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Abstract

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

The “Separation Minima” Solution assesses the feasibility of reducing the vertical separation minima to 500 ft in upwards-extended Reduced Vertical Separation Minima (RVSM) airspace with the use of improved altitude keeping expected with GNSS altimetry, also named the RVSM 2 concept. This report describes the results of the validation activities for the RVSM 2 concept at TRL2, focussing on safety.

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Green-GEAR

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

Green-GEAR

This document is part of a project that has received funding from the SESAR 3 Joint Undertaking under grant agreement No 101114789 under European Union's Horizon Europe research and innovation programme. UK participants in Green-GEAR have received funding from UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee [grant numbers 10087714 (NATS) and 10091330 (University of Westminster)].

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1 Executive summary

The present document outlines the experimental approach, validation objectives, methods and results of the experiments and validation activities of the "Separation Minima" Solution, which is one of three Solutions investigated in Green-GEAR.

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

The objectives of the validation activities were (1) to develop the tools for evaluation these reduced separation minima when geometric altimetry is used, while taking into account UAS & HAO aircraft; and (2) to conduct a safety study and qualitatively estimate the capacity potential of RVSM 2. To fulfil the objectives, the following three exercises have been executed::

- Collision risk analysis for RVSM 2, comprising the development of the necessary tools, through analytical modelling;
- Wake vortex encounter risk analysis for RVSM 2, comprising the development of the necessary tools, through fast-time simulations;
- Safety Case for RVSM 2, comprising the use of above tools to assess hazards of RVSM 2 in nominal and non-nominal operations, through analytical modelling.

The qualitative capacity assessment has not been formal part of the validation activities; it can be found in the ECO-EVAL with a few considerations here.

The activities have been guided by input from the Advisory Board (AB), with whom the planning, initial and intermediate simulation results have been discussed.

The collision risk was determined using the ICAO collision risk model which was adjusted to the RVSM 2 airspace; results show that it could possibly be met by a small margin. However, regulatory and legislative aspects 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. Possible mitigations are suggested. In the safety case, the operational risk has been quantitatively determined on a functional level, using a Functional Hazard Analysis (FHA), for risks due to non-nominal causes. The need for a controlled airspace and an update of airborne and ground-based safety nets was identified. In sum, the operational safety is a substantial challenge but not obviously infeasible.

With that in mind, RVSM 2 has the potential to increase en-route airspace traffic capacity; even if today they are (sector) capacity restrictions due to controller workload, these may be relieved with increased automation, and there are many bottlenecks due to unusable parts of airspace that would benefit from added capacity in usable ones.

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2 Introduction

2.1 Purpose of the document

According to the SESAR3 JU Project Handbook [21], the Exploratory Research Plan (ERP) aims to outline the plan for organising the exploratory research done in the project, the results of which are then described in the Exploratory Research Report (ERR). In this framework, the present Green-GEAR Exploratory Research Report for Solution 407 'Separation Minima' has the purpose to refer the assessment of the viability of RVSM 2 under the assumption of the use of geometric altimetry by all airspace users, as described in the OSED [33], and according to the ERP [28]. This initial research effort has focussed on the safety case.

The work covers two Green-GEAR top-level project objectives:

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

addressed in the following three exercises:

- Exercise #01 / TVAL.05.1 – Collision Risk RVSM 2;
- Exercise #02 / TVAL.06.1 – Wake Vortex Risk RVSM 2;
- Exercise #03 / TVAL.09 – Safety case for RVSM 2.

The present ERR is a structured summary of the research work. More detailed information on the three exercises can be found in two internal deliverables

- iD4.1, Separation Minima – Collision Risk Analysis [29] for exercise #01;
- iD4.2, Separation Minima – Wake Turbulence Risk Analysis [30] for exercise #02;

and an official one

- D4.3, RVSM 2 Safety Case [31]) for exercise #03.

2.2 Intended readership

The primarily intended readership of this report is on one hand the Green-GEAR Consortium contributing to the Solution research, assessing the quality of the results produced and consolidating the outputs of the project, and the SESAR 3 JU on the other to allow monitoring and control of the project. This includes integrative and overarching assessment activities such as those conducted by PEARL.

Further groups potentially benefitting from reading this document are the key stakeholders involved in the Green-GEAR Advisory Board in particular, relevant SESAR 3 projects especially those from the Green Deal Flagship, and finally the overall aviation community in general.

2.3 Background

Existing and planned research on the reduction of separation minima has been analysed, including work done and foreseen for SESAR, ICAO, EASA, European Commission and EUROCONTROL. This has resulted in a newly proposed Solution for reducing vertical separation during en-route flight in upwards extended RVSM airspace.

Worldwide aircraft separation standards are laid down in ICAO Doc 4444 (Procedures for Air Traffic Management) [36], ICAO Annex 2 (Rules of the Air) [39] and ICAO Annex 11 (Air Traffic Services) [40]. These standards ensure safe separation from the ground, from other aircraft and from protected airspace:

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

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

EUROCONTROL and NLR are responsible for pre-implementation [42][43] and post implementation safety studies of RVSM in ICAO's European and Africa Indian Ocean Regions respectively. These studies analyse data on the height keeping performance of aircraft to ensure that the risk of collision between aircraft is sufficiently low and properly mitigated. Collision risk models and tools endorsed by the ICAO Separation and Airspace Safety Panel (SASP) [35][36][36] are used by EUROCONTROL and NLR.

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

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

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

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

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

Green-GEAR aims to make significant contributions at two levels: (i) at the methodological level, by developing new concepts of operations while using geometric altimetry; (ii) at an applied level, by formulating and assessing test case reduced separation (SM) concept. The following subset of Green-GEAR's high-level objectives concern the present Solution. Objective 2.2 was amended after the production of the ERP and is cited in its current form.

Objective 2.1: Development of the tools for evaluation of a novel concept for reduced separation minima when geometric altimetry is used, while taking into account 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.

2.4 Structure of the document

This document is structured in six chapters and three appendices, according to the following scheme:

- Executive Summary (chapter 1), providing an overview of the core contents of the deliverable.
- Introduction (chapter 2), reporting the essential information for the use of the document and the background of the project.
- Context of the Exploratory Research Report (chapter 3), where the readers find the description of the RVSM 2 Solution (section 3.1) and a summary of the experimental research plan, notably its purpose, an overview of the individual Validations' objectives and success criteria, the assumptions used and a formal listing of the Validation exercises (section 3.2). Finally, section 3.3 reports on the deviations from the Exploratory Research Plan (ERP).

- Validation Results (chapter 4), setting out the assessments' results, starting with a summary table of the results per objective in section 4.1, followed by detailed results per objective in section 4.2, and finally discussing the confidence in the results in section 4.3.
- Conclusions and Recommendations (chapter 5), discussing the consolidated conclusions derived from the various exercise results in section 5.1 and the recommendations for further Research and Innovation in section 5.2.
- References (chapter 6), listing the references applicable to this ERP including but not limited to SESAR 3 framework documents.

The Appendices provide the assessment details, grouped per exercise:

- Appendix A – Collision Risk RVSM 2; Exercise #01 / TVAL.05.1, led by Royal NLR;
- Appendix B – Wake Vortex Risk RVSM 2; Exercise #02 / TVAL.06.1, led by DLR;
- Appendix C – Safety case for RVSM 2; Exercise #03 / TVAL.09, led by Royal NLR.

2.5 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)
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
Target Level of Safety	The level of risk considered to be the maximum tolerable value for a safe system.	ICAO [41]
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 2: glossary of terms

2.6 List of acronyms

Term	Definition
AAD	Assigned Altitude Deviation
AB	Advisory Board
ACAS	Airborne Collision Avoidance System
AFI	Africa - India Ocean
ANSP	Air Navigation Service Provider
AO	application-oriented
ASE	Altimetry System Error
ASS<*no.*>	assumption <*no.*>
ATC	Air Traffic Control
ATCO	Air Traffic Controller / ATC Officer
ATM	Air Traffic Management
CAP	capacity [performance indicator]
CBA	cost-benefit analysis
CORDIS	Community Research and Development Information Service
CPDLC	Controller–Pilot Data Link Communication
CRA	collision risk assessment
CRM	collision risk model
CRT<*no.*>	criterion <*no.*>
D<*no.*>	Deliverable <*no.*>
DES	Digital European Sky
EASA	European Union Aviation Safety Agency
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
ENV	environment [performance indicator]

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Term	Definition
ER	Exploratory Research
ERA5	ECMWF Reanalysis v5
ERP	Exploratory Research Plan
EU	European Union
EUR	European
EXE<*no.*>	exercise <*no.*>
FEFF	fuel efficiency [performance indicator]
FHA	Functional Hazard Analysis
FIR	Flight Information Region
FL	Flight Level
FTE	Flight Technical Error
GA	Grant Agreement
GDPR	General Date Protection Regulation
GeoAlt	Vertical Guidance using Geometric Altimetry
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GR<*no.*>	Grant risk <*no.*>
Green-GEAR	Green operations with Geometric altitude, Advanced separation & Route charging Solutions
GRIB	gridded binary
HAO	High-Altitude Operations
HLA	High-Level Airspace
ICAO	International Civil Aviation Organisation
IR	Industrial Research
JU	Joint Undertaking

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Term	Definition
KPA	Key Performance Area
KPI	Key Performance Indicator
L-bows	Land-Based and Onboard Wake Systems
M<*no.*>	project month <*no.*>
MTOM	maximum take-off mass
NAT	North Atlantic (Region)
NFE	Network Flow Environment
NM	Network Manager
OBJ<*no.*>	objective <*no.*>
OSED	Operational Service and Environment Description
OPS	operational efficiency [performance indicator]
PANS	Procedures for Air Navigation Services
PC	Personal Computer
PEARL	Performance Estimation, Assessment, Reporting and Simulation
PI	Performance Indicator
P2P	Probabilistic Two-Phase Wake Vortex Decay and Transport Model
P2P^a	Airborne P2P
PINGUIN	P2P Integration for Utilisation in NFE
PMUA	Procedure Multi Unable Altimetry
PSUA	Procedure Single Unable Altimetry
RA	[TCAS] Resolution Advisory
RC	Route Charging
RECAT	[wake turbulence] recategorisation
R&I	research and innovation
RMA	Regional Monitoring Agency

Term	Definition
RNP	Required Navigation Performance
R/T	Radio Telephony
RVSM	reduced vertical separation minima
SAF	safety [performance indicator]
SBAS	Space-Based Augmentation System
SEN	sensitive (limited under the conditions of the Grant Agreement)
SESAR	Single European Sky ATM Research
S3JU	SESAR 3 Joint Undertaking
SJU	SESAR Joint Undertaking
SM	Separation Minima
SOL	Solution
SRM	Safety Reference Material
SSR	Secondary Surveillance Radar
STELLAR	SESAR Tool Enabling collaborative ATM Research
T<*no.*>	task <*no.*>
TBS	Time-Based Separations
TCAS	Traffic Alert and Collision Avoidance System
TEFF	time efficiency [performance indicator]
TLS	Target Level of Safety
TMA	Terminal Manoeuvring Area
TRL	Technology Readiness Level
TVE	Total Vertical Error
UAS	Unmanned Aircraft Systems
UK	United Kingdom [of Great Britain and Northern Ireland]
UKRI	UK Research and Innovation

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Term	Definition
WA	Working Area
WEPS	Wake Encounter Prevention System
WGS	World Geodetic System
WP<*no.*>	Work package <*no.*>

Table 3: list of acronyms

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3 Context of the exploratory research report

3.1 SESAR solution 0407 “Separation Minima”: a summary

Traditionally vertical separation minima have been set to 1000 ft up to FL290. Because of the decreasing accuracy of barometric altimeters with increasing height the separation minima from FL290 to FL410 were set at 2000 ft. To increase capacity above FL290 the Reduced Vertical Separation Minima (RVSM) program was introduced, resulting in the reduction to 1000 ft minimal vertical separation between FL290 and FL410 [27].

In the current operation commercial, military and general aviation mainly rely on barometric measurements for determining the altitude of the aircraft. Even though aircraft are equipped with GNSS receivers and broadcast both geometric and barometric altitudes for surveillance purposes, navigation is usually done using barometric altimetry [27].

Geometric altimetry can achieve greater accuracy (i.e. lower Altimetry System Error (ASE), see Figure 1) at high altitudes than barometric altimetry, as it is not sensitive for local weather and is not impacted by the low atmospheric pressure. Green-GEAR’s Separation Minima solution therefore investigates whether the use of geometric altimetry would allow a reduction of the SM from the current 1000 ft in RVSM airspace (FL290 – FL410), or 2000 ft (FL410 – FL600) to 500 ft. As the added altimetry system errors of two passing aircraft are assumed to be less than 500 ft in the current standard, a reduction by this margin is not straightforward even in the hypothetical case of perfect altimetry [27].

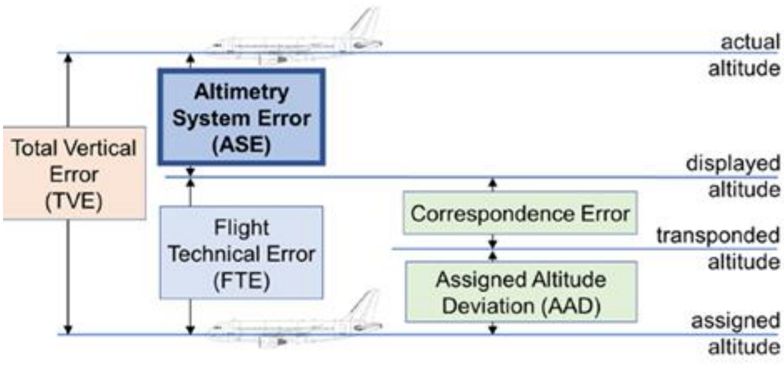

Figure 1: vertical errors definition (drawn after ICAO Doc 9574).

The main goals of the Green GEAR project (Green Geometric altitude, Advanced separation and Route charging) are to enable optimum green trajectories, accelerate decarbonisation and decrease the climate impact on flights. The present Solution, which is summarised in Table 4, investigates Separation Minima (SM) aiming to reduce CO_2 emissions and increase capacity by further reducing separation minima in en-route flight, while keeping the level of safety of operations at least as it is today. The reduction of separation includes aircraft currently in service, zero emissions aircraft and other new entrants, such as Unmanned Aircraft Systems (UAS) and High-Altitude Operations (HAO) aircraft [20][27], and targets RVSM airspace which is additionally extended upwards. This RVSM 2 concept results in an airspace as shown in Figure 2.

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A prerequisite is flight with geometric altimetry (i.e. the determination of altitude by GNSS measurements) instead of barometric altimetry as used in current operations. This is a commonality with Solution 0406, Vertical Guidance using Geometric Altimetry. The work (in both Solutions) has concentrated on the nominal case; non-nominal operations, notably jamming and spoofing, are issues far beyond the activities in Green-GEAR.. The present solution had the task to determine the specifications for nominal GNSS accuracy performance necessary to enable the RVSM 2 concept.

SESAR solution ID	SESAR solution title	SESAR solution definition	Justification (why the solution matters?)
Solution 0407	'Separation Minima'	The solution aims to transition from 1000 ft to 500 ft minimum vertical separation in upwards extended RVSM airspace (FL 290 to 600), enabled by increased altitude measurement accuracy through geometric altimetry. This RVSM 2 concept is applicable to civil and military aircraft and will allow the integration of novel concepts such as UAS and HAO aircraft which can use geometric altimetry far more easily. Reduced vertical separation will increase capacity, allowing more aircraft to fly closer to their optimal flight level and thus reducing CO_2 emissions. It can also be an enabler to limit the length of detours or extent of flight level changes that are flown to avoid airspaces of high climate impact ("climate hotspots"). The feasibility study of the concept at TRL 2 level focused on the safety aspects, most notably the collision risk, wake turbulence risk, and an overall safety case, where the EUR RVSM region served as a reference. Bottlenecks were identified (such as the need for advanced modes of wake vortex separation and the further development of safety nets), and vertical altitude keeping performance requirements were derived.	Reducing vertical separation minima increases the capacity in the airspace, while allowing aircraft to fly closer to their optimal altitude, thus reducing CO2 emissions.

Table 4: Green-GEAR solution scope

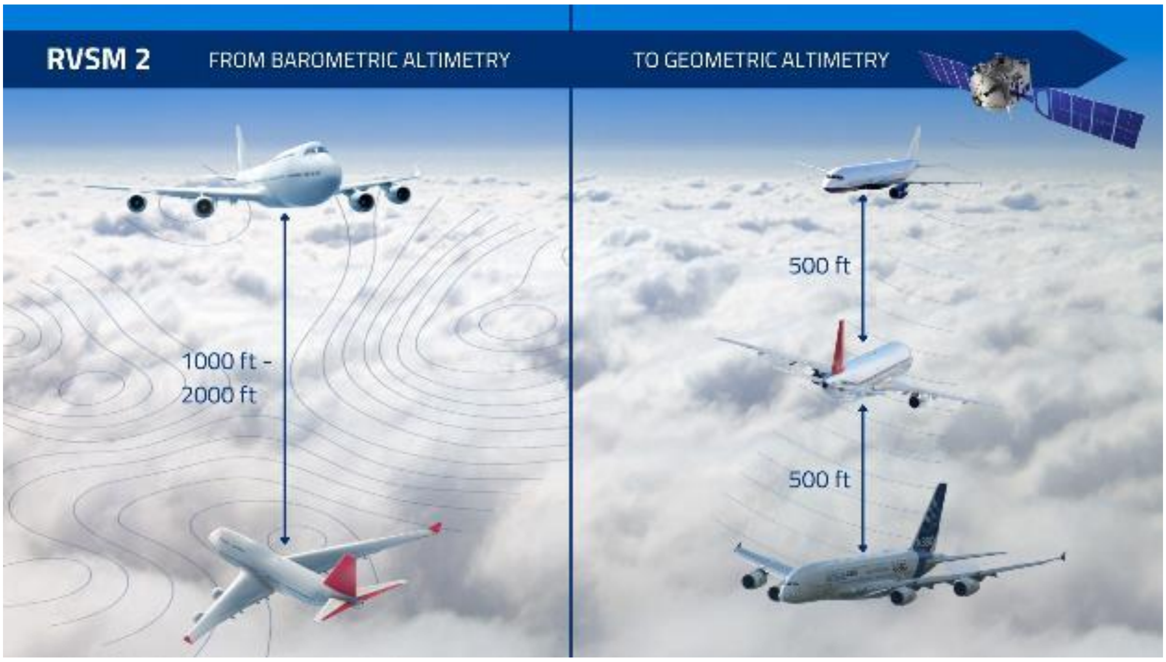

Figure 2: artist's impression of current operations and the RVSM 2 concept.

The present Solution addresses upper airspace only, but the use of geometric- instead of barometric altimetry is also relevant for air vehicles whose configuration complicates the measurement of static air pressure, such as many types of drones. Furthermore, HAO aircraft could benefit due to the decreasing pressure gradient with increasing height: the same absolute error in measuring the static air pressure translates into a larger vertical error with increasing height. It is therefore investigated whether geometric altimetry could allow extending RVSM airspace upwards from FL410 up to FL600 [27].

As the technical risk of loss of separation is dependent on the characteristics of the traffic, which varies by airspace, results of an investigation would not be universally applicable but dependent on the region chosen (see RVSM manual). Green-GEAR therefore addresses European (EUR) region en-route airspace (FL290 – FL600) [33].

3.2 Summary of the exploratory research plan

3.2.1 Exploratory research plan purpose

Scope of the Validation activities

Starting at a low TRL, there has been no prior evidence that the Solution scenario might work, but it is rather 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). In this first step we investigate the safety of operations in the 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.

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The work in Green-GEAR thus has focussed on the safety aspects of RVSM 2, which are not sufficient but obviously necessary for an implementation, and seen as the biggest potential showstopper. Therefore, the Validation activities have addressed:

- 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 [35] and included the development of the necessary tools and inputs [29];
- 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. Therefore, a comparative study has been performed. The necessary fast-time simulation tools have been (further) developed as part of the work [30];
- 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 [31].

A simple, qualitative estimation of the expectable capacity increase and the 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, is part of the Solution's ECO-EVAL [34].

Assumptions about operational and technical environment

As the current vertical separation minima are to a large extent sized to accommodate the considerable inaccuracies of geometric altimetry, the project investigates their potential reduction when employing geometric altimetry. We therefore assume that altitudes are defined geometrically (more specifically, with reference to the WGS84 coordinate system), and that there is no mix with pressure altitudes. This means that through appropriate access rules it is ensured that all airspace users have sufficient capabilities (as it is done analogously today for RVSM).

As the technical risk of loss of separation is dependent on the characteristics of the traffic, which varies by **airspace**, results of an investigation would not be universally applicable but dependent on the region chosen (see RVSM manual [35]). Also the wake vortex risk is a statistical figure and as such scenario dependent. A choice of a target airspace needed to be made: in accordance with SESAR requirements, Green-GEAR addresses the European (EUR) region en-route airspace (FL 290 – FL 600).

Obviously not only the accuracy of the **altitude source**, but especially also its integrity (capability of the system to issue timely warnings when the expected accuracy limit is not met) is crucial. It is questionable whether single-frequency GPS, widely in use today, could achieve the necessary requirements. Candidate approaches comprise the use of SBAS and/or dual-frequency and/or multiple constellation GNSS, possibly with dedicated aviation services. It was one of the research questions to determine the performance requirements, which could then be used to determine the viable option(s). It is noted here that SBAS availability is limited to most domestic regions of the northern hemisphere and not available worldwide, nor expected to become so.

For the wake turbulence study, we assume that altitude keeping accuracy (flight technical error, see Figure 1) is influenced by the characteristics of the altitude source and the performance of the flight control system but not by the **propulsion** concept. In view of the expected introduction of electrical

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aircraft in the future, it is quite conceivable that they will have more responsive propulsion (both as regards physical capability as willingness to modulate power in view of wear and tear issues) to counteract atmospheric disturbances so this appears a conservative assumption. Regarding collision risk, requirements on altitude keeping are determined (that future aircraft manufacturers will have to meet) but no specific assumptions are necessary.

The **fleet** is assumed to be comparable to nowadays in the sense especially that possible future all-electric transport aircraft will have comparable cruise speeds and physical dimensions. As an example, in the case of hydrogen-powered aircraft, the fuselage size very probably will increase but the vertical size of the aircraft is still determined by the height of the vertical tailplane. Any non-conventional future aircraft configurations are assumed to have at least the same attitude control power as existing conventional ones, meaning it is a conservative assumption to apply the same weight-dependent resistance to wake encounters. This may not be true for certain “high-altitude platform” type aircraft that would need to be treated separately.

With regard to the ATM environment, **Separation modes** are initially assumed to be unchanged, meaning that as per Doc 4444 [38] the separation requirement is fulfilled if either vertical or horizontal separation is ensured. With a reduction of vertical separation from 1000 ft (2000 ft) barometrically to 500 ft geometrically, from the collision risk angle it has been unclear a priori and from the wake turbulence risk doubtful whether this is safe without further means. However, the concept has been initially evaluated as described, as the definition of additional (advanced/combined) separation modes would need to be well justified.

The necessity for **safety nets** beyond universally available ones, or their improvement, should also be proven. It is assumed that SSR to enable conformance monitoring and real-time ground-airborne communications (via R/T or CPDLC) to solve conflicts by the ATCOs remain available, in other words that RVSM 2 airspace is a fully controlled airspace. This is a tighter requirement than for RVSM which (depending on the traffic mix) can be employed under procedural control. Due to the current alert limits of ACAS [76][77] it is already clear that the system would need to be modified.

3.2.2 Summary of validation objectives and success criteria

Following an amendment of project-level objective OBJ2.2 and SJU comments on the ERP [28], the validation objectives GreenGEAR-0407-TRL2-ERP-OBJ02 and GreenGEAR-0407-TRL2-ERP-OBJ03 as well as their respective success criteria have been adapted against the ERP. For completeness we list all objectives and success criteria below.

The validation objectives given in Table 5 cover and refine the two project objectives relating to this Solution (see section 2.1). The mapping of these solution validation objectives to the exercise objectives is captured in section 3.2.4.

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SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective
GreenGEAR-0407-TRL2-ERP-OBJ01 Provision of validated tools to quantify collision risk and wake turbulence risk for chosen scenarios employing novel concept for reduced vertical separation minima Consists of two parts at exercise level: GreenGEAR-0407-TRL2-ERP-OBJ01.1 GreenGEAR-0407-TRL2-ERP-OBJ01.2	**GreenGEAR-0407-TRL2-ERP-CRT01** The analysis / simulation results compare favourably to observations when applied to current operations and show plausible figures for the new concept. Consists of two parts at exercise level: GreenGEAR-0407-TRL2-ERP-CRT01.1 GreenGEAR-0407-TRL2-ERP-CRT01.2	Fully covered: in view of target TRL, real-world data for comparison are not available. The assessment needs to be done by expert judgement.
GreenGEAR-0407-TRL2-ERP-OBJ02 To determine whether RVSM 2 can be safely introduced from a collision risk, wake turbulence risk and operational risk perspective and identify the most important challenges. Consists of three parts at exercise level: GreenGEAR-0407-TRL2-ERP-OBJ02.1 GreenGEAR-0407-TRL2-ERP-OBJ02.2 GreenGEAR-0407-TRL2-ERP-OBJ02.3	**GreenGEAR-0407-TRL2-ERP-CRT02** The collision risk does not exceed the TLS of $2.5*10^{-9}$ fatal accidents per flight hour.	Fully covered
	GreenGEAR-0407-TRL2-ERP-CRT03 Quantification of the maximum TVE required to meet the TLS.	
	GreenGEAR-0407-TRL2-ERP-CRT04 The wake encounter risk is not unacceptably increased compared with current operations.	
	GreenGEAR-0407-TRL2-ERP-CRT05 Derive a quantitative or qualitative safety specification	

SESAR solution validation objective	SESAR solution success criteria	Coverage and comments on the coverage of SESAR solution validation objective
GreenGEAR-0407-TRL2-ERP-OBJ03 Estimate capacity potential for RVSM 2. Consists of three parts at exercise level: GreenGEAR-0407-TRL2-ERP-OBJ03.1 GreenGEAR-0407-TRL2-ERP-OBJ03.2 GreenGEAR-0407-TRL2-ERP-OBJ03.3	**GreenGEAR-0407-TRL2-ERP-CRT06** Initial capacity analysis delivers demonstrable capacity benefits; potential showstoppers are identified.	Partially covered: it is possible to specify a possible upper limit from the safety point of view. ATC ability to handle the traffic is out of scope. Part of the analysis is contained in the ECO-EVAL [34].

Table 5: Solution Validation Objectives for all exercises

3.2.3 Validation assumptions

The validation assumptions remain unchanged against the ERP [28]. They are explained in more detail in section 3.2.1 above. Table 6 below lists the assumptions that are applicable to all three validation exercises, whereas further assumptions for individual exercises are contained in the respective appendices.

Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
GreenGEAR-0407-TRL2-ERP-ASS01	Geometric Altimetry	We assume that altitudes are defined geometrically (more specifically, with reference to the WGS84 coordinate system), and that there is no mix with pressure altitudes.	The technical challenge of measuring static air pressure in a moving aircraft limits the obtainable accuracy of barometric altimetry as such, resulting in a relatively large altimetry system error (ASE).	This assumption is the foundation of a possible reduction of vertical separation minima. If proven feasible, transitions and interfaces to this envisaged end state will still need to be investigated.
GreenGEAR-0407-TRL2-ERP-ASS02	GNSS Environment	It is assumed that a, possibly augmented, GNSS positioning system of a given accuracy is available and that aircraft are appropriately equipped.	Treating GNSS system performance and availability as a free parameter is sensible as there are many technological advancements in this field.	Determining whether the necessary levels of performance in GNSS positioning are available can only be done post-hoc.

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Assumption ID	Assumption title	Assumption description	Justification	Impact Assessment
GreenGEAR-0407-TRL2-ERP-ASS03	Traffic mix – Fleet	Assume traffic mix is similar to the current one, possible new types having comparable cruise speeds and physical dimensions to current ones.	Predicting the traffic mix and aircraft performance in 10 to 20 years is very difficult.	The risk assessment is only valid if the traffic mix doesn't significantly change.
GreenGEAR-0407-TRL2-ERP-ASS04	Traffic mix – Propulsion	It is assumed that altitude keeping accuracy is influenced by the characteristics of the altitude source and the performance of the flight control system but not by the propulsion concept.	Many preliminary concepts for hydrogen or battery powered aircraft exist, but they are much too far from introduction to allow reliable assumptions.	The responsiveness of potential hydrogen-powered turbojet engines is not expected to differ significantly from that of conventional kerosene-powered ones. For electrical aircraft, it is quite conceivable that they will have more responsive propulsion to counteract atmospheric disturbances so this appears a conservative assumption
GreenGEAR-0407-TRL2-ERP-ASS05	Separation modes	Separation modes are initially assumed to be unchanged, meaning that as per Doc 4444 [38] the separation requirement is fulfilled if either vertical or horizontal separation is ensured.	While an unconditional reduction of vertical separation minima is possibly not safe from a wake vortex risk point of view, any changes to separation modes need to be justified.	The project will identify typical situations for wake vortex encounters and discuss possible remedies including adaptation of separation modes.

Table 6: validation assumptions overview

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3.2.4 Validation exercises list

The attribution of objective GreenGEAR-0407-TRL2-ERP-OBJ03 to the Validations TVAL.05.1 and TVAL.06.1 has been added against the ERP [28].

[EXE 4.1]

Identifier	TVAL.05.1-Green-GEAR-407-TRL2
Title	Collision Risk RVSM 2
Description	Altitude deviations are considered as an important hazard in the safety case exercise which could potentially lead to mid-air collisions. Therefore, a collision risk assessment is performed. The collision risk assessment is based on the ICAO collision risk models as described in the *ICAO Manual on airspace planning methodology for the determination of separation minima*.
KPA/TA addressed	Safety
Addressed expected performance contribution(s)	**SAF1.1**, Mid-air collision – En-Route. The collision risk will be set to a maximally allowable Target Level of Safety (TLS) and the height-keeping performance requirements will be derived.
Maturity level	TRL2 contribution
Use cases	Use case "RVSM 2" from the Initial OSED
Validation technique	Analytical Modelling
Validation platform	N/A
Validation location	Amsterdam, The Netherlands
Start date	01/07/2024
End date	31/01/2025
Validation coordinator	Royal NLR
Status	completed
Dependencies	Prerequisite for EXE 4.3

[EXE 4.1 Trace]

Linked Element Type	TVAL.05.1-Green-GEAR-407-TRL2
<SESAR Solution>	407 Green Gear – Separation Minima
<Project>	Green-GEAR
<Sub-Operating Environment>	En-route High-Capacity RVSM 2
<Validation Objective>	GreenGEAR-0407-TRL2-ERP-OBJ01.1 GreenGEAR-0407-TRL2-ERP-OBJ02.1 GreenGEAR-0407-TRL2-ERP-OBJ03.1

Table 7: validation exercise #01 layout

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[EXE 4.2]

Identifier	TVAL.06.1-Green-GEAR-407-TRL2
Title	Wake Vortex Risk RVSM2
Description	A wake turbulence risk analysis will be performed in order to determine the influence of RVSM 2 on the probability and severity of wake vortex encounters. Therefore, a previously developed software toolbox will be adapted and used for a statistical evaluation of the wake vortex encounters in a traffic scenario. Also, a hazard assessment of these encounters will be performed. If the risk of hazardous wake vortex encounters due to the introduction of RVSM 2 will be assessed as unacceptably high, then additional methods of risk mitigation will be suggested.
KPA/TA addressed	Safety
Addressed expected performance contribution(s)	Risk of encountering wake vortices in cruise will be compared to current state. Note: wake-related incidents / accidents in the en-route phase are not part of the list of PIs.
Maturity level	TRL2 contribution
Use cases	Use case “RVSM 2” from the Initial OSED
Validation technique	Fast-time simulation
Validation platform	DLR Software environment implemented in MATLAB, with C++ components
Validation location	Braunschweig, Germany
Start date	12/07/2024
End date	31/01/2025
Validation coordinator	DLR
Status	completed
Dependencies	Prerequisite for EXE 4.3

[EXE 4.2 Trace]

Linked Element Type	TVAL.06.1-Green-GEAR-407-TRL2
<SESAR Solution>	407 Green Gear – Separation Minima
<Project>	Green-GEAR
<Sub-Operating Environment>	En-route High-Capacity RVSM 2
<Validation Objective>	GreenGEAR-0407-TRL2-ERP-OBJ01.2 GreenGEAR-0407-TRL2-ERP-OBJ02.2 GreenGEAR-0407-TRL2-ERP-OBJ03.2

Table 8: validation exercise #02 layout

[EXE 4.3]

Identifier	TVAL.0X.1-Green-GEAR-407-TRL2
Title	Safety Case for RVSM 2
Description	The safety case exercise for 500 ft vertical separation with geometric altimetry is set up as a preliminary Functional Hazard Assessment (FHA); that is a top-down iterative process initiated at the beginning of a modification of an Air Navigation System. The modification under assessment is the reduction of the vertical separation minimum; some aspects of GNSS altimetry are considered, but the introduction of geometric altimetry is largely outside the scope of this FHA.
KPA/TA addressed	Safety
Addressed expected performance contribution(s)	Accident rate per flight hour
Maturity level	TRL2 contribution
Use cases	Use case “RVSM 2” from the Initial OSED
Validation technique	Analytical Modelling
Validation platform	N/A
Validation location	Amsterdam, The Netherlands
Start date	02/05/2024
End date	28/02/2025
Validation coordinator	Royal NLR
Status	completed
Dependencies	Requires results from EXE 4.1 and EXE 4.2

[EXE 4.3 Trace]

Linked Element Type	TVAL.0X.1-Green-GEAR-407-TRL2
<SESAR Solution>	407 Green Gear – Separation Minima
<Project>	Green-GEAR
<Sub-Operating Environment>	En-route High-Capacity RVSM 2
<Validation Objective>	GreenGEAR-0407-TRL2-ERP-OBJ02.3 GreenGEAR-0407-TRL2-ERP-OBJ03.3

Table 9: validation exercise #03 layout

3.3 Deviations

3.3.1 Deviations with respect to the S3JU project handbook

There is no intentional deviation from the SESAR 3 JU project handbook [21].

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3.3.2 Deviations with respect to the exploratory research plan (ERP)

During the work, project-level objective 2.2 was amended from:

“Objective 2.2: Determination 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 as produced in line with the SESAR SRM method for TRL2, namely collision and wake encounter risks, demonstrates adherence to the target level of safety (TLS) and the initial capacity analysis delivers demonstrable capacity benefits.”

to:

“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.”

as the *demonstration* of safety for RVSM 2 contradicts the very idea of a safety assessment, as it would imply that the result is known beforehand. It was decided to redirect the work into identification of the areas for further work following an FHA that assesses what can be quantified and sets specifications for what cannot (notably the ASE where no sufficient performance specifications are available yet, but also possible changes to FTE requirements).

The objectives and contents of the three Validation exercises described above have been adjusted against the ERP [28] to reflect this change in the top-level objective OBJ2.2.

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4 Validation results

4.1 Summary of SESAR Solution 0407 validation results

This section summarises the results of the executed validation exercises. These are the Collision Risk Analysis [29], the Wake Turbulence Risk Analysis [30] and the Safety Case [31]. In the Exploratory Research Plan (ERP) [28], the validation objectives were established; these were slightly modified to take into account the amendment of top-level objective OBJ2.2 as explained in section 3.2.2 and summarised in Table 5. Table 10 shows an overview of the validation objectives and the results of the validation exercises. In the last column of the table, the validation objective status is given. This can either be *OK* (the validation objective achieves the expectations), *NOK* (the validation objective does not achieve the expectations), or *Partially OK* (the validation objective achieves the expectations to a certain extent).

Project / SESAR solution validation objective ID and title	Project / SESAR solution success criterion and ID	Project / SESAR solution validation results	Project / SESAR solution validation objective status
GreenGEAR-0407-TRL2-ERP-OBJ01 Provision of validated tools to quantify collision risk and wake turbulence risk for chosen scenarios employing novel concept for reduced vertical separation minima.	**GreenGEAR-0407-TRL2-ERP-CRT01** The analysis results compare favourably to observations when applied to current operations and show plausible figures for the new concept.	The collision risk was determined using the ICAO collision risk model. This model was adjusted to the RVSM 2 airspace. For the wake turbulence risk the modelling results have been related to and were found to be in accordance with other studies and practical observations (pilot feedback). Their *possible* severity is rather an overestimation of the actual effects in most cases so must not be taken as a statement on actual severity, but consistence and plausibility of the results gives confidence that the relative comparison of the current operations and the proposed RVSM 2 scenario is valid.	OK
GreenGEAR-0407-TRL2-ERP-OBJ2 To determine whether RVSM 2 can be safely introduced	**GreenGEAR-0407-TRL2-ERP-CRT02** The collision risk does not exceed the TLS of $2.5*10^{-9}$	The technical risk could possibly be met by a small margin. However, regulatory and legislative aspects will likely pose a significant, possibly in-surmountable challenge.	Partially OK

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from a collision risk, wake turbulence risk and operational risk perspective and identify the most important challenges.	fatal accidents per flight hour.		
	GreenGEAR-0407-TRL2-ERP-CRT03 Quantification of the maximum TVE required to meet the TLS.	The collision risk analysis determined restrictions of the maximum allowable TVE to meet the TLS. This TVE is the sum of the ASE and the FTE. A mathematical analysis was executed to comprehend the condition on the TVE distribution in terms of the ASE and FTE distributions.	OK
	GreenGEAR-0407-TRL2-ERP-CRT04 The wake encounter risk is not unacceptably increased compared with current operations.	The simulation results show that the wake encounter risk is substantially increased (by a factor of 3 to 4 for occurrence with small changes in severity). A possible mitigation would be a safety net in the shape of an airborne or ground-based tool that predicts potentially hazardous wake encounters and suggests corrective action.	NOK
	GreenGEAR-0407-TRL2-ERP-CRT05 Derive a quantitative or qualitative safety specification.	In the safety case, the operational risk is quantitatively determined on a functional level, using a Functional Hazard Analysis (FHA). This was done for risks due to non-nominal causes.	OK
GreenGEAR-0407-TRL2-ERP-OBJ3 Estimate the capacity potential for RVSM 2.	**GreenGEAR-0407-TRL2-ERP-CRT06** Initial capacity analysis delivers demonstrable capacity benefits; potential showstoppers are identified.	NB that the focus of the project has shifted to the safety of RVSM 2 and capacity has only been addressed in a basic manner in the ECO-EVAL. With that in mind, RVSM 2 has the potential to increase traffic capacity; collision risk could be marginally within the TLS while wake turbulence risk needs to be mitigated. Whether this added capacity can be handled by ATC is out of the scope of the project. In fact, other studies show that the traffic levels that could fly without an undue number of conflicts in a hypothetical unrestricted airspace are much higher than current ATC capacities to control them [56] but	Partially OK

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

Table 10: summary of validation exercises results

4.2 Detailed analysis of SESAR solution validation results per validation objective

4.2.1 GreenGEAR-0407-TRL2-ERP-OBJ1 results

The first validation objective is the provision of validated tools to quantify collision risk and wake turbulence risk for chosen scenarios employing novel concept for reduced vertical separation minima.

For the quantification of the collision risk, performed in exercise #01, use is made of the ICAO Collision Risk Model (ICAO CRM). The ICAO CRM is a mathematical model that can be applied to aircraft flying at assigned flight levels, vertically separated by n (n = 1,2,3…) times the minimal vertical separation distance (S_z). [29]

Using the CRM, the expected number of fatal accidents per flight hour is determined. This is then compared to a pre-determined TLS to determine whether the operation is safe. More information into the specifics of the model and its assumptions can be found in [29].

The current ICAO CRM holds for RVSM airspace. Therefore, in order to use it in an RVSM 2 setting, a couple of things had to be adjusted:

1. Adopt the TLS of RVSM;
2. Adapt the ICAO CRM to RVSM 2;
3. Derive the requirements on the altitude-keeping performance;
4. Translate this into conditions on the ASE and FTE distributions;
5. Verify whether these conditions can be expected to be met, given the current state of technology.

With the adjusted model, the height keeping performance (i.e. TVE) was determined. This was done for the two potential distributions of the TVE, the Laplace and normal (Gaussian) distribution. For the Laplace distribution the standard deviation of the TVE should be equal or less than 34 ft, for the normal distribution this value is 58 ft.

For the wake turbulence risk analysis, performed in exercise #02, an agreed, maybe even regulatorily accepted general approach is not known. For the purpose of this study, data and models available at DLR were further developed and combined for the following simulation steps:

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- simulation of network flow and aircraft's sufficiently detailed trajectories, including adaptation to the new separation rules and modelling of altitude keeping under barometric (reference scenario) and geometric (solution scenario) altimetry using the findings from the collision risk study;
- prediction of generator's wake vortex evolution and transport using numerical weather prediction (NWP) data and atmospheric parameters derived from them;
- identification of sufficiently close pairings and collision detection of follower's position with wake corridor;
- assessment of encounter severity, which gives an upper bound of potential severity based on vortex strength and the encountering aircraft's ability to cope with the disturbance by relating induced rolling moment to available roll control power through the so-called roll control ratio (RCR) [58];
- aggregation of encounter "type" and severity for statistical evaluation and comparison between reference and solution scenario.

The overall modelling framework and its components are briefly described in appendix B.3 and in more detail in [30]. A summary of the results is given in section 4.2.2.3 below, with a full account in appendix B.3.1.

This being a pioneering study, no references for the Solution scenario, i.e .reduced vertical separation with geometric altimetry, are available. However, as a validation of the comparative approach, the results for the reference scenario (existing vertical separation with barometric altimetry) have been related to the, albeit scarce, available studies. In summary, it can be said that the main findings in literature studies generally coincide with the outcome of the present investigation. No contradictions are found, so the results can be regarded as reasonable. Particularly specific effects like in some cases vortices descending 1000 ft or more or even ascending are identified in agreement [30].

For any assessment of the risk, the aspect of wake encounter severity is essential, including effects of encounter geometry. This is not fully covered in any of the studies so far and is expected to require further detailed analyses. Generally, it can be observed that the crossing of a wake where forces or moments beyond the aircraft's control capabilities *could* be generated needs to be regarded as hazardous from a safety point of view *in the absence of further information*, but these effects may only persist for a fraction of a second and need not lead to relevant consequences on practical operations. It is actually quite common that atmospheric disturbances, particularly in convective weather, temporarily exceed the aircraft's control capabilities, i.e. could not be fully counteracted even in the hypothetical case of a perfect feed-forward control system.

The frequencies of encounters observed in the present simulation is in accordance with other studies (see appendix B.3.2.1 for details) and albeit anecdotical practical observations (pilot feedback) – wake encounters that are discernible as such but not a safety issue are actually quite frequent. Their *possible* severity is rather an overestimation of the actual effects in most cases so must not be taken as a statement on actual severity, but we can safely conclude from the above considerations that the relative comparison of the current operations and the proposed RVSM 2 scenario is valid.

4.2.1.1 Success criterion GreenGEAR-0407-TRL2-ERP-CRT01

In summary it can be said that the results meet the expectations of success criterion GreenGEAR-0407-TRL2-ERP-CRT01, “The analysis results compare favourably to observations when applied to current operations and show plausible figures for the new concept.”

4.2.2 GreenGEAR-0407-TRL2-ERP-OBJ2 results

The second validation objective is to determine whether RVSM 2 can be safely introduced from a collision risk, wake turbulence risk and operational risk perspective and identify the most important challenges. The success of this objective is determined using four criteria.

4.2.2.1 Success criterion GreenGEAR-0407-TRL2-ERP-CRT02

The first success criterion for a safe introduction of RVSM 2 is whether the collision risk does not exceed the TLS of $2.5*10^{-9}$ fatal accidents per flight hour.

In order to pass this criterion, the TVE standard deviation requirements as stated in section 4.2.1 should be met. However, in order to assess whether this can be met, the ASE and FTE should be assessed as they make up the TVE. The trade-off between the two error sources is depicted in Figure 3.

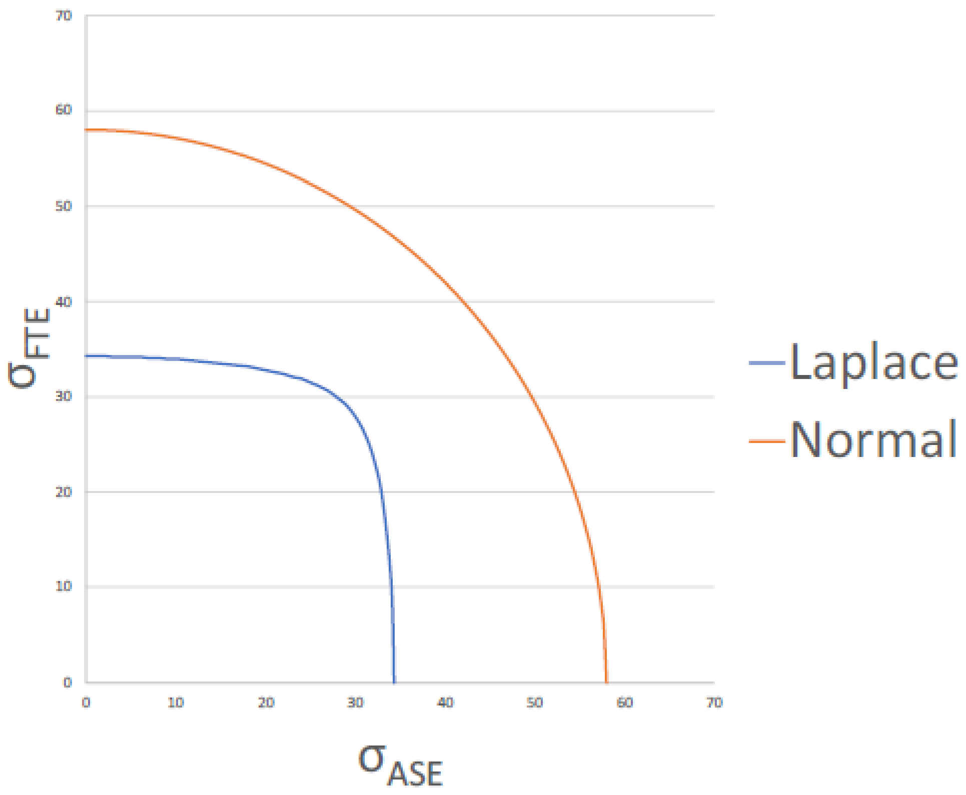

Figure 3: the maximal value of the standard deviation σ2 of the variable X2 to meet the TLS of 500 ft vertical separation, given the standard deviation σ1 of the variable X1 and given that the TVE is a sum of two independent variables X1 and X2 with X1 and X2 both Laplace (orange curve) or normal (blue curve), with zero mean. [29]

According to the currently applicable MASPS for RVSM approved aircraft, the FTE distribution has a standard deviation σ_{FTE} of maximally 43 ft. This value is insufficient to meet the ASE/FTE standard deviation restriction when assuming a Laplace distribution, as can be seen in Figure 3. So, if the current MASPS are the reference, RVSM 2 cannot be implemented sufficiently safe. There might however be an escape from this negative first conclusion. The value of the standard deviation σ_{FTE} as currently estimated in the ICAO EUR region is 33 ft. This would be just sufficient to meet the ASE/FTE standard deviation restriction if the standard deviation σ_{ASE} is 20 ft or less.

The ASE distribution within the RVSM 2 concept corresponds to the accuracy of the estimates of the altitude by means of GNSS. The performance of a GNSS system is described by many different parameters, of which the Vertical Positioning Error (VPE) is taken as the ASE.

In order to describe the magnitude of GNSS errors, research is done into the accuracy of GPS and Galileo. Furthermore, several options are considered such as Single Frequency (SF) and Dual Frequency (DF) signals, multi-GNSS navigation and the use of augmentation systems. In Table 11, an overview is given of the specified (expected minimal level of performance but not guaranteed) vertical positioning accuracy at average and worst user location. It can be concluded from this table that the performance is not sufficient to meet TLS.

	AUL	WUL
GPS Single Frequency	13 m	33 m
Galileo Single Frequency	8 m	16 m
Galileo Dual Frequency	8 m	16 m

Table 11: GPS and Galileo OS specified vertical positioning accuracy (95%) at average and worst user location. [44] [35]

However, both Galileo and GPS report their actual performance on a quarterly basis. The average VPE of the actual performance is shown in Table 12. It can be seen that this performance is much better than the specified performance. However, there is no guarantee that this performance is *always* achieved.

	VPE (95%)	VPE (1σ)
GPS Single Frequency	3.98 m = 13.1 ft	2.03 m = 6.7 ft
Galileo Dual Frequency	3.35 m = 11.0 ft	1.71 m = 5.6 ft

Table 12: average VPE (95%) of GPS and Galileo from quarterly performance reports. The values for GPS are the average of the average VPE per day for two quarters. The values of Galileo are said to not have exceeded these values on a per month basis for two months. [46][47][48][49]

To conclude, the validation objective status concerning the first success criterion GreenGEAR-0407-TRL2-ERP-CRT02, "The collision risk does not exceed the TLS of $2.5*10^{-9}$ fatal accidents per flight hour" is determined *Partially OK*. The TLS of $2.5*10^{-9}$ fatal accidents per flight hour can be met. However, this

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is dependent on the actual performance of the GNSS under consideration. Therefore, RVSM 2 could be introduced safely, considering technical risk only, if, apart from some relevant technicalities, it can be somehow be guaranteed that: $\sigma_{ASE} \leq 20$ ft; $\sigma_{FTE} \leq 33$ ft. Even if these conditions cannot be met, there might be an escape by for example showing that both the FTE and ASE distributions are normal. In that case, it would be sufficient to show that both standard deviations σ_{FTE} and σ_{ASE} are 40 ft or less.

4.2.2.2 Success criterion GreenGEAR-0407-TRL2-ERP-CRT03

The second success criterion for the present objective is GreenGEAR-0407-TRL2-ERP-CRT03, the "quantification of the maximum TVE required to meet the TLS". The validation objective status concerning this second success criterion is determined *OK*. As can be seen in section 4.2.2.1 above, the maximum TVE required to meet the TLS is calculated and depends on the distribution of the error source.

4.2.2.3 Success criterion GreenGEAR-0407-TRL2-ERP-CRT04

Success criterion GreenGEAR-0407-TRL2-ERP-CRT04 concerns the confirmation that "the wake encounter risk is not unacceptably increased compared with current operations."

With the simulation framework described briefly in section 4.2.1 above and in more detail in [30], fast-time simulations of two full-day traffic scenarios (comprising low- and high-wind situations) for the EUR region were performed, respectively, for the reference and the solution scenario. The two days with the respective lowest and highest average winds in the most-populated flight levels were determined from the numerical weather prediction data, forming the lower and upper limits on horizontal vortex travel and thus the two extremes regarding influence on identical and parallel tracks, respectively. 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) do influence the numerical results, as explained in Appendix B, but it seems reasonable to assume that comparisons between reference and envisaged future operations still hold sufficient significance (see section 4.2.1).

Results are summarised as follows:

Encounter frequency

In the low-wind-speed scenario with 1000 ft vertical separation, 791 wake encounters are predicted with an RCR value of 0.2 or more, i.e. of a strength that is not necessarily dangerous but cannot be regarded with certainty as safe under all possible circumstances. In the low-wind-speed scenario with 500 ft vertical separation, 2854 wake encounters are predicted, which is an increase by a factor of 3.6 compared to the baseline scenario. In the high-wind-speed scenario with 1000 ft vertical separation, 362 wake encounters are predicted. In the high-wind-speed scenario with 500 ft vertical separation, 1462 wake encounters are predicted, which is an increase by a factor of 4 compared to the baseline scenario. A comparison of the two scenarios with different wind speeds reveals that the overall number of encounters is decreased (even when considering the slightly lower number of aircraft) with higher wind speeds because for the aircraft's trajectories with a crosswind, the wake vortices drift away from the trajectory due to the wind influence which results in other aircraft on the same trajectory not encountering the wake vortices anymore. In some situations, the wake vortices that are influenced by the wind can affect aircraft on other trajectories that would not be affected if the wind

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speed would be lower. However, this increase of the number of wake encounters is outweighed by the decrease due to the wake vortices drifting away from the trajectory. Therefore, the overall number of encounters is lower in the high-wind-speed scenario. When reducing the vertical separation, the encounter frequency is increasing in both scenarios by approximately the same factor. Therefore, the results of this analysis suggest that, even though the absolute number of encounters is lower with higher wind speeds, the relative increase of the encounter frequency when reducing the vertical separation is not depending on the wind speed.

An increase of the encounter frequency when reducing the vertical separation can be considered as a realistic result because the aircraft are allowed to fly in closer proximity to each other and therefore in closer proximity to the wake vortices. In some cases, flying only 500 ft below the wake creator a few miles in trail might result in not encountering the wake vortex if the wake vortex has descended to about 1000 ft at that distance and thus it would have been encountered at 1000 ft vertical separation. Therefore, a reduction of the vertical separation does not only result in new encounters but can also eliminate some encounters that would have happened when applying a higher vertical separation. Nevertheless, it can be assumed that 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, which is confirmed by the results of this study.

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 [30], the SHAPe concept only claims that encounters with a severity below the threshold can be considered as non-hazardous, but encounters with a severity above the threshold are not necessarily always hazardous, but 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 in a full day in the European airspace can be considered as a realistic result (see appendix B.3.2.1 for more information).

Encounter severity

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. The encounters with an RCR above the threshold of 0.2 have been divided into three categories as shown in Table 13 and Table 14. It is clearly visible that when reducing the vertical separation, the number of encounters with a high RCR value above 0.5 in the low-wind-speed scenario and with a very high RCR value above 1.0 in the high-wind-speed scenario increases by an even larger factor than the number of encounters with lower RCR values. It must be noted that a wake vortex encounter with an RCR above 1.0 is not always directly resulting 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 and 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 [30]) increases the size of the envelope without increasing the actual vortex size.

Furthermore, most encounter durations are very short (a few seconds or even only a fraction of a second) and exceeding the control capabilities of the aircraft for a very short duration is not always hazardous. Also the Crow instability on average reduces the effects on the encountering aircraft [80]. However, for encounters with an RCR above 0.2, it cannot be *guaranteed* that the situation is safe, and encounters with a higher RCR (especially with an RCR above 1.0) should be considered as potentially dangerous situations and therefore should be avoided.

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

Table 13: 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 ft separation	171	96	95
500 ft separation	615	335	512
Increase by a factor of	3.6	3.5	5.4

Table 14: categorisation of the encounters in the high-wind-speed scenario by their RCR value

For the encounters with a severity above the RCR threshold of 0.2, the distribution of the encountered circulation is shown in Figure 4 for the low-wind-speed scenario and in Figure 5 for the high-wind-speed scenario. Even though the absolute number of encounters is lower with higher wind speeds (as discussed above), the overall distribution of the encountered circulations is not influenced by the wind speed. For both wind speed cases, in the scenario with 1000 ft vertical separation as well as in the scenario with 500 ft vertical separation, the encountered circulation is mostly in the range between 150 m^2/s and 250 m^2/s. In the Solution scenario with 500 ft vertical separation, a strong increase of encounters for all ranges of circulation values is apparent. The highest increase is visible in the range between 150 m^2/s and 200 m^2/s, but also in the range between 350 m^2/s and 400 m^2/s, a very high increase can be observed. For all encounters with an RCR above the threshold of 0.2, the average circulation in the low-wind-speed scenario with 1000 ft vertical separation is approximately 236 m^2/s while the average circulation in the low-wind-speed scenario with 500 ft vertical separation is approximately 224 m^2/s, which is a decrease of approximately 5%. The average circulation in the high-wind-speed scenario with 1000 ft vertical separation is approximately 227 m^2/s while the average circulation in the high-wind-speed scenario with 500 ft vertical separation is approximately 221 m^2/s, which is a decrease of approximately 2.6%. These values might be misleading and need to be considered with caution: even though the average circulation values are lower in the scenarios with 500 ft vertical separation, this does not mean that the reduction of the separation results in a safer situation. In fact, an increase of the number of encounters in all ranges of circulation values can apparently not result in a safer situation – the lower average circulation only shows that the increase

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of the number of encounters is highest for lower circulation values, but there is still a significant increase of encounters with a high circulation value.

A comparison of the circulation distributions for different RCR limits shows that the encounters with a very low circulation below 50 m^2/s disappear almost completely when increasing the RCR limit to 1.0 because only in a few cases with very light follower aircraft, a very low circulation is sufficient to induce a high RCR. For all other circulation ranges, the number of encounters is reduced by approximately the same factor when increasing the RCR limit because the dependency of the RCR not only on the circulation but also on the follower aircraft type results in cases with low circulation but still high RCR and also in cases with high circulation but still low RCR. This is also visible when analysing the distribution of the encountered circulation in relation to the follower aircraft MTOM as shown in Figure 6 and Figure 7. It is apparent that most encounters happen with a follower aircraft MTOM of approximately 70 tons because this corresponds to the MTOM range of the Airbus A320 family and the Boeing 737 family, which are the most commonly used aircraft types in European RVSM airspace by far. But also for heavy follower aircraft, encounters with a significant RCR can be found; this is in line with observations from operations (e.g. [74][75]). Also, it is visible that most encounters happen at a circulation of approximately 200 m^2/s and that there is a strong increase of these encounters when reducing the vertical separation for all categories of follower aircraft types.

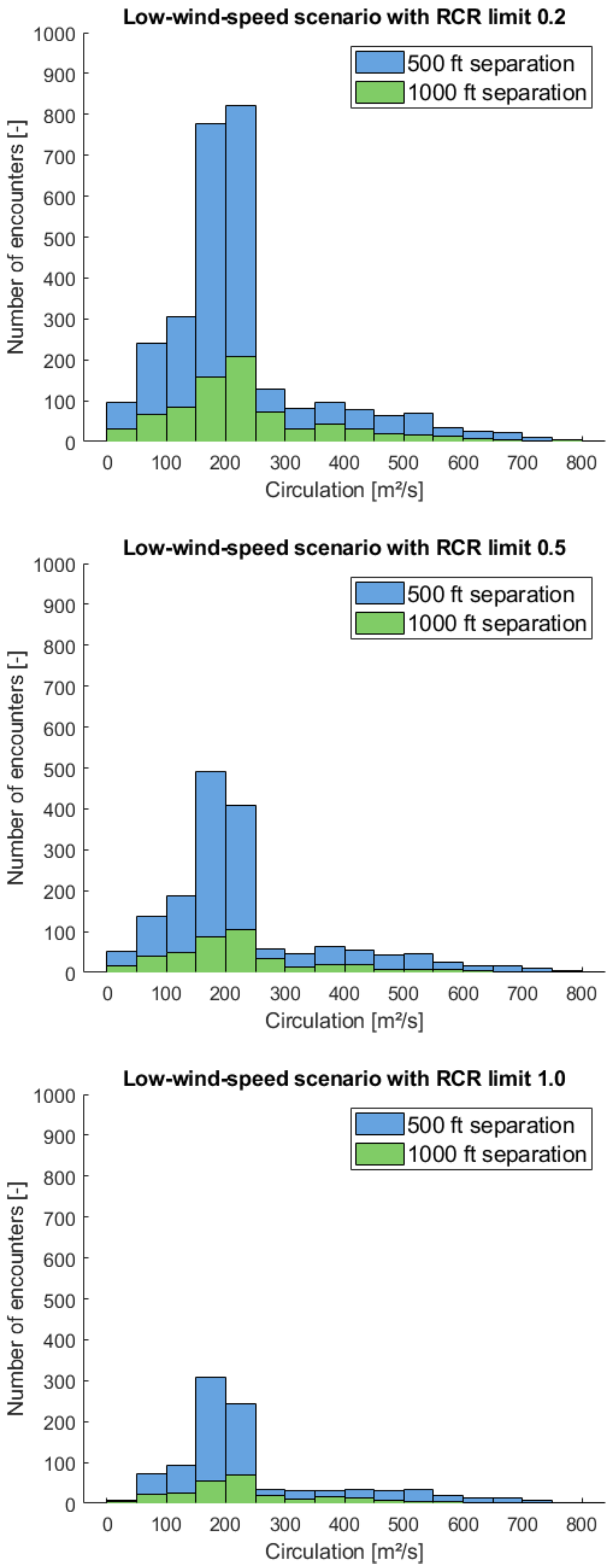

Figure 4: distribution of the encountered circulation in the low-wind-speed scenario

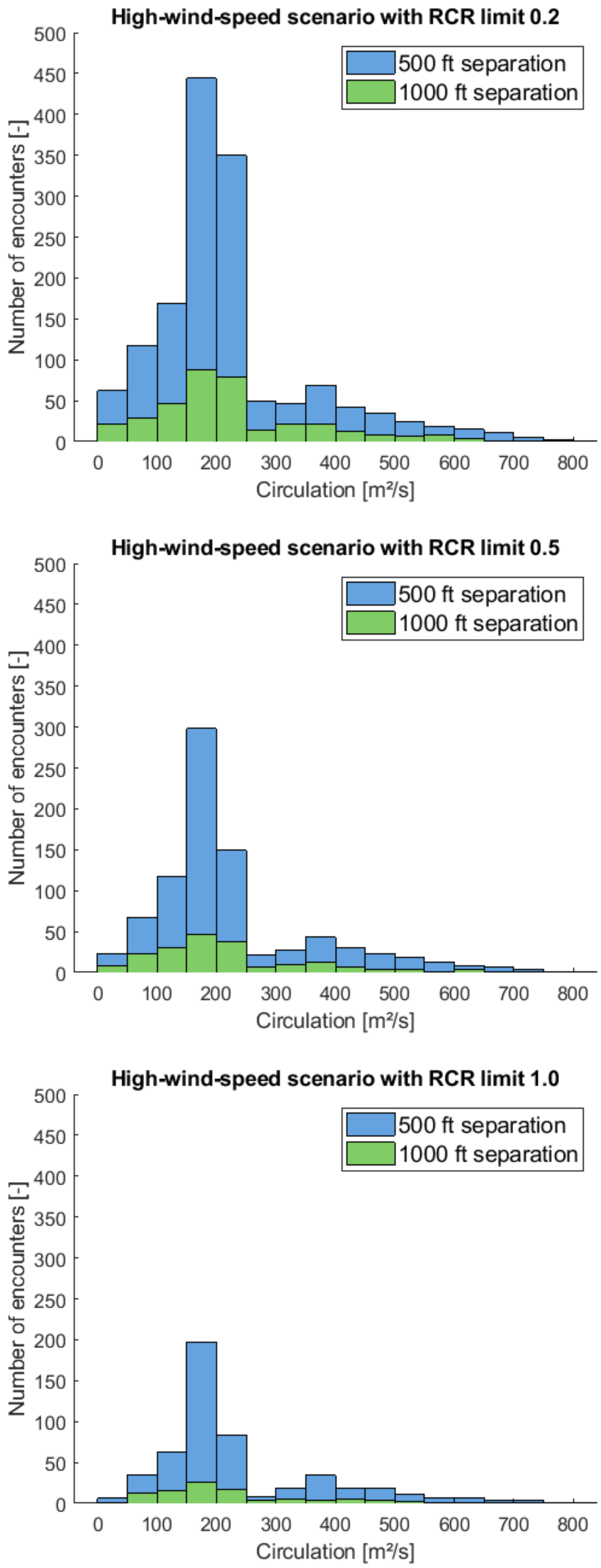

Figure 5: distribution of the encountered circulation in the high-wind-speed scenario

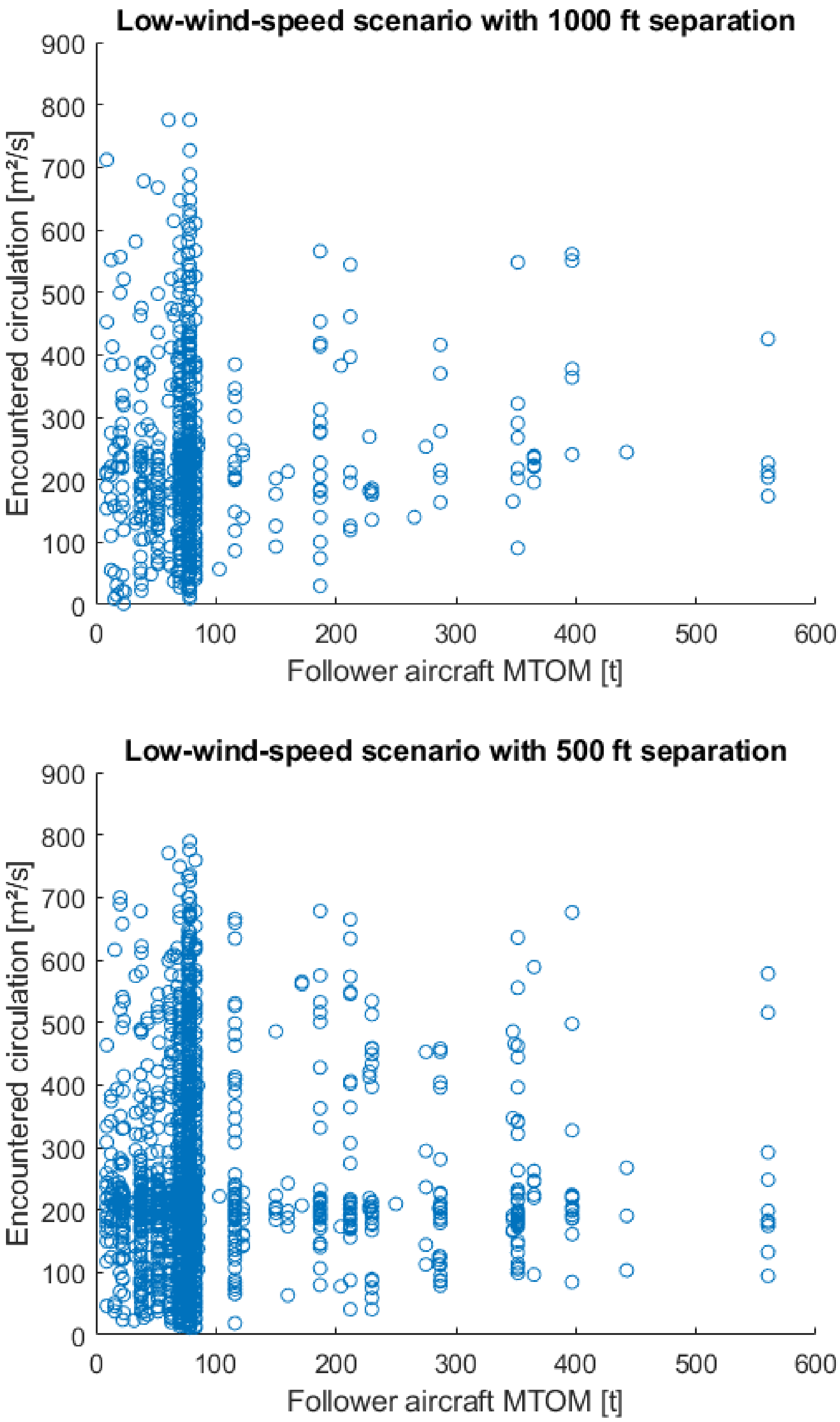

Figure 6: distribution of the encountered circulation in the low-wind-speed scenario in relation to the follower aircraft MTOM

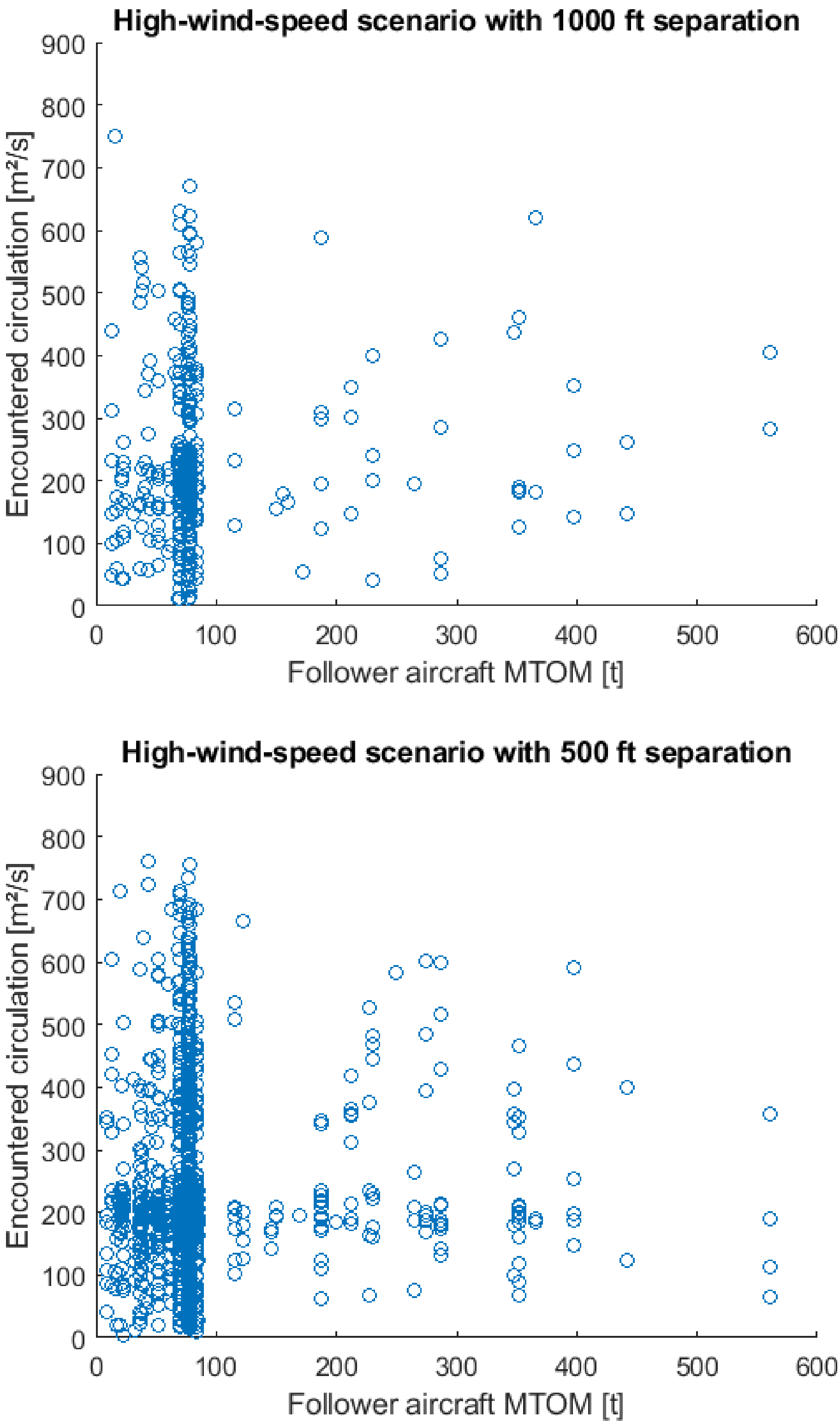

Figure 7: distribution of the encountered circulation in the high-wind-speed scenario in relation to the follower aircraft MTOM

More details about the results of this analysis can be found in the appendix B.3.2.2.

In summary, it must be concluded that the wake encounter risk (frequency of occurrence for all potential severities) is significantly increased against the status quo. There is no known target level of safety for the wake encounter risk against which the results could be compared in order to determine whether the new risk level would still be acceptable. So, the only means of assessment is a relative comparison, i.e. the comparison against figures for the current concept of operations (500 ft vertical separation with geometric altimetry vs. 1000 ft vertical separation with barometric altimetry). Obviously, success criterion GreenGEAR-0407-TRL2-ERP-CRT04, “the wake encounter risk is not unacceptably increased compared with current operations”, is *NOK*.

This does not come as a surprise, actually a different result would be difficult to understand. A means of mitigation for the wake encounter risk would therefore be required, as further elaborated in section 5.1.3 below and [30].

4.2.2.4 Success criterion GreenGEAR-0407-TRL2-ERP-CRT05

The fourth and final success criterion for the current objective is to derive a quantitative or qualitative safety specification. In the ‘Separation Minima’ safety case ([31]), safety specifications were derived qualitatively and semi-quantitively in the form of a Functional Hazard Analysis.

In the FHA, four primary functions were established, namely:

1. The altitude information domain provides altitude information in the entire airspace in a continuous way.
2. The airborne domain receives the altitude information and provides estimates of the altitude of each individual aircraft in a continuous way.
3. The ground domain assigns an altitude to each individual aircraft such that it is vertically separated if necessary.
4. The airborne domain receives the assigned altitudes and let each individual aircraft fly according to the assigned altitude.

Then, a hazard was formulated for the situation that a primary function is not executed properly. This leads to the following four hazards:

- 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.
- H4: An aircraft does not fly according to its assigned altitude.

The safety specifications were then established for each of the hazards. The probability of a hazard H1 occurrence is difficult to estimate, mainly as the development of jamming and spoofing events in the future is uncertain. However, due to the variety of potential causes of H1, the probability is not negligible. As the consequence of an undetected or not-mitigated occurrence of hazard H1 is an

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increase of the mid-air collision probability, this leads to the conclusion that there is a need for mitigation, independent of which precise safety criteria are applied.

These mitigations translate into the following safety specifications:

- Aircraft in RVSM 2 airspace should use Dual Frequency receivers.
- If there is no ground domain that takes coordinated actions in case altitude information is not provided properly in a part of the airspace, the PSUA should be designed such that it is safe when applied simultaneously by several aircraft in each other's vicinity.
- The altitude information domain should provide a lack of altimetry integrity message if there is uncertainty about the accuracy of the altitude estimate that can be derived from the altitude information. These messages should be received by the ground domain, at least by the ATC units providing services in and close to the part of the airspace where it applies. These messages should be received by the airborne domain, at least by the aircraft flying in and close to the part of the airspace where it applies.
- Each individual aircraft should send out own altitude signals in a continuous way. These signals include the altitude estimate, together with some kind of identification of the aircraft sending the signals out. These signals should be received by the ATC units providing services in or close to the part of the airspace in which that aircraft flies.
- The ATC units should receive the own altitude signals of each individual aircraft in a continuous way and verify if there are significant deviations from the assigned altitudes.
- Each aircraft should send out an unable altimetry message if a lack of availability, accuracy or integrity of the altitude estimate is detected. These messages should be received by the ground domain, at least by the ATC units providing service in and close to the part of the airspace in which the aircraft flies.
- The ATC units should detect inadequacy of the altitude information in a part of the airspace by processing the following information items: a) receipt of lack of altimetry integrity messages from the altitude information domain, b) receipts of lack of unable altimetry messages from several aircraft, c) detection of several aircraft deviating from their assigned altitude in a part of the airspace and d) other information items, such as indications of jamming or spoofing.
- If an ATC unit detects that there is a possibility that altitude information in a part of the airspace is inadequate, it should first inform all aircraft about this possibility. The aircrew having received this information should not initiate a PSUA.
- If an ATC unit has confirmation that altitude information in a part of the airspace is inadequate, it should coordinate with other ATC units and it should initiate a PMUA.
- The frequency of occurrence of altitude information being inadequate in a significant part of the airspace should be less than once in ten years.

The RVSM 2 concept focuses on the European RVSM airspace. This area is a tactically controlled airspace that has complete surveillance and communication coverage. The causes and likelihoods for H2, H3 and H4 are therefore the same as in current operations (with possibly an exception for H2, but

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the likelihood of failure can be specified to not be lower than barometric systems), but the consequences are likely to change due to the reduced separation. This would lead to the following three specifications related to the latter three hazards:

- GNSS altimetry systems should have a similar maximally allowed rate of failure as current barometric altimetry systems.
- An aircraft not having an altitude assigned to it such that separation is maintained will have the same maximally allowed occurrence rate as in current operations.
- In RVSM 2 an aircraft not flying to its assigned altitude should have a similar maximally allowed rate as in current RVSM operations.

To conclude, the validation objective status concerning the success criterion GreenGEAR-0407-TRL2-ERP-CRT05, “derive a quantitative or qualitative safety specification” is determined *OK*. Safety specifications were established for the four major hazards of the RVSM 2 concept. More detail on the reasoning behind the safety specifications can be found in Appendix A.

4.2.3 GreenGEAR-0407-TRL2-ERP-OBJ3 results

The third and final validation objective is to estimate the capacity potential for RVSM 2. NB that the focus of the project has shifted to the safety and feasibility of the implementation of RVSM 2, and capacity has only been addressed in a basic manner due to limited (also temporal) resources.

With that in mind, the success criterion for this objective is that initial capacity analysis delivers demonstrable capacity benefits. When moving from RVSM to RVSM 2, the number of available FLs increases by more than a factor of 2, since the vertical separation reduces from 1000 ft to 500 ft between FL290 and FL410, and from 2000 ft to 500 ft between FL410 and FL600 which is the extended upper limit of the RVSM 2 airspace. Obviously, there is the potential for a higher capacity in the same airspace block. Whether this higher capacity can be handled by ATC is beyond the scope of Green-GEAR; we can only give a few qualitative considerations.

From the collision risk perspective, a generous buffer has been applied to passing frequencies so an increase of the traffic is already considered in the model, effectively not restricting the use of the new flight levels.

From the wake turbulence risk perspective, existing traffic has been “compressed” against two pivotal flight levels as described in [30] to simulate increased population of the newly introduced flight levels rather than a spread of existing traffic among them. Results show a substantial increase of encounter frequency for all severity categories, meaning that additional means (advanced separation / warning tools) are required to maintain safety. The possible introduction of new separation standards to mitigate the wake encounter risk and the need to protect climbing and descending aircraft will likely limit practical gains.

From the safety case, conditions and safety requirements were derived that would allow safe operation in non-nominal operations. However, these are partially ambitious, not only technically but also legislatively / regulatorily. Further study is needed; the actual capacity increase in modified RVSM airspace is expected to fall well short of a theoretical doubling. The development of a comprehensive safety case will be essential in establishing an upper bound for achievable capacity enhancements.

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

The DLR internal project DIAL investigated the en-route airspace limits under the assumption of an approximately 150% traffic growth between 2019 and 2050, i.e. nearly 2.5 times the number of flights as 2019, or almost 310,000 daily flights worldwide. Free routing between origin and destination airports and a hypothetical appropriate extension of their runway capacities to handle the traffic was assumed. Furthermore a fully automated air traffic management at least for en-route traffic was envisaged, i.e. it was assumed that controller workload as one capacity limiting factor would no longer be relevant; instead the number of flights would be constrained by the required horizontal and vertical separations between them (i.e minima of 5 NM laterally, 3 to 8 NM in trail as per current wake vortex separation [38] and 1000 ft vertically). It was shown that current deconfliction methods (strategic conflict resolution using time shifts of a few minutes and tactical lateral detours or climb-above/descend-below manoeuvres) are generally able to provide a conflict-free scenario even for this high demand with very low average penalty on flight efficiency [56].

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

4.2.3.1 Success criterion GreenGEAR-0407-TRL2-ERP-CRT06

In summary, success criterion GreenGEAR-0407-TRL2-ERP-CRT06, "Initial capacity analysis delivers demonstrable capacity benefits; potential showstoppers are identified" is not strictly met, but the contrary has not been proven either. The wake turbulence risk needs to be mitigated, and the specifications for functions controlling the non-nominal operational risk would need to be further assessed. On the other hand, the collision risk analysis results do not constrain the use of the additional flight levels. Indeed, the ability of ATC to handle the traffic levels seems to be the current bottleneck, while under automated ATC and/or substantial restrictions of usable airspace significant improvements are conceivable. Therefore, the validation objective status is determined *Partially OK*.

4.3 Confidence in validation results

4.3.1 Limitations of validation results

The research has addressed the EUR region / ECAC area, for the collision risk by using the appropriate data on traffic mixes, passing frequencies and the like and for the wake encounter risk by simulating the traffic in the full ECAC area for two full days which represent two extremes in wind conditions in en-route airspace. Therefore, an extrapolation of results to a wider area is not necessary.

The wake vortex study is sensitive to weather conditions and traffic patterns, so additional simulation runs with different seasonal traffic patterns would yield somewhat different results. Also, the weather influence can never be the same, even if the two extremes for the wind, which is the main influencing factor for encounter probability, have been investigated. An increase of the data base size would require substantial computational effort (of the order of weeks per daily scenario on an ordinary PC) and could contribute to better understanding of the distribution of occurrence probabilities between the two extremes but this would be of limited value at TRL 2, especially as the worst-case scenario still would need to be acceptably safe.

The limitations of the validation results thus lie more in the assumptions made in the research and modelling accuracy. The latter, discussed in more detail in the following section, is partially also a consequence of the limited resources available. It is, however, considered adequate for an activity at TRL 2 whose main objective is to identify whether the underlying idea of a reduction to 500 ft minimum vertical separation appears feasible at all, and, as the case may be, define recommendations for further work.

Limitations from the assumptions comprise for example that the future airspace structure will be similar to the current one and so will be operations. Furthermore, the fleet was assumed to be the same in the RVSM 2 airspace, in terms of fleet mix and propulsion systems. Obviously, traffic patterns and mixes influence the outcome. For the wake study, historic traffic demand data for the whole EUR region have been used, in accordance with the Solution's scope, which include certain but limited numbers of particularly interesting aircraft types like VLJs and HAOs. Other possible future types like all-electric or hydrogen-powered types are necessarily absent but this can be regarded as negligible at the present level of detail. Further traffic growth is also not addressed (see next section).

Finally, the assumption was made that jamming and spoofing of GNSS signals do not influence the operation, i.e. the non-nominal case was not further considered. However, GNSS signal interference is a major problem in GNSS navigation nowadays, and it should be investigated how this issue can be dealt with in the RVSM 2 concept.

4.3.1.1 Quality of validation results

In detail, the computational studies (analytical for the collision risk and through fast-time simulation for the wake turbulence risk) have been subject to the following limitations that are mainly conceptual but are considered adequate for an activity at TRL 2

- In order to estimate current altimetry and height keeping performance, both for collision risk and wake turbulence studies, the most accurate values for the ASE and FTE were used that are available. Nevertheless, it is desirable that the accuracy of these parameters improves. Current GNSS performance was considered by using the Vertical Positioning Error (VPE) from the GPS and Galileo quarterly reports. These figures however were collected with a stationary receiver in standardised conditions. It would be preferable to obtain GNSS accuracy data directly from typical aircraft borne GNSS receivers. This is however, extremely difficult as a more accurate reference would be needed.

- In addition, the FTE data (approximated by the Assigned Altitude Deviation (AAD)) resulted from data collected using mode C, which has a granularity of 100 ft increments. Since the maximally allowed ASE and FTE are close to the values obtained from actual performance data, it is desirable collect more accurate figures.

- In order to calculate the maximally allowable ASE and FTE, certain parameters of the future operations were estimated, such as the probability of lateral overlap, kinematic factor and the passing frequency. However, a generous margin was applied to the parameters, such that if operational circumstances change (e.g. passing frequency increases by growing amount of traffic, or lateral navigation accuracy improves) the overall technical risk is still lower than the TLS.

- The wake turbulence study has evaluated the probability of an aircraft to fly into the habitation volumes of the wake vortices, so-called wake volumes, of a generator aircraft. While in any particular real-world situation the actual trajectories of the vortices are well-defined (even if not easily observable), it is in practice impossible to know all relevant variables for an exact *prediction*. Adopting a probabilistic approach to forecast the said wake volumes, their dimensions are determined by error propagation of the uncertainty of initial parameters and the stochastic nature of atmospheric behaviour and WV evolution. This approach is sufficiently conservative but the so-obtained wake volumes at typical encounter ages become much bigger than the actual wake and the encountering aircraft's dimensions. The approach adopted here was to combine a more deterministic wake prediction based on initial and atmospheric conditions chosen according to their respective probabilistic distributions but then regarded as known.

- Apart from not hitting the vortex although inside the corridor, the severity of an encounter if it actually happens is also an important factor. Indeed, minor incidents in cruise under IFR are quite common, from identifiable encounters that have no consequences beyond a short disturbance up to minor injuries of occupants. More serious incidents and accidents are much rarer but do happen. Consequently, for risk determination not only the frequency of occurrence, but also the severity of encounters needs to be modelled; several approaches have been devised by various authors but no universally agreed method exists. This study has used the SHAPe method that addresses the so-called roll control ratio (RCR), which is a relative measure of vortex induced roll disturbance vs. available control power. A quantification through (wake-induced) rolling moment coefficient (RMC) has often been used in literature [63][71] or safety analyses [70][72]; this RMC is easier to determine with publicly available aircraft data but does not relate the disturbance to the aircraft's ability to cope with it. Thresholds for acceptable RCR values with the SHAPe have been developed and tested for final approach. Extrapolating to the cruise situation in the absence of corresponding studies, for the present activity three encounter severity thresholds have been selected.

  The problem remains, both with RCR and RMC, that there is a big grey area between a situation that is objectively unsafe (injuries, exceedance of operational limits) and one that is subjectively rated as unsafe by the pilots, or where there is a nominal loss of control for a short time (typically a fraction of a second) that has no relevant consequences.

- A tool to simulate traffic that is separated (implying deconfliction by the Network Manager (NM) and at tactical level) by the proposed new rules was not available. Indeed, the most crucial obstacle for this activity is the necessity to use demand data which have been generated under assumption of the new flight level choices as per the OSED. Its generation at a high quality level requires sophisticated flight planning tools that are available only to operators and generally not batch processable. As a workaround, modifications to existing demand trajectories have been employed as explained in [30]. As the traffic volume was not increased, the modifications produce an even higher concentration of traffic in certain altitude bands than today – a behaviour that is to be expected though: there is no reason to assume that a bigger choice of flight levels will lead to a more uniform population, as already the current concentration is due to flight mechanical reasons and not capacity constraints.

- In the same vein, the reconstruction of flight paths from demand data suffers from the low resolution of the time stamps and the fact that wind is not taken into account in these plans. The true airspeed was calculated from the ground speed assumed in the flight plan and the wind given by the numerical weather prediction, where in reality given airspeed and wind would add to the observed ground speed. This is a common problem to many simulations in the ATM world and difficult to overcome with reasonable effort.

- Generally speaking, higher crosswinds will reduce the risk for aircraft following the same route in trail or at differing altitudes, while increasing the risk for those flying on parallel routes (or in general with a lateral separation). As the perception of a given wind direction as crosswind or head-/tailwind depends on the own track, the effects of a certain level of winds vary per pairing. Due to complexity of vortex transport and decay, it appears plausible but is not proven that low and high winds (as simulated here) are actually the most critical situations regarding horizontal vortex drift. Moreover, wind shear and temperature stratification play a role for the vertical drift of the vortices; these effects can counteract and even negate the vertical motion under albeit rare circumstances. Due to calculation times of several weeks per scenario the present study could not treat a large number of cases in terms of weather phenomena.

- The flight plans do not include actual take-off weights for the aircraft, and these are actually closely regarded commercial secrets of the operators as they could allow the competition easy access to estimating load factors. The study has therefore worked with weight estimations (variations of reference weight from BADA). One might consider taking the maximum take-off weight (MTOW): however, even if the relatively strongest wake for a type is certainly produced at its respective maximum weight, this approach is not really conservative: stronger vortices have a longer lifespan and a higher downward travel, but this assumption will overestimate the risk of encountering stronger vortices at greater vertical separation and underestimate that for encounters with weaker vortices at smaller vertical separations. A model deducting at least fuel use as derived from the BADA database is possible, but for more realism it would be necessary to take into account the segment lengths as many flights operate far from the type's range and thus far from MTOW at take-off.

4.3.1.2 Significance of validation results

By definition, exploratory research addresses a low TRL and operational realism is limited. Only computational studies have been performed. On the other hand, for the collision risk study, the established ICAO model has been used with the necessary adaptations. This corresponds to what would be done pre-implementation and is therefore sufficiently representative. Also, the safety case is always a paper exercise and as such represents real-world methods, only at a necessarily low detail level. The significance of these results is hence determined by the accuracy of the input data.

The wake turbulence risk study, by contrast, has been a fast-time exercise that could not take all possible traffic patterns and weather situations into account. It is assumed, yet not proven, that the two scenarios chosen for minimum and maximum average wind speeds throughout the area represent the two extreme cases for encounter probabilities. As explained above, wind shear and temperature stratification play a role for the vertical drift of the vortices; these effects are rare but not negligible from a safety point of view. A certain variability of weather effects has been implemented in that individual values for typical deviations between actual and nominal weather (and between nominal and actual altitude of the aircraft) have been employed using the corresponding probability distributions.

Due to calculation times of several weeks per one full-day scenario with different combinations of input parameters, the present study could not treat a large number of cases in terms of weather phenomena and/or traffic patterns but this is no fundamental problem, especially as the upgraded simulation environment is now available. If full conservatism is required, it would be possible to simulate and average traffic and weather over a full year, albeit with a considerable computational effort.

More information on these points can be found in the section above.

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5 Conclusions and recommendations

5.1 Conclusions

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

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 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 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.

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.

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. 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.

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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. 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. In addition, the 93% allowed effectiveness is based on the availability of ATC collision prevention. This was not a requirement in traditional RVSM, and would result in the requirement of RVSM 2 only being allowed in controlled airspace with tactical control and radar surveillance (procedural control, as in the NAT HLA (North Atlantic High-Level) airspace today, would not suffice).

In summary, it can be said that the application of the RVSM 2 concept depends on primarily regulatory advance regarding GNSS and flight control performance (FTE) to fulfil the collision risk target level of safety, a solution to the jamming and spoofing threat to GNSS altimetry, and finally a remedy for the increase in wake encounter risk. Only the former and the latter are specific to the Solution, whereas jamming and spoofing generally limit the applicability of GNSS-based positioning for all safety-of-life or high-availability applications.

Apart from that, a 'one size fits all' approach to separation needs to be conservative, whereas more flexibility in applicability depending on factors like the weather situation (including convective activity) or the involved aircraft parings may be required, as already indicated by the R-WAKE study [73]. The complexity of this approach has been regarded as a fundamental problem so far, but today the notion of supportive tools for ATC is less controversial. Thus, 500 ft minimum vertical separation may be a possible solution for fitting circumstances, to be applied in specific airspaces and under specific conditions, and not necessarily feasible to be applied across the whole European airspace at all times.

5.1.1 Conclusions on SESAR solution maturity

This ERR addresses some of the maturity criteria for Solution 0407. The FRD, Final OSED and ECO-EVAL address other of the maturity criteria; the two former have been submitted while the latter is completed in parallel with this report.

With that in mind, the expected subset of (TRL2) maturity criteria to be assessed based on the content of this document concerns

- Human performance questions, which have not been addressed explicitly. For exercises #01 and #02 human performance is out of scope, whereas exercise #03 attributes failure modes and probabilities to functions which may or may not be executed by humans but without further detail;
- Impact on the most significant KPAs such as capacity and fuel efficiency, which have been addressed in briefly in section 4.2.3 and in more detail in the ECO-EVAL [34][33], and have

demonstrated positive impact on capacity and fuel efficiency albeit in a mostly qualitative assessment;

- Interaction with other SESAR Solutions; this has partially been performed by studying other uses of geometric altimetry: Solution 0406, “Vertical Guidance using Geometric Altimetry”, has found the use of geometric altitude references beneficial in the TMA and seen operational and performance disbenefits to using it in cruise. This latter verdict, however, came with the caveat that in a holistic view, such as when enabling reduced vertical separation, the assessment might change. A comprehensive assessment of the overall KPA impact has been out of scope unfortunately.
  However, we note that Solution 0408, “Green Route Charging”, deals with the avoidance of airspaces characterised as so-called “climate hotpots”, and the necessary (lateral or vertical) detours could be significantly limited if additional capacity provided by this Solution would be available;
- Identification of relevant R&D needs and recommendations for further work; these have been developed and are documented later in this chapter.

The pending investigation into a possible conditional implementation of the concept means that it cannot be fully assessed whether the Solution could be permanently and ubiquitously implemented, but it is generally applicable throughout the European airspace for which the studies were done. However, it is not a requirement of the Separation Minima Solution that is it introduced all over Europe, or even the globe, at the same time, even if an introduction at least in one full ICAO region would be desirable.

There are several open points from the Validation activities documented here which concern the allocation of the requirements on the altitude keeping performance to altimetry and flight control systems and the need to have tighter specifications on GNSS performance (which may actually be sufficient as observed but is not guaranteed to be so). A need for improvements/modifications of existing safety functions (ACAS/STCA) was identified, and also the wake vortex risk needs a more thorough treatment. However, at a TRL 2 level the identification and documentation of these issues might suffice.

A final caveat concerns the safety and security threat stemming from jamming (which may be intentional or accidental) and spoofing (which is usually intentional[2]). Methods to deal with that are being developed by activities in line with joint EUROCAE / RTCA standards development, and the required operational performance standards for dual-frequency multi-constellation augmented GNSS are also addressed by these organisations, with a timeframe for completion of a few years. Again under the interpretation that the TRL2 maturity criteria require identification and discussion but not solution

[2] The generation of a signal that can spoof a GNSS receiver is not conceivably an unintentional by-product of a completely different activity (by contrast to jamming). However, cases are known where misuse or malfunction of GPS technology on the ground, such as the replay of recorded signals for testing purposes, unintentionally affected operational traffic.

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of these safety and security problems, this situation would not prevent TRL2 ongoing being reached even if it would prevent implementation of the Solution.

In summary, with the caveat that a formal and more comprehensive self-maturity assessment is pending, we conclude that the Validation activities described in this ERR appear to justify the appraisal that the (TRL2) criteria to be addressed here have been achieved at least partially, with the possible exception of the human factors criteria whose applicability is to be discussed.

5.1.2 Conclusions on concept clarification

In the initial OSED [27] 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 [27] 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 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 prevent 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.

5.1.3 Conclusions on technical aspects

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.

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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) [50][52] and also research demonstrations (e.g. at DLR [53][54]) 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 [55][51]. 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.

5.1.4 Conclusions on performance assessments

The Benefit Impact Mechanism (BIM) analysis is included in D4.6 - Final OSED [33]. The schematic in the appendix of that document shows how the Key Performance Area's (KPAs) are affected according to the validation exercises. The KPAs are also listed in D4.2 – ERP [28].

The KPA that was studied most extensively in this solution was Safety (SAF), in all three validation exercises: the CRA, Safety Case and WTRA. In the former two the safety was assessed using an evaluation against a threshold. A maximally allowable level of risk was defined, and requirements were deduced, using a 'top down' approach. As such it is guaranteed that the safety remains within acceptable limits. Even though the overall level of risk is likely to increase within the system, it is within acceptable bounds, and therefore the outcome for this KPA for the CRA and Safety Case can be regarded as neutral.

The latter, the WTRA, used a comparative approach, using current 1000 ft minimal vertical separation as the reference. It was shown that safety is negatively affected when the vertical separation minima are reduced to 500 ft. Considering the results of all validation exercises combined, it can be stated that within the RVSM 2 concept as currently defined, the safety will be negatively affected overall.

As the number of available flight levels doubles, the potential Capacity (CAP) is likely to increase significantly. Capacity is dependent, however, on multiple factors, and capacity issues mostly occur in certain bottleneck areas. The Operational Efficiency (OPS) is also expected to increase. As aircraft fly closer to their preferred flight level, due to increased capacity and finer granularity of the flight levels, and a possible reduction in the need for detours, the average fuel burn per flight is likely to decrease. A decrease in fuel burn will directly be beneficial for the CO_2 production per flight, thereby positively affecting the Environment (ENV) KPA. The ECO-EVAL [34] reports more on these KPAs; a first estimation shows that the finer granularity alone overcompensates the efficiency disadvantages stemming from the use of geometric instead of barometric altitude guidance as evidence by WP3 / Solution 0406 analysis [26].

5.2 Recommendations

As the study has focussed very much on the safety issue, there remain open questions regarding further operational and technical aspects, beyond the further development of the functions/systems that would be required to ensure the safety of operations.

5.2.1 Recommendations for next R&I phase

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

- The CRA showed that the TVE, and consequently the FTE is a crucial factor in determining whether the collision risk will be within the TLS for RVSM 2. The only FTE data available in this study however is 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. This analysis could be done directly from the available data, or could be done in close coordination with the EUROCONTROL department that is responsible for the EUR RMA CRA.

- The ASE is the second term in the TVE, next to the FTE. 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.

- 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. This point is not necessarily specific to the Separation Minima solution and thus further elaborated in the next section.

- 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. Also, as 500 ft separation will be considered nominal operations in RVSM 2, it is undesirable to have resolution advisories at such separations. A further study should investigate whether and how ACAS can be adapted to the 500 ft minimal vertical separation case. It needs to be taken into account that ACAS needs a different altitude source than the one operationally used for altitude keeping to maintain its independence.

- 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.

- 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, as current FTE and ASE performance, with the best applicable figures available, seems to be just sufficient to meet the TLS. A limited increase in the separation minimum may relax the conditions on the FTE and ASE such that it will be easier to safely implement the concept from a collision risk perspective. Note, however, that such separation minima may pose challenges from a human factors perspective.

- As coarsely estimated in the ECO-EVAL [34], the finer granularity of flight level availability in the RVSM 2 concept might outweigh the penalty from flying with geometric reference instead of barometric reference (as determined in WP3 / Solution 0406 [26]), as the latter is consistent with flight performance. A reduction of vertical separation based on barometric altimetry as it is today is infeasible because of the high allowable ASE [29]. However, this ASE seems to be mainly a property of the respective airframe; for various reasons the pitot-static system cannot be calibrated better on ground. On the other hand, GNSS altitude in flight is potentially at least one order of magnitude more accurate than barometric altitude (assuming more sophisticated equipment than what is in use today). Even if those two altitudes have different references, the offset is determined by the weather and thus not completely unknown. Comparing the actual offset with the one expectable as determined from numerical weather prediction data [78] and/or through improved long-term height monitoring [79], it might be possible to introduce a kind of online calibration of the barometric altitude that could allow to improve on the barometric ASE.

- A detailed categorisation of 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 [73].

- The severity assessment for wake vortex encounters is still not convincingly solved; several approaches have been devised by various authors but no universally agreed method exists. A quantification of encounter severity through rolling moment coefficient (RMC) has often been used; this RMC is easier to determine with publicly available aircraft data but does not relate the disturbance to the aircraft's ability to cope with it. The problem remains, both with RCR and RMC, that there is a big grey area between a situation that is objectively unsafe (injuries, exceedance of operational limits) and one that is subjectively rated as unsafe by the pilots, or where predictions show a possible nominal loss of control for a short time (typically a fraction of a second) that would need to be regarded as hazardous in theory while it might have no relevant consequences in practice.

- There is also the aspect of trajectory following capabilities (vertical and lateral guidance errors) and its influence on the encounter probability. Lateral (cross-track) errors have historically been of the order of several hundred metres using classical radio navigation combined with inertial navigation, and now decreased by one order of magnitude through the introduction of satellite navigation as primary means for horizontal navigation. This means that there is less variation on the lateral distance against the nominal state, which can be beneficial or detrimental dependent on the situation. In the vertical dimension, barometric altimetry is relatively inaccurate, very roughly characterised by an airframe-dependent offset due to calibration errors, meaning that there is still a certain bandwidth of actual physical separations around the nominal one. Geometric altimetry via satellite navigation is expected to decrease the variance of altimetry system errors (ASE), so a possible change in nominal separation based on this would be accompanied by a qualitatively different distribution of actual separations. The consequences of this change have not been systematically studied, although a simple model for the total vertical error (TVE) characteristics has been applied here.

5.2.2 Recommendations for future R&I activities

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. Even if the growth of the VLJ fleet is a bit stalled after the global financial crisis of 2018, this particularly vulnerable type of aircraft that did not exist when the ICAO rules were written – there were virtually no LIGHT category aircraft in upper airspace. Emerging special configurations like very large and light HAO aircraft designed for loitering and observation or communication are particularly sensitive to wake turbulence, expectably primarily when climbing or descending through the densely populated cruise flight levels of current transport aircraft. Even if it is conceivable that these special aircraft can be dealt with ad hoc, generally 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 [50][52][53][54]. 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. The 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 should likely include the broader aviation sector into the discussion.

5.2.3 Other recommendations

Finally, the experience with the execution of the present research activity leads us to recommend that

- the duration of the validation activities, i.e. the technical phase of the Exploratory Research, should be extended to at least 24 months net (i.e. until the first delivery of the last technical Deliverable to the SJU). The level of modelling that is necessary to guarantee significant results, plus possibly time-consuming execution of simulations cannot be fully parallelised. The time for evaluating the results, including relation to other activities, is perceived too short especially in view of the considerable insights this could bring at small additional cost.

- the duration of the validation activities, i.e. the technical phase of the Exploratory Research, should be extended to at least 24 months net (i.e. until the first delivery of the last technical Deliverable to the SJU). The level of modelling that is necessary to guarantee significant results, plus possibly time-consuming execution of simulations, cannot be fully parallelised. The time

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for evaluating the results, including relation to other activities, is perceived too short especially in view of the considerable insights this could bring at small additional cost.

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6 References

6.1 Applicable documents

This ERR 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.

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

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

6.2 Reference documents

Green-GEAR Project Documents

[25] Bolić, T.: "SESAR 3 ER 1 Green-GEAR – D2.2 – Updated data management plan"" ed. 02.00, 30th Aug 2024.

[26] Nelson, T.; Donaghey, R. M.; Melendez, J.; Zapata Arenas, D., Rouquette, P., Vechtel, D., Koloschin, A. and Bauer, T.: "SESAR 3 ER 1 Green GEAR – ERR – Geometric Altimetry", Deliverable D3.3, ed. 01.00, 28th February 2025.

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

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

[29] Jonk, P.; Klein Obbink, B.; Smeltink, J.W. and Boshuizen, I.T.: "Green-GEAR – iD 4.1 – Separation Minima – Collision Risk Analysis". Project internal report, v1.0, 31st January 2025.

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

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

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

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

[34] Bauer, T.; Jonk, P., Boshuizen, I. and Castelli, L.: "SESAR 3 ER 1 Green-GEAR – D4.7 – ECO-EVAL – Separation Minima. Version 01.00, submitted 28th May 2025.

External references

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

[36] ICAO European and North Atlantic Office: *Guidance*: Guidance *Material on the Implementation of a* 300 m (1000 ft) *Vertical Separation Minimum in the European* RVSM *Airspace.* International Civil Aviation Organization, 2001.

[37] ICAO: *Air*: Air *Traffic Control Operations Manual for Implementation of Reduced Vertical Separation Minimum in the AFI Region*. International Civil Aviation Organization, 2008.

[38] ICAO: Doc 4444, *Procedures for Air Navigation Services (PANS) – Air Traffic Management.* International Civil Aviation Organization, 16th Edition, 2016.

[39] ICAO: Annex 2 to the Convention on International Civil Aviation. *Rules of the Air*. International Civil Aviation Organization, 12th Edition, 2005

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

[41] ICAO, Doc 9689-AN/953, *Manual on Airspace Planning Methodology for the Determination of Separation Minima*. International Civil Aviation Organization, 1998.

[42] EUROCONTROL: *The EUR RVSM Pre-Implementation Safety Case*, RVSM 691. EUROCONTROL, 2001.

[43] Smeltink, J.and Moek, G.: *Pre-Implementation Collision Risk Assessment for RVSM in the Africa Indian Ocean Region*, 2005.

[44] GSC, "Galileo Open Service - Service Definition Document (OS SDD)," 2023.

[45] United States Department of Defense, "Global Positioning System Standard Positioning Service Performance Standard," 2020.

[46] GMV, "Global Positioning System (GPS) Performance - Quarterly report 1 (January to March)," 2024.

[47] GMV, "Global Positioning System (GPS) Performance - Quarterly report 2 (April to June)," 2024.

[48] GSC, "European GNSS (Galileo) Services - Open Service - Quarterly Performance report - October - December 2023," 2023.

[49] GSC, "European GNSS (Galileo) Services - Open Service - Quarterly Performance report - January - March 2024," 2024.

[50] Kauertz, S. and Reinke, A: *SESAR projects 9.11 & 9.30 'Aircraft Systems for Wake Encounter Alleviation'*, 3rd Major WakeNet3-Europe Workshop, Southampton, 10th /11th May 2011.

[51] SESAR 1 P09.11 "Aircraft Systems for Wake Encounter Alleviation".

[52] SESAR 1 P09.30 "Weather Hazards / Wake Vortex Sensor".

[53] Bauer, T.; Vechtel, D.; Abdelmoula, F. and Immisch, Th.: *In-Flight Wake Encounter Prediction with the Wake Encounter Avoidance and Advisory System (WEAA)*. 6th AIAA Atmospheric and Space Environments Conference, AVIATION 2014, Atlanta, Georgia, 16.-20.06.2014, Paper AIAA-2014-2333.

[54] Bauer, T.: *Bordgestützte Wirbelschleppenvorhersage und -vermeidung mit dem Wake Encounter Avoidance and Advisory System (WEAA)*. Deutscher Luft- und Raumfahrtkongress 2017, München, 06.09.2017.

[55] Fezans, N.; Schwithal, J. and Fischenberg, D.: *In-Flight Remote Sensing and Identification of Gusts, Turbulence, and Wake Vortices.* Deutscher Luft- und Raumfahrtkongress (German

Aerospace Congress) 2015, Rostock, Germany, 22nd – 24th September 2015. DocumentID: 370254.

[56] Kuenz, A.; Gelhausen, M.; Grimme, W.; Knabe, F.; Mollwitz, V. and Störmer, M.: "Filling En-Route Airspace – Where are the Limits?" *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*, Portsmouth, VA, USA. https://doi.org/10.1109/DASC55683.2022.9925814

[57] Brown, A. and Holzäpfel, F.: "*Case Studies in Modelling Cruise-generated trailing Vortices*". AIAA Aviation forum and ASCEND 2024, July 29 – August 2, 2024, Las Vegas, NV, https://doi.org/10.2514/6.2024-3773.

[58] Hahn, K.-U.; Schwarz, C. and Friehmelt, H.: *A simplified hazard area prediction (SHAPe) model for wake vortex encounter avoidance*. ICAS 2004, Yokohama, 29.08. – 03.09.2004. proceedings: Edinburgh, 2004.

[59] Hahn, K.-U. and Schwarz, C.: *Safe limits for wake vortex penetration*. AIAA GNCC 2007, Hilton Head, 20.-23.08. 2007. Paper AIAA-2007-6871.

[60] Holzäpfel, F., *A Probabilistic Two-Phase Wake Vortex Decay and Transport Model, Journal of Aircraft*, Vol. 40, 2003, pp. 323-331, https://doi.org/10.2514/2.3096.

[61] Holzäpfel, F., *Probabilistic Two-Phase Aircraft Wake-Vortex Model: Further Development and Assessment*, Journal of Aircraft, Vol. 43, 2006, pp. 700-708, https://doi.org/10.2514/1.16798.

[62] Holzäpfel, F., "*Effects of Environmental and Aircraft Parameters on Wake Vortex Behavior*," Journal of Aircraft, Vol. 51, Issue 5, 2014, pp. 1490-1500, https://dx.doi.org/10.2514/1.C032366.

[63] Schumann, U. and Sharman, R.: ""Aircraft Wake-Vortex Encounter Analysis for Upper Levels", Journal of Aircraft 2015 52:4, 1277-1285, https://doi.org/10.2514/1.C032909.

[64] Skamarock, W. C., and Klemp, J. B., "A Time-Split Nonhydrostatic Atmospheric Model for Weather Research and Forecasting Applications," Journal of Computational Physics, Vol. 227, No. 7, March 2008, pp. 3465–3485. doi:10.1016/j.jcp.2007.01.037.

[65] Fan, Z.; Schroeder, N.; Swol, D. and Trani, A.: "*Potential wake turbulence encounters analysis in current and NextGen flight operations*," 2013 Integrated Communications, Navigation and Surveillance Conference (ICNS), Herndon, VA, USA, 2013, pp. 1-7, doi: 10.1109/ICNSurv.2013.6548576.

[66] Münster, C. and Schwarz, C.: "*Auswertung von Wirbelschleppenmeldungen im US Aviation Safety Reporting System (ASRS)*" [Analysis of wake encounter reports of the US Aviation Safety Reporting System (ASRS)], DLR report IB 111-2010/33, 2010.]

[67] Hoogstraten, M.; Visser, H.; Hart, D.; Trève, V. and Rooseleer, F., "*An Improved Understanding of En-Route Wake Vortex Encounters*," 4th International Air Transport and Operations Symposium, ATOS Paper 2013-2.3-2, Toulouse, France, July 2013, p. 15. Available from http://www.skybrary.aero/bookshelf/books/2510.pdf.

[68] European Union: Regulation (ec) no 551/2004 of the European Parliament and of the Council of 10 March 2004 on the Organisation and Use of the Airspace in the Single European Sky. Official Journal of the European Union, March 2004..

[69] Woodfield, A.A.: *En-route encounters with wake vortices, and the implications of reduced vertical separation minima RVSM*. 1999. Woodfield Aviation Research Report No. 9901]

[70] Rooseleer, F., and Trève, V.: *"RECAT-EU" European Wake Turbulence Categorisation and Separation Minima on Approach and Departure.* EUROCONTROL, 2018.

[71] Rooseleer, F.; Trève, V.; De Visscher, I. and Graham, R.: *Wake Turbulence Re-Categorisation on Approach and Departure for Safe and More Efficient Air Traffic Management.* 30th ICAS Congress, Daejeon / Korea, 25th to 30th September 2016.

[72] EUROCONTROL, *Approach and Departure Optimised Wake Turbulence Re-Categorisation and Pair-Wise Separation minima (RECAT-EU-PWS scheme)*. Ed. 1.0, 31st May 2022, available from https://skybrary.aero/sites/default/files/bookshelf/33096.pdf.

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

[74] National Transportation Safety Board (NTSB): In-Flight Separation of Vertical Stabilizer, American Airlines Flight 587, Airbus Industrie A300-605R, N14053, Belle Harbor, New York, November 12, 2001. Aircraft Accident Report NTSB/AAR-04/04, Washington, DC / USA, 2004.

[75] N.N.: *Incident: Qantas A388 and Qantas A388 over Pacific on Jun 10th 2018, wake turbulence causes altitude deviation* – online: https://avherald.com/h?article=4b9da5b2&opt=0, accessed 28/01/2025.

[76] Federal Aviation Administartion (FAA): Introduction to TCAS II Version 7.1. Retrieved from https://www.faa.gov/documentlibrary/media/advisory_circular/tcas%20ii%20v7.1%20intro%20booklet.pdf, 2011.

[77] ICAO: *Airborne Collision Avoidance System (ACAS) Manual*. International Civil Aviation Organization, 2006.

[78] Narayanan, S.; Osechas, O. Enhanced Vertical Navigation Using Barometric Measurements. *Sensors* 2022, *22*, 9263. https://doi.org/10.3390/s22239263, 2022.

[79] Christmann, C. Long-term monitoring of barometric altitude measurement performance using the example of a research aircraft. *CEAS Aeronaut J,* 23rd May 2025. https://doi.org/10.1007/s13272-025-00843-0.

[80] Vechtel, D.: *Wirbeldeformierung und ihr Einfluss auf die Gefährdungsbewertung von Wirbelschleppeneinflügen*. DLR-Forschungsbericht DLR-FB-2017-24 and PhD thesis, TU Braunschweig.

Appendix A Validation exercise #01 report

A.1 Summary of the validation exercise #01 plan

This validation exercise was executed as described in the ERP [28]. More specifically, 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.

A.1.1 Validation exercise description and scope

Height deviations are considered as an important hazard in the safety case exercise which could potentially lead to mid-air collisions. Therefore, a collision risk assessment is performed. The collision risk assessment is based on the ICAO collision risk models as described in the *ICAO Manual on airspace planning methodology for the determination of separation minima* [41].

A.1.2 Summary of validation exercise #01 validation objectives and success criteria

The validation objectives and their success criteria are outlined in Table 15.

SESAR solution validation objective ID and title	SESAR solution success criterion and ID
GreenGEAR-0407-TRL2-ERP-OBJ01.1 Provision of validated tools to quantify collision risk for chosen scenarios employing novel concept for reduced vertical separation minima.	**GreenGEAR-0407-TRL2-ERP-CRT01.1** The collision risk analysis results compare favourably to observations when applied to current operations and show plausible figures for the new concept.
GreenGEAR-0407-TRL2-ERP-OBJ02.1 To determine whether RVSM 2 can be safely introduced from a collision risk perspective and identify the most important challenges.	**GreenGEAR-0407-TRL2-ERP-CRT02** The collision risk does not exceed the TLS of $2.5*10^{-9}$ fatal accidents per flight hour.
	GreenGEAR-0407-TRL2-ERP-CRT03 Quantification of the maximum TVE required to meet the TLS.
GreenGEAR-0407-TRL2-ERP-OBJ3.1 To Identify potential showstoppers for capacity increase for RVSM 2 from collision risk perspective.	**GreenGEAR-0407-TRL2-ERP-CRT06.1** Initial capacity analysis from collision risk perspective does not preclude demonstrable capacity benefits.

Table 15: validation exercise #01 objectives and success criteria.

A.1.3 Summary of validation exercise #01 validation scenarios

This section was taken from the ERP. The use case is the RVSM 2 concept as described in the initial OSED.

The reference scenario is the current operation in RVSM airspace in the EUR RMA region. Altimetry is done using barometric measurements and the minimal vertical separation is 1000 ft. The corresponding passing frequencies, traffic mix and TLS apply. This is a scenario that will not strictly be researched but the methods used in the introduction and yearly assessment of the RVSM collision risk form the basis of the evaluation of the RVSM2 concept.

The solution scenario will focus on FL290 to FL600 inclusive in the EUR RMA region. Geometric altimetry is used, and the minimal vertical separation is reduced to 500 ft. A Collision Risk Assessment is typically performed for a period of one year. As such, the solution scenario will focus on a period of one year. A typical passing frequency and traffic mix is determined based on data of the past few years of this region as a reference.

A.1.4 Summary of validation exercise #01 validation assumptions

The following validation assumptions are applicable to the present validation exercise on top of those Solution-level ones identified in section 3.2.3.

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
GreenGEAR-0407-TRL2-ERP-ASS06	Single mode geometric altimetry	Assume all airspace users will use the same mode of GNSS altimetry.	This is the intended end state of the concept. If the level of safety cannot be met in this configuration, further study is not warranted as mixed mode operations are expected to be more challenging in terms of safety.	If the concept turns out to be feasible in the ideal end state, mixed mode operations or the transition to this end state may still form a crucial limiting factor.
GreenGEAR-0407-TRL2-ERP-ASS07	GNSS integrity	For the collision risk assessment, it is assumed that GNSS height measurements of sufficient quality are available at all times.	It can be argued that it is likely that in the end state the GNSS system will have to have a high degree of availability.	Adversarial actions such as jamming and spoofing may prove to be essential technical hurdles.

Table 16: validation exercise #01 assumptions overview

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A.2 Deviation from the planned activities

During the work, objective 2.2 was amended from:

"Objective 2.2: Determination 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 as produced in line with the SESAR SRM method for TRL2, namely collision and wake encounter risk, demonstrates adherence to the target level of safety (TLS) and the initial capacity analysis delivers demonstrable capacity benefits."

to:

"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."

Initial calculations showed that it was not certain that the TLS could be met for the RVSM 2 concept, which sparked a discussion. In order to meet the TLS and thereby to achieve the project objectives the concept may have had to be updated. The design of such a concept however is an iterative process, and fully solving all possible challenges would exceed the scope of the Green-GEAR project. In addition, the objective of a safety assessment should be to assess the safety of a system and not to judge the safety of system as sufficient.

Therefore, it was decided to amend the objective and success criterium. Instead of proving that the concept is safe, the maximally allowed risk was fixed with a TRL and requirements on the relevant subsystems were derived. The solution thereby aimed to identify the factors that are crucial to the introduction of the concept and serve as a basis for future research and design.

A.3 Validation exercise #01 results

A.3.1 Summary of validation exercise #01 results

SESAR solution validation objective ID and title	SESAR solution success criterion and ID	SESAR solution validation results	SESAR solution validation objective status
GreenGEAR-0407-TRL2-ERP-OBJ01.1 Provision of validated tools to quantify collision risk	**GreenGEAR-0407-TRL2-ERP-CRT01.1** The collision risk analysis results compare favourably	The collision risk was determined using the ICAO collision risk model. This model was adjusted to the RVSM 2 airspace.	OK

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for chosen scenarios employing novel concept for reduced vertical separation minima.	to observations when applied to current operations and show plausible figures for the new concept.		
GreenGEAR-0407-TRL2-ERP-OBJ02.1 To determine whether RVSM 2 can be safely introduced from a collision risk perspective and identify the most important challenges.	**GreenGEAR-0407-TRL2-ERP-CRT02** The collision risk does not exceed the TLS of $2.5*10^{-9}$ fatal accidents per flight hour.	The technical risk could possibly be met by a small margin. However, regulatory and legislative aspects will likely pose a significant, possibly insurmountable challenge.	Partially OK
	GreenGEAR-0407-TRL2-ERP-CRT03 Quantification of the maximum TVE required to meet the TLS.	The collision risk analysis determined restrictions of the maximum allowable TVE to meet the TLS. This TVE is the sum of the ASE and the FTE. A mathematical analysis was executed to comprehend the condition on the TVE distribution in terms of the ASE and FTE distributions.	OK
GreenGEAR-0407-TRL2-ERP-OBJ3.1 To Identify potential showstoppers for capacity increase for RVSM 2 from collision risk perspective.	**GreenGEAR-0407-TRL2-ERP-CRT06.1** Initial capacity analysis from collision risk perspective does not preclude demonstrable capacity benefits.	In order to calculate the maximally allowable ASE and FTE, certain parameters of the future operations were estimated, such as the probability of lateral overlap, kinematic factor and the passing frequency. However, a generous margin was applied to the parameters, such that if operational circumstances change (e.g. passing frequency increases by growing amount of traffic, or lateral navigation accuracy improves) the overall technical risk is still lower than the TLS.	OK

Table 17: validation exercise #01 results

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A.3.2 Analysis of validation exercise #01 results per validation objective

A.3.2.1. GreenGEAR-0407-TRL2-ERP-OBJ01.1 Results

The first validation objective is the provision of validated tools to quantify collision risk for chosen scenarios employing a novel concept for reduced vertical separation minima. For the quantification of the collision risk, use is made of the ICAO Collision Risk Model (ICAO CRM). The ICAO CRM is a mathematical model that can be applied to aircraft flying at assigned flight levels, vertically separated by n (n = 1,2,3…) times the minimal vertical separation distance (S_z). [29]

Using the CRM, the expected number of fatal accidents per flight hour is determined. This is then compared to a pre-determined TLS to determine whether the operation is safe. More information into the specifics of the model and its assumptions can be found in [29].

The current ICAO CRM holds for RVSM airspace. Therefore, in order to use it in an RVSM 2 setting, a couple of things have to be adjusted:

1. Adopt the TLS of RVSM;
2. Adapt the ICAO CRM to RVSM 2;
3. Derive the requirements on the altitude-keeping performance;
4. Translate this into conditions on the ASE and FTE distributions;
5. Verify whether these conditions can be expected to be met, given the current state of technology.

With the adjusted model, the height keeping performance (i.e. TVE) can be determined. This is done for the two potential distributions of the TVE, the Laplace and normal distribution. For the Laplace distribution is holds that the standard deviation of the TVE should be equal or less than 34 ft, for the normal distribution this value is 58 ft.

With the provision of the validated, further developed method for collision risk estimation criterion GreenGEAR-0407-TRL2-ERP-CRT01.1 for this objective is met.

A.3.2.2. GreenGEAR-0407-TRL2-ERP-OBJ02.1 Results

Green-GEAR-0407-TRL2-ERP-CRT02

The second validation objective is to determine whether RVSM 2 can be safely introduced from a collision risk perspective and identify the most important challenges. The success of this objective is determined using two criteria. The first of them is whether the collision risk does not exceed the TLS of $2.5*10^{-9}$ fatal accidents per flight hour.

In order to pass this criterion, the TVE standard deviation requirements as stated in section 4.2.1 should be met. However, in order to assess whether this can be met, the ASE and FTE should be assessed as they make up the TVE. The trade-off between the two error sources is depicted in Figure 8.

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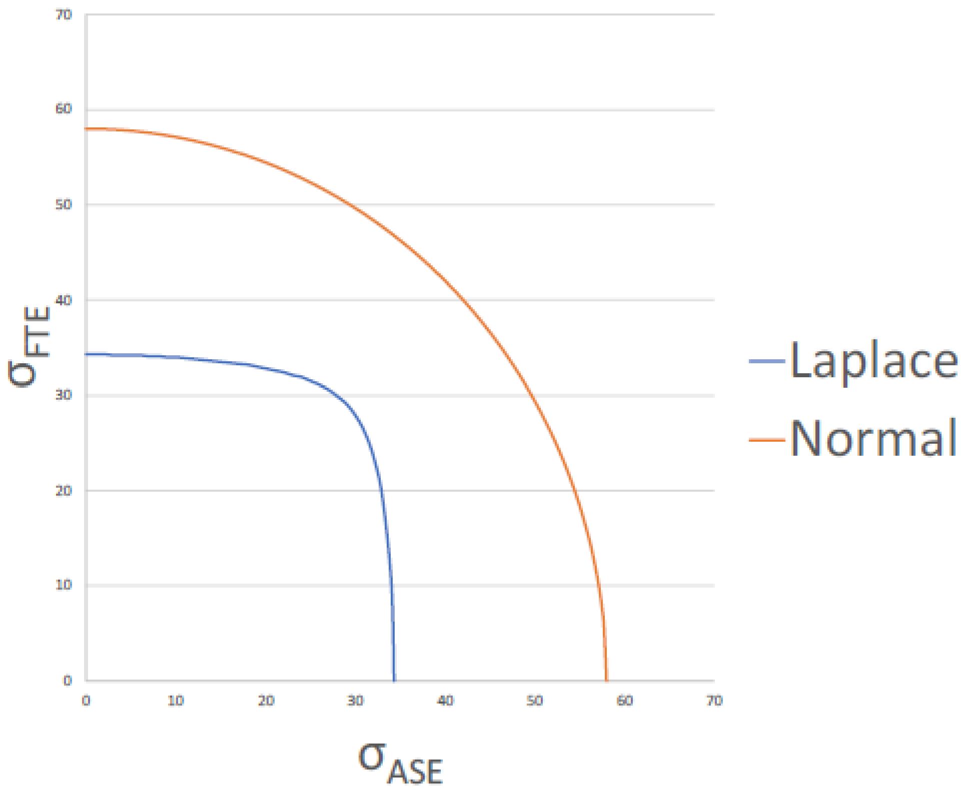

Figure 8: the maximal value of the standard deviation σ2 of the variable X2 to meet the TLS of 500 ft vertical separation, given the standard deviation σ1 of the variable X1 and given that the TVE is a sum of two independent variables X1 and X2 with X1 and X2 both Laplace (orange curve) or normal (blue curve), with zero mean. [29]

According to the currently applicable MASPS for RVSM approved aircraft, the FTE distribution has a standard deviation σ_{FTE} of maximally 43 ft. This value is insufficient to meet the ASE/FTE standard deviation restriction when assuming a Laplace distribution, as can be seen in Figure 8. So, if the current MASPS are the reference, RVSM 2 cannot be implemented sufficiently safe. There might however be an escape from this negative first conclusion. The value of the standard deviation σ_{FTE} as currently estimated in the ICAO EUR region is 33 ft. This would be just sufficient to meet the ASE/FTE standard deviation restriction if the standard deviation σ_{ASE} is 20 ft or less.

The ASE distribution within the RVSM 2 concept corresponds to the accuracy of the estimates of the altitude by means of GNSS. The performance of a GNSS system is described by many different parameters, of which the Vertical Positioning Error (VPE) is taken as the ASE.

In order to describe the magnitude of GNSS errors, research is done into the accuracy of GPS and Galileo. Furthermore, several options are considered such as Single Frequency (SF) and Dual Frequency (DF) signals, multi-GNSS navigation and the use of augmentation systems. In Table 11, an overview is given of the specified vertical positioning accuracy at average and worst user location. It can be concluded from this table that the performance is not sufficient to meet TLS.

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	AUL	WUL
GPS Single Frequency	13 m	33 m
Galileo Single Frequency	8 m	16 m
Galileo Dual Frequency	8 m	16 m

Table 18: GPS and Galileo OS specified vertical positioning accuracy (95%)at average and worst user location. [44][35]

However, both Galileo and GPS report their actual performance on a quarterly basis. The average VPE of the actual performance is shown in Table 12. Figure 9 shows the behaviour of the VPE through time and provides insight on how the values in Table 12 are obtained. It can be seen that this performance is much better than the specified performance. However, there is no guarantee that this performance is *always* achieved.

	VPE (95%)	VPE (1σ)
GPS Single Frequency	3.98 m = 13.1 ft	2.03 m = 6.7 ft
Galileo Dual Frequency	3.35 m = 11.0 ft	1.71 m = 5.6 ft

Table 19: average VPE (95%) of GPS and Galileo from quarterly performance reports. The values for GPS are the average of the average VPE per day for two quarters. The values of Galileo are said to not have exceeded these values on a per month basis for two months. [46][47][48][49]

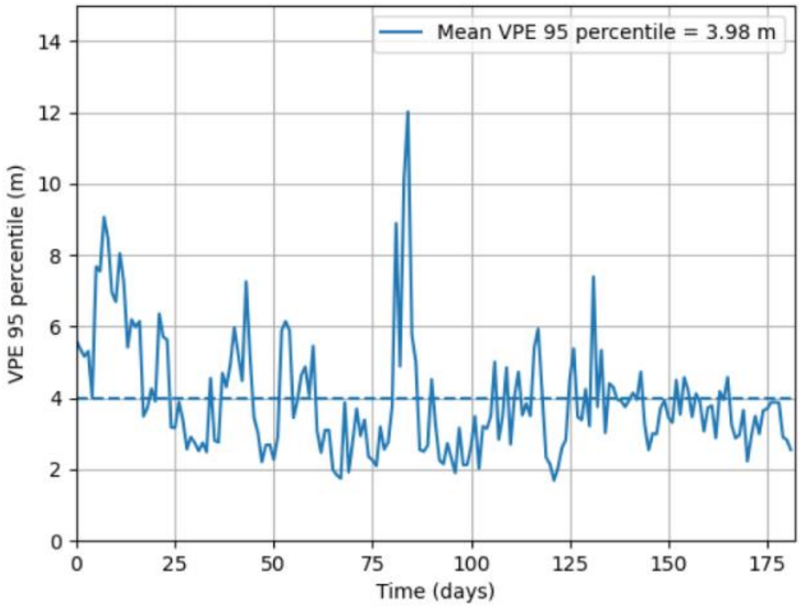

Figure 9: VPE 95 percentile from the GPS Performance Quarterly Report 1 and 2 of 2024. [46][47]

LIABILITY

To conclude, the validation objective status concerning the first success criterion is determined *Partially OK*. The TLS of $2.5*10^{-9}$ fatal accidents per flight hour can be met. However, this is dependent on the actual performance of the GNSS under consideration. Therefore, RVSM 2 could be introduced safely, considering technical risk only, if, apart from some relevant technicalities, it can be somehow be guaranteed that: $\sigma_{ASE} \leq 20$ ft; $\sigma_{FTE} \leq 33$ ft. Even if these conditions cannot be met, there might be an escape by for example showing that both the FTE and ASE distributions are normal. In that case, it would be sufficient to show that both standard deviations σ_{FTE} and σ_{ASE} are 40 ft or less.

Green-GEAR-0407-TRL2-ERP-CRT03

The second success criterion is the quantification of the maximum TVE required to meet the TLS. The validation objective status concerning this second success criterion is determined *OK*. As can be seen in the above section, the maximum TVE required to meet the TLS is calculated and depends on the distribution of the error source.

A.3.2.3. GreenGEAR-0407-TRL2-ERP-OBJ03.1 Results

The third and last objective of this exercise is to identify potential showstoppers for capacity increase for RVSM 2 from collision risk perspective. In order to calculate the maximally allowable ASE and FTE, certain parameters of the future operations were estimated, such as the probability of lateral overlap, kinematic factor and the passing frequency. However, a generous margin was applied to the parameters, such that if operational circumstances change (e.g. passing frequency increases by growing amount of traffic, or lateral navigation accuracy improves) the overall technical risk is still lower than the TLS.

Hence initial capacity analysis from collision risk perspective does not preclude demonstrable capacity benefits from RVSM 2; this observation means fulfilment of the success criterion GreenGEAR-0407-TRL2-ERP-CRT06.1.

A.3.3 Unexpected behaviours/results

There was no unexpected behaviour or result in the preparation, execution or analysis of the validation exercise.

A.3.4 Confidence in results of validation exercise #01

A.3.4.1. Level of significance/limitations of validation exercise results

The limitations of the validation results lie in the assumptions made in the research. For example that the future airspace structure will be similar to the current one and so will be operations. Furthermore, the fleet was assumed to be the same in the RVSM 2 airspace, in terms of fleet mix and propulsion systems. Finally, the assumption was made that jamming and spoofing of GNSS signals do not influence the operation. However, this is a major problem in GNSS navigation nowadays and it should be investigated how this issue can be dealt with in the RVSM 2 concept.

A.3.4.2. Quality of validation exercises results

In order to estimate current altimetry and height keeping performance, the most accurate values for the ASE and FTE were used that are available. Nevertheless, it is desirable that the accuracy of these parameters improves. Current ASE performance was checked by considering the Vertical Positioning Error (VPE) from the GPS and Galileo quarterly reports. These figures however were collected with a stationary receiver in standardised conditions. I would be preferable to obtain GNSS accuracy data directly from typical aircraft borne GNSS receivers.

In addition, the FTE data (approximated by the Assigned Altitude Deviation (AAD)) resulted from data collected using mode C, which has a granularity of 100 ft increments. Since the maximally allowed ASE and FTE are close to the values obtained from actual performance data, it is desirable collect more accurate figures.

In order to calculate the maximally allowable ASE and FTE, certain parameters of the future operations were estimated, such as the probability of lateral overlap, kinematic factor and the passing frequency. However, a generous margin was applied to the parameters, such that if operational circumstances change (e.g. passing frequency increases by growing amount of traffic, or lateral navigation accuracy improves) the overall technical risk is still lower than the TLS.

A.3.4.3. Significance of validation exercises results

For the collision risk study, the established ICAO model has been used with the necessary adaptations. This corresponds to what would be done pre-implementation and is therefore sufficiently representative. The significance of these results is hence determined by the accuracy of the input data, as explained above.

A.4 Conclusions

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 collision risk is dependent on the sum of the ASE and FTE, also named the Total Vertical Error. 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 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.

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, GPS nor Galileo assume legal responsibility regarding the system performance, and it is not guaranteed that past performance levels will always be met.

A.4.1 Conclusions on concept clarification

See section 5.1.2 in the main body.

A.4.2 Conclusions on technical feasibility

See section 5.1.3 in the main body.

A.4.3 Conclusions on performance assessments

See section 5.1.4 in the main body.

A.5 Recommendations

The main recommendations from the CRA are:

- The CRA showed that the TVE, and consequently the FTE is a crucial factor in determining whether the collision risk will be within the TLS for RVSM 2. The only FTE data available in this study however is 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. This analysis could be done directly from the available data, or could be done in close coordination with the part of EUROCONTROL that is responsible for the EUR RMA CRA.

- The ASE is the second term in the TVE, next to the FTE. The values for the ASE used in the CRA are based on GPS and Galileo Quarterly Performance Reports. Even though this seems to be most representative data available, a more accurate characterisation reflecting the high-altitude aviation domain and possibly typical aircraft equipment is recommended.

- 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. The 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 should likely include the broader aviation sector on the discussion.

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Appendix B Validation exercise #02 report

B.1 Summary of the validation exercise #02 plan

This validation exercise was executed as described in the ERP [28]. More specifically, the approach was to perform fast-time simulations of large traffic scenarios. A detailed description of this approach can be found in [30].

B.1.1 Validation exercise description and scope

A wake turbulence risk analysis has been performed in order to determine the influence of RVSM 2 on the probability and severity of wake vortex encounters. Therefore, a previously developed software toolbox has been adapted and used for a statistical evaluation of the wake vortex encounters in a traffic scenario. Also, a hazard assessment of these encounters has been performed. Because the risk of hazardous wake vortex encounters due to the introduction of RVSM 2 has been assessed as unacceptably high, additional methods of risk mitigation have been suggested.

B.1.2 Summary of validation exercise #02 validation objectives and success criteria

The first validation objective of exercise #02 is the provision of validated tools to quantify wake turbulence risk for chosen scenarios employing a novel concept for reduced vertical separation minima, contributing to the overall objective GreenGEAR-0407-TRL2-ERP-OBJ01. The second validation objective is to determine whether RVSM 2 can be safely introduced from wake turbulence risk perspective and identify the most important challenges, contributing to the overall objective GreenGEAR-0407-TRL2-ERP-OBJ02. Finally, the exercise tries to identify showstoppers to a potential capacity increase from the wake turbulence risk perspective, contributing to overall objective GreenGEAR-0407-TRL2-ERP-OBJ03. This is summarised in Table 20.

SESAR solution validation objective ID and title	SESAR solution success criterion and ID
GreenGEAR-0407-TRL2-ERP-OBJ01.2 Provision of validated tools to quantify wake turbulence risk for chosen scenarios employing novel concept for reduced vertical separation minima.	**GreenGEAR-0407-TRL2-ERP-CRT01.2** The wake turbulence risk analysis results compare favourably to observations when applied to current operations and show plausible figures for the new concept.
GreenGEAR-0407-TRL2-ERP-OBJ02.2 To determine whether RVSM 2 can be safely introduced from a wake turbulence risk perspective and identify the most important challenges.	**GreenGEAR-0407-TRL2-ERP-CRT04** The wake encounter risk is not unacceptably increased compared with current operations.
GreenGEAR-0407-TRL2-ERP-OBJ03.2 To Identify potential showstoppers for capacity increase for RVSM 2 from wake turbulence risk perspective.	**GreenGEAR-0407-TRL2-ERP-CRT06.2** Initial capacity analysis from wake turbulence risk perspective does not preclude demonstrable capacity benefits.

Table 20: validation exercise #02 objectives and success criteria.

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B.1.3 Summary of validation exercise #02 validation scenarios

The risk assessment is made relatively by comparing a **full-day scenario** for the EUR region under current separation rules with a modified scenario with vertical separation minima reduced to 500 ft. Because of wake transport being strongly influenced by the wind, two days with particularly high and particularly low wind speeds in the relevant altitude band are investigated. The two days with particularly high and particularly low wind speeds in the relevant altitude band for the chosen year are 14th February 2014 and 3rd June 2014, respectively.

For both full-day scenarios, the reference scenario is an original traffic sample that comprises flight plan trajectories based on flight levels with the current separation scheme (1000 ft vertical separation in RVSM airspace). The solution scenario is a modified version of the same traffic samples based on flight levels with 500 ft vertical separation. Details about the modification of the traffic samples can be found in [30]. This results in four full-day scenarios: the low-wind-speed scenario and the high-wind-speed scenario both with 1000 ft vertical separation and with 500 ft vertical separation.

In order to provide a more detailed analysis of the wake encounter severity, additional sub-scenarios have been simulated in which the RCR limit has been changed from 0.2 to 0.5 or 1.0 respectively. 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.

Because the traffic samples contain about 20,000 trajectories each and because the simulations are performed over a full day with a temporal resolution of one second, the calculation of the wake corridors and their temporal evolution as well as the detection of wake encounters require a high computational effort of a few days for one full-day scenario. Thus, for the twelve sub-scenarios in total, several weeks of calculation time have been required for each simulation run. Because additional refinements of the simulation models have been implemented in an iterative process, several full simulation runs that required many weeks of calculation time have been performed. Therefore, it should be emphasised that the computational effort is an important issue for such an analysis with this number of simulation scenarios.

B.1.4 Summary of validation exercise #02 validation assumptions

The following validation assumptions are applicable to the present validation exercise on top of those Solution-level ones identified in section 3.2.3.

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Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
GreenGEAR-0407-TRL2-ERP-ASS08	Traffic mix – Aircraft manoeu-vrability	Any non-conventional future aircraft configurations are assumed to have at least the same attitude control power as existing conventional ones, meaning it is a conservative assumption to apply the same weight-dependent resistance to wake encounters.	Although many preliminary concepts exist, they are much too far from introduction to allow assumptions on their flight control performance.	The frequency of wake encounters cannot be made negligible while maintaining any capacity. Current safety levels are ensured by the fact that the vast majority of encounters are not hazardous.

Table 21: validation exercise #02 assumptions overview

B.2 Deviation from the planned activities

During the work, objective 2.2 was amended from:

"Objective 2.2: Determination 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 as produced in line with the SESAR SRM method for TRL2, namely collision and wake encounter risk, demonstrates adherence to the target level of safety (TLS) and the initial capacity analysis delivers demonstrable capacity benefits."

to:

"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."

Initial calculations showed that it was not certain that the TLS could be met for the RVSM 2 concept. The (iterative) design of an updated concept, however, is an iterative process, and fully solving all possible challenges would exceed the scope of the Green-GEAR project. In addition, the objective of a safety assessment should be to assess the safety of a system and not to judge the safety of system as sufficient. Therefore, it was decided to amend the objective and success criterion. It was aimed to identify the factors that are crucial to the introduction of the concept and serve as a basis for future research and design. The capacity potential could thus only be initially estimated.

One deviation from the planning is that due to problems with the **weather data provision** – a change of model and data format by the German Weather Services, whose COSMO-EU model is the input for the weather data interpolation rather than the ECMWF data used for the analyses of the wind situation – it was not possible to use traffic data from 2019 as originally planned. Therefore, an existing scenario from 2014 was used as fall-back.

Additionally, the original project plan did not foresee the development of a **traffic scenario** for RVSM 2 that could be usable for the fast-time simulation, as it was erroneously assumed that this would be a by-product of the collision risk study. Based on the cruise level distribution on European airspace for a reference day, a concept for the compression of traffic towards certain 'pivotal' flight levels was developed: aircraft tend to concentrate slightly above the lower RVSM boundary and especially around FL380, the latter the typical economical cruise altitude for jet transports (see [30] for more details). There is no reason to assume that after a reduction of vertical separation minima aircraft will be distributed more evenly over altitude; on the contrary, the finer granularity of the altitudes allows an even higher concentration.

B.3 Validation exercise #02 results

B.3.1 Summary of validation exercise #02 results

Exercise #02 validation objective	Exercise #02 success criterion	Sub-operating environ-ment	Exercise #02 validation results	Exercise #02 validation objective status
GreenGEAR-0407-TRL2-ERP-OBJ01.2 Provision of validated tools to quantify wake turbulence risk for chosen scenarios employing novel concept for reduced vertical separation minima.	**GreenGEAR-0407-TRL2-ERP-CRT01.2** The analysis results compare favourably to observations when applied to current operations and show plausible figures for the new concept.	En-route	For the wake turbulence risk the modelling results have been related to and were found to be in accordance with other studies and practical observations (pilot feedback). Their *possible* severity is rather an overestimation of the actual effects in most cases so must not be taken as a statement on actual severity, but consistence and plausibility of the results gives confidence that the relative comparison of the current operations and the proposed RVSM 2 scenario is valid.	OK

GreenGEAR-0407-TRL2-ERP-OBJ02.2 To determine whether RVSM 2 can be safely introduced from a wake turbulence risk perspective and identify the most important challenges.	**GreenGEAR-0407-TRL2-ERP-CRT04** The wake encounter risk is not unacceptably increased compared with current operations.	En-route	The simulation results show that the wake encounter risk is substantially increased (by a factor of three to four for occurrence with small changes in severity). A possible mitigation would be a safety net in the shape of an airborne or ground-based tool that predicts potentially hazardous wake encounters and suggests corrective action.	NOK
GreenGEAR-0407-TRL2-ERP-OBJ03.2 To Identify potential showstoppers for capacity increase for RVSM 2 from wake turbulence risk perspective.	**GreenGEAR-0407-TRL2-ERP-CRT06.2** Initial capacity analysis from wake turbulence risk perspective does not preclude demonstrable capacity benefits.	En-route	Even with current traffic levels the new flight levels could not be used in an unrestricted way if one assumes that separation modes are unchanged; a relative increase of the wake vortex encounter risk by a factor of three to four is predicted. However, the introduction of procedural or technical risk mitigation is conceivable; suggestions are made.	Partially OK

Table 22: validation exercise #02 results

B.3.2 Analysis of validation exercise #02 results per validation objective

The wake turbulence risk has been evaluated in fast-time simulations; the input is a traffic sample from a Network Flow Environment (NFE) on which basis 4D flight plan trajectories are generated. The algorithm predicts the evolution of the generator’s flight path and state taking into account the prevailing weather, and based on this the evolution (transport and decay) of its wake using the well-established P2Pa model [60][61][62]. Once temporal and geometric proximity between a potential encounter aircraft (that may actually fly an opposite course at a different altitude) and the so-called generator is found, a conflict detection is initiated. An encounter is identified if the aircraft’s flight path crosses the predicted habitation volume of the generator’s wake. The possible severity of the encounter if it occurs is subsequently assessed with the SHAPe method [58][59].

Note that after a few minutes, due to uncertainties in atmospheric parameters, these probable habitation volumes grow significantly larger than the follower’s physical dimensions so that a passing of the corridor need not mean an actual encounter. Indeed, during initial simulations, it became clear that a full probabilistic approach is not productive as it masks the changes in separation through the sheer extent of the *possible* wake locations. Eventually, a combination of deterministic and probabilistic elements was employed. Details on the modelling approach can be found in chapter 4 of [30].

The risk assessment is made relatively by comparing a **full-day scenario** for the EUR region under current separation rules with a modified scenario with vertical separation minima reduced to 500 ft. A statistical analysis of traffic in RVSM airspace has revealed a predominant occupation of FL350 to FL400, with the maximum traffic density at FL380 (see Figure 10). Because of wake transport being strongly influenced by the wind, two days with particularly high and particularly low wind speeds in the relevant altitude band are investigated. The two days with particularly high and particularly low wind speeds in the relevant altitude band for the chosen year are 14th February 2014 and 3rd June 2014, respectively.

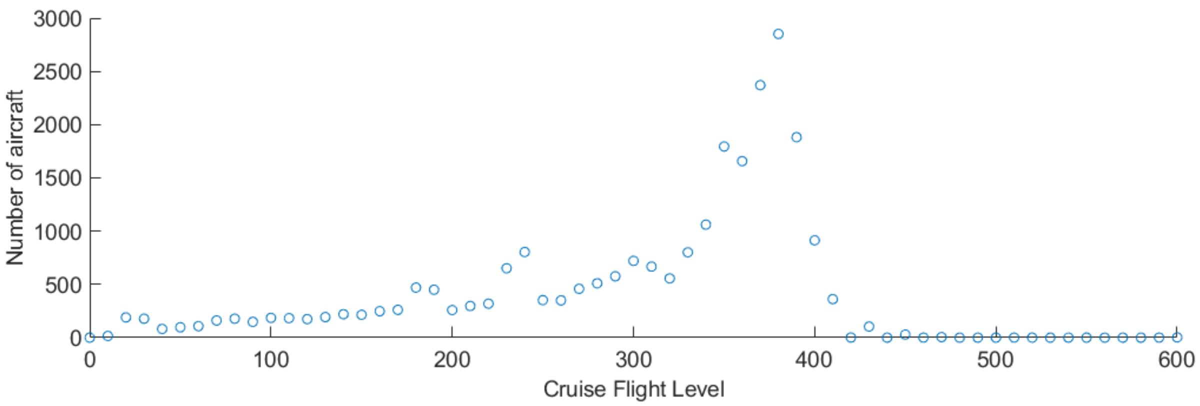

Figure 10: plot of occupancy numbers over cruise flight level for 14th February 2014

B.3.2.1. GreenGEAR-0407-TRL2-ERP-OBJ01.2 Results

GreenGEAR-0407-TRL2-ERP-OBJ01.2

Provision of validated tools to quantify wake turbulence risk for chosen scenarios employing novel concept for reduced vertical separation minima.

This being a pioneering study, no references for the Solution scenario, i.e. reduced vertical separation with geometric altimetry, are available. However, as a validation of the comparative approach, we relate our results for the reference scenario (existing vertical separation with barometric altimetry) to the, albeit scarce, available studies.

An aircraft wake vortex encounter analysis for upper airspace is presented by Schumann et al. [63]. The analysis comprises 46 days of air traffic (radar observations) for North America in combination with meteorological data (numerical weather prediction model “Weather Research and Forecasting Rapid Refresh model” [64]). Wake vortex descent and decay are considered with an established two-phase wake evolution model [62][60] based on atmospheric stratification and turbulent-kinetic-energy dissipation rate, and the advection with ambient horizontal and vertical wind. A wake encounter is defined based on the distance between encountering aircraft and wake centreline and wake induced lift and rolling moment. Results are validated against pilot reports and automated in situ turbulence reports. Most encounters are found for medium-sized aircraft on nearly parallel flight tracks during descent. Only a very small part of the identified encounters occurs for horizontal flight of both aircraft. En-route wake encounters with wakes of heavy aircraft flying 1000 ft above are relatively rare. Of the latter encounters, most are at slant or perpendicular angles. Severe encounters with large wake induced vertical force or rolling moment are relatively rare. Hence most of the identified encounters can be considered as less safety critical.

Potential wake turbulence encounters for state-of-the-art and future “NextGen” flight operations for North America are simulated with a dedicated Wake Encounter Model in [65]. Simulation results are considered by the authors of that study to overestimate the number of relevant wake encounters and the underlying models may require adjustment. As a reference, it is referred to the NASA Aviation Safety Reporting System (ASRS) listing 389 reported wake encounters in the period 2009 – 2012.

An analysis by DLR (only documented with a DLR report in German) of the NASA Aviation Safety Reporting System is listing 488 wake encounter report in the period February 1999 – November 2009. 58 cases of these included injuries and/or damage. 25% of these are for the en-route flight phase [66].

A simulation for en-route wake encounters by Delft University of Technology and EUROCONTROL is aiming to identify reported wake encounters [35]. Apart from the size of the wake generating aircraft, situations with climb or descent have increased risk of wake encounters. Furthermore, below the tropopause atmospheric conditions are found to be favourable for wake persisting for a longer time. Long-living wake particularly for heavier aircraft with a maximum take-off mass higher than 350,000 kg may potentially descend to the next usable flight level (1000 ft below). The simulation study is reproducing 75% of 12 analysed wake encounter reports based on available data. Between July 2009 and July 2012, 73 wake turbulence incidents above 5000 ft were reported, 26 of which above FL285, which is considered upper airspace in Europe [35].

A study of en-route wake encounters and implications for Reduced Vertical Separation Minima (RVSM) is presented by Woodfield [35]. Vortices are considered to be possibly present for up to about 2-3 minutes in calm conditions, equivalent to a distance of around 16-25 nm (30-46 Km) in high altitude cruise conditions. Usually vortices are found to only descend about 400-500 ft before becoming uncritical, but occasionally they will descend further and be encountered by aircraft flying only 1000 ft below when Reduced Vertical Separation Minima (RVSM) are in operation. On even fewer occasions vortices may rise above the flight level of the generating aircraft.

Brown and Holzäpfel [57] discuss in-situ measurements of the wakes of aircraft of the HEAVY and SUPER category, which have been made with a probe aircraft against a small number of actual flights. The small number of test cases does not allow to deduct any statistical observations but confirms that downward travel of 2000 ft of an initially sufficiently strong vortex can occur under the right atmospheric conditions, as predicted by the P2Pa vortex model.

In summary, it can be said that the main findings in literature studies generally coincide with the outcome of the present investigation. No contradictions are found, so the results can be regarded as reasonable. Particularly specific effects like in some cases vortices descending 1000 ft or more or even ascending are identified in agreement.

For any assessment of the risk, the aspect of wake encounter severity is essential, including effects of encounter geometry. This is not fully covered in any of the studies so far and is expected to require

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further detailed analyses. Generally, it can be observed that the crossing of a wake where forces or moments beyond the aircraft's control capabilities *could* be generated needs to be regarded as hazardous from a safety point of view *in the absence of further information*, but these effects may only persist for a fraction of a second and need not lead to relevant consequences on practical operations. It is actually quite common that atmospheric disturbances, particularly in convective weather, temporarily exceed the aircraft's control capabilities, i.e. could not be fully counteracted even in the hypothetical case of a perfect feed-forward control system.

The frequencies of encounters observed in the present simulation is in accordance with other studies and albeit anecdotical practical observations (pilot feedback) – wake encounters that are discernible as such but not a safety issue are actually quite frequent. Their *possible* severity is rather an overestimation of the actual effects in most cases so must not be taken as a statement on actual severity, but we can safely conclude from the above considerations that the relative comparison of the current operations and the proposed RVSM 2 scenario is valid.

Evaluation of criterion GreenGEAR-0407-TRL2-ERP-CRT01.2

In summary, it can be said that the results meet the expectations of success criterion GreenGEAR-0407-TRL2-ERP-CRT01.2: "The analysis results compare favourably to observations when applied to current operations and show plausible figures for the new concept."

B.3.2.2. GreenGEAR-0407-TRL2-ERP-OBJ02.2 Results

GreenGEAR-0407-TRL2-ERP-OBJ02.2

To determine whether RVSM 2 can be safely introduced from a wake turbulence risk perspective and identify the most important challenges.

The main results of this analysis can be found in 4.2.2.3. More details about these results are shown here in this appendix.

The wake encounters have also been categorised according to the wake turbulence category (WTC) of the wake generator and the follower aircraft. The results of this categorisation are shown in Table 23 and Table 24 for the low-wind-speed scenario and in Table 25 and Table 26 for the high-wind-speed scenario. For a very small number of trajectories, no aircraft type has been provided in the traffic data and therefore no WTC could be determined. Thus, these few encounters are not represented in the following tables. Wake vortices of aircraft of the WTC "light" have not been calculated but they have been conflict checked as follower aircraft. It is clearly visible that, for the aircraft types included in the data, most encounters happen to medium aircraft behind other medium aircraft or to medium aircraft behind heavy aircraft. This corresponds to the high ratio of these aircraft types in the traffic mix. No conflicts have been found for "light" encounter aircraft. Actually, the number of light aircraft in the RVSM airspace is very low in the traffic sample, with even most business jets already categorised as "medium". Therefore, a number of zero encounters for "light" encounter aircraft is statistically reasonable, but this does not mean that "light" encounter aircraft are not susceptible to wake encounters – a wake encounter with a "light" encounter aircraft just did not happen by chance in the analysed scenarios. On the other hand, some encounters happen to heavy aircraft and a few encounters even to A380 aircraft, which are the only aircraft in the category "super". This modelling result is in line with observations that show that even the A380 can be affected by wake vortices [75].

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Wake Turbulence Category (WTC)		Follower			
		Light	Medium	Heavy	Super
Wake Generator	Light	0	0	0	0
	Medium	0	501	48	3
	Heavy	0	189	32	2
	Super	0	15	1	0

Table 23: categorisation of the wake encounters by wake turbulence categories for the low-wind-speed scenario with 1000 ft separation

Wake Turbulence Category (WTC)		Follower			
		Light	Medium	Heavy	Super
Wake Generator	Light	0	0	0	0
	Medium	0	2023	197	6
	Heavy	0	505	75	4
	Super	0	36	8	0

Table 24: categorisation of the wake encounters by wake turbulence categories for the low-wind-speed scenario with 500 ft separation

Wake Turbulence Category (WTC)		Follower			
		Light	Medium	Heavy	Super
Wake Generator	Light	0	0	0	0
	Medium	0	218	20	0
	Heavy	0	95	17	2
	Super	0	9	1	0

Table 25: categorisation of the wake encounters by wake turbulence categories for the high-wind-speed scenario with 1000 ft separation

Wake Turbulence Category (WTC)		Follower			
		Light	Medium	Heavy	Super
Wake Generator	Light	0	0	0	0
	Medium	0	1061	76	3
	Heavy	0	271	33	1
	Super	0	15	2	0

Table 26: categorisation of the wake encounters by wake turbulence categories for the high-wind-speed scenario with 500 ft separation

For all encounters with an RCR above the threshold of 0.2, a categorisation by the distance between the two aircraft at the start time of the encounter is shown in Table 27 and Table 28 for the low-wind-speed scenario and in Table 29 and Table 30 for the high-wind-speed scenario. To provide an easier overview of the tables, arbitrary colours have been used to indicate the range of the values. It is clearly visible that the self-induced descent of the wake vortices results in the vertical separation of the encounters shifting towards negative values (i.e. the follower aircraft is below the wake generator) with most encounters happening slightly below the wake generator at a distance between 5 NM and 15 NM. When the vertical separation is reduced to 500 ft, there is a strong increase of the overall number of encounters with most of the encounters at a vertical separation of 500 ft below the wake generator. These encounters are not shifted from 1000 ft separation to 500 ft separation, but instead these are completely new encounters that do not happen at 1000 ft separation at all. Some encounters that happen in the scenarios with 1000 ft separation are avoided with 500 ft separation when the wake vortices descend fast enough to be already more than 500 ft below the wake generator at the time of a possible encounter, but it is clearly visible that when reducing the separation to 500 ft, the generation of new encounters heavily outweighs the avoidance of some encounters and thus results in a much higher total number of encounters.

Some encounters can be found at positive vertical separations (i.e. the follower aircraft is above the wake generator) with the vertical separation even being above 2000 ft in some cases, but this does not mean that the wake vortices have ascended more than 2000 ft. While it is true that in some weather conditions, wake vortices can actually ascend to higher altitudes, the encounters with a positive vertical separation primarily happen when the wake generator is descending and therefore at a lower altitude than the follower at the time of the encounter. The same principle applies to some encounters below the altitude of the wake generator that are not only a result of the self-induced descent of the wake vortices but can also result from the wake generator climbing to a higher altitude until the follower aircraft reaches the wake vortices.

When comparing the low-wind-speed and the high-wind-speed scenario, it can be seen that the overall number of encounters is decreasing with increasing wind speed as described in section 4.2.2.3, but the effects that are visible in these tables remain independent of the wind speed.

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Distance at the start of the wake encounter		Horizontal distance [NM]						
		[0 ; 5)	[5 ; 10)	[10 ; 15)	[15 ; 20)	[20 ; 25)	[25 ; 30)	[30 ; ∞)
Vertical distance of the follower in reference to the wake creator [ft]	(2000 ; ∞)	0	20	27	20	10	4	1
	2000	0	4	1	0	0	0	0
	(1500 ; 2000)	7	9	1	0	1	0	0
	1500	0	0	0	0	0	0	0
	(1000 ; 1500)	21	1	1	0	0	0	0
	1000	1	0	2	0	0	0	0
	(500 ; 1000)		2	4	0	0	0	0
	500		0	0	0	0	0	0
	(0 ; 500)		8	2	1	0	0	0
	0		179	14	7	2	0	0
	(-500 ; 0)		82	30	9	0	1	0
	-500		2	1	0	0	0	0
	(-1000 ; -500)		59	22	18	9	1	1
	-1000	0	6	16	21	30	14	10
	(-1500 ; -1000)	3	24	7	3	4	1	0
	-1500	0	0	0	0	0	0	0
	(-2000 ; -1500)	0	13	7	4	3	0	0
	-2000	0	1	1	5	1	0	0
	(-∞ ; -2000)	1	0	12	12	3	1	3

Table 27: categorisation of the wake encounters by the distance between the two aircraft in the low-wind-speed scenario with 1000 ft minimum vertical separation (grey area is below the minimum horizontal and vertical separation and thus would be prevented by the air traffic controller)

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Distance at the start of the wake encounter		Horizontal distance [NM]						
		[0 ; 5)	[5 ; 10)	[10 ; 15)	[15 ; 20)	[20 ; 25)	[25 ; 30)	[30 ; ∞)
Vertical distance of the follower in reference to the wake creator [ft]	(2000 ; ∞)	1	20	43	18	6	3	0
	2000	0	0	0	0	0	0	0
	(1500 ; 2000)	5	13	3	2	0	0	0
	1500	0	0	1	1	0	0	0
	(1000 ; 1500)	14	5	2	1	0	0	0
	1000	0	1	0	0	1	0	0
	(500 ; 1000)	31	5	3	1	0	0	0
	500	0	5	5	0	0	0	0
	(0 ; 500)		10	9	1	1	0	0
	0		115	13	3	2	0	0
	(-500 ; 0)		126	40	9	3	1	0
	-500	89	670	972	244	36	2	2
	(-1000 ; -500)	26	76	59	27	9	3	1
	-1000	0	6	19	3	3	1	0
	(-1500 ; -1000)	1	19	13	3	1	1	0
	-1500	0	0	5	1	1	0	1
	(-2000 ; -1500)	0	3	7	1	0	0	0
	-2000	0	1	1	0	0	0	0
	(-∞ ; -2000)	1	1	11	12	2	0	0

Table 28: categorisation of the wake encounters by the distance between the two aircraft in the low-wind-speed scenario with 500 ft minimum vertical separation (grey area is below the minimum horizontal and vertical separation and thus would be prevented by the air traffic controller)

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Distance at the start of the wake encounter		Horizontal distance [NM]						
		[0 ; 5)	[5 ; 10)	[10 ; 15)	[15 ; 20)	[20 ; 25)	[25 ; 30)	[30 ; ∞)
Vertical distance of the follower in reference to the wake creator [ft]	(2000 ; ∞)	1	7	9	7	4	3	1
	2000	0	0	0	0	0	0	0
	(1500 ; 2000)	0	3	0	0	1	0	0
	1500	0	0	0	0	0	0	0
	(1000 ; 1500)	5	3	0	0	0	0	0
	1000	2	0	0	0	0	0	0
	(500 ; 1000)		2	0	0	0	0	0
	500		0	0	0	0	0	0
	(0 ; 500)		4	0	0	0	0	0
	0		58	3	0	0	0	0
	(-500 ; 0)		31	11	2	1	0	0
	-500		0	2	0	0	1	0
	(-1000 ; -500)		22	27	11	4	0	1
	-1000	0	14	8	13	20	9	4
	(-1500 ; -1000)	1	17	4	3	1	0	0
	-1500	0	0	0	1	0	0	0
	(-2000 ; -1500)	0	5	11	0	0	0	1
	-2000	0	0	2	1	2	0	0
	(-∞ ; -2000)	0	1	1	11	4	1	1

Table 29: categorisation of the wake encounters by the distance between the two aircraft in the high-wind-speed scenario with 1000 ft minimum vertical separation (grey area is below the minimum horizontal and vertical separation and thus would be prevented by the air traffic controller)

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Distance at the start of the wake encounter		Horizontal distance [NM]						
		[0 ; 5)	[5 ; 10)	[10 ; 15)	[15 ; 20)	[20 ; 25)	[25 ; 30)	[30 ; ∞)
Vertical distance of the follower in reference to the wake creator [ft]	(2000 ; ∞)	0	5	10	9	1	0	0
	2000	0	0	0	0	0	0	0
	(1500 ; 2000)	0	5	1	0	0	0	0
	1500	0	1	0	2	0	0	0
	(1000 ; 1500)	6	3	2	1	0	0	0
	1000	0	1	0	0	0	0	0
	(500 ; 1000)	6	4	2	0	0	0	0
	500	2	3	2	0	0	0	0
	(0 ; 500)		8	3	1	0	0	0
	0		48	5	2	0	0	0
	(-500 ; 0)		48	30	9	1	0	1
	-500	40	367	507	177	10	1	0
	(-1000 ; -500)	13	21	29	12	4	0	1
	-1000	0	4	9	3	0	1	0
	(-1500 ; -1000)	0	6	7	0	2	2	0
	-1500	0	0	1	0	0	2	0
	(-2000 ; -1500)	1	3	3	2	1	1	0
	-2000	0	0	0	1	0	0	0
	(-∞ ; -2000)	0	0	3	4	1	1	1

Table 30: categorisation of the wake encounters by the distance between the two aircraft in the high-wind-speed scenario with 500 ft minimum vertical separation (grey area is below the minimum horizontal and vertical separation and thus would be prevented by the air traffic controller)

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Evaluation of criterion GreenGEAR-0407-TRL2-ERP-CRT04

In summary, it can be said that the expectations of success criterion GreenGEAR-0407-TRL2-ERP-CRT04 are not met: "The wake encounter risk is not unacceptably increased compared with current operations."

B.3.2.3. GreenGEAR-0407-TRL2-ERP-OBJ03.2 Results

To Identify potential showstoppers for capacity increase for RVSM 2 from wake turbulence risk perspective.

As the number of available flight levels doubles, the potential Capacity (CAP) is likely to increase significantly. The current exercise has found that even with current traffic levels the new flight levels could not be used in an unrestricted way if one assumes that separation modes are unchanged. In the absence of a TLS there is no absolute criterion of safety, but it is hardly conceivable that a relative increase of the wake vortex encounter risk by a factor of three to four would be acceptable.

However, the introduction of procedural or technical risk mitigation is possible. Wake encounters occur in typical situations that could be avoided by advanced separation modes (see appendix B.4.1), and also a wake vortex warning tool could be introduced (see appendix B.4.2).

Evaluation of criterion GreenGEAR-0407-TRL2-ERP-CRT06.2

In summary, it can be said that the results do not meet the expectations of success criterion GreenGEAR-0407-TRL2-ERP-CRT06.2: "Initial capacity analysis from wake turbulence risk perspective does not preclude demonstrable capacity benefits" *if one assumes that only vertical separation is changed*. However, remedies have been suggested. Therefore, the criterion is assessed as "partially OK".

B.3.3 Unexpected behaviours/results

There was an initial problem with suitability of the probabilistic wake vortex corridors for this exercise. For an operational prediction, typically the uncertainties (in the shape of standard deviations) of all parameters are considered, large uncertainties in input data and environmental quantities leading to very large uncertainty intervals. Initial simulation runs with reasonable atmospheric data uncertainties, allowances for the generator aircraft mass and higher probability (99%) envelopes for the vortex habitation had led to the implausible result that the vertical separation has no significant influence on the encounter probability for the two scenarios. On closer inspection it became clear that the vertical dimension of the vortex corridors grows significantly bigger than the change in vertical separation (see Figure 11, which is roughly to scale except for the lateral wind drift) so that it is basically a question of where the volume is crossed, not if. However, as the volume encapsulates 99% of cases, it is quite possible to cross it without an encounter, and more probably so towards the boundaries of the volume (Figure 12).

A refinement of the approach was sought. In a simulation at least the aircraft data are controllable, and in principle a well-known atmospheric state can be assumed, e.g. as derived by interpolation of numerical weather prediction (NWP) or reanalysis data. This is the other extreme: a perfectly smooth atmosphere leads to unchanging vortex predictions. This is neither realistic nor suitable for the purpose.

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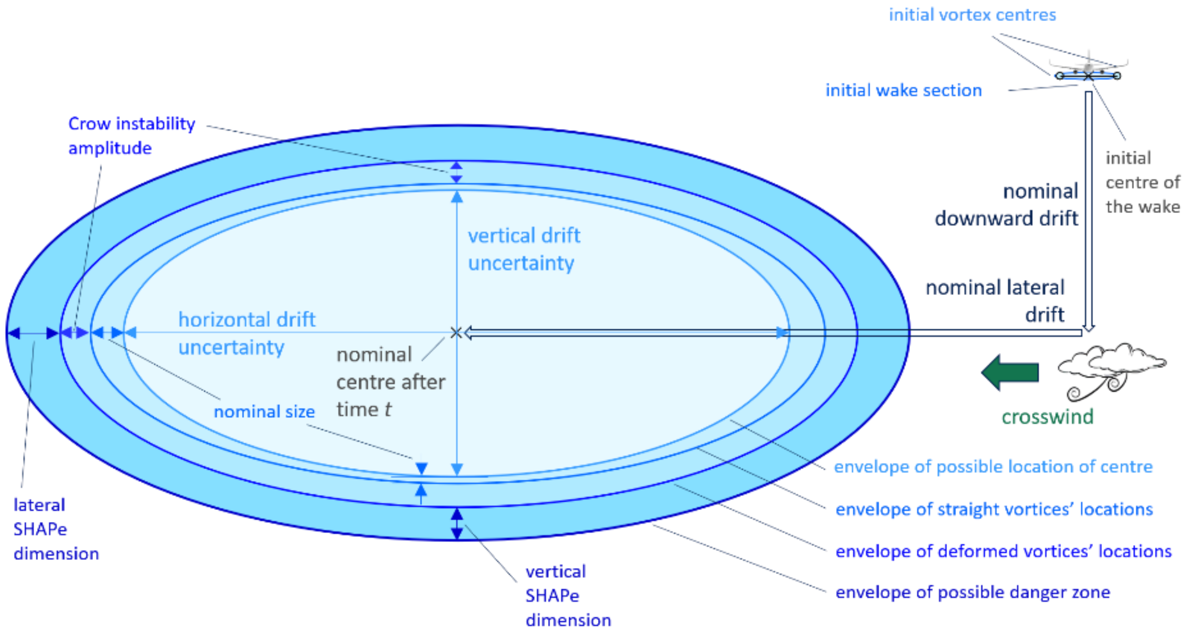

Figure 11: roughly-to-scale depiction of probabilistic wake volume cross sections at creation and typical encounter distances

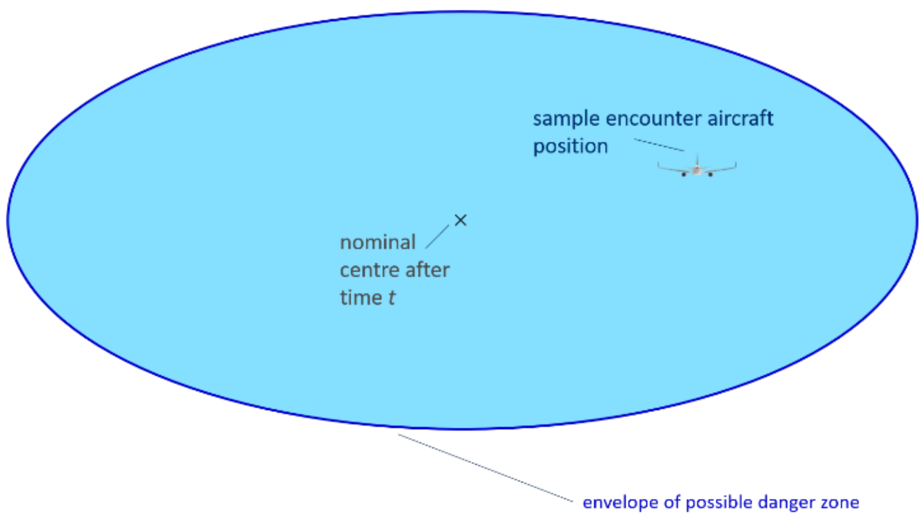

Figure 12: roughly-to-scale depiction of probabilistic wake volume cross sections at typical encounter distances and encounter aircraft size

The approach finally adopted is to consider the methodological uncertainty and the degree of turbulence only and from the thus obtained prediction range choose a nominal wake centreline at random. This choice respects the (Gaussian) probability distribution of the positions within the range. In order to ensure repeatability, this random number was seeded from the flight number, i.e. stayed the same for one flight segment. To this nominal vortex trajectory the size increase by the Crow instability, which is a physical enlargement of the vortex wake, is added. By this approach, realistic sizes of the vortex habitation volumes with respect to the aircraft size were obtained at all times, as sketched in Figure 13, and a realistic distribution of evolutions overall.

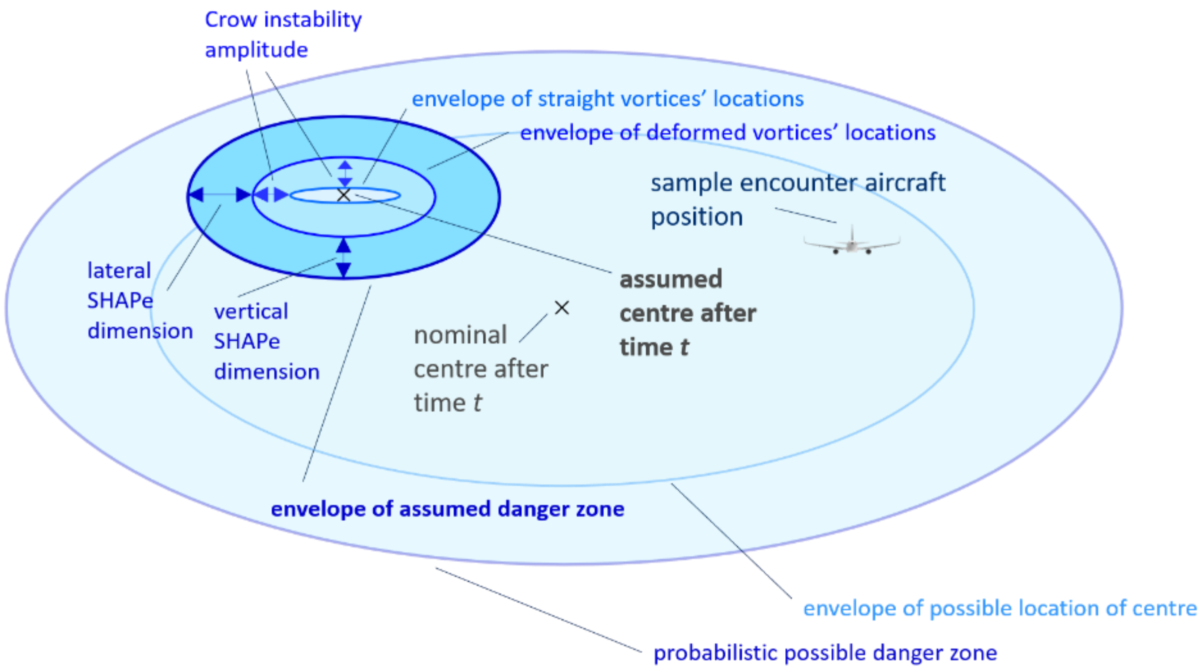

Figure 13: explanation of pseudo-deterministic wake volume cross section determination

Monte Carlo simulations employing deterministic predictions might give maximum realism but are not possible with reasonable resources, as already the approach with one set of vortex predictions per flight segment needs an overall simulation time of several weeks with current desktop computers.

B.3.4 Confidence in results of validation exercise #02

B.3.4.1. Limitations of validation exercise results

The research has addressed the EUR region / ECAC area for the wake encounter risk by simulating the traffic in the full ECAC area for two full days which represent two extremes in wind conditions in en-route airspace. Therefore, an extrapolation of results to a wider area is not necessary.

The wake vortex study is sensitive to weather conditions and traffic patterns, so additional simulation runs with different seasonal traffic patterns would yield somewhat different results. Also, the weather influence can never be the same, even if the two extremes for the wind, which is the main influencing factor for encounter probability, have been investigated. An increase of the data base size would require substantial computational effort (of the order of weeks per daily scenario on an ordinary PC) and could contribute to better understanding of the distribution of occurrence probabilities between the two extremes but this would be of limited value at TRL 2, especially as the worst-case scenario still would need to be acceptably safe.

The limitations of the validation results thus lie more in the assumptions made in the research and modelling accuracy. The latter, discussed in more detail in the following section, is partially also a consequence of the limited resources available. It is, however, considered adequate for an activity at

TRL 2 whose main objective is to identify whether the underlying idea of a reduction to 500 ft minimum vertical separation appears feasible at all, and, as the case may be, define recommendations for further work.

Limitations from the assumptions comprise for example that the future airspace structure will be similar to the current one and so will be operations. Furthermore, the fleet was assumed to be the same in the RVSM 2 airspace, in terms of fleet mix and propulsion systems. Obviously, traffic patterns and mixes influence the outcome. For the wake study, historic traffic demand data for the whole EUR region have been used, in accordance with the Solution's scope, which include certain but limited numbers of particularly interesting aircraft types like VLJs and HAOs. Other possible future types like all-electric or hydrogen-powered types are necessarily absent but this can be regarded as negligible at the present level of detail. Further traffic growth is also not addressed (see next section).

Finally, the assumption was made that jamming and spoofing of GNSS signals do not influence the operation, i.e. the non-nominal case was not further considered. However, GNSS signal interference is a major problem in GNSS navigation nowadays, and it should be investigated how this issue can be dealt with in the RVSM 2 concept.

B.3.4.2. Quality of validation exercises results

The present study has been subject to the following limitations that are mainly conceptual but partially also a consequence of the limited resources available. They are considered adequate, however, for an activity at TRL 2 whose main objective is to identify whether the underlying idea of a reduction to 500 ft minimum vertical separation appears feasible at all, and, as the case may be, define recommendations for further work.

- The study has evaluated the probability of an aircraft to fly into the habitation volumes of the wake vortices, so-called wake volumes, of a generator aircraft[3]. While in any particular real-world situation the actual trajectories of the vortices are well-defined (even if not easily observable), it is in practice impossible to know all relevant variables for an exact *prediction*. Adopting a probabilistic approach to forecast the said wake volumes, their dimensions are determined by error propagation of the uncertainty of initial parameters (weight, airspeed, to a lower extent heading) – which are controllable in a simulation (with difficulties for weight though in typical ATM simulation tools) – and the stochastic nature of atmospheric behaviour and WV evolution. This approach is sufficiently conservative but the so-obtained wake volumes at typical encounter ages become much bigger than the aircraft's dimensions, especially in the vertical to account for rare atmospheric effects. Effectively this leads to a situation where flying through a wake volume does not mean the vortex is actually encountered. It is thus difficult to give absolute figures for the encounter frequency; indeed even relative changes are difficult to quantify as the sheer size of the possible wake habitation

[3] It is also possible to fly into one's own wake, but usually the manoeuvres required for that (such as a quick 360° turn) are outside of normal airline operations. The only mechanism in civil air transport would be to hit one's own wake during a descent in a holding and with high crosswinds. For this investigation, it is a moot point as holdings are not modelled.

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volumes obtained in this approach is several times bigger than the change in separation investigated. A possible solution could be to look at the distance between the axis of the wake volume and the nominal encounter point; this is not straightforward, however; as the possible wake locations in the volume are not symmetrically distributed. The approach adopted here was to combine a more deterministic wake prediction based on initial and atmospheric conditions chosen according to their respective probabilistic distributions but then regarded as known.

- Apart from not hitting the vortex although inside the corridor, the severity of an encounter if it actually happens is also an important factor. Indeed, minor incidents in cruise under IFR are quite common, from identifiable encounters that have no consequences beyond a short disturbance up to minor injuries of occupants. More serious incidents and accidents are much rarer but do happen. Consequently, for risk determination not only the frequency of occurrence, but also the severity of encounters needs to be modelled; several approaches have been devised by various authors but no universally agreed method exists. This study uses the SHAPe method that has been developed and tested for final approach. Here on one hand the aircraft's occupants are seated with seatbelts fastened, limiting the risk of injury and thus allowing to tolerate higher accelerations in the cabin, and on the other ground proximity leads to a much higher criticality of flight path deviations. Extrapolating to the cruise situation in the absence of corresponding studies, for the present activity the three encounter severity threshold from the SHAPe experiments have been selected. The lowest threshold has been accepted as safe by all pilots participating in the studies under the aspect of not even necessitating a missed approach. It must be noted that this approach defines a threshold below which an encounter can be regarded as safe, which does not imply that all encounters above this threshold are unsafe.

  A quantification of encounter severity through rolling moment coefficient (RMC) has often been used in in literature [63] or safety analyses [70]; this RMC is easier to determine with publicly available aircraft data but does not relate the disturbance to the aircraft's ability to cope with it. It would be interesting to see the comparison between RCR and RMC, which is unfortunately not possible at short term due to limitations of recording intermediate simulation data. The problem remains, both with RCR and RMC, that there is a big grey area between a situation that is objectively unsafe (injuries, exceedance of operational limits) and one that is subjectively rated as unsafe by the pilots, or where there is a nominal loss of control for a short time (typically a fraction of a second) that has no relevant consequences.

- Obviously, traffic patterns and mixes influence the outcome. Here historic traffic demand data for the whole EUR region have been used, in accordance with the Solution's scope, which include certain but limited numbers of particularly interesting aircraft types like VLJs and HAOs. Other possible future types like all-electric or hydrogen-powered types are necessarily absent but as explained in the assumptions, their differences in wake vortex generation and penetration can be regarded as negligible at the present level of detail. Seasonal patterns in the traffic patterns were not studied – this is a limitation simply due to amount of available resources –, and further traffic growth is also not addressed (see below).

- A tool to simulate traffic that is separated (implying deconfliction by the Network Manager (NM) and at tactical level) by the proposed new rules was not available. Indeed the most crucial obstacle for this activity is the necessity to use demand data which have been

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generated under assumption of the new flight level choices as per the OSED. Its generation at a high quality level requires sophisticated flight planning tools that are available only to operators and generally not batch processable. As a workaround, modifications to existing demand trajectories have been employed as briefly mentioned in section 4.2.1.1 and explained in more detail in [30]. As the traffic volume was not increased, the modifications produce an even higher concentration of traffic in certain altitude bands than today – a behaviour that is to be expected though: there is no reason to assume that a bigger choice of flight levels will lead to a more uniform population, as already the current concentration is due to flight mechanical reasons and not capacity constraints.

- In the same vein, the reconstruction of flight paths from demand data suffers from the low resolution of the time stamps and the fact that wind is not taken into account in these plans. The true airspeed was calculated from the ground speed assumed in the flight plan and the wind given by the numerical weather prediction, where in reality given airspeed and wind would add to the observed ground speed. This is a common problem to many simulations in the ATM world and difficult to overcome with reasonable effort.

- In order to estimate current altimetry and altitude keeping performance, the most accurate values for the ASE and FTE were used that are available. Nevertheless, it is desirable that the accuracy of these parameters improves. Current ASE performance was checked by considering the Vertical Positioning Error (VPE) from the GPS and Galileo quarterly reports. These figures however were collected with a stationary receiver in standardised conditions. It would be preferable to obtain GNSS accuracy data directly from typical aircraft borne GNSS receivers. This is however, extremely difficult as a more accurate reference would be needed.

- In addition, the FTE data (approximated by the Assigned Altitude Deviation (AAD)) resulted from data collected using mode C, which has a granularity of 100 ft increments. Since the maximally allowed ASE and FTE are close to the values obtained from actual performance data, it is desirable collect more accurate figures to be used in the modelling.

- Generally speaking higher crosswinds will reduce the risk for aircraft following the same route in trail or at differing altitudes, while increasing the risk for those flying on parallel routes (or in general with a lateral separation). As the perception of a given wind direction as crosswind or head-/tailwind depends on the own track, the effects of a certain level of winds vary per pairing. Due to complexity of vortex transport and decay, it appears plausible but is not proven that low and high winds are actually the most critical situations regarding horizontal vortex drift. Moreover, wind shear and temperature stratification play a role for the vertical drift of the vortices; these effects can counteract and even negate the vertical motion under albeit rare circumstances. From a safety point of view, however, they are not negligible. Due to calculation times of several days per one full-day scenario the present study could not treat a large number of cases in terms of weather phenomena but this is no fundamental problem, especially as the upgraded simulation environment is now available. If full conservatism is required, it would be possible to simulate and average traffic and weather over a full year, albeit with a considerable computational effort.

- The flight plans do not include actual take-off weights for the aircraft, and these are actually closely regarded commercial secrets of the operators as they could allow the competition easy access to estimating load factors. The study has therefore worked with weight estimations

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(variations of reference weight from BADA). One might consider taking the maximum take-off weight (MTOW): however, even if the relatively strongest wake for a type is certainly produced at its respective maximum weight, this approach is not really conservative: stronger vortices have a longer lifespan and a higher downward travel, but this assumption will overestimate the risk of encountering stronger vortices at greater vertical separation and underestimate that for encounters with weaker vortices at smaller vertical separations. A model deducting at least fuel use as derived from BADA database is possible, but for more realism it would be necessary to take into account the segment lengths as many flights operate far from the type's range and thus far from MTOW at take-off.

B.3.4.3. Significance of validation exercises results

By definition, exploratory research addresses a low TRL and operational realism is limited. Only computational studies have been performed.

The wake turbulence risk study has been a fast-time exercise that could not take all possible traffic patterns and weather situations into account. It is assumed, yet not proven, that the two scenarios chosen for minimum and maximum average wind speeds throughout the area represent the two extreme cases for encounter probabilities. As explained above, wind shear and temperature stratification play a role for the vertical drift of the vortices; these effects are rare but not negligible from a safety point of view. A certain variability of weather effects has been implemented in that individual values for typical deviations between actual and nominal weather (and between nominal and actual altitude of the aircraft) have been employed using the corresponding probability distributions.

Due to calculation times of several weeks per one full-day scenario with different combinations of input parameters, the present study could not treat a large number of cases in terms of weather phenomena and/or traffic patterns but this is no fundamental problem, especially as the upgraded simulation environment is now available. If full conservatism is required, it would be possible to simulate and average traffic and weather over a full year, albeit with a considerable computational effort.

More information on these points can be found in the section above.

B.4 Conclusions

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, and to identify whether this could be a showstopper for a potential capacity increase.

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 mitigation means and/or limiting conditions for its application.

B.4.1 Conclusions on concept clarification

In the initial OSED [27] 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 is not feasible for the wake turbulence risk. More flexibility in 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. Also mitigation functions could be applied (see next section). Limited resources prevent further investigations into this topic in the present project.

B.4.2 Conclusions on technical feasibility

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.

B.4.3 Conclusions on performance assessments

The KPA that was studied most extensively in this exercise was Safety (SAF). A comparative approach was employed, using current 1000 ft minimal vertical separation as the reference. It was shown that safety is negatively affected when the vertical separation minima are reduced to 500 ft.

As the number of available flight levels doubles, the potential Capacity (CAP) is likely to increase significantly. Capacity is dependent, however, on multiple factors, and capacity issues mostly occur in certain bottleneck areas. The current exercise has found that the new flight levels could not be used in an unrestricted way without the introduction of procedural or technical risk mitigation.

B.5 Recommendations

The main recommendations of the Wake Turbulence Risk Assessment are:

- A detailed categorisation of 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 [73].

- The severity assessment for wake vortex encounters is still not convincingly solved; several approaches have been devised by various authors but no universally agreed method exists. A quantification of encounter severity through rolling moment coefficient (RMC) has often been used; this RMC is easier to determine with publicly available aircraft data but does not relate the disturbance to the aircraft's ability to cope with it. The problem remains, both with RCR and RMC, that there is a big grey area between a situation that is objectively unsafe (injuries, exceedance of operational limits) and one that is subjectively rated as unsafe by the pilots, or where predictions show a possible nominal loss of control for a short time (typically a fraction of a second) that would need to be regarded as hazardous in theory while it might have no relevant consequences in practice.

- 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. Even if the growth of the VLJ fleet is a bit stalled after the global financial crisis of 2018, this particularly vulnerable type of aircraft that did not exist when the ICAO rules were written – there were virtually no LIGHT category aircraft in upper airspace. Emerging special configurations like very large and light HAO aircraft designed for loitering and observation or communication are particularly sensitive to wake turbulence, expectably primarily when climbing or descending through the densely populated cruise flight levels of current transport aircraft. Even if it is conceivable that these special aircraft can be dealt with ad hoc, generally 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 [50][52][53][54]. 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.

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Appendix C Validation exercise #03 report

C.1 Summary of the validation exercise #03 plan

This validation exercise was executed as described in the ERP [28]. The safety case exercise for 500 ft vertical separation with geometric altimetry was set up as a preliminary Functional Hazard Assessment (FHA); that is a top-down iterative process initiated at the beginning of a modification of an Air Navigation System. The modification under assessment is the reduction of the vertical separation minimum; the introduction of geometric altimetry is outside the scope of this FHA. The objective of the FHA process is to determine how safe the system and its subsystems need to be, basically by first identifying potential failure modes and hazards and then allocating, implicitly, risk budgets. These risk budgets are deduced from overarching safety criteria, and the allocation results in safety objectives and, later on, safety requirements allocated to different sub-systems. The overarching safety criteria correspond to one Key Performance Indicator (KPI) for Safety, which might be expressed as a maximal allowable accident rate per flight hour.

C.1.1 Validation exercise description and scope

The safety case exercise for 500 ft vertical separation with geometric altimetry is set up as a preliminary Functional Hazard Assessment (FHA); that is a top-down iterative process initiated at the beginning of a modification of an Air Navigation System. The modification under assessment is the reduction of the vertical separation minimum; some aspects of GNSS altimetry are considered, but the introduction of geometric altimetry is largely outside the scope of this FHA.

C.1.2 Summary of validation exercise #03 validation objectives and success criteria

SESAR solution validation objective ID and title	SESAR solution success criterion and ID
GreenGEAR-0407-TRL2-ERP-OBJ02.3 To determine whether RVSM 2 can be safely introduced from an operational risk perspective and identify the most important challenges.	**ERP-OBJ05** Derive a quantitative or qualitative safety specification.
GreenGEAR-0407-TRL2-ERP-OBJ03.3 To Identify potential showstoppers for capacity increase for RVSM 2 from operational risk perspective.	**GreenGEAR-0407-TRL2-ERP-CRT06.3** Initial capacity analysis from operational risk perspective does not preclude demonstrable capacity benefits.

Table 31: validation exercise #03 objectives and success criteria.

C.1.3 Summary of validation exercise #03 validation scenarios

This section was taken from the ERP. The use case is the RVSM 2 concept as described in the initial OSED.

The reference scenario is the current operation in RVSM airspace in the EUR RMA region. Altimetry is done using barometric measurements and the minimal vertical separation is 1000 ft. The

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corresponding passing frequencies, traffic mix and TLS apply. This is a scenario that will not strictly be researched but the methods used in the introduction and yearly assessment of the RVSM collision risk form the basis of the evaluation of the RVSM2 concept.

The solution scenario will focus on FL290 to FL600 inclusive in the EUR RMA region. Geometric altimetry is used, and the minimal vertical separation is reduced to 500 ft. A Collision Risk Assessment is typically performed for a period of one year. As such, the solution scenario will focus on a period of one year. A typical passing frequency and traffic mix is determined based on data of the past few years of this region as a reference.

C.1.4 Summary of validation exercise #03 validation assumptions

The following validation assumptions are applicable to the present validation exercise on top of those Solution-level ones identified in section 3.2.3.

Assumption ID	Assumption title	Assumption description	Justification	Impact assessment
GreenGEAR-0407-TRL2-ERP-ASS06	Single mode geometric altimetry	Assume all airspace users will use the same mode of GNSS altimetry.	This is the intended end state of the concept. If the level of safety cannot be met in this configuration, further study is not warranted as mixed mode operations are expected to be more challenging in terms of safety.	If the concept turns out to be feasible in the ideal end state, mixed mode operations or the transition to this end state may still form a crucial limiting factor.
GreenGEAR-0407-TRL2-ERP-ASS07	GNSS integrity	For the collision risk assessment it is assumed that GNSS height measurements of sufficient quality are available at all times.	It can be argued that it is likely that in the end state the GNSS system will have to have a high degree of availability.	Adversarial actions such as jamming and spoofing may prove to be essential technical hurdles.

Table 32: validation exercise #03 assumptions overview

C.2 Deviation from the planned activities

During the work, objective 2.2 was amended from:

“Objective 2.2: Determination 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 as produced in line with the SESAR SRM method for TRL2, namely collision and wake encounter risk, demonstrates adherence to the target level of safety (TLS) and the initial capacity analysis delivers demonstrable capacity benefits.”

to:

“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.”

Initial calculations showed that it was not certain that the TLS could be met for the RVSM 2 concept, which sparked a discussion. In order to meet the TLS and thereby to achieve the project objectives the concept may have had to be updated. The design of such a concept however is an iterative process, and fully solving all possible challenges would exceed the scope of the Green-GEAR project. In addition, the objective of a safety assessment should be to assess the safety of a system and not to judge the safety of system as sufficient.

Therefore, it was decided to amend the objective and success criterium. Instead of proving that the concept is safe, the maximally allowed risk was fixed with a TRL and requirements on the relevant subsystems were derived. The solution thereby aimed to identify the factors that are crucial to the introduction of the concept and serve as a basis for future research and design.

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C.3 Validation exercise #03 results

C.3.1 Summary of validation exercise #03 results

Exercise #03 validation objective ID	Exercise #03 success criterion ID	Exercise #03 validation results	Exercise #03 validation objective status
GreenGEAR-0407-TRL2-ERP-OBJ02.3 To determine whether RVSM 2 can be safely introduced from an operational risk perspective and identify the most important challenges.	**GreenGEAR-0407-TRL2-ERP-CRT05** Derive a quantitative or qualitative safety specification.	In the safety case, the operational risk is quantitatively determined on a functional level, using a Functional Hazard Analysis (FHA). This was done for risks due to non-nominal causes.	OK
GreenGEAR-0407-TRL2-ERP-OBJ3.3 To Identify potential showstoppers for capacity increase for RVSM 2 from operational risk perspective.	**GreenGEAR-0407-TRL2-ERP-CRT06.3** Initial capacity analysis from operational risk perspective does not preclude demonstrable capacity benefits.	From the safety case above, conditions and safety requirements were derived that would allow safe operation. However, these are partially ambitious, not only technically but also legislatively / regulatorily. Further study is needed	Partially OK

Table 33: validation exercise #03 results

C.3.2 Analysis of validation exercise #03 results per validation objective

C.3.2.1. GreenGEAR-0407-TRL2-ERP-OBJ02.3 Results

The success criterion for this activity is to derive a quantitative or qualitative safety specification. In the ‘Separation Minima’ safety case ([31]), safety specifications were derived qualitatively and semi-quantitively in the form of a Functional Hazard Analysis.

In the FHA, four primary functions were established, namely:

1. The altitude information domain provides altitude information in the entire airspace in a continuous way.

2. The airborne domain receives the altitude information and provides estimates of the altitude of each individual aircraft in a continuous way.

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3. The ground domain assigns an altitude to each individual aircraft such that it is vertically separated if necessary.
4. The airborne domain receives the assigned altitudes and let each individual aircraft fly according to the assigned altitude.

Then, a hazard was formulated for the situation that a primary function is not executed properly. This leads to the following four hazards:

- 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.
- H4: An aircraft does not fly according to its assigned altitude.

The safety specifications were then established for each of the hazards. The probability of a hazard H1 occurrence is difficult to estimate, mainly as the development of jamming and spoofing events in the future is uncertain. However, due to the variety of potential causes of H1, the probability is not negligible. As the consequence of an undetected or not-mitigated occurrence of hazard H1 is an increase of the mid-air collision probability, this leads to the conclusion that there is a need for mitigation, independent of which precise safety criteria are applied.

The probability of a hazard H1 occurrence is difficult to estimate, mainly as the development of jamming and spoofing events in the future is uncertain. However, due to the variety of potential causes of H1, the probability is not negligible. As the consequence of an undetected or not-mitigated occurrence of hazard H1 is an increase of the mid-air collision probability, this leads to the conclusion that there is a need for mitigation, independent of which precise safety criteria are applied.

Some causes, such as the unintended interference, can be mitigated by the use of Dual Frequency receivers. As the prevention of a hazard H1 occurrence is preferred over the mitigation of its consequences, this leads to the following safety specification:

➢ Aircraft in RVSM 2 airspace should use Dual Frequency receivers.

Some causes, such as in the GNSS control segment or due to a low VDOP related to the dynamic GNSS constellation, can be mitigated by the use of multiple GNSSs. This might lead to a safety specification prescribing that but this might also have other drawbacks. A more detailed analysis about the pros and cons of such specification is therefore postponed to the PSSA.

There are basically two types of counteractions against a hazard H1 occurrence: with and without coordination of the aircraft involved. The main candidate for the coordinating actor is the ground domain. As indicated before, there is not however a priori need for a ground domain that can communicate in a continuous way with all aircraft in RVSM 2 operations; just like RVSM operations are applied in airspaces without ATC surveillance and communication. Therefore, first the situation without such ground domain is considered.

➢ If there is no coordination to counteract the consequences of a hazard H1 occurrence, it might be possible that aircraft coordinate their actions among them. This is however a way of operating without a solid analogue in the current operations and therefore disregarded in this report. If there is no coordination, individual aircrew might apply the *Procedure Single Unable Altimetry*, as described in section 3.4, being aware that their altitude estimate is not proper but possibly not being aware that aircraft in the vicinity suffer the same problem. This likely imposes severe conditions on the PSUA design in order to maintain safe operations. This leads to the following safety specification:

- If there is no ground domain that takes coordinated actions in case altitude information is not provided properly in a part of the airspace, the PSUA should be designed such that it is safe when applied simultaneously by several aircraft in each other's vicinity.

If there is however a ground domain that might coordinate actions in case of a hazard H1 occurrence, this is preferred above uncoordinated action as such precautionary actions are more effective. Moreover, in case the RVSM 2 airspace is controlled tactically, the ATC units involved have means for secondary surveillance and two-way air-ground communications, easing not only the detection of a hazard H1 occurrence but the implementation of subsequent actions. A coordinated action by the ground domain requires the last secondary function described in section 3.3.2: the ground domain detects inadequacy of the altitude information in a part of the airspace. This can be done by processing one or a combination of the following information items: a) receipt of a *lack of altimetry integrity* message from the altitude information domain, b) receipts of *unable altimetry* messages from several aircraft, c) the deduction of several aircraft deviating from their assigned altitude and d) other information items, such as an indication of jamming or spoofing. If the ground domain has detected the inadequacy of the altitude information, it might initiate the Procedure Multiple Unable Altimetry.

However, an individual crew that has detected that the altitude estimate is not proper might initiate the PSUA before the PMUA is initiated. This is not preferred, as coordination might be lost, when some aircraft execute the PSUA and others do not. In order to prevent this, the ground domain should detect a potential inadequacy of the altitude information in a part of the airspace fast and first inform aircraft even before aircraft are instructed to manoeuvre to regain separation. These considerations lead to the following set of safety specifications.

- The altitude information domain should provide a lack of altimetry integrity message if there is uncertainty about the accuracy of the altitude estimate that can be derived from the altitude information. These messages should be received by the ground domain, at least by the ATC units providing services in and close to the part of the airspace where it applies. These messages should be received by the airborne domain, at least by the aircraft flying in and close to the part of the airspace where it applies.
- Each individual aircraft should send out own altitude signals in a continuous way. These signals include the altitude estimate, together with some kind of identification of the aircraft sending the signals out. These signals should be received by the ATC units providing services in or close to the part of the airspace in which that aircraft flies.
- The ATC units should receive the own altitude signals of each individual aircraft in a continuous way and verify if there are significant deviations from the assigned altitudes.
- Each aircraft should send out an unable altimetry message if a lack of availability, accuracy or integrity of the altitude estimate is detected. These messages should be received by the

ground domain, at least by the ATC units providing service in and close to the part of the airspace in which the aircraft flies.

- The ATC units should detect inadequacy of the altitude information in a part of the airspace by processing the following information items: a) receipt of lack of altimetry integrity messages from the altitude information domain, b) receipts of lack of unable altimetry messages from several aircraft, c) detection of several aircraft deviating from their assigned altitude in a part of the airspace and d) other information items, such as indications of jamming or spoofing.

- If an ATC unit detects that there is a possibility that altitude information in a part of the airspace is inadequate, it should first inform all aircraft about this possibility. The aircrew having received this information should not initiate a PSUA.

- If an ATC unit has confirmation that altitude information in a part of the airspace is inadequate, it should coordinate with other ATC units and it should initiate a PMUA.

The PMUA is not designed yet. Despite of that, one can imagine a procedure in which the ATC units start separating aircraft horizontally if possible. In case this is not possible and there are only concerns about the limited accuracy of the altitude estimates, aircraft might be separated vertically by 1000 ft or 2000 ft. As this is not possible in each situation, the use of barometric altimetry might be required, possibly in combination with declaring a reference barometric pressure to avoid large height adaptation when aircraft change from a geometric altitude to a corresponding barometric altitude. These considerations show that the operational consequences of a PMUA implementation are likely critical, especially if several ATC units are involved. These considerations also show that there might be a need for a flexible procedure, that depends on the circumstances (e.g. the potential conflicts, the local air traffic density, the possibilities to divert horizontally) and leaves options for the air traffic controller. This might however make the procedure also complex. It seems to be required that the PMUA is only applied rarely, in the order of once in ten years for an airspace as the ICAO EU Region, although this is not deduced from solid grounds. In order to have a reference, this is however formulated as a safety specification.

- The frequency of occurrence of altitude information being inadequate in a significant part of the airspace should be less than once in ten years.

The RVSM 2 concept focuses on the European RVSM airspace. This area is a tactically controlled airspace that has complete surveillance and communication coverage. The causes and likelihoods for H2, H3 and H4 are therefore the same as in current operations (with possibly an exception for H2, but the likelihood of failure can be specified to not be lower than barometric systems), but the consequences are likely to change due to the reduced separation. This would lead to the following three specifications related to the latter three hazards:

- GNSS altimetry systems should have a similar maximally allowed rate of failure as current barometric altimetry systems.

- An aircraft not having an altitude assigned to it such that separation is maintained will have the same maximally allowed occurrence rate as in current operations.

- In RVSM 2 an aircraft not flying to its assigned altitude should have a similar maximally allowed rate as in current RVSM operations.

To conclude, the validation objective status concerning the success criterion GreenGEAR-0407-TRL2-ERP-CRT05 is determined *OK*. Safety specifications were established for the four major hazards of the RVSM 2 concept and the most important challenges identified.

C.3.2.2. GreenGEAR-0407-TRL2-ERP-OBJ03.3 Results

The second and last objective of this exercise is to identify potential showstoppers for capacity increase for RVSM 2 from an operational risk perspective. From the safety case above, conditions and safety requirements were derived that would allow safe operation. However, these are partially ambitious, not only technically but also legislatively / regulatorily. Further study is needed.

Hence initial capacity analysis from an operational risk perspective does not preclude demonstrable capacity benefits from RVSM 2 but cannot confirm them either; this observation means partial fulfilment of the success criterion GreenGEAR-0407-TRL2-ERP-CRT06.3.

C.3.3 Unexpected behaviours/results

There was no unexpected behaviour or result in the preparation, execution or analysis of the validation exercise.

C.3.4 Confidence in results of validation exercise #03

C.3.4.1. Level of significance/limitations of validation exercise results

The limitations of the validation results lie in the assumptions made in the research. For example that the future airspace structure will be similar to the current one and so will be operations. Furthermore, the fleet was assumed to be the same in the RVSM 2 airspace, in terms of fleet mix and propulsion systems. Finally, the assumption was made that jamming and spoofing of GNSS signals do not influence the operation. However, this is a major problem in GNSS navigation nowadays and it should be investigated how this issue can be dealt with in the RVSM 2 concept.

C.3.4.2. Quality of validation exercises results

The safety case has been performed at a highly abstracted functional level, following the established method for the RVSM introduction. The method as such is valid, the quality of the outcome obviously depends on the quality of the estimations for the respective values. At the current TRL, these are assumptions rather than values derived from operational experience.

C.3.4.3. Significance of validation exercises results

By definition, exploratory research addresses a low TRL and operational realism is limited. The safety case is always a paper exercise and as such represents real-world methods, only at a necessarily low detail level.

C.4 Conclusions

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 RVSM of traditional 1000 ft RVSM was adopted. Four primary functions were defined, the failure 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. 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. 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. In addition, the 93% allowed effectiveness is based on the availability of ATC collision prevention. This was not a requirement in traditional RVSM, and would result in the requirement of RVSM 2 only being allowed in controlled airspace with permanent surveillance.

C.4.1 Conclusions on concept clarification

See section 5.1.2 in the main body.

C.4.2 Conclusions on technical feasibility

See section 5.1.3 in the main body.

C.4.3 Conclusions on performance assessments

See section 5.1.4 in the main body.

C.5 Recommendations

The main recommendations of the Safety Case are:

- 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. Also, as 500 ft separation will be considered nominal operations in RVSM 2, it is undesirable to have resolution advisories at such separations. A further study should investigate whether and how ACAS can be adapted to the 500 ft minimal vertical separation case.
- 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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