (non-blocking)	Safety considerations are included as part of validation outcomes documented in ERR and Solution design considerations documented in the OSED and the FRD. A dedicated Safety Assessment Report (SAR) is not expected in OSED template for Exploratory Research phase.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.4.03	For preliminary safety assessment only: Does the Preliminary Safety Assessment perform a safety impact assessment, in terms of determining whether and how each hazard inherent to aviation is impacted in terms of the efficiency of safety barriers or of the occurrence of accident precursors, through: - analysis based on the relevant AIM models - preliminary identification of hazards newly introduced or modified by the solution functional system (that supposes the initial identification of operational hazards generated by the reference functional system)	partial (non-blocking)	Safety considerations are included as part of validation outcomes documented in ERR (D3.3) and Solution design considerations documented in OSED (D3.5) and FRD (D3.4). A dedicated Safety Assessment Report (SAR) is not expected in OSED template for Exploratory Research phase.
PER.TRL2.4.04	For preliminary safety assessment only: Does the Preliminary Safety Assessment contain a list of suitable Safety Criteria for the solution operations and the justification for their selection? Any Solution safety validation objectives included in the ERP TRL2 (if applicable) shall be traced to the Safety Criteria and demonstrated (to the extent possible in TRL2) in ERR TRL2	partial (non-blocking)	Safety considerations are included as part of validation outcomes documented in ERR (D3.3) and Solution design considerations documented in the OSED (D3.5) and the FRD (D3.4). A dedicated Safety Assessment Report (SAR) is not expected in OSED template for Exploratory Research phase.
PER.TRL2.4.05	Are any other safety issues / uncertainties that were identified during the Preliminary safety (support) Assessment documented?	partial (non-blocking)	Safety considerations are included as part of validation outcomes documented in the ERR (D3.3) and Solution design considerations documented in the OSED (D3.5) and the FRD (D3.4).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.5	Has the TRL2 preliminary security assessment been carried out in conformance with the SESAR Security Reference Material?	partial (non-blocking)	Consistently with the approved ERP (3.2), no dedicated Security Assessment has been performed, but the main security threat for the Solution (GNSS jamming & spoofing) has been taken into account in the Solution's documentation.
PER.TRL2.6	Has a TRL2 environmental assessment been performed following SESAR Environmental Reference Material? Note: In the corresponding ERP TRL2, these criteria and sub-criteria should have been already covered and they might constitute quality acceptance criteria of the ERP TRL2 itself	partial (non-blocking)	Consistently with the approved ERP (D3.2), validation objectives addressed Fuel/CO2 KPIs. Associated outcomes are documented in the ERR (D3.3) and the ECO-EVAL (D3.6). A dedicated Environmental Assessment Report (EnvAR) is not expected in OSED template for Exploratory Research phase.
PER.TRL2.6.01	Have the SESAR Solution environmental benefits and risks mechanisms been identified?	partial (non-blocking)	Consistently with the approved ERP (D3.2), environmental impact has only been assessed regarding CO2 equivalent emissions directly derived from fuel burn. The association benefit mechanism is captured in the BIM (OSED appendix A.2)
PER.TRL2.6.02	Have the environmental impacts (Noise, Local and Global emissions) that should be investigated for the SESAR Solution been identified?	partial (non-blocking)	Consistently with the approved ERP, environmental impact has only been assessed regarding CO2 equivalent emissions directly derived from fuel burn. Qualitative considerations have been provided regarding noise (i.e. instrument procedures with fixed vertical paths may lead to increased noise). Other emissions such as Local Air Quality or Global non-CO2 effects have not been addressed.
S&R.TRL2.1	Have the standardisation context been captured and an initial list of potential standardisation needs been identified?	achieved	Consistently with the project plan, no dedicated STD & REG task has been conducted at this level of maturity. Only a non-exhaustive appraisal is included in section 3.2.3 of the OSED (D3.5).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRA.TRL2.1	Are there recommendations proposed to be addressed during TRL4 related activities? E.g. additional testing conditions, open HP issues to be addressed in TRL4,… Note 1: these recommendations should be based on an evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level. Note 2: these recommendations could also be part of the Exploitation information to be produced by the project	achieved	ERR section 5.2 captures the main identified recommendations for next R&I phase of this Solution and for future R&I activities.
VAL.TRL2.1	Are the relevant R&D needs identified and documented? Have the validation objectives covered by TRL2 validation activities addressed the relevant and Key SESAR Solution R&D needs? Note: R&D needs state major questions and open issues to be addressed during the development, verification and validation of a SESAR Solution. They justify the need to continue research on a given SESAR Solution, and the definition of validation exercises and validation objectives in following maturity phases.	achieved	The relevant R&D needs were identified in the approved ERP (D3.2) and are recalled in the ERR (D3.3). All related Validation Objectives have been addressed by validation activities and their outcomes have been documented in the ERR.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PRG.TRL2.1	Is there a clear identification and definition of the ATM solution e.g. SESAR Solution title and definition, etc.? Note: the objective is to ensure the ATM solution can be included in the ATM Master Plan (e.g. ATM solution description is complete and coherent with the obtained results at all levels (solution, enablers, etc.)).	achieved	An initial solution definition has been written and agreed with the SJU. It is available in the standalone Solution slides cited in the Updated PMP (D1.3). However, the STELLAR Solution definition has not yet been aligned with the outcomes of the project captured in the final OSED (D3.5) and Project Summary report (D1.4).
PRG.TRL2.2	Have the operational and technical assumptions that may have impact on the integration of the ATM solution in the European ATM system been described and documented?	achieved	Operational and technical assumptions are provided in OSED (D3.5) sections 3 and 4.

Table 18: Geometric altimetry Solution maturity assessment for TRL2

3.2.2 Solution 0407, Separation Minima

The Separation minima Solution is self-assessed against TRL1 and TRL2 criteria in Table 19 and Table 20, respectively. We find a fulfilment of TRL1 criteria now, which means progress against the initial state and that at the Intermediate Review. While no definite showstopper has been identified during project work, the (intended) focus on safety due to limited resources has left many questions unaddressed, in addition to the not fully conclusive results on necessary implementation effort, to warrant a progress of the TRL beyond TRL2 ongoing. The main deficiencies are the lack of a human performance assessment for both ground and airborne sides, the question whether the technical effort for implementation is at an acceptable level, and a missing quantification of the benefits, namely environmental ones (fuel consumption / CO_2 emission), at network level. The verdict at the Maturity Gate has been that TRL1 is fully reached.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.01	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? - Where does the problem lie? - Has the ATM problem/challenge/need(s) been quantified that justify the research done? Note: an initial estimation is sufficient	achieved	Reduced vertical separation minima have the potential to increase capacity and have environmental benefits by capacity increase in key areas. Furthermore, geometric altimetry facilitates the integration of new types of airspace users. The rationale is documented in the Final OSED. (D4.6). see D4.6 - Final OSED.
TRL-1.02	Have the solutions (concepts/capabilities/methodologies) under research been defined and described?	achieved	The concept for RVSM2, reduced vertical separation minima to 500 ft in RVSM airspace, extended to FL 600, enabled by geometric altimetry, is documented in the initial OSED, final OSED, Safety Case and FRD. The Project Summary Report contains a short version of the Solution Definition and the Solution Description. see Solution Definition as of 03/06/2024 (reproduced in D1.3 - Updated PMP), and D4.1 - Initial OSED, D4.3 - RVSM 2 Safety Case, D4.5 - FRD, D4.6 - Final OSED plus D1.4 - PSR.
TRL-1.03	Have assumptions applicable for the innovative concept/technology been documented?	achieved	Assumptions for the analysis have been documented particularly in the ERP. The initial concept focuses on the 'end state', where all airspace users use the same mode of altimetry. The relevant operational and functional assumptions can be found in the FRD and the Final OSED. see D4.2 - ERP, D4.4 - ERR, D4.5 - FRD and D4.6 - Final OSED.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.04	Have the research hypothesis been formulated and documented?	achieved	The central hypothesis, implicitly expressed by the validation objectives, is that adequate levels of safety are maintained when transitioning to 500 ft minimal vertical separation in RVSM airspace and up to FL 600 when using geometric altimetry, with a special consideration for collision risk and wake turbulence risk; furthermore that this leads to a capacity increase against current RVSM. see D4.4 - ERR.
TRL-1.05	Do the obtained results from the fundamental research activities suggest innovative solutions (e.g. concepts/methodologies/capabilities? - What are these new concepts/methodologies/capabilities? - Can they be technically implemented?	achieved	The concept for RVSM2, reduced vertical separation minima to 500 ft in RVSM airspace, extended to FL 600, enabled by geometric altimetry is suggested and documented in the final OSED. The preliminary safety study showed that the wake vortex risks would need to mitigated by new functions/tools, but the collision risk and operational risk could meet the target level of safety (TLS) under assumptions. At the current level of exploration these translate into several critical system functions and specifications that may be ambitious especially regarding legislative/regulatory considerations but are not obviously technically infeasible. Whether the expected benefits would warrant the effort would need to be further examined in ongoing work. see D4.6 - Final OSED and D4.4 - ERR.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.06	Have the potential strengths and benefits of the solution identified and assessed? If applicable, are the potential safety benefits identified and justified? - Qualitative assessment on potential benefits. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it should be used.	achieved	The solution is expected to offer capacity benefits and environmental benefits by way of increased capacity in key areas and generally by improving the granularity of available flight levels, as explained in the ERR and the ECO-EVAL, which contains a qualitative assessment of these KPIs. Even if safety was the focus of the work, the concept is intended to meet the target level of safety (TLS) and as such is safety neutral. see D4.2 - ERP, D4.4 - ERR and D4.7, ECO-EVAL.
TRL-1.07	Have the potential limitations, weaknesses and constraints of the solution under research been identified and assessed? Do they include potential safety considerations (wrt. maintaining the current safety level)? Do they include potential security considerations? - The solution under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others. - Qualitative assessment on potential limitations. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it may be used.	achieved	Due to the nature of the collision risk assessment models used by ICAO, certain assumptions about the airspace are necessary. As documented in the OSED, the EUR RMA region has been chosen for the analysis so that the results are universally applicable in European airspace. The wake turbulence risk assessment used existing traffic demand, modified to the new separation rules, leading to a comparative evaluation again in the complete European airspace. It may be necessary to limit the application of the reduced separation to certain aircraft (category) pairings or weather conditions. The safety analysis has been the core of the work and is extensively documented in the RVSM 2 safety case and the ERR. Security concerns arise around GNSS jamming and spoofing activities, which are a threat to many other activities and as such outside the project scope. These are documented in the ERR and the Final OSED. see D4.3 - RVSM2 Safety Case, D4.4 - ERR and D4.6 - Final OSED.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.08	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM Master Plan level, strategic research and innovation agenda (SRIA) and multiannual work programme (MAWP)?	achieved	The work is in line with the SESAR 3 ER1 call definition, more precisely the WA 2.7 ATM application-oriented Research for Aviation Green Deal. The solution is expected to offer capacity benefits and environmental benefits by way of increased capacity in key areas. The key R&I needs identified and the expected performance contributions are documented in the ERP. A qualitative assessment is available in the ECO-EVAL, indicating positive impacts on capacity and environmental efficiency. see D4.2 - ERP and D4.7 - ECO-EVAL.
TRL-1.09	Have stakeholders been identified, consulted and involved in the assessment of the results? Has their feedback been documented in project deliverables? Have stakeholders shown their interest on the proposed solution? Note: In the corresponding TRL1 ERP, this criterion should have been already covered and it might constitute quality acceptance criteria of the TRL1 ERP itself	achieved	Stakeholders have been identified and a number of them consulted in the first Advisory Board meeting, as noted in the ERP (section 4.2) and other documents. Academia and research organisation partners, ATCos' organisations, Air Navigation Service Provider and regulators have been consulted. Their input has been used in the concept development (Initial OSED). In the second Advisory Board meeting the results were presented to the same stakeholders and their feedback was collected. This was processed in the ERR and subsequent deliverables. see D4.2 - ERP, D4.4 - ERR and D4.6 - Final OSED.
TRL-1.10	Are recommendations for further scientific research documented?	achieved	Recommendations for further work have been documented in the ERR and the ECO-EVAL and aggregated in the Project Summary Report. see D4.4 - ERR, D4.7 - ECO-EVAL and D1.4 - PSR.

Table 19: Separation minima Solution maturity assessment for TRL1

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
OPS.TRL2.1	Is the initial documented description of the ATM solution justified by the ATM Master Plan and/or Multi-Annual Work Programme (MAWP) e.g. reference to specific section or paragraph? Note: For U-space, the references are the latest applicable version of CORUS Concept (confirmed by the S3JU)	achieved	The work is in line with the call definition of the ER1 call, specifically the R&I need: optimum green trajectories, and thus by definition in line with the MAWP. This is referenced in section 3.3 of the ERP (D4.2)
OPS.TRL2.2	Is there an initial identification and description of the ATM SESAR Solution?	achieved	A Solution definition has been provided and accepted by the SJU, and can be found in the ERR (D4.4, section 3.1). The solution description has also been provided and accepted; it is available in the PSR (D1.4, section 3.1).
OPS.TRL2.3	Have different options for the new operating method been described and assessed?	achieved	By definition, RVSM2 is either applied in an airspace or not, there are no options. There are technical options for implementation (e.g. the Collision Risk Analysis lists performance for difference GNSS constellations and technological options (such single frequency, dual frequency, etc.)) but is above this TRL to assess them.
OPS.TRL2.4	Have potential operating environments been identified where, if deployed, the ATM SESAR Solution could bring performance benefits?	achieved	The Solution focuses on implementing reduced vertical separation minima in RVSM airspace (and expanding RVSM airspace to higher altitudes), with the EUR RMA region as test case. This part of the operating environment seems to be the most sensible and feasible. The ECO-EVAL has indicated capacity and environmental efficiency benefits. note: Solution #0406 focuses on implementing geometric altimetry in other airspace domains such as a TMA area, but reduced vertical separation is not the key focus here and the work is outside the scope of the present solution. see the final OSED (D4.6) and ECO-EVAL (D4.7).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
OPS.TRL2.5	Have representative stakeholders been identified, are their needs and expectations for the ATM SESAR solution documented?	achieved	Stakeholders have been identified and a representative number of them consulted in the first Advisory Board meeting, as noted in the ERP (section 4.2) and other documents. Academia and research organisation partners, ATCos' organisations, Air Navigation Service Provider and regulators have been consulted. Their input has been used in the further development of the concept and overall considerations in the rest of the work.
SYS.TRL2.1	Has the potential impact of the ATM solution on the target architecture been identified? e.g. what systems may be impacted? Note: For U-space, the references are the latest applicable version of CORUS Concept (confirmed by the S3JU)	achieved	These results were generated in the OSEDs, Collision Risk Analysis, Safety Case and Wake Turbulence Risk Analysis, and were summarised in the FRD. see FRD (D4.5).
SYS.TRL2.2	Have several architectural options for the ATM solution been proposed / investigated?	achieved	A number of architectural options are presented, mostly in the Safety Case, which serve as a first suggestion, to be iterated on in later stages. Being on a functional level, several requirements are not attributed to certain systems yet but leave room for architecture choices in higher-TRL work. see RVSM2 Safety Case (D4.3) and FRD (4.5).
SYS.TRL2.3	Are there needs for supporting CNS infrastructure (if any) adequately identified and justified for the different operating environments relevant for the ATM SESAR Solution?	achieved	As presented in the Safety Case and FRD, RVSM 2 will likely require additional services regarding GNSS, such as GNSS performance monitoring and alerting. Also ACAS, STCA and a new wake vortex warning function are affected. see RVSM2 Safety Case (D4.3), ERR (D4.4), FRD (D4.5) and final OSED (D4.6).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.1	Has a TRL2 Human Performance assessment been performed and documented following SESAR HP Reference Material? Note: In the corresponding ERP TRL2, these criterion should have been already covered and it might constitute quality acceptance criteria of the ERP TRL2 itself	not achieved	In light of limited resources this WP focused on the technical safety related areas, as these are crucial to the feasibility of the concept. If the concept is deemed feasible from a technical perspective, human performance considerations can later be taken into account and incorporated in the concept design.
PER.TRL2.1.01	Have the most relevant HP arguments been identified (scoping and change assessment) and addressed at the level required in TRL2? Note: template for the scoping and change assessment is available in the HP reference material.	not achieved	In light of limited resources this WP focused on the technical safety related areas, as these are crucial to the feasibility of the concept. If the concept is deemed feasible from a technical perspective, human performance considerations can later be taken into account and incorporated in the concept design.
PER.TRL2.1.02	Are the ATM SESAR solution benefits and issues in terms of human performance identified and sufficiently assessed at the level required for TRL2 i.e. through subjective feedback from main involved actors or stakeholders?	not achieved	In light of limited resources this WP focused on the technical safety related areas, as these are crucial to the feasibility of the concept. If the concept is deemed feasible from a technical perspective, human performance considerations can later be taken into account and incorporated in the concept design.
PER.TRL2.1.03	Have potential interactions (if any) from HP point of view with other SESAR Solutions been considered?	not achieved	In light of limited resources this WP focused on the technical safety related areas, as these are crucial to the feasibility of the concept. If the concept is deemed feasible from a technical perspective, human performance considerations can later be taken into account and incorporated in the concept design.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.1.04	Is the level of human performance needed to achieve the desired system performance for the proposed ATM SESAR solution consistent with human capabilities?	not achieved	In light of limited resources this WP focused on the technical safety related areas, as these are crucial to the feasibility of the concept. If the concept is deemed feasible from a technical perspective, human performance considerations can later be taken into account and incorporated in the concept design.
PER.TRL2.1.05	Have the major factors been identified that influence the transition feasibility (e.g. changes in automation levels)?	not achieved	This WP focused on showing the feasibility of the end state of the system. If the end state is deemed feasible, the transition can be further studied. It is mentioned that as with the introduction of current RVSM, a kind of shadow mode operation might be necessary to monitor the vertical navigation performance before actually applying the new rules.
PER.TRL2.1.06	Has the next maturity phase been sufficiently prepared in terms of open issues/benefits and recommendations for further assessment?	achieved	Recommendations for further work have been listed and explained in the ERR and are recapitulated in the project summary report. see ERR (D4.4) and PSR (D1.4).
PER.TRL2.2	Has a TRL2 Performance Assessment been performed and documented following SESAR Performance Reference Material? Note: In the corresponding ERP TRL2, these criteria and sub-criteria should have been already covered and they might constitute quality acceptance criteria of the ERP TRL2 itself	partial (blocking)	A performance assessment according to SESAR performance reference material has been performed. Safety has been extensively studied and quantified whereas capacity has been addressed quantitatively and environmental/operational efficiency indicatively. Results are documented in the ERR and ECO-EVAL; they are not detailed enough to judge the cost-benefit relation. see ERR (D4.4) and ECO-EVAL (4.7).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.2.01	Is there a documented analysis and description of the initial set of benefit Impact mechanisms (BIMs) and associated Influence Factors (and the rationale for their selection) for the different alternatives to the solution, aligned with SESAR guidelines e.g. Performance Framework KPAs and KPIs?	achieved	The list of KPAs / KPIs are available in section 3.4 of the ERR, the BIMs and Influence Factors are included in the Final OSED. see ERR (D4.4) and OSED (D4.6).
PER.TRL2.2.02	Do validation results provide the qualitative and quantitative (at least estimated by expert judgement) evidences about impact on the most significant KPAs which are relevant (e.g. Capacity, Operational Efficiency, Cost-efficiency, Predictability, Flexibility etc.), using KPIs/PIs from SESAR Performance Framework (or a clear description of the mathematical translation mechanism when using other metric)? Note: In the corresponding ERP TRL2, the project should have planned per SESAR Solution the requires activities to initially estimate (qualitatively and quantitatively (if possible, or at least estimated)) the impact on those KPAs that are applicable to the SESAR Solution and confirmed through validations	partial (blocking)	Safety has been extensively studied and quantified whereas capacity has been addressed qualitatively and environmental efficiency indicatively, as the latter would have been a significant task to quantify at ECAC level. The quantification methods are documented in the ERP, results in the ERR and ECO-EVAL. The environmental/operational efficiency needs to be addressed at network level to be relevant. see ERP (D4.2), ERR (D4.4) and ECO-EVAL (D4.7).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.2.03	Are the validation results in line with what is estimated for the SESAR Solution? In case of deviation, has the project identified a concept/solution refinement to mitigate the gap?	achieved	In case of wake turbulence risk, it was shown that this risk is likely to increase when transitioning RVSM 2. Suggestions for updates to the concept have been made to mitigate this. For the collision risk, whether or not the TLS can be met is inconclusive. A more detailed characterisation of ASE and FTE is advised. The qualitative safety study and the indicative estimate of operational/environmental efficiency are in line with expectations. see ERR (D4.4) and ECO-EVAL (D4.7).
PER.TRL2.2.04	Were the TRL2 Validation exercises executed in validation scenarios that are representative of the (sub) operating environments where the solution could be deployed?	achieved	The validation exercises used the appropriate scenarios. Both collision and vortex risk studies addressed the whole of the European airspace with its existing traffic mix, the appropriate figures were used for the safety case. Only the wake vortex risk is weather dependent; here suitable scenarios with real weather data were selected. see ERR (D4.4).
PER.TRL2.2.05	Are Baseline, Reference and Solution scenarios definition aligned with SESAR guidelines?	achieved	The scenarios are defined according to the SESAR guidelines, and available in the ERR (D4.4).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.2.06	Have potential interactions with related SESAR Solutions been considered? What are the solution relationship (e.g. cross effect, interdependent, mutually exclusive) and relative contribution to performance (e.g. weight per KPA) with the other solutions once the solutions will be deployed?	achieved	There may be some interactions between this solution and Solution #0408 Green Route Charging, which may increase demand for certain regions. Reduced vertical separation minima may offer a key capacity benefit. The usage of geometric altimetry also inside the TMA (Solution #0406 Vertical Guidance using Geometric Altimetry) is complementary in the sense that it makes use of the same aircraft equipage, thus reducing relative cost. These considerations are given in section 3.2.1 of the ECO-EVAL (D4.7).
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? Are the following elements clearly described in the TRL2 ECO-EVAL: (1) scope of the solution (in particular considering the cost-drivers) (2) interdependencies with other solutions (3) implementation/deployment options, (4) identification of the impacted stakeholders, (5) qualitative description of the benefits, in line with the BIMs in the OSED TRL2, including the most impacted KPAs and KPIs. (6) identification of cost drivers.	achieved	In the ECO-EVAL, both costs and benefits have been qualitatively assessed. Given the low TRL (TRL 2), quantitative evaluations have been conducted only partially; the corresponding analysis is reported in Section 4.6. The scope of the solution is described in section 2.2 and cost-drivers are described in section 5. Interdependencies with other solutions are described in section 3.2.1. Implementation and deployment options are described in section 3.5. The impacted stakeholders have been identified and described in section 3.4. The benefits have been described in accordance with the BIM and related to the investigated KPIs (see section 4). The major cost drivers have been identified and described in section 5. see D4.7 (ECO-EVAL).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.4	Has a TRL2 Scoping and change assessment been performed and documented in a Preliminary safety (support) assessment in the OSED in line with E-SRM Guidance A On scoping and change assessment? Note: In the Preliminary safety (support) assessment, these criteria and sub-criteria should be covered and they might constitute quality acceptance criteria of the OSED. The Preliminary Safety (Support) assessment shall justify the type of assessment (safety assessment or safety support assessment) expected to be conducted in later stages (beyond TRL2)	achieved	While possibly not fully in line with the SESAR formalities, the project has performed a formal preliminary safety assessment according to established methodologies, evaluating technical (nominal) and operational (non-nominal) risks and deriving safety requirements. see RVSM2 Safety Case (D4.3), ERR (D4.4) presenting the results and FRD (D4.5) citing the derived requirements.
PER.TRL2.4.01	Does the Preliminary Safety (Support) assessment clearly identify the scope of the change and describe the key properties of the Operational Environment that are relevant to the preliminary safety (support) assessment?	achieved	The proposed new operational concept has been defined in the OSED, and the ERP and ERR contain the assumptions used in the preliminary safety assessment. see ERP (D4.2) with details on the assumptions, RVSM2 Safety Case (D4.3) and ERR (D4.4) with the results, and OSED (D4.6) with the operational environment description.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.4.02	For preliminary safety assessment only: Does the OSED document the identification of the hazards that are inherent in aviation within the scope of the Solution operations? For preliminary safety support assessment: Does the OSED perform a preliminary identification of the safety implications of the Solution based on the analysis of the new/impacted services delivered to the User(s) with due consideration of their safety needs?	achieved	Hazards are identified in the Safety Case. see RVSM 2 Safety Case (D4.3).
PER.TRL2.4.03	For preliminary safety assessment only: Does the Preliminary Safety Assessment perform a safety impact assessment, in terms of determining whether and how each hazard inherent to aviation is impacted in terms of the efficiency of safety barriers or of the occurrence of accident precursors, through: - analysis based on the relevant AIM models - preliminary identification of hazards newly introduced or modified by the solution functional system (that supposes the initial identification of operational hazards generated by the reference functional system)	achieved	AIM models have been considered as part of the Safety Case. see RVSM 2 Safety Case (D4.3).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.4.04	For preliminary safety assessment only: Does the Preliminary Safety Assessment contain a list of suitable Safety Criteria for the solution operations and the justification for their selection? Any Solution safety validation objectives included in the ERP TRL2 (if applicable) shall be traced to the Safety Criteria and demonstrated (to the extent possible in TRL2) in ERR TRL2	achieved	Safety criteria are included in the Safety Case. see RVSM 2 Safety Case (D4.3).
PER.TRL2.4.05	Are any other safety issues / uncertainties that were identified during the Preliminary safety (support) Assessment documented?	achieved	All relevant safety issues and uncertainties have been documented. see RVSM 2 Safety Case (D4.3) and ERR (D4.4).
PER.TRL2.5	Has the TRL2 preliminary security assessment been carried out in conformance with the SESAR Security Reference Material?	not achieved	This has not been part of the work.
PER.TRL2.6	Has a TRL2 environmental assessment been performed following SESAR Environmental Reference Material? Note: In the corresponding ERP TRL2, these criteria and sub-criteria should have been already covered and they might constitute quality acceptance criteria of the ERP TRL2 itself	partial (blocking)	Operational/environmental efficiency has been assessed indicatively, as it would have been a significant task to quantify at ECAC level. The results are documented in the ECO-EVAL. The indications show that flight closer to the optimum flight level can outweigh the penalty from flying at geometric (instead of barometric) cruise levels, but this environmental/operational efficiency needs to be addressed at network level to be relevant. see ECO-EVAL (D4.7).
PER.TRL2.6.01	Have the SESAR Solution environmental benefits and risks mechanisms been identified?	achieved	The benefits are explained in the ERP and the final OSED (BIMs concerning environmental KPIs). see ERP (D4.2) and Final OSED (D4.6).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.6.02	Have the environmental impacts (Noise, Local and Global emissions) that should be investigated for the SESAR Solution been identified?	achieved	Noise and Local Emissions are out of scope as the Solution addresses the en-route airspace. Environmental KPIs have been identified in section 3.4 of the ERP (D4.2).
S&R.TRL2.1	Have the standardisation context been captured and an initial list of potential standardisation needs been identified?	achieved	An initial appraisal is available in section 3.2.4 of the OSED. see D4.6, Final OSED.
TRA.TRL2.1	Are there recommendations proposed to be addressed during TRL4 related activities? E.g. additional testing conditions, open HP issues to be addressed in TRL4,… Note 1: these recommendations should be based on an evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level. Note 2: these recommendations could also be part of the Exploitation information to be produced by the project	achieved	Future recommendations are part of the final OSED and ERR. The ECO-EVAL contains further recommendations for the cost-benefit assessment. The recommendations are summarised in the Project Summary Report. see ERR (D4.4), OSED (D4.6), ECO-EVAL (D4.7) and PSR (D1.4).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
VAL.TRL2.1	Are the relevant R&D needs identified and documented? Have the validation objectives covered by TRL2 validation activities addressed the relevant and Key SESAR Solution R&D needs? Note: R&D needs state major questions and open issues to be addressed during the development, verification and validation of a SESAR Solution. They justify the need to continue research on a given SESAR Solution, and the definition of validation exercises and validation objectives in following maturity phases.	achieved	Relevant R&D needs to further mature the Solution and covering topics that arose during the validations are part of the final OSED and ERR. They are summarised in the Project Summary Report. see ERR (D4.4), OSED (D4.6) and PSR (D1.4).
PRG.TRL2.1	Is there a clear identification and definition of the ATM solution e.g. SESAR Solution title and definition, etc.? Note: the objective is to ensure the ATM solution can be included in the ATM Master Plan (e.g. ATM solution description is complete and coherent with the obtained results at all levels (solution, enablers, etc.)).	achieved	The solution definition has been included in the Final OSED (D4.6).
PRG.TRL2.2	Have the operational and technical assumptions that may have impact on the integration of the ATM solution in the European ATM system been described and documented?	achieved	The assumptions have been documented in the ERR and final OSED. see ERR (D4.4) and Final OSED (D4.7).

Table 20: Separation minima Solution maturity assessment for TRL2

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3.2.3 Solution 0408, Green Route Charging

The maturity assessment for the Initial Solution, addressing CO_2 and congestion (or, at the strategical level, rather demand-capacity imbalance), can be found in Table 21 and Table 22. The self-assessment shows full achievement of TRL1 and subsequently TRL2. The Full Solution, addressing additionally non-CO_2 effects and having started from scratch, is at a lower maturity but – in the project's self-assessment – has fully achieved TRL1 as documented in Table 23.

As there is formally only one Solution with two "flavours", the Full Solution's lower maturity led to the overall verdict of TRL1 at the Maturity Gate.

GRC Initial Solution

The Initial Solution addresses the reduction of demand-capacity imbalance and fuel use / CO_2 emission. Green-GEAR's self-assessment amounts to a fulfilment of both TRL1 criteria (see Table 21) TRL2 criteria (Table 22).

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.01	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? - Where does the problem lie? - Has the ATM problem/challenge/need(s) been quantified that justify the research done? Note: an initial estimation is sufficient	achieved	The European Green Deal aims for net-zero emissions by 2050 and promotes sustainable mobility. Aviation needs to reduce emissions, but technologies such as electric aircraft and sustainable fuels will take time. In this context, the Green-GEAR project is investigating green route charges to encourage eco-friendly flight paths.
TRL-1.02	Have the solutions (concepts/capabilities/methodologies) under research been defined and described?	achieved	The Green Route Charging (GRC) Initial Solution introduces new en-route charging mechanisms aimed at reducing CO_2 emissions and improving horizontal flight efficiency. Initial Solution starts at TRL1. Concepts, capabilities, and methodologies have been defined and described in D5.1 (Initial OSED) and D5.4 (Final OSED).
TRL-1.03	Have assumptions applicable for the innovative concept/technology been documented?	achieved	Operational, performance, and regulatory assumptions has been defined in D5.1 (Initial OSED) and D5.4 (Final OSED).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.04	Have the research hypothesis been formulated and documented?	achieved	The main research hypothesis is that the modulation of route charges can effectively reduce CO2 emissions and enhance airspace efficiency, and eventually reduce the total climate impact of aviation. The detailed research hypotheses have been formulated in D5.1 (Initial OSED) and D5.2 (ERP).
TRL-1.05	Do the obtained results from the fundamental research activities suggest innovative solutions (e.g. concepts/methodologies/capabilities? - What are these new concepts/methodologies/capabilities? - Can they be technically implemented?	achieved	Regarding the Initial solution, previous studies have shown that modulation of route charges should be able to induce airlines to choose different routes (redistribution of air traffic). The modulation would take the form of a modification of the current formula for calculating route charges. The technical implementation is done by formulating appropriate mathematical models. Details are available in D5.1 (initial OSED) and D5.2 (ERP).
TRL-1.06	Have the potential strengths and benefits of the solution identified and assessed? If applicable, are the potential safety benefits identified and justified? - Qualitative assessment on potential benefits. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it should be used.	achieved	The potential advantages of the Initial Solution have been identified and are outlined in D5.1 (Initial OSED). With regard to operational efficiency, the options have been designed to reduce CO_2 emissions, primarily through the reduction of distance. As distance is directly proportional to fuel consumption, which in turn is proportional to CO_2 emissions, a decrease in fuel consumption is anticipated. Safety: not applicable.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.07	Have the potential limitations, weaknesses and constraints of the solution under research been identified and assessed? Do they include potential safety considerations (wrt. maintaining the current safety level)? Do they include potential security considerations? - The solution under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others. - Qualitative assessment on potential limitations. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it may be used.	achieved	Identified risks and mitigation actions have been described in D5.2 (ERP). The GRC Solution does not impact safety nor security, thus their considerations are not needed.
TRL-1.08	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM Master Plan level, strategic research and innovation agenda (SRIA) and multiannual work programme (MAWP)?	achieved	The GRC Initial Solutions addresses CO_2 effects, as detailed in both D5.1 (Initial OSED) and D5.2 (ERP), and is mainly linked to the environmental performance ambitions in the MP.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.09	Have stakeholders been identified, consulted and involved in the assessment of the results? Has their feedback been documented in project deliverables? Have stakeholders shown their interest on the proposed solution? Note: In the corresponding TRL1 ERP, this criterion should have been already covered and it might constitute quality acceptance criteria of the TRL1 ERP itself	achieved	The GRC Solution impacts various stakeholders including States, Air Navigation Service Providers, EUROCONTROL's Central Route Charges Office, the Network Manager, and airlines. It aims to balance capacity supply and demand, enhance airspace efficiency, and ensure revenue neutrality for ANSPs. Stakeholders have been identified and consulted as described in D5.1 (Initial OSED), D5.2 (ERP) and D5.6 (ECO-EVAL).
TRL-1.10	Are recommendations for further scientific research documented?	achieved	The ERP outlines some limitations of the approach, which will be useful to address in further work. Recommendations for further work are available in D5.7 (Final ERR) and D1.4 (Project Summary Report).

Table 21: Green route charging Initial Solution maturity assessment for TRL1

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
OPS.TRL2.1	Is the initial documented description of the ATM solution justified by the ATM Master Plan and/or Multi-Annual Work Programme (MAWP) e.g. reference to specific section or paragraph? Note: For U-space, the references are the latest applicable version of CORUS Concept (confirmed by the S3JU)	achieved	The work is in line with the call definition of the ER1 call, specifically the R&I need: optimum green trajectories, and thus by definition in line with the MAWP. In addition, it is compliant with the European commission targets net-zero greenhouse gas emissions by 2050, demanding smarter, sustainable mobility. The Solution will contribute to the "Digital European Sky: making Europe the most efficient and environmentally friendly sky to fly in the world" as described in the Master Plan. The justifications are referenced in section 3.3 of D5.2 (ERP). A more detailed reference is included in the Final OSED / Final ERR (D5.4, D5.7).
OPS.TRL2.2	Is there an initial identification and description of the ATM SESAR Solution?	achieved	The Green Route Charging (GRC) Solution introduces new en-route charging mechanisms: Initial and Full. The Initial Solution starts at TRL1 ongoing. D5.1 (initial OSED) contains the Solution definition.
OPS.TRL2.3	Have different options for the new operating method been described and assessed?	achieved	The Initial Solution introduces two novel route charging mechanisms designed to minimise horizontal inefficiencies caused by differences in unit rates. By discouraging the practice of flying unnecessarily longer trajectories to avoid more expensive airspace, these mechanisms aim to reduce environmental impact. These new operating methods are detailed in D5.1 (Initial OSED). Validation and assessment have been carried out and are detailed in the Final OSED (D5.4) and Final ERR (D5.7).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
OPS.TRL2.4	Have potential operating environments been identified where, if deployed, the ATM SESAR Solution could bring performance benefits?	achieved	The operational environment for the GRC Solution encompasses the 41 EUROCONTROL contracting States adhering to the Multilateral Agreement on Route Charging, specifically for en-route charges. The geographical scope is limited to en-route airspace. It is assumed that traffic, airspace, and airport characteristics are the same as today, as the GRC Solution can apply irrespective of the operational environment. D5.1 (Initial OSED) and D5.4 (Final OSED) document in detail the operational environment.
OPS.TRL2.5	Have representative stakeholders been identified, are their needs and expectations for the ATM SESAR solution documented?	achieved	An Advisory board has been established. Representative stakeholders have been identified and their expectations documented in D5.1 (Initial OSED), D5.2 (ERP), D5.4 (Final OSED) and D5.6 (ECO-EVAL).
SYS.TRL2.1	Has the potential impact of the ATM solution on the target architecture been identified? e.g. what systems may be impacted? Note: For U-space, the references are the latest applicable version of CORUS Concept (confirmed by the S3JU)	achieved	The impact of the Initial Solution on the target architecture has been identified, and it is documented in section 3.3 of D5.5 (FRD).
SYS.TRL2.2	Have several architectural options for the ATM solution been proposed / investigated?	achieved	The Solution employs modulation of route charges to impact the route choices in flight planning, several options are discussed in D5.7 (Final ERR). The respective interactions between Central Planner, Network Manager and Airspace Users to establish the modulation are detailed in section 3.2 of D5.5 (FRD).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
SYS.TRL2.3	Are there needs for supporting CNS infrastructure (if any) adequately identified and justified for the different operating environments relevant for the ATM SESAR Solution?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there is no impact on CNS systems connected with the Solution.
PER.TRL2.1	Has a TRL2 Human Performance assessment been performed and documented following SESAR HP Reference Material? Note: In the corresponding ERP TRL2, these criterion should have been already covered and it might constitute quality acceptance criteria of the ERP TRL2 itself	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no HP issues connected with the Solution.
PER.TRL2.1.01	Have the most relevant HP arguments been identified (scoping and change assessment) and addressed at the level required in TRL2? Note: template for the scoping and change assessment is available in the HP reference material.	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no HP issues connected with the Solution.
PER.TRL2.1.02	Are the ATM SESAR solution benefits and issues in terms of human performance identified and sufficiently assessed at the level required for TRL2 i.e. through subjective feedback from main involved actors or stakeholders?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no HP issues connected with the Solution.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.1.03	Have potential interactions (if any) from HP point of view with other SESAR Solutions been considered?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no HP issues connected with the Solution.
PER.TRL2.1.04	Is the level of human performance needed to achieve the desired system performance for the proposed ATM SESAR solution consistent with human capabilities?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no HP issues connected with the Solution.
PER.TRL2.1.05	Have the major factors been identified that influence the transition feasibility (e.g. changes in automation levels)?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no HP issues connected with the Solution.
PER.TRL2.1.06	Has the next maturity phase been sufficiently prepared in terms of open issues/benefits and recommendations for further assessment?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no HP issues connected with the Solution.
PER.TRL2.2	Has a TRL2 Performance Assessment been performed and documented following SESAR Performance Reference Material? Note: In the corresponding ERP TRL2, these criteria and sub-criteria should have been already covered and they might constitute quality acceptance criteria of the ERP TRL2 itself	achieved	The Initial Solution has been assessed across a list of SESAR performance framework key performance areas, and other performance indicators, to obtain the comprehensive assessment of the proposed Initial Solution. The complete estimated performance contributions are documented in D5.1 (ERP). The final TRL2 assessment is documented in D5.4 (Final OSED) and D5.7 (Final ERR).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.2.01	Is there a documented analysis and description of the initial set of benefit Impact mechanisms (BIMs) and associated Influence Factors (and the rationale for their selection) for the different alternatives to the solution, aligned with SESAR guidelines e.g. Performance Framework KPAs and KPIs?	achieved	Benefit impact mechanisms for Initial Solution are documented in D5.1 (Initial OSED) and D5.4 (Final OSED).
PER.TRL2.2.02	Do validation results provide the qualitative and quantitative (at least estimated by expert judgement) evidences about impact on the most significant KPAs which are relevant (e.g. Capacity, Operational Efficiency, Cost-efficiency, Predictability, Flexibility etc.), using KPIs/PIs from SESAR Performance Framework (or a clear description of the mathematical translation mechanism when using other metric)? Note: In the corresponding ERP TRL2, the project should have planned per SESAR Solution the requires activities to initially estimate (qualitatively and quantitatively (if possible, or at least estimated)) the impact on those KPAs that are applicable to the SESAR Solution and confirmed through validations	achieved	The Initial Solution has been validated across multiple operational scenarios, confirming its feasibility and effectiveness in reducing horizontal inefficiencies, capacity violations and route charges for AUs (on average). The detailed validation results are described in D5.7 (Final ERR).
PER.TRL2.2.03	Are the validation results in line with what is estimated for the SESAR Solution? In case of deviation, has the project identified a concept/solution refinement to mitigate the gap?	achieved	Validation results for Initial Solution are in line with what has been estimated. Details are present in D5.7 (Final ERR).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.2.04	Were the TRL2 Validation exercises executed in validation scenarios that are representative of the (sub) operating environments where the solution could be deployed?	achieved	The validation exercises for Initial Solution have been executed in validation scenarios that are representative of the operating environment, i.e., 28 days of high traffic and 28 days of low traffic periods. Validation scenarios are described in D5.4 (Final OSED) and D5.7 (Final ERR).
PER.TRL2.2.05	Are Baseline, Reference and Solution scenarios definition aligned with SESAR guidelines?	achieved	Baseline, Reference and Solution scenarios definition are defined for each validation exercises presented in D5.2 (ERP), and they are aligned with SESAR guidelines.
PER.TRL2.2.06	Have potential interactions with related SESAR Solutions been considered? What are the solution relationship (e.g. cross effect, interdependent, mutually exclusive) and relative contribution to performance (e.g. weight per KPA) with the other solutions once the solutions will be deployed?	achieved	As introduced in D5.6 (ECO-EVAL) and D4.7 (WP4 ECO-EVAL), interdependencies exist between the GRC Initial Solution and Solution #407 (Reduced Separation Minima). Both solutions have the objective of reducing the environmental impact of flights while enhancing airspace efficiency. Reduced separation minima enable more direct trajectories through increased capacity, whereas green route charging provides incentives for airlines to adopt fuel-efficient routing. The implementation of both solutions requires accurate emissions data, effective stakeholder coordination, and potential adjustments to airspace design, and together they contribute to the objectives of the Aviation Green Deal.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
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? Are the following elements clearly described in the TRL2 ECO-EVAL: (1) scope of the solution (in particular considering the cost-drivers) (2) interdependencies with other solutions (3) implementation/deployment options, (4) identification of the impacted stakeholders, (5) qualitative description of the benefits, in line with the BIMs in the OSED TRL2, including the most impacted KPAs and KPIs. (6) identification of cost drivers.	achieved	In D5.6 (ECO-EVAL), both costs and benefits have been qualitatively assessed. Given the low TRL (TRL 2), quantitative evaluations have been conducted only partially and limited to specific validation scenarios; the corresponding analysis is reported in Section 4.6. The scope of the solution is described in section 2.2 and cost-drivers are described in section 5. Interdependencies with other solutions are described in section 3.2.1. Implementation and deployment options are described in section 3.5. The impacted stakeholders have been identified and described in section 3.4. The benefits have been described in accordance with the BIM and related to the investigated KPIs (see section 4). The major cost drivers have been identified and described in section 5.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.4	Has a TRL2 Scoping and change assessment been performed and documented in a Preliminary safety (support) assessment in the OSED in line with E-SRM Guidance A On scoping and change assessment? Note: In the Preliminary safety (support) assessment, these criteria and sub-criteria should be covered and they might constitute quality acceptance criteria of the OSED. The Preliminary Safety (Support) assessment shall justify the type of assessment (safety assessment or safety support assessment) expected to be conducted in later stages (beyond TRL2)	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no safety issues connected with the Solution.
PER.TRL2.4.01	Does the Preliminary Safety (Support) assessment clearly identify the scope of the change and describe the key properties of the Operational Environment that are relevant to the preliminary safety (support) assessment?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no safety issues connected with the Solution.
PER.TRL2.4.02	For preliminary safety assessment only: Does the OSED document the identification of the hazards that are inherent in aviation within the scope of the Solution operations? For preliminary safety support assessment: Does the OSED perform a preliminary identification of the safety implications of the Solution based on the analysis of the new/impacted services delivered to the User(s) with due consideration of their safety needs?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no safety issues connected with the Solution.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.4.03	For preliminary safety assessment only: Does the Preliminary Safety Assessment perform a safety impact assessment, in terms of determining whether and how each hazard inherent to aviation is impacted in terms of the efficiency of safety barriers or of the occurrence of accident precursors, through: - analysis based on the relevant AIM models - preliminary identification of hazards newly introduced or modified by the solution functional system (that supposes the initial identification of operational hazards generated by the reference functional system)	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no safety issues connected with the Solution.
PER.TRL2.4.04	For preliminary safety assessment only: Does the Preliminary Safety Assessment contain a list of suitable Safety Criteria for the solution operations and the justification for their selection? Any Solution safety validation objectives included in the ERP TRL2 (if applicable) shall be traced to the Safety Criteria and demonstrated (to the extent possible in TRL2) in ERR TRL2	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no safety issues connected with the Solution.
PER.TRL2.4.05	Are any other safety issues / uncertainties that were identified during the Preliminary safety (support) Assessment documented?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no safety issues connected with the Solution.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PER.TRL2.5	Has the TRL2 preliminary security assessment been carried out in conformance with the SESAR Security Reference Material?	not applicable	The Solution impacts the route choices in flight planning, but the tactical execution of the flight is not affected, i.e. there is no impact on the way ATC operates. Therefore, there are no security issues connected with the Solution.
PER.TRL2.6	Has a TRL2 environmental assessment been performed following SESAR Environmental Reference Material? Note: In the corresponding ERP TRL2, these criteria and sub-criteria should have been already covered and they might constitute quality acceptance criteria of the ERP TRL2 itself	achieved	For Initial Solution the environmental assessment has been performed following SESAR Environmental Reference Material. Details are present in D5.4 (Final OSED) and D5.7 (Final ERR).
PER.TRL2.6.01	Have the SESAR Solution environmental benefits and risks mechanisms been identified?	achieved	Environmental benefits and risks mechanisms have been identified and described for each validation exercise described in D5.2 (ERP).
PER.TRL2.6.02	Have the environmental impacts (Noise, Local and Global emissions) that should be investigated for the SESAR Solution been identified?	achieved	Environmental impacts have been identified and described in D5.2 (ERP).
S&R.TRL2.1	Have the standardisation context been captured and an initial list of potential standardisation needs been identified?	achieved	The list of Applicable standards and regulations is captured in OSED (D5.4) - section 3.2.4.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRA.TRL2.1	Are there recommendations proposed to be addressed during TRL4 related activities? E.g. additional testing conditions, open HP issues to be addressed in TRL4,… Note 1: these recommendations should be based on an evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level. Note 2: these recommendations could also be part of the Exploitation information to be produced by the project	achieved	Recommendations have been included in D5.4 (Final OSED) and D5.7 (Final ERR).
VAL.TRL2.1	Are the relevant R&D needs identified and documented? Have the validation objectives covered by TRL2 validation activities addressed the relevant and Key SESAR Solution R&D needs? Note: R&D needs state major questions and open issues to be addressed during the development, verification and validation of a SESAR Solution. They justify the need to continue research on a given SESAR Solution, and the definition of validation exercises and validation objectives in following maturity phases.	achieved	The relevant R&D needs have been identified and documented in D5.7 (Final ERR), Section 5.
PRG.TRL2.1	Is there a clear identification and definition of the ATM solution e.g. SESAR Solution title and definition, etc.? Note: the objective is to ensure the ATM solution can be included in the ATM Master Plan (e.g. ATM solution description is complete and coherent with the obtained results at all levels (solution, enablers, etc.)).	achieved	An initial solution definition has been written and agreed with the SJU. It is available in the standalone Solution slides and has been cited in the Updated PMP (D1.3). It has been updated in view of the results for inclusion in the Final OSED (D5.4) and the present document (D1.4).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
PRG.TRL2.2	Have the operational and technical assumptions that may have impact on the integration of the ATM solution in the European ATM system been described and documented?	achieved	Operational, performance, and regulatory assumptions have been defined in D5.1 (Initial OSED) and in D5.4 (Final OSED).

Table 22:Green route charging Initial Solution maturity assessment for TRL2

Full Solution

The Full Solution additionally addresses the reduction of non-CO_2 emissions by avoidance of so-called climate hotspots, aiming at an overall reduction of climate impact. As such it is a much more tactical activity than the Initial Solution. Green-GEAR has developed the basic concept and self-assesses it to have fulfilled TRL1 criteria, as explained in Table 23.

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.01	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? - Where does the problem lie? - Has the ATM problem/challenge/need(s) been quantified that justify the research done? Note: an initial estimation is sufficient	achieved	The European Green Deal aims for net-zero emissions by 2050 and promotes sustainable mobility. Aviation needs to reduce emissions, but technologies such as electric aircraft and sustainable fuels will take time. In this context, the GRC Solution is proposing new route charging mechanism to encourage eco-friendly flight paths. The Full Solution shows a slight increase of fuel consumption (and thus related CO_2 emissions, about 1%) with total emissions decreasing with the EI rate, and optimal solutions found at different states of the system (in terms of capacities), with decreased emissions overall (14% in a typical scenario, as measured by ATR20 indicator). These results are documented in D5.4 (Final OSED) and D5.7 (Final ERR).
TRL-1.02	Have the solutions (concepts/capabilities/methodologies) under research been defined and described?	achieved	The Full GRC Solution investigates the possibility of reduction of total climate impact of aviation. Concepts, capabilities, and methodologies are defined and described in D5.4 (Final OSED).
TRL-1.03	Have assumptions applicable for the innovative concept/technology been documented?	achieved	Operational, performance, and regulatory assumptions are defined in D5.4 (Final OSED).
TRL-1.04	Have the research hypothesis been formulated and documented?	achieved	The main research hypothesis is that the modulation of route charges can effectively reduce the overall climate impact of aviation and enhance airspace efficiency. The detailed research hypotheses have been formulated in D5.4 (Final OSED) and reported on in D5.7 (ERR).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.05	Do the obtained results from the fundamental research activities suggest innovative solutions (e.g. concepts/methodologies/capabilities? - What are these new concepts/methodologies/capabilities? - Can they be technically implemented?	achieved	The Full GRC Solution validation exercises show that total emissions could be reduced by 14% (as measured by ATR20) by the application of environmental modulation of route charges. The new concept is the environmental modulation (and subsequent reduction) of route charges. The technical implementation is possible. It requires 1 new function and 2 changes to services, and most of all regulatory changes, that would still require an extensive feasibility study. Details are available in D5.7 (Final ERR) and D5.6 (ECO-EVAL).
TRL-1.06	Have the potential strengths and benefits of the solution identified and assessed? If applicable, are the potential safety benefits identified and justified? - Qualitative assessment on potential benefits. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it should be used.	achieved	The potential strengths and benefits of the Full Solution are identified and described in the ERR and ECO-EVAL. The ERR contains the recommendations for future validations and additional R&I activities. The KPA that apply to the solution and that were assessed are capacity, cost-efficiency and efficiency. Details can be found in D5.4 (Final OSED) and D5.7 (Final ERR). Safety: not applicable

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.07	Have the potential limitations, weaknesses and constraints of the solution under research been identified and assessed? Do they include potential safety considerations (wrt. maintaining the current safety level)? Do they include potential security considerations? - The solution under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others. - Qualitative assessment on potential limitations. This will help orientate future validation activities. Optional: It may be that quantitative information already exists, in which case it may be used.	achieved	The limitations are identified, and recommendations for next validation and R&I steps are listed in the ERR. Details can be found in D5.4 (Final OSED) and D5.7 (Final ERR). The GRC Solution does not impact safety nor security, thus their considerations are not needed.
TRL-1.08	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM Master Plan level, strategic research and innovation agenda (SRIA) and multiannual work programme (MAWP)?	achieved	The Full Solution addresses both CO_2 and non-CO_2 effects, with the aim of reducing the overall climate impact, as detailed in D5.7 (Final ERR) and D5.6 (ECO-EVAL), mainly linked to the environmental performance ambitions in the MP. The validations show 14% reduction in total climate impact, on a partial network. Details can be found in D5.7 (Final ERR) and D5.6 (ECO-EVAL).

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ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.09	Have stakeholders been identified, consulted and involved in the assessment of the results? Has their feedback been documented in project deliverables? Have stakeholders shown their interest on the proposed solution? Note: In the corresponding TRL1 ERP, this criterion should have been already covered and it might constitute quality acceptance criteria of the TRL1 ERP itself	achieved	The Full GRC Solution impacts various stakeholders including States, Air navigation service providers, EUROCONTROL's Central Route Charges Office, the Network Manager and airlines. Stakeholders have been identified and consulted as described in D5.1 (Initial OSED), D5.2 (ERP), and D5.6 (ECO-EVAL, see Appendix B).
TRL-1.10	Are recommendations for further scientific research documented?	achieved	The recommendations are detailed and documented in the ERR and ECO-EVAL documents. Please refer to the Final ERR (D5.7) and the ECO-EVAL (D5.6).

Table 23: Green route charging Full Solution maturity assessment for TRL1

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4 Conclusions and Lessons Learned

4.1 Conclusions

Vertical guidance using geometric altimetry

Conclusions related to the Solution concept in TMA (core Solution scope)

Airspace designers can use geometrically-defined vertical paths to create greater flight efficiencies at a TMA, or network, level, than can be achieved using current day (barometric) principles. The benefits of removing uncertainty around the Transition Layer (manual pressure change, large vertical buffers and lost Flight Levels) and climb or descent interruptions such as level-offs can outweigh the detrimental effect of forcing aircraft to maintain a constant climb or descent rate, which is typically non-optimal for performance, and deliver significant net benefits in terms of fuel and emissions.

These benefits primarily come in densely utilised airspace, e.g. high or very high-capacity TMAs, where the efficiency of the design of each individual instrument flight procedure (IFP) is a compromise influenced by the design of each other IFP. For example, a SID needs to be levelled-off and held beneath a STAR, or a STAR needs to follow a suboptimal (longer) route to be procedurally separated from a SID, or flights need to be tactically managed to avoid traffic on other procedures that are not procedurally separated on high- or low-pressure days.

Using of geometric altimetry for vertical navigation provides a consistency of altitude (an aircraft's geometric altitude remains independent of local pressure variation) and of procedure (the geometric constraints do not change with local pressure variation) at all levels. Removing the variability of barometric altimetry enables the definition of prescriptive, repeatable descent or climb profiles, which means arrivals and departures can be more easily slotted between one another in the airspace design, minimising the inefficiencies of compromises between IFPs in the TMA, or network, design.

However, it has been shown that the detrimental effects of forcing aircraft to maintain a constant climb or descent rate cannot be ignored. In the case of the climb phase alone, it may not be possible to achieve a net benefit. As well as having a detrimental effect on fuel, compared to an unrestricted climb or descent, it also has knock-on impacts on speed management and, consequently, noise.

Indeed, in the descent phase, if the aircraft is not provided with a sufficiently shallow descent, it may not be able to reduce speed for the Approach without the use of speed brakes, which are less fuel efficient and create noise, as well as increased maintenance costs. Also, aircraft deceleration along a fixed vertical angle is not the most operationally efficient, since in some cases aircraft may need to start deceleration very soon and with a low deceleration rate, both of which may be operationally unpractical for flight crew and ATC. Therefore, the design of the descent could be broken into two parts: a nominal flight path angle (FPA) with constant speed, followed by a shallower FPA (still not a level-off) allowing for a nominal deceleration rate.

In the climb phase, forcing an aircraft to climb at a fixed gradient may not allow it to accelerate to meet its speed schedule, which could have both a fuel and time impact, or even not be flyable at all. Indeed, there is a huge variety of aircraft climb performance among all expected aircraft types and weather conditions, and, for a given flight, the climb performance decreases with altitude. A conservative (low) climb gradient would ensure flyability but would also degrade fuel efficiency.

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Regarding the Human Performance assessment (conducted with the ground side, i.e. ATCOs, but not the airborne side, i.e. pilots), it was found that switching from barometric to geometric altimetry within the current airspace structure would likely have minimal impact on controllers' daily tasks, workload, and situational awareness. However, transitioning to a systemised airspace with geo-based prescribed lateral and vertical paths would shift the controller's role from active control to a primarily monitoring role, potentially decreasing situational awareness. In case of non-nominal conditions requiring fallback to traditional baro-based traffic management, this may lead controllers to experience a significant increase in workload.

Conclusions related to geometric altimetry in Cruise (outside of core Solution scope)

While the Solution scope was focused on Climb, Descent & Approach phases, the use of geometric altimetry for Cruise operations was also explored. It has been found not operationally suitable for Cruise phase by itself, due to significant challenges inherent to the dependency of aircraft performance on barometric conditions, particularly regarding flight envelope (e.g. maximum operating altitude) and cruise altitude optimisation.

Indeed, geometric-based cruise would require flight crew to monitor the barometric altitude in order to keep the aircraft within its flight envelope and as close as possible to its optimum cruise altitude, potentially leading to an increased number of cruise level changes following isobar variations. Such operational complexity would be undesirable from Airspace Users and ATC perspective.

To prevent such increased complexity, an alternative solution would be to plan the flights at lower than optimal cruise altitude to minimise the need for safety-related step-down level changes, and briefing flight crews to limit optimisation-related level changes. This would bring a negative impact on environment, operational efficiency and potentially also capacity due to reduced use of the upper flight levels.

Due to these operational challenges and the quantitative results (fuel penalty) identified during validation activities, it has been concluded that the implementation of geometric Cruise is detrimental when considered in isolation.

Geometric Cruise could be worth considering in the future as part of a holistic geometric navigation solution, removing altitude datum transitions and potentially enabling other ATM Solutions relying on geometric altimetry in Cruise (e.g. Solution 0407 / RVSM 2), if the associated benefits were demonstrated to outweigh the drawbacks identified so far.

Conclusion on GNSS operational environment - Jamming & Spoofing threats

In the context of the increased GNSS jamming & spoofing threats, it is recommended to postpone the deployment of Geometric Altimetry solutions in all phases of flight until the implementation of the necessary mitigations to avoid excessive operational burden for flight crews and air traffic controllers.

Beside ongoing airborne standards evolutions, the following mitigations to deal with the unavailability of GNSS-based altitude sources due to jamming & spoofing threats should be considered:

- A reversion to barometric altitude will be required on-board the aircraft (automatic or manual) upon detection but more likely preferable before entering the interference area.
- A reversion to barometric based airspace and management of all aircraft affected in the area by air traffic controllers such as clearance and RVSM constraints must be performed.

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- A robust jamming and spoofing detection tool (on the ground and/or on-board) must be operational in order to ensure aircraft can timely and concurrently revert to barometric altitude approximately at the same locations.
- The management of the transition between an airspace managed in barometric altitude and a geometric altitude: This is already needed under normal conditions but this situation might occur very often in some regions near conflict zones, which could lead to decide to not switch to geometric altitude at all in some airspaces.
- Standardised and agreed upon phraseology and SQUAWK notices.

Conclusions regarding the Economic Evaluation

At the current TRL of 2, a preliminary benefits assessment could be performed quantitively but the cost assessment could only be performed qualitatively. Thus, further research is required to conclude whether the solution is also viable not only from a technical perspective, but also from the cost benefit.

Also, it must be highlighted that the benefit assessment was based on a deployment of GeoAlt in London TMA only. Despite the qualitative cost assessment being more or less generic for the involved stakeholders, the benefit assessment was likely influenced by the particular characteristics of the deployment environment. Thus, it is recommended to enlarge the validation scope to other operational environments.

Separation Minima

The work focussed on the safety aspects of RVSM 2, which are not sufficient but necessary for a possible implementation of the concept. 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.

The **Collision Risk Analysis** focused on the technical (or nominal) risk. When aircraft pass on adjacent flight levels, the Altimetry System Error (ASE) and Flight Technical Error (FTE) induce a small probability of lateral and vertical overlap (i.e., a collision).

The collision risk is dependent on the sum of the ASE and FTE, also named the Total Vertical Error (TVE). The TLS was shown to be met if the TVE ≤ 34 ft if it is Laplace distributed, or TVE ≤ 58 ft if it is normal distributed. The error budget available for either the ASE or the FTE directly depends on the budget that is reserved for the other. For example, under certain conditions, if either the ASE or the FTE distribution has a standard deviation σ_1 = 30 ft, this would allow the other distribution to have a standard deviation $\sigma_2 \leq$ 28 ft or $\sigma_2 \leq$ 50 ft respectively if both were Laplace or if both were normal distributions. The collision risk is highly dependent on the tails of the error distributions, which is reflected in the aforementioned requirements.

The current MASPS for traditional RVSM prescribes a maximal standard deviation for the FTE of 43 ft. This would not be sufficient to meet the TLS. The observed FTE that is estimated in the context of RVSM Collision Risk Analysis is shown to be 33 ft, which could be sufficient to meet the TLS. A more detailed characterisation of these figures, perhaps through ADS-B data, is likely possible and required.

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Neither GPS nor Galileo guarantee a Vertical Positioning Error, the equivalent of the current ASE, that is likely to meet the requirements. However, quarterly performance reports, from actual standardised measurements, show a performance that seems just sufficient to meet the TLS when taking the current FTE estimates into account. This is however the actual performance. In order for a system to be practically feasible a margin between the actual performance and the requirements is necessary. Also, the measurements from these reports are collected under standardised conditions. The high-altitude aviation domain may be such that the accuracy is better or worse under these conditions. In addition, neither GPS nor Galileo operators assume legal responsibility regarding the system performance, and it is not guaranteed that past performance levels will always be met.

The **Wake Turbulence Risk** study had the objective to identify the changes in wake vortex encounter risk that can be expected from a reduction of vertical separation minima in RVSM 2 airspace to 500 ft as envisaged to be feasible with improved altitude keeping from a collision risk point of view.

Through fast-time simulations of several full-day scenarios (comprising low- and high-wind situations) for the EUR region the expected en-route wake encounter frequencies and severities were investigated and compared between baseline and new concept of operations. It must be noted that the assumptions and the detail level of the modelling (particularly as regards atmospheric properties) does influence the numerical results, but it seems reasonable to assume that comparisons between reference and envisaged future operations (Solution scenario) still hold sufficient significance.

With that caveat in mind, we find a substantial increase in the number of wake encounter occurrences over all magnitudes of the circulation encountered. As vortices drift downwards in the majority of cases and decay during this downward motion, this result is plausible. However, with no official definition of a target level of safety (TLS) for the wake encounter risk, nor any means of quantification for the encounter severity defined by regulation, a statement whether the new situation is still safe cannot be made at this point. Prior activities modifying separation standards have adopted a comparative approach, postulating the current situation as safe and demonstrating no (unfavourable) change of risk through the new concept of operation. With the results from the validation study, this cannot be done, so the conceivable options are to either demonstrate that even with the increased wake turbulence risk, the new concept of operations is still safe (which is very improbable), or to identify mitigations means and/or limiting conditions for its application.

Indeed, further analysis of the results especially regarding particular aircraft (category) pairings, relative flight path geometries or weather situations is desirable, so as to possibly identify criteria when or where the new separation standards could be applied safely, or should not be applied. It is quite conceivable that the reduced vertical separations would not be universally and ubiquitously applicable but subject to conditions. An alternative approach could be 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 of such a tool, it might be able to be implemented by a retrofittable software solution, rendering large potential benefit as operational limits, and thus capacities, would no longer need to be dictated by the worst-case assumption.

The **Safety Case** was structured as a Functional Hazard Analysis (FHA) in which a combination of qualitative and quantitative requirements was derived. Like in the Collision Risk Analysis, the approach of traditional 1000 ft RVSM was adopted. Four primary functions were defined, the failures of which directly correspond with the four functional hazards that were identified.

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The most important hazard that was identified, the equivalent of which does not exist in barometric operations, is when the altitude information (i.e. GNSS signals) is not provided properly in part of the airspace (i.e. at the environmental side of the sensor). This could occur through intended or unintended interference, and would result in multiple, if not all users in a given airspace to be affected. Solutions such as Dual Frequency GNSS receivers will likely be necessary to reduce the likelihood of this hazard, but it can still not be considered as negligible.

Procedures will be necessary to mitigate the risk when this hazard occurs. If there is no ground domain that can take coordinative actions, a Procedure Single Unable Altimetry (PSUA) should be in place that multiple aircraft safely execute individually. Having a ground domain that coordinates a contingency procedure, Procedure Multiple Unable Altimetry (PMUA), when multiple aircraft lose the ability to determine altitude, would likely be preferable. This would likely also require a function for the ground domain to detect inadequacy of the altitude domain, which could be provided through different means, such as lack of altimetry integrity messages from the altitude information domain, or unable altimetry messages from the airborne domain. Because such a procedure would constitute a serious disruption of the air traffic operations, it is rather loosely concluded that it should not be required to be enacted more than once every ten years.

Due to the reduced separation, it was recognised that a number of barriers would become less effective when transitioning to 500 ft separation, and that ACAS would require a complete reconsideration due to incompatibility of the systems that are currently in use with 500 ft minimal separation. Assuming a recalculated effectiveness of the ATC collision prevention barrier and a maximally allowable risk of a mid-air collision of $2.5 \cdot 10^{-9}$ led to a minimal effectiveness requirement of the combined visual- and ACAS based avoidance of at least 93%, as opposed to the 97% effectiveness at 1000 ft in traditional RVSM. Even though a less effective ACAS is permissible in RVSM 2, achieving such a system is no trivial task.

Conclusions regarding the Economic Evaluation

The ECO-EVAL [49] addressed in a qualitative manner the expected key benefits 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. Indications for capacity increase and improved operational and environmental efficiency were given, but 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. As 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; further research is required on this topic.

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Green route charging

The validation exercises for the Green Route Charging (GRC) Solution have shown significant progress in assessing the economic and environmental impacts of performance-based en-route charging. The GRC Solution is being developed in two stages: the Initial Solution, which addresses horizontal inefficiencies related to unit rates, and the Full Solution, which encourages climate-friendly trajectories by considering both CO_2 and non-CO_2 emissions.

The Initial Solution, incorporating the MRC and ODC+MRC models, has been validated across multiple scenarios, confirming its feasibility and effectiveness in reducing horizontal inefficiencies while meeting stakeholder requirements. Exercise #01, conducted on a small-scale European air traffic instance, verified cost efficiency, capacity balancing, and revenue neutrality, achieving a 1.81% reduction in global distance flown. Exercise #02, covering two full AIRAC cycles, reinforced these results, showing CO_2 reductions (ENV1) ranging from 0.25% to 1.36% (especially for flights within ECAC airspace) and a 91.2% to 94.1% decrease in capacity violations.

The ODC+MRC model showed similar performance, further supporting the robustness of the approach. While this indicates the effectiveness of both mechanisms, the ODC+MRC model requires substantial regulatory changes. In contrast, the MRC has a much lower impact on existing rules, suggesting that future development efforts should likely focus on this simpler yet equally effective framework.

Despite its promising outcomes, the validation is constrained by the reliance on 2019 data, partial annual traffic coverage, and sensitivity to fuel cost assumptions, underscoring the need for further testing. Nonetheless, consistent results across scenarios support the model's operational applicability. The exercises represent a key milestone for performance-based charging under the Digital European Sky framework, demonstrating clear benefits in environmental efficiency, congestion reduction, and cost-effectiveness.

The Full GRC Solution incorporates full climate considerations, using a simplified hotspot-based model to address non-CO_2 emissions. Initial results show airlines can be incentivized to avoid hotspots, flight level changes improve environmental impact, and congestion reduces efficiency. Exercise #02, on a larger sample, showed most KPIs were slightly or neutrally affected, except full emissions, which showed a reduction of 14% (ATR20, i.e. climate impact expressed in temperature increase at the 20 years horizon). Including CO_2 in total impact had limited effect on fuel use and airline costs.

4.2 Technical Lessons Learned

Vertical guidance using geometric altimetry

For the use of **geometric altimetry with altitude constraints (Method 1)**, the airborne impact assessment identified some design considerations with no technical showstopper identified so far for Climb, Descent and Approach.

For the use of **geometric altimetry with prescribed vertical paths (Method 2**), the airborne impact assessment identified some design considerations with no technical showstopper identified so far for Descent and Approach, while further R&D work would be required to establish technical feasibility for Climb.

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The identified design considerations for both Methods are summarised hereafter.

Conclusions common to the use of geometric altimetry with or without prescribed vertical path (i.e. both Method 1 and Method 2)

Navigation Systems (other than FMS)

Geometric-referenced altitudes based on GNSS already exist in aircraft navigation architecture, but it is necessary to identify which among those available can be used for the GeoAlt Solution use-cases to answer the following needs:

- Meet the required performance in terms of accuracy, integrity, sufficient availability and continuity in the target airspace
- Be as much as possible independent of the source used in surveillance functions (see dedicated topic).

Design considerations addressing this topic are provided in the Solution data pack, with no technical showstopper identified so far.

Flight Management System (FMS) Predictions

The FMS is responsible for providing predictions to the flight crew from preflight to landing, among which fuel & time are the most operationally critical since these predictions are used by the crew to conduct the flight follow-up to ensure that the safety and mission needs are satisfied. Most of the FMS predicted parameters (e.g. time, altitude, speed) can be downlinked to ATC through ADS-C EPP and might also be used for ATC operations.

The FMS predictions computation would be impacted by the switch to geometric reference as the performance of the aircraft is always tied to barometric conditions, and the FMS does not currently have the capability to anticipate the pressure altitudes associated to the expected geometric altitudes.

It seems necessary to also update FOC flight planning tools, as inconsistencies between the OFP predictions and the FMS predictions are unlikely to be operationally acceptable considering that flight crew is expected to perform fuel monitoring based on FMS predictions compared to the OFP.

In addition to impacts on FMS and FOC flight planning tools detailed in the Solution data pack, Solution 0406 may have further impact on the ATM architecture depending on the chosen way forward:

- Potential impact on MET services in case of need for providing MET aloft gridded forecast data referenced to geometric altitudes, and possibly including pressure altitude in addition to wind, temperature, etc.
- Potential impact on AIM services in case of need for publishing static data supporting the conversion between geo and baro altitudes in ISA conditions, possibly with a similar approach as for current data supporting conversion between magnetic and true headings.

Even if the advanced solutions for airborne predictions involve significant systems impact and further R&D work seems necessary to consolidate the way forward on this topic, no technical showstopper has been identified so far.

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Compatibility with Surveillance Functions

Independence between Navigation and Surveillance functions is required by airworthiness authorities. This is particularly relevant when GPS-based altitude is utilised for navigation since, in most cases, GPS altitude (and sometimes SBAS altitude) is utilised by surveillance functions such as the Terrain Awareness and Warning System (TAWS).

This should be possible by considering different sources of GPS-based altitudes for surveillance and navigation, for instance one using SBAS altitude or GPS altitude whereas the other would be the GPS-IRS hybrid altitude.

Regarding the ADS-B out reporting, the barometric altitude is reported as of today as per RTCA DO-260 and, if the GPS-based altitude is to be used for navigation, therefore the transponder standard and the interface must be modified to use this altitude source in order to be used by the air traffic controller.

No technical showstopper regarding this topic has been identified so far.

Cockpit HMI – Provision of both geo and baro altitudes to flight crew

Even if, at a given time, the aircraft navigation is based on geometric altimetry only, it is deemed necessary to provide the flight crew with a means to access the barometric altitude for the management of non-nominal conditions as a means of troubleshooting by checking the consistency of both altitude sources.

From a HP perspective, it would be misleading to present both altitudes to flight crew in their primary instruments (e.g. PFD), so the most appropriate solution is probably through a dedicated page in MCDU/MFD, in a similar way as today's GPS MONITOR page where the crew can find, among others, the GPS position computed by the onboard receivers.

Manual vs Automatic altitude reference switching

Automatic altitude reference (baro and geo) switching capability can be particularly useful in two different use case:

- Nominal operation: when reaching known transition gates (e.g. the ToD or a baro-geo transition altitude),
- Fallback operation: when a reversion from geo to baro reference is required due to unavailable or unreliable geometric altitude (e.g. due to jamming or spoofing threats).

For the first use case, if the transition between baro and geo is the ToC or the ToD (e.g. fully geometric Climb, Descent & Approach, with fully barometric Cruise), the FMS is aware of those points. However, if the transitions are located at a geo-baro transition altitude or a baro-geo transition level, they would need to be available in the FMS NavDB or manually entered by the crew, similarly to current STD-QNH transition altitude/level.

For the second use case, as mentioned in the "Management of Jamming & Spoofing Threats" topic, automatic reversion from geo to baro could be possible thanks to the implementation of robust airborne detection tools.

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However, manual switching capability is still necessary to deal with degradations of the geometric altitude capability not detected by airborne systems, as well as to enable anticipated fallback operation foreseen by ATC due to known perturbations. Indeed, in the latter situation, it is recommended to apply the reversion to baro reference before entering the perturbed zone.

Conclusions specific to the use of geometric altimetry with prescribed vertical path (Method 2)

FMS climb profile computation

In today's design, no profile exists for the Climb phase (unlike the descent), the aircraft is never guided on a vertical trajectory. The published altitudes constraints on the procedures are matched by the aircraft by simply preventing it from climbing above any downstream applicable constraint, and the aircraft flight path compliance status for each altitude constraint (achieved or missed) is published accordingly on FMS pages / ND / VD thanks to the FMS prediction computation.

Introducing a requested vertical path in the form of a straight line between two constraints would have a significant impact on the FMS and the operation. A climb profile would have to be computed by the FMS and a new type of guidance would have to be defined to ensure proper tracking of said profile. Technical feasibility assessment of such a major change would require further R&D work in collaboration with FMS suppliers.

Cockpit HMI for V-RNP onboard monitoring and alerting

At this stage of the R&D work, it has not yet been possible to determine the most appropriate HMI and SOP to support the related flight crew operation, but it has been suggested that the HMI design could be inspired from the one currently used for RNP AR approaches, which provides vertical deviation symbology (VDEV) similar to the PBN-based lateral deviation symbology (LDEV).

In addition to vertical deviation monitoring, further work would need to address the potential needs for alerting such as excessive vertical deviation or navigation performance degradation no longer ensuring the V-RNP requirements.

Separation Minima

In the initial OSED [30] it has been assumed as starting point that procedural control might be sufficient (no permanent surveillance and ATC action in case of conflicts), as is the case in RVSM airspace in the North Atlantic region today. Also the effectiveness of the ATC collision prevention barrier in terms of a STCA tool was initially assumed as zero, i.e. the presence of such a tool was not required a priori. These assumptions were made to ensure that no requirements were defined that are not actually necessary but just an extrapolation of existing practices. The safety case has shown, however, that both of these assets are required for safe operation of RVSM 2, i.e. permanent surveillance by ATC (including tactical control) and a tool to automatically detect conflicts on ground that the controller has failed to see.

Also in the initial OSED [30] there were intentionally no limitations of applicability of the concept, like as today 1000 ft of vertical separation are universally applicable in RVSM airspace. This 'one size fits all' approach to separation needs to be conservative, and the present study has shown that this may just be the case for the collision risk but is not feasible for the wake turbulence risk. More flexibility in

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applicability of the concept depending on factors like the weather situation, relative flight path geometries or the involved aircraft parings may be required, as already indicated by the R-WAKE study. Limited resources prevented further investigations into this topic in the present project.

Procedures will be necessary to mitigate the risk of loss of geometric altimetry to one or multiple aircraft. If there is no ground domain that can take coordinative actions, a Procedure Single Unable Altimetry (PSUA) should be in place that multiple aircraft safely execute individually. Having a ground domain that coordinates a contingency procedure, Procedure Multiple Unable Altimetry (PMUA), when multiple aircraft lose the ability to determine altitude, would likely be preferable. This would likely also require a function for the ground domain to detect inadequacy of the altitude domain, which could be provided through different means, such as lack of altimetry integrity messages from the altitude information domain, or unable altimetry messages from the airborne domain.

Due to the reduced separation, it was recognised that ACAS would require a complete reconsideration due to incompatibility of the systems that are currently in use with 500 ft minimal separation. Even though a less effective ACAS would be permissible in RVSM 2, achieving such a system is no trivial task. First of all, ACAS would have to be redesigned not to issue warnings at 500 ft vertical separation. In addition, the parameters of ACAS, such as the look-ahead time would likely have to be updated to accommodate the reduced available time for conflict resolution, but this is not allowed to result in unacceptable levels of nuisance resolution advisories. Finally, it is important to consider that ACAS needs an independent altitude source from the one that is used for navigation.

The wake encounter prevention does not need to be entirely procedural. A possible mitigation of the wake encounter risk, especially in view of raising concerns about the status quo, is also a predictive function for ATC and/or an onboard tool to identify potentially dangerous situations. For the latter, prior work in SESAR (Wake Encounter Prevention System, WEPS) [90][100] and also research demonstrations (e.g. at DLR [72][73]) have shown general feasibility. Also, methods to counteract the upset through a wake encounter by means of specialised flight control modes have been conceptually studied [79][99]. The added complexity of this approach and the financial effort to implement it needs to be traded off against an increase of flight safety on one hand and the expected environmental and operational benefits on the other. Higher capacity by finer granularity of flight levels would enable flights to operate closer to their optimal altitude. As evidenced by real-world flight plan data, aircraft tend to concentrate on certain flight levels that can become saturated even if the overall upper airspace capacity limit is not reached.

Green route charging

The validation exercises clarified the operational concept and demonstrated the feasibility of the GRC Solution within the SESAR framework. The two-stage approach proved conceptually sound: the Initial Solution was experimentally validated and showed improvements across efficiency, capacity and environmental KPIs, including stable performance under different traffic conditions.

The Full Solution builds logically on these principles by incorporating climate considerations through hotspot-based modulation. Although a simplified model had to be used due to complexity, the first exercise showed that airlines can be incentivised to select more environmentally friendly trajectories, that flight-level changes enhance the mechanism’s effectiveness, and that full-emissions schemes (paying for all emissions instead of hotspot-based) may not perform significantly better, particularly under congestion. The second exercise clarified limited or neutral KPI impacts (except for a PI on full

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emissions), and showed that including CO_2 emissions reduces fuel consumption impacts and therefore airline cost changes.

The GRC Solution introduces new route charging mechanisms without impacting ATM systems. However, during the project, key functions were identified, including a central planner to determine environmental modulation and hotspots and communicate them to airlines, MET forecasts to support hotspot determination with potential additional requirements, and flight planning software capable of incorporating new information (e.g., EI rate) to optimise trajectories.

Overall, the GRC Solution aligns well with Digital European Sky objectives and the validation results provide sufficient confidence to justify continuation of the research, while identifying specific areas that require further refinement before deployment.

4.3 Plan for the next R&D phase (next steps)

Vertical guidance using geometric altimetry

The Green-GEAR project has demonstrated that it is possible to design TMA airspace based on geometric altitude. It has also identified a range of operational and technical hurdles to be addressed, and concluded that there are no absolute showstoppers. However, there are significant technical challenges, particularly for the use of geometric altimetry with prescribed vertical paths (Method 2).

There is a range of recommendations for follow-on R&I work:

1) Higher fidelity assessment of Method 2 (i.e., V-RNP-type solutions), such as:

- Human-in-the-loop assessment of managing geometric-based prescribed vertical paths.
- Procedure development
- Development and assessment of ground-system conformance monitoring capability to Geo path.
- Air/Ground communications of barometric and geometric altitudes in parallel, and/or
- Display and management of barometric and geometric altitudes at controller working positions (CWPs)

2) Quantitative analysis of Method 1 and/or transition states, e.g.:

- Straight switch of barometric to geometric altitude reference (no airspace change)
- Geometric path in descent and approach with geometric constraints (only) in climb
- Geometric altitude below TL and barometric altitude (FL) above

3) Consolidate outcomes for descent and approach, particularly regarding speed management challenges for Method 2

4) Assess the most appropriate way forward for FMS predictions on geometric-referenced departure and arrival & approach procedures (applicable to both methods). In addition to FMS and OCC systems impact, assess the potential need for impact on MET services to have forecast data (e.g., pressure,

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wind and temperature) referenced to geometric altitudes, and/or AIM services to have static data supporting conversion between geometric and barometric altitudes.

5) Collaboration with FMS suppliers to assess the technical feasibility of the introduction of vertical profile computation and guidance capability in the climb phase for Method 2.

6) Assess if a discrete number of authorised climb profiles (e.g. high/medium/low) for Method 2 would satisfy operational needs.

7) Assess the potential challenges associated with the transitions between segments with different vertical angles in the climb for Method 2.

8) Ground support to aircraft technical capability development for both methods

9) Assess having a transition between geometric and STD barometric altitudes somewhere, instead of today's barometric QNH to barometric STD. As part of this consider, manual versus automatic altitude reference switching, e.g. to include changes to the interface between baro in cruise and geo in descent or airspace border interfaces between baro to geo.

10) Assess whether GeoAlt in cruise might enable finer granularity of flight levels (see Solution 0407 / Green-GEAR WP4), supporting flight closer to optimum altitude.

11) Progress on the Solution costs assessment.

12) Assess the Solution benefits for operational environments other than London TMA.

Separation Minima

The following recommendations arise from identified questions regarding the concept maturation and are directly connected to maturing the Separation Minima Solution:

- The only FTE data available in this study were based on Mode-C, for which the altitude is emitted in 100 ft increments. Using Mode-S the FTE could possibly be characterised more accurately, both the distribution type and the standard deviation, and could provide important insights into the feasibility of the concept.
- The values for the ASE used in the CRA are based on GPS and Galileo Quarterly Performance Reports. Even though these seem to be most representative data available, a more accurate characterisation reflecting the high-altitude aviation domain and possibly typical aircraft equipment is recommended.
- A study into the necessary adaptations of ACAS is recommended. At a vertical separation of 500 ft current ACAS will issue warnings and resolution advisories. This will possibly lead to unacceptable levels of nuisance warnings. In addition, the reduced vertical separation in RVSM 2 may result in a shorter time to resolve conflicts. The necessary adaptations will have to be investigated.
- The safety case showed that the PSUA and PMUA are crucially different factors, not present in current operations. As such, it is recommended to assess the feasibility and to develop the procedures into greater detail.

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- It should be investigated whether a slight increase of the separation minimum, e.g. to 600 ft / 700 ft or 200 m, while being less intuitive, could solve the marginal TVE requirements. Note, however, that such separation minima may pose challenges from a human factors perspective.

- A reduction of vertical separation to 500 ft based on barometric altimetry as it is today is infeasible because of the high allowable ASE [43]; for various reasons the pitot-static system cannot be calibrated better on ground. Comparing the actual offset between barometric and GNSS altitude with the one expectable as determined from numerical weather prediction data [92] and/or through improved long-term height monitoring [78], it might be possible to introduce a kind of online calibration of the barometric altitude to improve on the barometric ASE.

- A detailed categorisation of wake encounter situations should be undertaken as basis for the decision whether the concept could be applicable under certain, well-defined conditions. A universally applicable approach to separation needs to be conservative, whereas more flexibility in applicability depending on factors like the weather situation (including wind or convective activity), relative flight path geometries or the involved aircraft parings may be required, as already indicated by the R-WAKE study [77].

- The severity assessment for wake vortex encounters is still not generally solved; several approaches have been devised by various authors but no universally agreed method exists.

- There is also the aspect of lateral guidance errors and their influence on the encounter probability. Lateral (cross-track) errors have decreased by one order of magnitude through the introduction of satellite navigation as primary means for horizontal navigation. The consequences of this change have not been systematically studied.

- 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. Note that the latter could be influenced by the deployment region (e.g. airspace congestion).

- The assessment of the benefits particularly concerns airspace capacity and operational efficiency, 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, see also the GeoAlt Solution. These necessary developments are not considered as part of the Separation Minima solution as such.

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- In addition, it is obviuously necessary to address the TRL2 maturity criteria that had intentionally been excluded from Green-GEAR's work plan (Human Performance Assessment, Security Assessment beyond jamming and spoofing, Environmental Assessment).

More details on the above technical questions are available in D4.4 (ERR) [50] and D4.7 (ECO-EVAL) [49].

Green route charging

The validation results demonstrate promising trends in environmental efficiency, demand-capacity imbalance reduction, and cost savings, supported by consistent performance across different traffic scenarios. However, the limited sample size and reliance on historical data temper the statistical certainty, while operational realism is constrained by the absence of edge cases, and potential shifts in aviation dynamics since 2019.

To enhance the robustness of future validations, efforts should focus on expanding dataset diversity (including additional AIRAC cycles and extreme traffic conditions), integrating recent operational and fuel-performance data, and testing key assumptions through sensitivity analyses and Monte-Carlo simulations. It will also be essential to assess equity impacts across AUs and ANSPs, evaluate forecast-related uncertainties, and carry out a technical and operational requirements analysis for the three new functions (central planner, MET provision of non-CO_2 forecast, and inclusion into flight-planning tools).

Further research is needed to better quantify climate-impact uncertainties and define appropriate thresholds for minimising aviation impact. This requires close collaboration between atmospheric experts and operational stakeholders to identify feasible mitigation actions. To ensure transparency and consistency in future charging mechanisms, all actors must rely on a common data source, which implies establishing new functions to generate and distribute climate-impact information across stakeholders.

4.4 Recommendations

Vertical guidance using geometric altimetry

In the context of increased GNSS jamming and spoofing threats, it is recommended to postpone the deployment of Geometric Altimetry solutions in all phases of flight until the implementation of the necessary mitigations to avoid excessive operational burden for flight crews and air traffic controllers. In addition to the operational mitigations identified by the project (see Conclusions section above), it is recommended that future R&I activities are progressed in relation to industrial standards addressing this topic.

Regarding the use of geometric altimetry in the TMA, it has been concluded that the most suitable way forward for the climb phase is to use geometric altitude constraints at waypoints (Method 1) and only consider prescribed vertical paths (Method 2) in highly congested airspace when required for deconfliction as part of a composite solution together with Geo Path in descent and approach. New procedure design criteria would need to be created to take account of geo-based vertical track keeping.

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Regarding geometric cruise, it has been concluded that it is detrimental when considered in isolation due to operational challenges and fuel penalties, and only worth considering in the future as part of a holistic geometric navigation solution, removing altitude datum transitions and potentially enabling other ATM Solutions relying on geometric altimetry in cruise (e.g. Solution 0407 / RVSM 2), if the associated benefits were demonstrated to outweigh the drawbacks identified so far. Application to high altitude operations may also be explored.

Separation Minima

Further recommended activities that are more loosely connected to maturing the Separation Minima Solution and/or applicable in a wider scope comprise the following:

- The current wake vortex separation rules have been established using expert judgement in the 1970s, and their only modification at ICAO level so far has been the introduction of the SUPER category that is currently exclusively populated by the A380. A universally agreed approach to possible modification of these rules has not been developed. Such modification would be necessary for the implementation of the Solution's RVSM 2 concept, but also appears desirable in view of changes to air transport operations since the introduction of the rules. Traffic densities have increased, the mix of aircraft types has changed, and new classes of aircraft such as VLJ have been introduced. Several incidents and accidents have raised concerns that an adaptation of the current standards for en-route separations might be necessary.

- As a wake encounter may pose a significant hazard to the affected aircraft, as evidenced by incidents and accidents, flight safety could be increased by a wake vortex safety net that could be airborne (cf. ACAS for the collision risk) or ground-based (cf. STCA for the identification of loss of separation). Initial investigations have been performed and shown general feasibility [90][100][72][73]. Such systems could also help to better use airspace capacity as the separation would not need to be statically defined by the reasonable worst case under all operational and weather conditions.

- An exploration into the matter of GNSS liability and responsibility, and what would be required in this regard for the RVSM 2 concept to be introduced. GPS and Galileo do not accept liability for the performance of their systems. Current performance may not guarantee similar performance at every other moment in the future. GNSS performance is not a factor in current en-route operations as it will be in RVSM 2. Some future study should likely expand on this topic and include the broader aviation sector in the discussion.

Green route charging

The validation has revealed several research directions for future SESAR or other R&I programmes – which are reported in detail in Section 5.2 of D5.7 (Final ERR) [56]. Future studies should test more diverse operational scenarios (e.g. extreme weather and major disruptions) to assess robustness. Further work is required to explore dynamic charge modulation (including AI-based approaches) and to develop methods able to handle high computational complexity. Given the significant uncertainty surrounding non-CO_2 effects, research is also needed to determine acceptable uncertainty levels and improve model accuracy.

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New aircraft types (including low or zero-emission models) should be included to assess future route charge modulation effects on both environmental performance and traffic distribution.

General recommendations not limited to a specific Solution

The experience gained during the execution of the present research activity leads us to recommend extending the duration of the validation activities – i.e. the technical phase of the Exploratory Research – to at least 24 net months (up to the first delivery of the last technical Deliverable to the SJU). The level of modelling required to ensure significant results, together with the potentially time-consuming execution of simulations, cannot be fully parallelised. The time available for evaluating the results, and relating them to other activities, is perceived as too limited, especially considering the valuable insights that could be obtained at relatively small additional cost.

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5 References

5.1 SESAR Reference Documents

The work done in Green-GEAR 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.

[23] Horizon Europe ethics guidelines – essentials_1 (1_0).pptx

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5.2 Project Deliverables

Deliverables are listed by publication date, the latter being the date of submission of the approved version where applicable, of the latest submission for issues that have not been approved yet (marked as "submitted"), or provision on Stellar / the project website for documents that need not be approved (e.g. internal deliverables). Note that superseded versions intentionally are not listed.

All public project Deliverables are available from the project's website under https://sesar-green-gear.eu/deliverables-docs or the Commission's Community Research and Development Information

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Service (CORDIS) server under https://cordis.europa.eu/project/id/101114789 or DOI: https://doi.org/10.3030/101114789 → Results → Deliverables.

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5.3 Project Publications

With the present report submitted at the end of the technical phase, the 6-month dissemination phase is just beginning so most of the scientific publications are not yet completed. The project website [64] will be continuously updated with the links to all open-access publications also after formal project closure.

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5.4 Other

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Appendix A List of acronyms

A.1 Glossary of terms

Term	Definition	Source of the definition
Geometric Altitude / Geo Alt	Defining routes and procedures using geometric altitude. Aircraft navigation systems constructing vertical paths based on geometric altitude and navigating to geometric altitude.	Project Definition (WP3 / Solution 0406)
Transition Layer	The airspace between the transition altitude and the transition level, where the Transition Altitude is the altitude at or below which the vertical position of an aircraft is controlled by reference to altitudes and the Transition Level is the lowest flight level available for use above the transition altitude.	ICAO PANS OPS [88]
RVSM 2	The concept [studied in this Solution,] 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 (WP4/ Solution 0407)
Target Level of Safety	The level of risk considered to be the maximum tolerable value for a safe system.	ICAO [81]
Wake Encounter Resistance	Ability of an aircraft, due to geometry, mass and moment of inertia on one hand and flight control capabilities on the other, to safely limit the effects of a wake encounter on aircraft accelerations, changes of attitude and flight state as well as flight path excursions.	Project Definition
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 24: glossary of terms

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A.2 Acronyms and Terminology

Acronym	Description
A/G comms	Air-Ground communications
ACAS	Airborne Collision Avoidance System
AIM	Aeronautical Information Management
AIRAC	Aeronautical Information Regulation And Control
ALT	Altitude
ANS	Air Navigation Services
APCH	Approach
ASE	Altimetry System Error
ATC	Air Traffic Control
ATR20	[climate impact metric calculated algorithmic climate change functions, expressed in nanoKelvin of increase of temperature at the 20 years horizon]
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATRA	Advanced Technology Research Aircraft (DLR A320 test aircraft)
AU	Airspace User
AUC	Airspace User Cost [performance indicator]
AIM	Accident Incident Model
AIXM	Aeronautical Information Exchange Model
BAT	Barometric Alerting Tool
BIM	Benefit and Impact Mechanism
BNN	Brookmans Park navigation point (UK)
BNN27L	[transition to runway 27L via BNN waypoint] (Heathrow)
CAP	Capacity [performance indicator]
CDA	Continuous Descent Approach
CEAS	Council of European Aerospace Societies
CFSP	Computerised Flight Scheduling Plan
CFL/SFL	Cleared Flight Level / Selected Flight Level
CLIMaCCF	[Python library for computing individual and merged non-CO_2 algorithmic climate change functions]

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Acronym	Description
CNS	Communication, Navigation, Surveillance
CO2e	Carbon dioxide equivalent
CORDIS	Community Research and Development Information Service
CORUS	Concept of Operations for European U-Space Services
CRA	Collision Risk Analysis
CRCO	Central Route Charges Office (EUROCONTROL)
CWP	Controller Working Position
CDA	Continuous Descent Approach
DMP	Data Management Plan
DES	Digital European Sky
DesignAir	[NATS in-house airspace design tool]
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
ECAC	European Civil Aviation Conference
ECO EVAL	Economic Evaluation
EI	Environmental Indicator
ENR	En route
ENV	Environment [performance area]
ERA5	ECMWF Reanalysis v5
ERP	Exploratory Research Plan
ERR	Exploratory Research Report
ER	Exploratory Research
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
EUR	ICAO European Region
EUROCONTROL	European Organisation for the Safety of Air Navigation
FCS	Flight Control System
FEFF	fuel efficiency [performance indicator]
FHA	Functional Hazard Assessment
FIR	Flight Information Region

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Acronym	Description
FL	Flight Level
FMS	Flight Management System
FOC	Flight Operations Control
FPA	Flight Path Angle
FRD	Functional Requirements Document
GCD	Great Circle Distance
GBAS	Ground-Based Augmentation System
GeoAlt	Vertical Guidance using geometric altimetry
GLS	GNSS Landing System
GNSS	Global Navigation Satellite System
GRC	Green Route Charging
Green RC	Green Route Charging
Green-GEAR	Green operations with geometric altitude, Advanced separation & Route charging Solutions
HAO	High-Altitude Operations
HE	Horizon Europe
HMI	Human-Machine Interface
HP	Human Performance
ICAO	International Civil Aviation Organization
IFP	Instrument Flight Procedure
ILS	Instrument Landing System
ISA	International Standard Atmosphere
KPA	Key Performance Area
KPI	Key Performance Indicator
LDEV	Lateral Deviation
LNAV	Lateral Navigation
LPV	Localiser Performance with Vertical guidance
MAC	Mid-Air Collision
MAWP	Multi-Annual Work Programme
MASPS	Minimum Aviation/Aircraft System Performance Specification

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Acronym	Description
MCDU	Multifunction Control and Display Unit
MFD	Multifunction Display
MET	Meteorology / meteorological [data]
MLS	Microwave Landing System
Mode-C	[Altitude-reporting transponder mode]
Mode-S	[Selective secondary surveillance radar mode]
MOPS	Minimum Operational Performance Standards
MRC	Modulation of Route Charges
MSL	Mean Sea Level
MTOM	Maximum Take-Off Mass
NATS	[UK] National Air Traffic Services
ND	Navigation Display
NFE	Network Flow Environment
PINGUIN	P2P Integration for Utilisation in NFE
NavDB	Navigation Database
NM	Network Manager (EUROCONTROL)
NLR	Royal Netherlands Aerospace Centre
NUGRA1H	[standard instrument arrival in London TMA]
OD	Origin-destination
ODC	Origin Destination Charging
OFP	Operational Flight Plan
OI	Operational Improvement
OPT	Optimum
OSED	Operational Services and Environment Description
PANS	Procedures for Air Navigation Services
PBN	Performance-Based Navigation
PD	Pilot Display
PI	Performance Indicator
PMUA	Procedure Multi Unable Altimetry

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Acronym	Description
PMP	Project Management Plan
P2P	Probabilistic Two-Phase Wake Vortex Decay and Transport Model
PSUA	Procedure Single Unable Altimetry
PU	Public
QFE	[Atmospheric pressure at aerodrome elevation]
QNH	[Altimeter setting to indicate altitude above mean sea level]
REC MAX	Recommended Maximum Altitude
R&D	Research and Development
R-WAKE	SESAR 3 JU Project: Wake Vortex simulation and analysis to enhance en-route separation management in Europe
RCR	Roll Control Ratio
RMA	Regional Monitoring Agency
RNP	Required Navigation Performance
RNP AR	Required Navigation Performance – Authorisation Required
RTCA	Radio Technical Commission for Aeronautics
RSVM	Reduced Vertical Separation Minima
S3JU	Single European Sky ATM Research 3 Joint Undertaking
SAF	Sustainable Aviation Fuel
SESAR	Single European Sky ATM Research
SESAR3 JU	SESAR 3 Joint Undertaking
SHAPe	Simplified Hazard Area Prediction
SID	Standard Instrument Departure
SLS	Satellite Landing System
SM	Separation Minima
SOP	Standard Operating Procedure
SP	Service Provider
SRIA	Strategic Research and Innovation Agenda
SQUAWK	[Aircraft Transponder Code]
STAR	Standard Instrument Arrival [Route]
STD	Standard atmospheric pressure (1013 hPa)

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Acronym	Description
STCA	Short-Term conflict alert
TA	Transition Altitude
TAWS	Terrain Awareness and Warning System
TEFF1	average gate-to-gate flight time [performance indicator]
TMA	Terminal Manoeuvring Area
TLS	Target Level of Safety
TL	Transition Level
TVE	Total Vertical Error
UAS	Unmanned Aircraft System
UoW	University of Westminster
UK	United Kingdom
UKRI	UK Research and Innovation
UNITS	University degli Studi di Trieste
U-space	European unmanned traffic management system
VD	Vertical Display
VDEV	Vertical Deviation
V-RNP	Vertical Required Navigation Performance
WOBUN	Woburn navigation point (UK)
WP	Work Package
WTP	Willingness to pay
WTRA	Wake Turbulence Risk Analysis
XLS	[generic abbreviation for different precision approach and landing systems, e.g. ILS, MLS, GLS]

Table 25: list of acronyms

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